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1966

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This volume, "Mineral Resources of California", is Part I of a larger work, *Mineral and Water Resources of California.* It was prepared by members of the staffs of the U.S. Geological Survey, the U.S. Bureau of Mines, and the California Division of Mines and Geology, at the request of Senator Thomas H. Kuchel. It is issued by the California Division of Mines and Geology as number 191 in the Bulletin series. Part II, a companion volume dealing with water, is not distributed by the Divison of Mines and Geology.

STATE OF CALIFORNIA
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THE RESOURCES AGENCY
Hugo Fisher, *Administrator*
DEPARTMENT OF CONSERVATION
DeWitt Nelson, *Director*

DIVISION OF MINES
AND
GEOLOGY

Ian Campbell, *State Geologist*

BULLETIN 191
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AUTHOR INDEX

AUTHOR INDEX—Continued

89th Congress }
2d Session }

COMMITTEE PRINT

MINERAL AND WATER RESOURCES OF CALIFORNIA

PART I

MINERAL RESOURCES

REPORT

OF THE

UNITED STATES GEOLOGICAL SURVEY

IN COLLABORATION WITH

THE CALIFORNIA DIVISION OF MINES
AND GEOLOGY

AND THE

UNITED STATES BUREAU OF MINES

PREPARED AT THE REQUEST OF

Senator THOMAS H. KUCHEL
OF CALIFORNIA

OF THE

COMMITTEE ON INTERIOR AND
INSULAR AFFAIRS
UNITED STATES SENATE

Printed for the use of the Committee on Interior and Insular Affairs

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FOREWORD

On November 13, 1964, I requested the Secretary of the Interior to determine if a comprehensive summary report on the mineral and water resources of California could be prepared for the use of citizens, professional personnel, and government, civic, and industrial leaders interested in mining, water, and industrial development.

This report, prepared in response to my request by members of the U.S. Geological Survey, the U.S. Bureau of Reclamation, the U.S. Bureau of Mines, the California Division of Mines and Geology, and the California Department of Water Resources, with the cooperation of other individuals, is a thorough, detailed, and comprehensive work which I am sure will be of great value to all interested in the mineral and water resources of the State of California.

I wish to express my thanks and appreciation to Secretary of the Interior Udall and to those in his Department, to the State of California agencies, and to all the individuals who contributed their efforts in compiling this very valuable and comprehensive report.

Thomas H. Kuchel,
U.S. Senator.

LETTER OF SUBMITTAL

DEPARTMENT OF THE INTERIOR,
Washington, D.C., March 26, 1966.

HON. THOMAS H. KUCHEL,
U.S. Senator, Washington, D.C.

DEAR SENATOR KUCHEL: We are pleased to transmit herewith part I of a summary report on the mineral and water resources of California which has been prepared in response to your request of November 13, 1964. Part I is a summary report on the mineral resources. It has been prepared by the Geological Survey in collaboration with the California Division of Mines and Geology and the Bureau of Mines.

This report covers all mineral commodities known to exist in potentially significant amounts in California. Because of the comprehensiveness of the report, the discussion of each commodity is necessarily brief. The distribution and availability of the commodities are portrayed graphically in numerous maps, charts, and diagrams. It is hoped that the report will provide the needed data and in a form that meets with your approval.

A summary report on the water resources of California, which you also requested, is nearing completion. It is being prepared as a companion volume to the report on minerals and will comprise Part II of the report. The manuscript for Part II will be transmitted to you as promptly as possible.

Sincerely yours,

STEWART L. UDALL,
Secretary of the Interior.

MINERAL AND WATER RESOURCES OF CALIFORNIA

PART I. MINERAL RESOURCES

REPORT
OF THE
UNITED STATES GEOLOGICAL SURVEY
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PREPARED AT THE REQUEST OF
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OF CALIFORNIA
OF THE
COMMITTEE ON INTERIOR AND INSULAR AFFAIRS
UNITED STATES SENATE

PREFACE

(By J. P. Albers, U.S. Geological Survey, Menlo Park, Calif.)

This report describes in summary form the mineral resources of California and includes a brief description of the geology. The use, manner of occurrence, distribution, and outlook for all known mineral commodities in the State are discussed, and, where available, statistics on the production of the commodities are summarized.

It is the purpose of this report to present an objective appraisal of California's mineral resources, based on information presently available. The treatment of each commodity is necessarily brief, but those who wish to make deeper inquiry will find the list of references after each article useful.

The term "resources" as used in this report applies to materials in the ground that are known to be minable, and to materials that are not minable at present but which may come into such demand as to become minable in the future. "Reserves" are materials that may or may not be completely explored but may be quantitatively estimated and are considered to be economically exploitable at the time of the estimate. Reserves fluctuate because they are dependent on economic conditions, technologic factors, and available information. A low-reserve figure does not necessarily mean that the resource is near exhaustion. It may indicate that exploration is lacking or that a depressed market has lowered the value of the commodity to the point where the material can no longer be considered economically exploitable. "Ore" is mineral material that may be mined at a profit.

The subject material and outline and the selection of authors of articles was worked out jointly by staff members of the U.S. Geological Survey and the California Division of Mines and Geology; the majority of the articles in this part were written by members of the U.S. Geological Survey, the California Division of Mines and Geology, and the U.S. Bureau of Mines, but three articles were written by university staff members who have special knowledge of the topic discussed; one author, now employed by a private firm, was until recently with the U.S. Bureau of Mines. The organization with which an author is affiliated is shown with his name under the title of each article.

John P. Albers, of the Geological Survey, with the editorial and coordination assistance of Richard M. Stewart, of the California Division of Mines and Geology, assembled and edited the report.

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THE MINERAL INDUSTRY OF CALIFORNIA

(By Ian Campbell, Chief, California Division of Mines and Geology,
San Francisco, Calif.)

In 1965, 117 years after John Marshall's historic discovery of gold at Sutter's mill, the California legislature enacted a bill (SB 265) designating native gold as the official "State Mineral." In the same bill, the legislature designated serpentine as the official "State Rock." The one designation may be somewhat overdue; the other is assuredly timely. For in 1852, only four years after Marshall's discovery, California's gold production reached a total of more than $81,000,000 (at the current price of gold, this would be almost $140,000,000), a figure never since equaled. In that year serpentine was virtually unnoticed—except as "hungry rock," i.e., known to be barren of gold and therefore something to be shunned by prospectors.

In 1964, however, California's gold production had dropped to less than $2,500,000—the lowest figure since 1848. Serpentine (in the form of chrysotile asbestos), which until very recently California had never produced in amounts of more than a few hundreds of tons annually, had increased in value from less than $25,000 in 1960 to nearly $4,500,000 in 1964, with promise of further increases over the next many years. Wittingly or not, the legislature, in calling attention to gold and serpentine, had most appropriately commemorated nearly four generations of mining history and economics.

In 1962, California became the "first state" (in population). Yet she had already achieved more "firsts" in mineral production than had any other state. In 1963, she stood first among the states in annual production of:

TABLE 1

[In thousands]

Asbestos	$1, 547	Pumice	$2, 017
Boron	54, 981	Rare earths	(1)
Cement	147, 656	Sand and gravel	128, 178
Diatomite	(1)	Talc	1, 427
Mercury	2, 575	Tungsten	(1)

[1] Figures are confidential.

And California, in addition to these current "firsts," has been at various times in recent years among the top three States in the production of:

TABLE 2

Bromine
Calcium chloride
Chromite
Feldspar
Gold
Gypsum
Iodine
Iron ore
Lithium salts
Refractory and caustic magnesia
Natural gas liquids
Peat
Petroleum
Platinum
Potash
Pyrite
Sodium carbonate
Sodium sulfate
Strontium
Sulfur ore
Tin
Wollastonite

Only three States surpass California in the value of their total production of fuels; a few exceed California in the total value of metallic minerals; a very few are ahead in the total of industrial minerals. But no State comes even close to California in averaged rank with respect to all three of the components of the minerals industry. Nor does any other State approach California in the number (80) and diversity of commercial mineral products. What has led to this preeminence? The answers lie in the history and in the geology of the State.

Inadequate as the early records are, there is no doubt but that metals, nonmetals, and fuels had all been produced in California, in small amounts, long before the coming of the Forty-niners. Yet it was not until 1849 that mining became significant in the history or the economy of the State. From that date, thenceforward for many years, mining (and this meant essentially gold mining) was a dominant factor. The "California gold rush," precipitated by Marshall's 1848 discovery, represented a mass movement of people and a redirection of the hitherto well-established pastoral economy that, even in the hindsight of history, is difficult fully to appraise or appreciate. Thus the Californian of the mid-twentieth century complains, or boasts, or stands in awe (as the case may be) of "the population explosion" that saw the State's population, between 1948 and 1960, increase by a factor of about 57 percent. He has forgotten (or never knew) that between 1848 and 1860 the State's population expanded from 14,000 to 380,000—an increase of 2700 percent! It was gold that brought about that phenomenal growth, and it was gold that, for many years, principally sustained the State's burgeoning economy. Gold constituted new wealth, provided new capital in lavish amounts, and made possible new investments which in turn expanded and diversified the economy. If California's annual production of gold today seems minuscule by comparison with the production of grapes, or cotton, or airplanes, or motion pictures, California should never forget the legacy she owes to her gold which, in a very real sense, made possible the State's present preeminence and her affluent economy.

In retrospect, it is a remarkable circumstance that such an army of gold seekers as constituted the Forty-niners and their immediate followers, most of them wholly unsuited to, and inexperienced in, mining practice, should have been so successful. Although it would be impossible to document, it would probably be a fair statement to say that in so short a time no mining venture, before or since, has attracted so large a number of people; and that of these so few had had any previous mining experience. Yet their success—whatever may have been the ups and downs in the fortunes of individuals—is attested by the more than half a billion dollars of gold produced in just the first decade after the discovery. And this success—whatever it may have owed to the perseverance and ingenuity of amateurs turned miners—was largely conditioned by the favorable geology. Nowhere, before or since, has so much gold been laid out, almost ready to hand, by nature. Here is not the place to detail the metallogenic and geomorphic events that conspired to spread these riches along the foothills of the Sierra Nevada and elsewhere in the State. Suffice it to say that the values in the first, easily discovered and easily worked placers, provided the capital and the modicum of exerience necessary to develop the more difficult, but often more rewarding "high bench gravels" and so on to the "drift mines" and, eventually, the great "hydraulic mines," the gold dredges and the lode mines which, with the pittances now being added by the recent innovation of "skin-diving for gold," have brought the State's total production of gold to the impressive figure of more than 2⅓ billion dollars. The bulk of this, be it remembered, was produced when the price of gold was only $20.67 an ounce, and when a dollar was worth many times what it is today.

If the favorable-to-mining character of California's geology had first been demonstrated in the distribution of placer gold in a region where it was relatively easy to win, and where life was relatively easy to sustain, it was further demonstrated in the distribution of mercury, which for many years was second only to gold in the State's mineral production. Nowhere else in the world have important deposits of mercury existed within easy access of major deposits of gold. Yet the fact is that the New Almaden mine, the largest producer of mercury in North America, had been discovered in 1845 and lay less than 100 miles from the gold of the Mother Lode! Nor was the New Idria, second in total production to the New Almaden, much farther away. These convenient and relatively economical sources of quicksilver made for ready application of the amalgamation process, then the most efficient method for extraction of free gold from gangue, and thereby further enhanced the mining economy of the State.

If the early gold seekers were largely amateurs when they arrived at the "gold diggins," they of necessity soon became professionals. California's isolation from the manufacturing centers of the eastern seaboard not only called for development of ingenuity and innovation in local mining enterprise, but led also to local foundries, local machine shops, and to adaptations to local needs—many of which contributed to widespread improvements in mining and milling methods. The first major transportation of water in the State (still an item of utmost concern to California) came about in order to supply the huge hydraulic mines, themselves a major mining development of the time. Philip Diedesheimer, at Georgetown, California, in 1859, perfected square-set timbering, later to prove so important on the Comstock lode. Stamp mills, of a size and efficiency never before dreamed of, became realities. Years later (in 1918) another California development, the Gould Furnace with its greatly increased efficiency, proved a boon to mercury mining in the State and throughout the world. Nor should it be forgotten that the Cottrell Filter, a significant step in making mineral processing compatible with agriculture and even with urbanization was initially a California development.

Nevertheless, despite discoveries of new deposits, new developments in mining practice, and greater experience on the part of the miners, the inexorable economics of a non-renewable resource (increasing costs of operation and/or exhaustion of the mines) inevitably became felt in the gold-mining industry of the State. In addition, three other widely spaced events contributed to what currently amounts almost to the demise of this industry. The first (in 1880) was the "Sawyer decision" making illegal any mining activity which dumped excessive amounts of silt into streams, with consequent harmful effects on fishing and agriculture. Next there came, in 1941, the somewhat misnomered "gold mine closing act" (L–208), an order issued by the War Production Board primarily as a means of furthering needed war industries, but which nevertheless did effect the closing of most gold mines. And the third factor has been the postwar continuing rise in the costs of labor and materials which has essentially squeezed—against the pegged price of gold of $35 an ounce—the remaining life out of such mines as were able to resume production following World War II.

Because gold has constituted such a large proportion of California's output of metallic minerals, the very significant production of other metallic minerals has not always been fully appreciated. Mercury has already been mentioned as antedating gold and as being currently, and for many years past, one of the "California firsts," both in total and in annual rank of production. As early as the 1850's, prospectors, whether disappointed in their gold mines or otherwise seeking diversification, discovered and developed deposits of silver, copper, lead, and zinc. Beginning about 1870, California was for some years the leading producer of chromite in the country, and was even exporting to England. This industry incidentally underwent spectacular revival in the State, under the impetus of greatly increased prices, during the two world wars, contributing significantly to supplies of this strategic metal. Manganese and tungsten mining have likewise been highly responsive to war demands and price increases. Lacking war-time bonuses and post-war subsidies, manganese is no longer being mined in the State; tungsten—by virtue of the tremendous developments at the Pine Creek deposit in the eastern Sierra Nevada—still is being produced, along with significant amounts of by-product molybdenum.

One war-torn development, among the metal mines, has grown and is continuing to grow: mining of iron ore. Until the onset of World War II, California was virtually without an iron and steel industry. Mineral economists, although aware of deposits of iron ore within the State, had tended to discount the deposits as "too erratic" and, since the State lacked any local sources of coal and coke, many predicted that there would never be an iron and steel industry in the State. They had not fully foreseen the impetus of war demands, and the needs of the post-war expanding population. Currently, iron ore is being produced not only in amounts sufficient to supply the fully integrated Fontana plant of the Kaiser Steel Co., but also in significant amounts for export to Japan.

Important as all of these metallic minerals have been, and are, they constitute today only a very minor part of California's mineral industry. Almost unheralded, the industrial minerals ("nonmetals") long since overtook the metals in terms of value in the State's economy (figure 1). The figures stand today at more than $500,000,000 annually for the industrial minerals, versus slightly less than $60,000,000 for the metals. And the trend of the industrial minerals has been steeply upward for over twenty years.

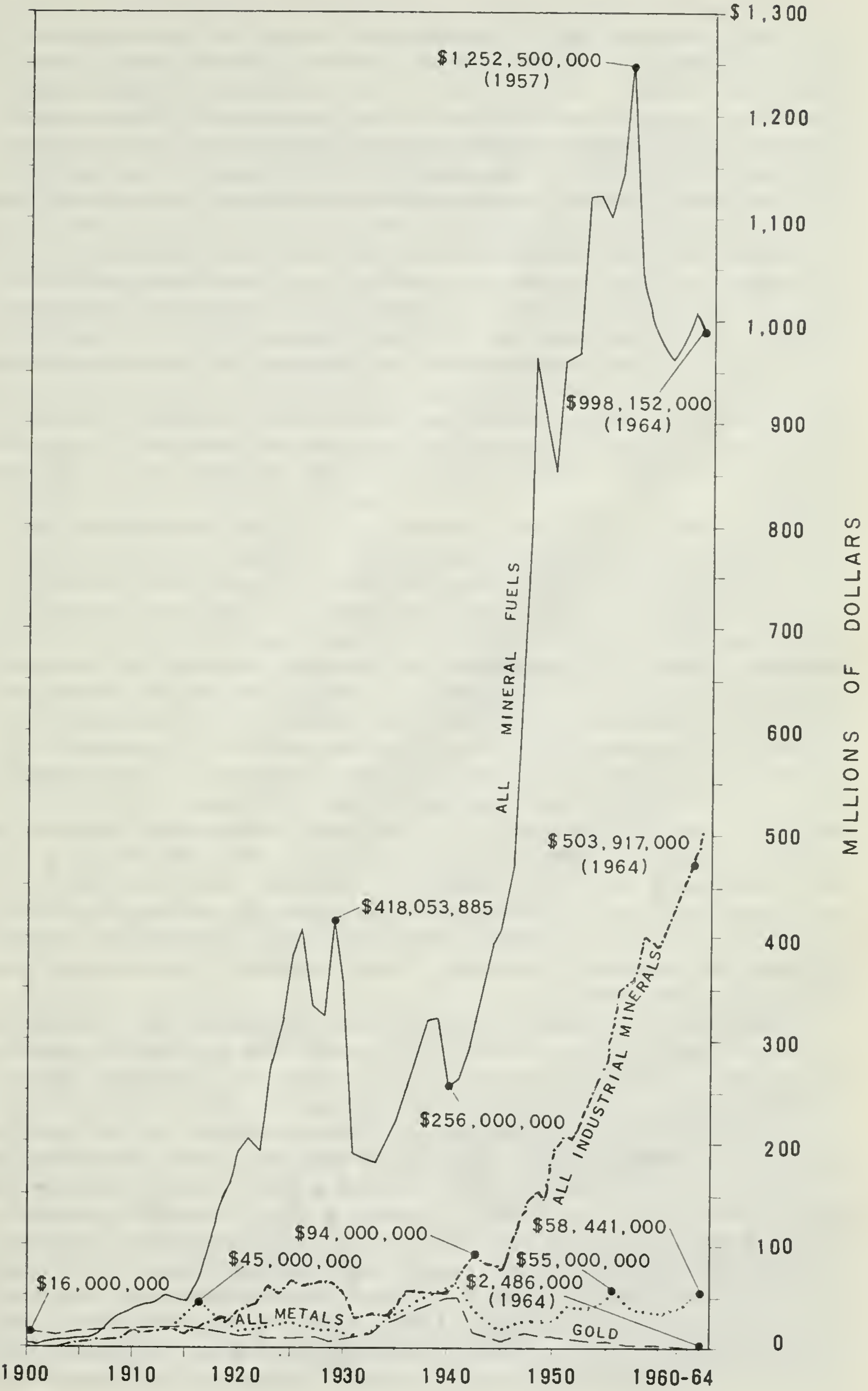


FIGURE 1. Mineral production in California, 1900–64.

As far back as the late 1850's, a San Francisco physician, Dr. John A. Veatch, was spending his summers traversing the State in horse and buggy, looking for sources of borax, then in demand chiefly for its medicinal virtues. His discovery of borax crystals in the muds of Borax Lake, and the subsequent story of borax in California constitutes one of the more fascinating records of nonmetallic mining history. It is a story of how the geography of the industry shifted from the lake muds in Lake County, to the "salt marshes" of southeastern California and Nevada, to Death Valley and to Calico, and eventually to Searles Lake and the Kramer district; of how the geology and mineralogy shifted from borax to ulexite, to colemanite, to kernite, and now to brines and to borax again (with colemanite once more looming over the horizon); and of how prices have dropped (vis-a-vis the Consumer Price Index) and of how demand and production have increased—to the point where boron and boron compounds have for many years exceeded in value the State's gold production and have constituted the State's principal export mineral, contributing significantly to the "favorable balance of trade" enjoyed by the State's economy.

If the history of California borax mining provides contrasts with gold, other industrial minerals provide additional contrasts—with both gold and borax. This is particularly true of the construction materials, especially rock, sand and gravel. These are commodities that, unlike gold and borax and many other minerals, depend for their demand on density of population more than upon special qualities and rarity of occurrence. And these are commodities which, because of their bulk, seldom enter significantly into interstate—much less international—commerce. They are therefore relatively immune to the effects of changing tariffs, subsidies, import quotas, and international cartels, and to this extent provide a less fluctuating and a sounder element in the mineral economy. Yet sand and gravel, except such as was mined incidental to the recovery of gold, did not even figure in the early records of the State's mineral production. Today, with an annual output of nearly 113,000,000 tons, valued at nearly $130,000,000, sand and gravel is the State's leading mineral industry in terms of volume, and shares with cement the top place in value among the State's "hard minerals."

Nevertheless, the industrial minerals are not without their problems. If the sand and gravel industry is dependent on population growth, the *spread* of population is rapidly threatening to become a deterrent to the industry, in that "suburbia" is already in competition with the needs of the industry for the acreage that constitutes its "ore." Like any other mineral, suitable deposits of sand and gravel are severely limited in their occurrences by the facts of geology. And deposits are further limited by the facts of economics: bulk materials cannot be moved long distances without incurring prohibitive cost. Yet, in a number of instances, the sand and gravel industry is being "zoned out of its own holdings" through the spread of urbanization and the lack of understanding, on the part of the public, of the geology and economics of the situation. Without an understanding, "suburbia" will soon be in the position of denying to itself (except at greatly increased costs) the very materials on which its own growth (homes, streets, schools, public buildings, etc.) depends. The problem—be it noted—is basically a man-made problem and offers hope, therefore, that man will eventually resolve it.

Is oil a mineral; is natural gas a mineral? Even to suggest that these are minerals would raise the hackles of some semantically inclined mineralogists; but to suggest that they are not will *assuredly* raise the hackles of every mining and petroleum engineer and economic geologist. Although the definition may be "largely of academic interest," the practical fact is that petroleum and related products constitute mineral resources as truly as do gold and silver and borax and asbestos. Principles of exploration and extraction and processing, and even of marketing, may differ in details but in broad fundamentals of geology and of economics they are the same. Certainly, therefore, any introductory discussion of the State's mineral industry must call attention to the "black gold" which for many years has been its premier mineral resource. Inasmuch, however, as there is extensive discussion of this most important industry in a following chapter, only certain salient features will here be mentioned.

Although oil seeps and tar sands were known to the Indians and were very locally exploited during the Spanish regime, significant commercial production of oil did not get under way in California until 1876, with the initial development of the Newhall field. This was at a time (further evidence that the gods continued to smile on California!) when the production of the "yellow metal" had declined drastically from the flush years of the 1850's and 1860's (see fig. 27). As a result the growth of the "black gold" industry came at a particularly opportune time for the State's economy. Subsequent production records (see fig. 54) have placed California second only to Texas in total production of oil, and have clearly placed oil as the State's No. 1 mineral resource. It is of interest, too, to note that the banner year for gold came in 1852; the banner year for oil, 105 years later, in 1957. From this, one might perhaps predict that significant amounts of oil will still be produced in the State 100 years from now, just as gold is still a multi-million dollar industry more than 100 years after Marshall's discovery. That decline in petroleum production has set in, is shown by the charts, but that the decline is recently being arrested is also shown. This comes about through important new discoveries—particularly of gas fields; through improved secondary recovery methods (primary recovery, even with modern methods, still leaves 50 to 75 percent of the oil in the ground); and through adjudication of jurisdictions which now permit development of off-shore oil potential, in particular of the East Wilmington field, destined to be one of the country's great oil fields.

All of California's oil and gas occurrences are directly related to her complex geology which—because of the complexity—has called for exceptionally sophisticated (and expensive) geological and geophysical approaches to the problems of discovery and exploitation. For the same reason, successful solutions have been exceptionally rewarding. Thus the yield of the average California oil well is anticipated to be more than three times that of the average well in the United States, and in some fields as many as 10 separate zones, over depth intervals of more than 6,000 feet, have been commercially developed. Small wonder, then, that the California petroleum industry has long enlisted exceptionally able management, exploration and engineering teams in order successfully to develop this major mineral resource.

Production records for the major components of California's mineral industry have been given in figure 1. To what extent can growth lines justifiably be extended into the future? Projections are no more than predictions, but prediction can in this case be based on the facts of geology and history. California has been peculiarly blessed with a complex geology, doubtless in part the result of the "unease" of the crust, described in the chapter on Geologic History of California. The distinctive geology has in turn provided an unequalled diversity of minerals, many in notable concentrations. The chapter headings in the Table of Contents of this volume document the great diversity of useful mineral products enjoyed by the State—a most favorable factor in her economy. Mineral-wise, California is far from the "one-crop" State she once was in the hey-day of gold mining. Moreover, a greater number of different minerals (over 700 distinct species) are known to occur in California, and more minerals (45) not as yet known anywhere else in the world, occur in California than in any other state. And, mining history in California has built a tradition of exploration and innovation—a recent example being the successful harnessing of geothermal power at The Geysers—the first, and still the only such development in North America.

With the combination of men and minerals to be found in the State, the future of the mineral industry should indeed be bright. But there are many who, with considerable justification, view it with misgivings. These stem from a recognition of two trends. One of these is the growing conflict over land use. As mining turns more and more to open pit, and to larger and larger operations, more acreage is involved, and more public pressure develops to insist on other uses for such acreage, whether for recreation, for urbanization, for "wilderness," or just "*anything* but mining!" The other trend is towards lesser involvement of fewer people in the mineral industries. This results partly from changes within the industry whereby smaller operations, involving in the aggregate many men, are giving way to larger operations involving huge capital outlays and often fewer men. (For example, to install the new Redding operation of the Calaveras Cement Co.—a relatively small operation, as some cement plants go—required some $16,000,000 in capital outlay. On a weekend, when the mine is shut down, the largely automated mill, which has an annual capacity of 1,500,000 barrels, can operate with only five men! And the conversion a few years ago of the underground mine of the U.S. Borax and Chemical Corp. at Kramer to an open-pit operation, and installation of a new mill, required an initial capital investment of around $20,000,000. Yet the number of miners and millmen has decreased at the same time that output was being increased.) The increasing number of mergers, and the absorption of small companies by larger in the petroleum industry is further testimony to the changes that are going on. The net effect of these trends—greatly amplified by population growth, per se—is that, whereas 100 years ago almost every Californian had some familiarity, and many were directly involved, with the mineral industry, today scarcely one in a thousand has any concept of how dependent he is, at virtually every turn of his everyday life, on the products of mines and oil wells. Far less does he have any concept of mineral industry operations, economics, or geology. It is these people who now frame the laws under which the industry must operate. It has been well said that government—Federal, State, and local—"calls the turns" on the fortunes of the mineral industry as never before. California has most favorable geology; she has the mineral resources; she has the wherewithal for maintaining a minerals industry second to none. Will her citizens prove sufficiently knowledgeable to meet the challenge? That is the question that now looms largest in California's unfolding mining history.

TOPOGRAPHIC AND GEOLOGIC MAPS

(By J. P. Albers, U.S. Geological Survey, Menlo Park, Calif.)

Topographic maps show the surface features of a region, including mountains, valleys, rivers, lakes, and man-made features. Such maps are essential to the comprehensive development of the natural resources of the State and are extremely useful to engineers, geologists, administrators, conservationists, foresters, economists, planners, farmers, and many others.

Topographic maps are prepared at different scales, depending on the map's purpose. Larger-scale maps show more details than small-scale maps. The standard topographic map scales of the U.S. Geological Survey are 1:24,000 and 1:62,500. A topographic quadrangle map at scale 1:24,000 (1 inch=2,000 feet) covers a rectangular area measuring 7½ minutes of latitude by 7½ minutes of longitude, and a map at 1:62,500 scale (approximately 1 inch=1 mile) covers a rectangular area measuring 15 minutes of latitude by 15 minutes of longitude. Topographic maps of much larger areas at scales of 1:250,000, 1:500,000, and 1:1,000,000 are commonly prepared by compilation processes from the 7½-minute and 15-minute topographic maps.

A map showing the topography of California has been published by the U.S. Geological Survey (1953) at a scale of 1:500,000, and maps prepared by the Army Map Service covering 2° of longitude by 1° of latitude at a scale of 1:250,000 are also available for the entire State. Fifteen-minute quadrangle maps are available for nearly the entire State, and 7½-minute quadrangle maps cover much of the western part of the State. Any of these maps may be purchased by mail from the U.S. Geological Survey, Denver, Colorado, or over the counter at Los Angeles, Menlo Park, and San Francisco, California.

Geologic maps show the distribution of rock units at the surface of the earth. Such maps are fundamental for the intelligent exploration, development, and appraisal of mineral and water resources of a region, and they are being used increasingly in planning and engineering urban development and highway construction. The geology is generally plotted on topographic base maps, and consequently geologic maps are usually published at the same scale as the topographic base. Most geologic mapping is done at scales of 1:24,000 or 1:62,500 but larger scales (1:12,000 and larger) are becoming increasingly widespread, particularly for pointing out geologic conditions and hazards that need to be evaluated in areas of mushrooming urban development. Large-scale maps are also commonly employed in the evaluation of highly mineralized areas, but other scales are also employed, depending on the purpose.

A geologic map of California is being prepared by the California Division of Mines and Geology on topographic base maps at 1:250,000 scale. Of the 27 sheets required to cover the State, 21 had been published at the end of 1965. Much of the geology on these sheets is necessarily based on reconnaissance geologic mapping as less than 25 percent of the State has been mapped at scales considered adequate for most purposes. Plate 1 of this report is a geologic map at scale 1:2,500,000 compiled from the 1:250,000-scale sheets. It therefore portrays the geology only in a very generalized form.

TOPOGRAPHY

(By J. P. Albers, U.S. Geological Survey, Menlo Park, Calif.)

California's landscape, embracing 158,297 square miles, is, like its geology, extremely varied. Viewed overall, the dominant topographic features of the State are the Great Valley (also known as the Central Valley), the Sierra Nevada, and the Coastal mountains (fig. 2). The Great Valley is a vast elliptical bowl 400 miles long by about 50 miles wide whose floor stands a few tens to a few hundred feet in altitude. It is bounded on the east by the mighty Sierra Nevada with its southwestward extension the Tehachapi Mountains, on the northeast by the rugged Cascade Mountains, and on the west by the Coastal mountains, including the Klamath Mountains and California Coast Ranges. The northern part of the Great Valley is drained by the southward-flowing Sacramento River system and the southern part is drained by the northward-flowing San Joaquin River system. About 30 miles west of the city of Stockton, the two drainage systems converge, and the waters find their way to the ocean through the only exit from the mountain-rimmed valley via San Francisco Bay and the Golden Gate.

Lofty mountain peaks that tower above precipitous gorges and canyons characterize the contour of the Sierra Nevada. The highest peaks, including Mount Whitney (14,495 feet) are in the southern part of the 385-mile-long range, and the altitude of the range crest in general declines toward the north, where the altitude of the highest peaks is less than 8,500 feet. The Sierra Nevada is a gigantic fault block about 80 miles wide tilted westward, and the gentle western slope is traversed by about a dozen major streams that flow into the Sacramento and San Joaquin Rivers in the Great Valley. Many of these westward-flowing streams occupy deep valleys—some as much as half a mile deep. By far the most rugged and spectacular valley is "The Incomparable Valley"—Yosemite—carved largely by ice many thousands of years ago and through which now flows the Merced River. The east side of the Sierra Nevada through much of its length drops precipitously into Owens Valley. In the vicinity of Mount Whitney the relief measures nearly 2 miles in a horizontal distance of only 6 miles.

North of the Great Valley and north of the Sierra Nevada the landscape is dominated by two volcanic mountains, Lassen Peak (10,457 feet), and towering Mount Shasta (14,162 feet). East of these peaks is the Modoc Plateau with an average altitude of about 5,000 feet but above which numerous volcanic cones rise as much as 2,000 feet. In the extreme northeast corner of the State, the rugged Warner Mountains, culminating in Eagle Peak (9,883 feet), tower nearly a mile above the general level of the Plateau.

Northwest of the Great Valley is an area of complex rugged topography known as the Klamath Mountains. The highest peaks—Mount

Eddy, and Thompson Peak—ascend to about 9,000 feet, and the principal rivers—the Klamath and Trinity—have cut deep twisting gorges. In contrast to the Klamath Mountains, the California Coast Ranges, extending for nearly 600 miles south-southeast from the Oregon border, and lying between the Great Valley and the ocean, are markedly linear in character. They consist of numerous, often indistinct, ridges from 2,000 to 7,500 feet high separated by the valleys of such rivers as the Eel, Mad, Russian, and Salinas, as well as smaller streams.

FIGURE 2. Relief map of California, showing geomorphic province boundaries.

South and southeast of the Sierra Nevada, and extending to the California border at the Colorado River is a great expanse of desert terrain characterized by short rugged mountain ranges, immense sandy valleys, and dried lake bottoms. Most of this area is known as the Mojave Desert, but the extreme southern part of the area is referred to as the Colorado Desert (Salton Trough geomorphic province). A feature peculiar to the region is that most of the rivers dry up in the valleys by evaporation. The Salton Sea in the southern part of the desert region is about 250 feet below sea level and the highest peaks in the region rise to nearly 7,500 feet.

The region north of the Mojave Desert and east of the Sierra Nevada is also desert, made up of extremely rugged, linear ranges that attain altitudes of more than 14,000 feet. The highest peak is White Mountain Peak (14,242 feet) near the Nevada border. Other prominent topographic features of this region, which is part of the Great Basin geomorphic province, are Owens Valley and Death Valley; the latter includes the lowest point on the North American Continent at 282 feet below sea level. This lowest point is only 80 miles from Mount Whitney, the highest point in the conterminous United States.

West of the Mojave Desert and south of the Great Valley and Coast Ranges a group of linear ranges trends generally west, across the northwestward grain of topography that typifies much of the rest of the State. These ranges, of which Santa Rosa and Santa Cruz Islands are a seaward extension, attain maximum altitudes of about 10,000 feet in the San Gabriel Mountains just north of Los Angeles. The metropolitan area of Los Angeles is built on a broad coastal valley that stands in general only a few tens of feet above sea level. Hence, the relief in the immediate vicinity is nearly 2 miles. Southeast of the valley in which Los Angeles is situated a group of northwest-trending ranges extends southward into Baja California and is known collectively as the Peninsular Ranges. The highest peak in these ranges (San Jacinto) rises to 10,831 feet but the general altitude of the range crests is variable and in general much lower.

GEOLOGIC HISTORY OF CALIFORNIA

(By P. B. King, U.S. Geological Survey, Menlo Park, Calif.)

To the earth scientist, California is a region of surpassing interest, as it is a virtual laboratory of geology in the making. Scientists and non-scientists alike are aware of its frequent earthquakes, some of destructive intensity. These are manifestations of the region's uneasy crust; the geologist finds even more eloquent manifestations of such unease in the great faults that interlace the State, along which the rocks have been shifted even in modern time, and in the steep upending of some of the very youngest stratified rocks.

California's crustal unease is related to its coastal position; the State is, in fact, but one segment of a zone of unease that extends nearly around the Pacific Ocean border, into South America in one direction, and through Alaska, Japan, and Indonesia, in the other, whose bolder manifestations are its many erupting volcanoes and destructive earthquakes. California is the daughter of the North American continent and the Pacific Ocean basin; according to one plausible hypothesis it was once a part of the ocean basin, and since has been built up by earth forces to become part of the continent.

Mostly, we know California's geologic history during the last 230 million years (during Mesozoic and Cenozoic times). The record of earlier times is known only in places; elsewhere it has been obliterated by the crowded events of later times.

PRECAMBRIAN AND PALEOZOIC TIME

The record of earlier events is most plentiful nearest the continental interior—in the desert ranges east of the Sierra Navada and in southeastern California (the Great Basin and Mojave Desert of the map). Here, the oldest rocks that emerge are a basement complex of Precambrian granites and gneisses that has yielded isotopic ages of 1,000 million to 1,300 million years. (Some granites and gneisses of about the same age also occur nearer the coast in the highly faulted Transverse Ranges north of Los Angeles and San Bernardino, but their relations to the surrounding rocks are not as clear.) In the desert ranges this basement is followed in places by sedimentary strata of younger Precambrian age, and is covered even more widely by Paleozoic strata (formed between 600 million and 230 millions years ago); in some areas the latter total 10,000 or 20,000 feet in thickness. For the most part, these strata are the products of sedimentation in shallow, quiet seas which spread from time to time over the edges of the continent. Many of the strata are limestone, containing fossils of shelly marine organisms; some strata are quartz sandstone and mudstone, derived from the waste of the continental interior.

Paleozoic strata are preserved farther west, in the Sierra Nevada and Klamath Mountains, but in smaller fragments that are greatly interrupted by younger rocks. Here limestone is very subordinate, and most of the strata are mudstone and coarser, poorly washed, dirty sediments (graywackes), interrupted in places by lava flows, some of which contain a pillow structure which indicates that they were erupted under water. In this western area we have seemingly entered another Paleozoic world—one not truly a part of the continent, but rather, a world along the border of the Pacific Ocean.

MESOZOIC TIME

In the Sierra Nevada and Klamath Mountains these Paleozoic strata are succeeded by others of Triassic and Jurassic age (formed between 230 and 135 million years ago), which are so similar to them that they are difficult to distinguish except for occasional happy discoveries of diagnostic fossils. Evidently the world of the Pacific Ocean border still persisted here in these times—with its muddy and dirty sediments and its eruption of submarine lavas.

But mighty events were in the making, which reached a climax late in Jurassic time. In the Sierra Nevada we find that all the strata—Paleozoic, Triassic, and Jurassic—have been turned steeply on end, and have been so changed by heat and pressure that they are now hornfels, slate, or even crystalline schist. They have, further, been invaded, distended, or broken off by granitic rocks, which ascended into them from deeper levels in the crust. In the western foothills of the Sierra Nevada the granitic rocks form small dispersed bodies, but in the higher parts of the present range to the east they coalesce into a vast, nearly continuous body, known as the "Sierra Nevada batholith." Emplacement of the granitic rocks occurred during and after the upending of the strata in which they are embedded; isotopic determinations indicate that emplacement extended through a period of nearly 100 million years, or from early in the Jurassic until late in the Cretaceous, but the greatest volumes were emplaced mainly during Late Jurassic and Early Cretaceous times.

Similar granitic rocks, enclosing small to large remnants of the earlier strata, occur in the higher mountains throughout the length of California—the Klamath Mountains, the Sierra Nevada, the Transverse Ranges, and the Peninsular Ranges (from which they continue southward into Baja California). An outlier of such rocks occurs nearer the Pacific in a long strip in the Coast Ranges south of San Francisco Bay; these rocks front the coast in the northern Santa Lucia Range, and project at sea in the Farallon Islands.

These mighty events—upending of the strata, emplacement of granitic rocks, and the rest—produced mountain ranges which are the first in California for which there is good documentation. The events have been called the "Nevadan orogeny." By this orogeny, a belt of considerable width was subtracted from the Pacific Ocean border and was added to the North American continent.

During and after the orogeny, in Late Jurassic and Cretaceous time (140 to 70 million years ago), sedimentation continued along the ocean border, west of the newly formed mountain ranges. Remnants of these younger sediments lap up on the edge of the deformed rocks of the Sierra Nevada, as though toward a shoreline. Farther west, along the west side of the Great Valley, they attain a thickness of 20,000 to 30,000 feet and have been called the Knoxville, Paskenta, Horsetown, and Chico Formations. These are a vast sequence of dominantly muddy sedimentary rocks, with frequent thin sandy intercalations, that contain shelly fossils in many places. Probably they were laid down on a shelf at the edge of the continent.

A significant feature of these Upper Jurassic and Cretaceous sedimentary rocks is the nature of their feldspar content. Mineralogical studies indicate that they contain grains of potassium feldspar, and that these grains are rather sparse in the lower beds but become very abundant in the higher beds, where they dominate over all other kinds of feldspar. Potassium feldspar is characteristic of coarse granitic rocks like those in the Sierra Nevada and elsewhere in the Nevadan orogenic belt, and the increasing abundance of its grains in the higher strata indicates that as time went on the granitic rocks of this orogenic belt were being more and more penetrated and worn down by erosion.

Within the Coast Ranges west of the Great Valley, however, the place of these shelf sediments is taken by a more enigmatic sequence, the Franciscan Formation. The Franciscan contains fewer fossils, but what fossils have been found indicate that it was laid down at nearly the same time as the shelf sediments to the east. The Franciscan is a mass of great but unknown thickness, pervasively sheared and disturbed, composed of mudstóne and coarser dirty sedimentary rocks (graywackes), pillow lavas, bedded chert, glaucophane schist, and rare limestone lenses. Seemingly it was deposited in much deeper water than the shelf sediments previously described, and farther out from the Pacific Ocean shoreline.

CENOZOIC TIME

The stage was now set for the evolution of California into its present form, which was accomplished during Cenozoic time, or during the last 70 million years.

Sierra Nevada

During the early part of this time the site of the Sierra Nevada had been worn down to low hills and ridges, representing the stumps of the mountains that were produced during the Nevadan orogeny. Streams with gentle gradients drained westward across it, heading somewhere east of the present crest. Their ancient channels are still preserved in places on the hilltops of the Sierra Nevada, filled with water-worn gravels—the "auriferous gravels" so eagerly sought by the 49'ers and their successors. During Miocene time (25 to 12 million years ago) the northern half of the range was also buried by sheets of lava and volcanic debris, related to the volcanism in the Cascade Range to the north (see below).

The present Sierra Nevada occupies only part of the area of the earlier Nevadan mountains, which had extended the length of California and beyond to the north, south, and east. The part which forms the present range was blocked out after Miocene time (perhaps beginning 12 million years ago). Then, the block was broken from the land to the east along great faults; its eastern side was raised along the faults to form the present range crest, and the western slope was tilted toward the Great Valley (which is, in fact, the depressed and buried western part of the block). This uplift was progressive and was accomplished during several stages. It was virtually completed by the end of Pliocene time (about 3 million years ago), although some faulting and uplift continued during succeeding Quaternary time.

Northeastern California

The northeastern corner of California is quite different from the remainder of the State, as it is built almost wholly of young volcanic rocks; it is one edge of an extensive volcanic region that extends far northward and northeastward across Oregon, Washington, and Idaho.

Here, especially during Miocene and Pliocene time, lava flows and sheets of fragmental volcanic debris spread widely over the land as a result of eruptions from fissures and volcanic vents. These rocks range in composition from basalt through andesite to rhyolite. The eruptive material accumulated to great thickness; in the Warner Range in the northeasternmost part of the State at least 7,500 feet of the accumulations have been raised to view by faulting, with their base not visible. Farther west, the volcanic accumulations have built up the Cascade Range that extends with increasing height into Oregon.

Volcanic activity continued into late Cenozoic time. In the western part of the volcanic area, two great volcanic cones that dominate the landscape of northern California—Mount Shasta (altitude 14,162 feet) and Mount Lassen (altitude 10,457 feet)—were formed very late in geologic time. The lofty cone of Shasta, covered most of the year by snow and supporting a few permanent glaciers, seems now to be inactive, but the lesser cone, Lassen, underwent a minor eruption in 1915—the only volcano south of Alaska that has erupted during modern times within the continental United States. Surrounding these larger cones are myriads of smaller cones and craters which, as on their surrounding lava flows and other volcanic products, vegetation has scarcely regained its foothold—all testifying the relative recency of volcanic activity in this part of California.

Coastal Mountains

During the evolution of the present Sierra Nevada and Cascade Range in Cenozoic time many more and varied events were transpiring on the sites of the coastal mountains to the west—the Coast Ranges north and south of San Francisco Bay, the Transverse Ranges, and the Peninsular Ranges.

An outstanding feature of these ranges is the high-angle faults that traverse them, which have had a large but uncertain influence on their evolution. The largest and most famous of these faults is the San Andreas, which extends nearly the length of California, from Punta Arena north of San Francisco, 620 miles southeastward, almost to if not across the Mexican border. But branching from or paralleling the San Andreas are other faults of nearly equal magnitude, and they are crossed in the region of the Transverse Ranges by other high-angle and low-angle faults of east-west trend.

Nearly everything about these high-angle faults has been hotly debated by geologists—the time of their inception, their subsequent history, and the magnitude and nature of the movements among them.

Most of the streams which cross the San Andreas fault turn to the right at the fault line for a few hundred or a thousand feet before resuming their normal course, giving eloquent testimony of a lateral shift of the geography on the two sides by these amounts during the last 25,000 years or so; similar shifts of a few feet occurred on the San Andreas fault during the San Francisco earthquake of 1906. Can movements of the same kind be projected farther into the past?

The Temblor Range west of Bakersfield, bordering the San Andreas fault on the east, is formed chiefly of Miocene marine strata (25 million to 12 million years old), which contain masses of shattered blocks of granitic and metamorphic rocks that taper to the east—evidently landslide debris derived from highlands west of the fault. Yet just west of the fault in the latitude of the Temblor Range the surface is now formed only of non-marine Miocene strata. The highlands from which the landslides came have disappeared, and there is a strong suspicion that they have been shifted from their Miocene location by lateral movement along the San Andreas fault; a possible source of the landslide material is in highlands of granitic and metamorphic rocks on the west side of the fault which are now 60 to 80 miles to the northwest.

This, and similar lines of evidence, suggest the existence of the San Andreas and other faults at least during the last 25 million years. But still greater anomalies exist in the Jurassic and Cretaceous granitic and stratified rocks, which are commonly quite unlike on the opposite sides of the faults. For a long distance south of San Francisco, for example, the older rocks east of the San Andreas fault are Franciscan Formation, and those west of it are granitic and metamorphic. Also, distinctive granitic and metamorphic rocks west of the San Andreas fault in the longitude of Los Angeles are very much like those east of the fault near the Salton Sea, 130 miles to the southeast. The full meaning of these anomalies remains to be explained, but they imply not only the existence of high-angle faults before Miocene time, but of very great movements along them, whether lateral or otherwise.

If lateral shifts in the position of the blocks enclosed by the high-angle faults has been as extensive and as long-persistent as has been suggested, there is a large factor of uncertainty in any attempt to reconstruct the succession of geographies of California during Cenozoic time.

Almost as striking as the high-angle faulting in the coastal mountains is the strong folding and tilting of their strata—not only of the earlier Jurassic and Cretaceous strata, but also of those which formed during Cenozoic time, including even some of the youngest. The relation (or lack of it) between this tilting and folding and the high-angle faulting remains one of the vexing problems of California geology.

The record of tilting and folding in the coastal mountains of California during Cenozoic time is unusually well documented, because it went on hand in hand with sedimentation. Thus, strata which were folded at some time are likely to have been eroded, and their eroded surface to be overlain unconformably by younger strata—the strata both below and above the unconformity (that is, the strata which were laid down before and after the folding) being datable by means of their contained fossils.

The stratigraphic sequences in the coastal mountains of California contain many such unconformities, indicating that folding occurred at many times. Moreover, the magnitude, or even the existence of the unconformities varies greatly from place to place, indicating that each folding was essentially a local event. A record so complex is difficult to generalize into any climaxes or widespread orogeny, but it seems possible that there were several gross times of orogeny, or genuine formation of mountains, as we shall see.

The results of these movements are suggested by the reconstructions of the geography, in the form of paleogeographic maps, which have been made of the coastal area of California for various stages of Cenozoic time. These reconstructions indicate that parts of the area were at various depths beneath the sea and received marine deposits, that other parts were low plains or basins along the coast that received non-marine deposits, and that still other parts were hills or mountain ridges that were undergoing erosion. Many of these ridges projected as islands or peninsulas, surrounded or nearly so by the sea. The geography of all the coastal area through Cenezoic time was thus much like that which still persists in southern California—with the offshore Channel Islands surrounded by shallow to deep marine waters, and the mountain-girt plains or basins onshore, such as the Los Angeles and Ventura basins.

The reconstructions of the geography during the Cenozoic show great variations through time (which incidentally implies the ephemeral nature of the seemingly immutable present geography of southern California). Seas waxed and waned in extent, mountain ranges came up only to disappear—all presumably in response to successive pulses of folding, and possibly also to movements along the high-angle faults.

The deposits laid down on the sites of the present coastal mountains are largely of clastic nature. Marine deposits that were principally mud and sand in varying proportions, are now distinctive formations of shale and sandstone. Gravelly beds occur near some of the former shorelines, and dominate altogether in some of the non-marine areas farther inland. Some deposits contain volcanic debris and interbedded lava flows, especially those of Miocene age. Among the non-clastic deposits, limestone is either lacking altogether or is very subordinate; much more important are the diatom-bearing siliceous shales, altered in part to chert, whose white, thin-bedded outcrops are a characteristic feature of the Coast Range landscape. They are typified by the Miocene Monterey Shale.

The Cretaceous and older deposits of the coastal mountains seem nearly everywhere to be unconformable beneath the Cenozoic deposits, as though an important orogeny occurred before the latter were laid down. In some areas, to be sure, the Cretaceous is succeeded by Paleocene, Eocene, and younger strata, and any intervening break is little apparent. Elsewhere, however, much younger Cenozoic strata lie on the deeply eroded surface of the Cretaceous and older rocks, as a result of movements near the end of Cretaceous time and later. North and south of San Francisco Bay and west of the San Andreas fault, Miocene strata have been deposited directly over Cretaceous granites of deep-seated origin. One can picture these granites as having been forced up into mountain ridges late in Cretaceous or early in Cenozoic time, and the ridges not worn down to low ground again until the Miocene.

Miocene time (25 million to 12 million years ago) marked a great spreading of the seas and their deposits over the site of the coastal mountains, and eastward across the Great Valley toward the Sierra Nevada, where the marine deposits pass into deposits laid down on the land. But a succession of movements in the later part of Miocene time produced much folding and faulting of the Miocene and older strata, and raised many areas into lands or even mountains—all adding up to a general time of orogeny.

After this orogeny, marine incursions in the area of the coastal mountains never equalled their former extent. During Pliocene and Quaternary time (the last 12 million years), sedimentation was confined to smaller, generally mountain-girt areas—embayments along the coast which received marine deposits, and basins farther inland which received non-marine deposits; for part of the time, however, seas also extended over much of the San Joaquin Valley. Notably among the coastal embayments are the Los Angeles and Ventura basins, which received as much as 17,000 feet of the younger Cenozoic marine deposits. These basins subsided very rapidly early in Pliocene time and were covered to great depth by marine water; thereafter, they gradually filled with sediments, whose contained Foraminifera indicate that they were laid down in progessively shallower water, until filling of the basins was completed.

During later Cenozoic time, as earlier, sedimentation was interrupted from time to time and place to place by folding and faulting. Important movements occurred in places during the Pliocene, but the last climax of movement was during the middle of the Pleistocene, one or two million years ago; this has been called the "Coast Range" or "Pasadenan orogeny." It is well displayed in the Palos Verdes Hills southwest of Los Angeles, where older Pleistocene marine deposits have been up-ended and folded to the same extent as the strata beneath, and their eroded surfaces overlain by later Pleistocene marine terrace deposits which have been uplifted from beneath the sea, but are otherwise only gently tilted.

Manifestations of this orogeny also occur in the Ventura basin, and at many other places farther north, but its effects were variable—in some places producing steep folding of the older Pleistocene strata, in others vertical uplift of mountain areas with little accompanying folding, and in still others little or no disturbance between the older and younger Pleistocene deposits. Nevertheless, this orogeny, combined with the times of deformation which preceded it, has made the coastal mountains of California essentially what they are today. Subsequent modifications have been minor, although, as we have seen, California is still an uneasy land.

A final feature of coastal California deserves mention, as an indication of the fluctuating relations between sea and land. All along the coast one can observe terraces on the mountain slopes, rising step-like from the sea. The lowest terraces, a few hundred feet or less above the present sea, are well preserved and are covered by deposits containing marine shells; clearly, these are old shoreline or beach deposits, now raised above the water. The higher terraces, some more than a thousand feet above the water, are progressively more and more eroded and destroyed the higher one ascends, yet many of these preserve marine deposits also.

Modern oceanographic surveys offshore have produced the additional interesting fact that much of the sea bottom sloping away from the land is terraced also. Former shorelines thus exist, not only above present sea level, but at least 400 feet beneath it. Sea level along the California coast has thus not only fluctuated downward, but upward.

Great fluctuations in sea level with respect to the land along the Califorina coast are thus indicated. However, at least a part of these fluctuations were not caused by actual crustal movement; the locking up of ocean water in the great continental glaciers during the Pleistocene ice ages, and the subsequent melting of the glaciers, produced worldwide variations in sea level amounting to hundreds of feet, both below and above present sea level. Nevertheless, the higher marine terraces along the California coast could not easily have been produced in this manner, and these at least imply that various parts of the coast have been greatly uplifted at very late periods in geologic time.

GEOMORPHIC PROVINCES

(By J. P. Albers, U.S. Geological Survey, Menlo Park, Calif.)

Because of the size of California and its extremely varied and complex geology, it is desirable to divide the State into eleven physical or geomorphic provinces and describe the geology of each of these separately. Each province is characterized by rather similar land forms or combinations of land forms throughout its area, and by a geologic record that contrasts with that of neighboring provinces, especially in the later part of its geologic history. Certain kinds of mineral deposits tend to occur within particular geomorphic provinces.

The eleven geomorphic provinces into which California is divided are (fig. 2) : (1) Coast Ranges—a system of northwest-trending longitudinal mountain ranges made up of Mesozoic and Cenozoic rocks, controlled by faulting and folding; (2) Klamath Mountains—a group of complex rugged mountains made of Paleozoic and Mesozoic rocks intruded by granitic and ultramafic rocks, and characterized by irregular drainage; (3) Southern Cascade Mountains—a chain of volcanic mountains most prominent of which are Mount Shasta and Lassen Peak; (4) Modoc Plateau—a plateau-like surface built of volcanic rocks, bounded indefinitely on the west by the Cascade Mountains and on the east by the Great Basin; (5) Sierra Nevada—a great westward-tilted fault block made mainly of granitic rocks, subordinate Paleozoic and Mesozoic sedimentary and volcanic rocks, numerous inclusions and pendants of metamorphic rocks, and elongate bodies of ultramafic rocks; (6) Great Valley (also known as the Central Valley)—an elliptical plain bounded by mountains on all sides and underlain by Mesozoic and Cenozoic rocks; (7) Great Basin—northwest-trending fault-block mountains made of Precambrian to Cenozoic rocks, and broad intervening alluvial-filled valleys and playas with no drainage to the sea; (8) Transverse Ranges—west-trending ranges made of Precambrian to Cenozoic rocks; (9) Mojave Desert—area wedged between San Andreas and Garlock faults and consisting of isolated northwest-trending mountain ranges made of Precambrian to Cenozoic rocks; well over 50 percent of the terrain is broad intermontane valleys with playas and interior drainage; (10) Salton Trough—a low-lying desert basin filled with alluvial deposits: the Salton Sea is a prominent feature; (11) Peninsular Ranges—northwest-trending ranges made chiefly of Mesozoic granitic and metamorphic rocks.

The geology of the individual provinces is described on subsequent pages, following a résumé of the geologic history of the State. The correlation chart (fig. 3) gives in generalized form the sequence and age of formations in the individual provinces and the approximate correlation of units between provinces. The authors of the individual province descriptions are responsible for the stratigraphic column given for their province. The stratigraphic nomenclature and age assignments used in this report are derived from many published sources and do not necessarily follow the usage of the U.S. Geological Survey.

GEOLOGY OF THE CALIFORNIA COAST RANGES

(G. B. Oakeshott, California Division of Mines and Geology, San Francisco, Calif.)

The Coast Ranges province includes a series of north-northwest-trending mountain ranges and intermontane valleys bounded on the east by the Great Valley and on the west by the Pacific Ocean. A narrow segment of the province extends northward into coastal Oregon. The boundary between the northern Coast Ranges (north of San Francisco Bay) and the Klamath Mountains province is the South Fork Mountain fault zone. The south end of the southern Coast Ranges (south of San Francisco Bay) is marked by the abrupt change to east-west topographic and structural trends of the Transverse Ranges in Santa Barbara and Ventura Counties.

The Coast Ranges include numerous rugged, individual mountain ranges which extend in elevation from sea level to maximum heights of 6,000 to 7,000 feet; they are separated by short, narrow, intermontane valleys.

Geology of the province is extremely complex. Each of the ranges has had a more or less independent and individual history, although major episodes in that history link the Coast Ranges into a province which is geologically and physiographically distinctive.

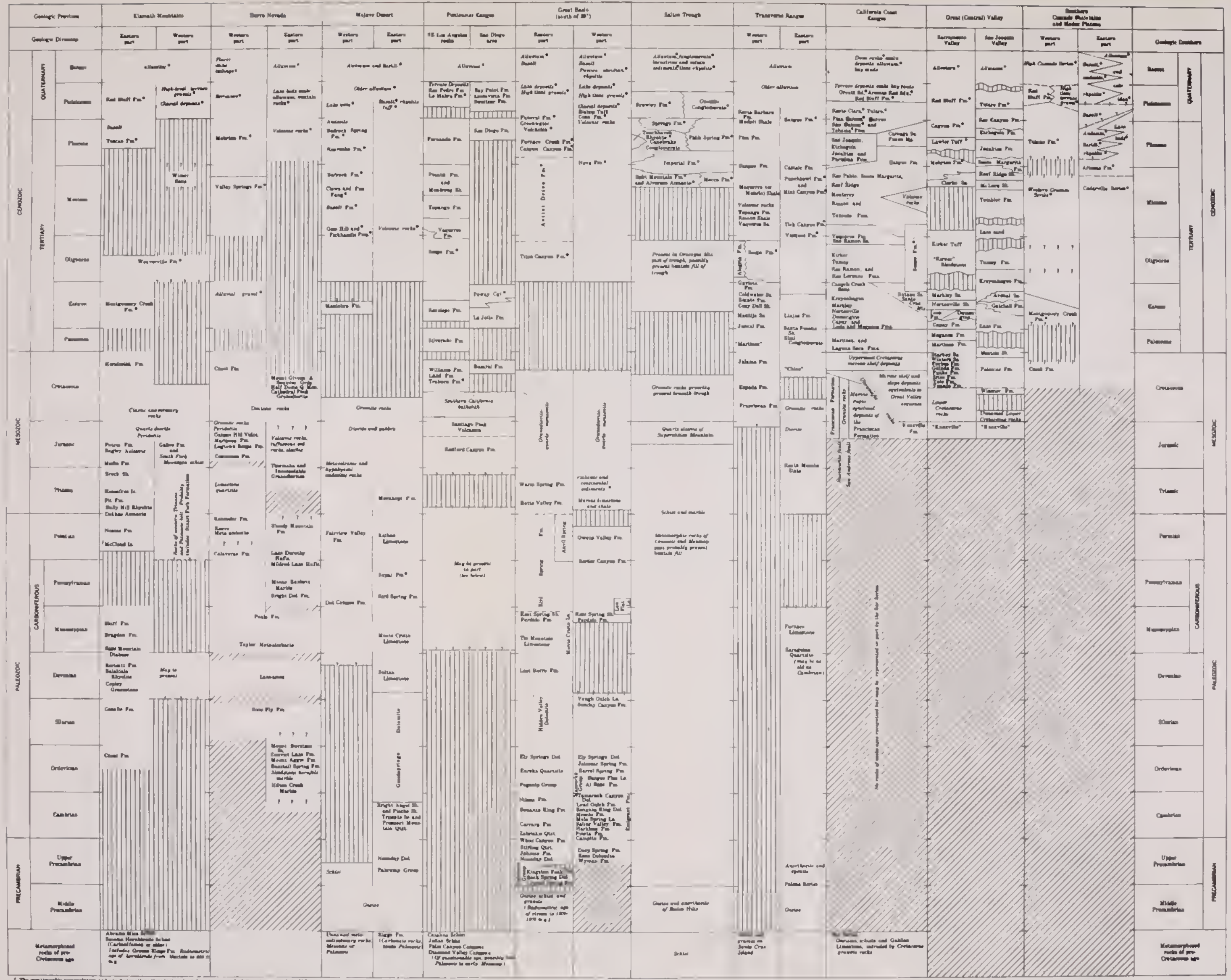
The Precambrian history of the Coast Ranges is unknown as no rocks of that age have been recognized. Neither are there any rock formations of known Paleozoic or Triassic age, although it is quite likely that the Sur Series represents part of this time, perhaps late Paleozoic.

Great thicknesses of Upper Jurassic to Recent sedimentary, volcanic, and plutonic rocks reveal a complex history of deposition on the continental shelves and in deep, narrow marine troughs. Intermittent volcanism, plutonic intrusion, and orogenic activity were interspersed throughout this time. The last major orogeny, which developed the present "Coast Ranges province," occurred during late Pliocene to mid-Pleistocene time. Late Jurassic orogeny and granitic intrusion affected the Coast Range region to some extent as it did the Transverse Ranges, Sierra Nevada, Klamath Mountains, and much of the rest of California. Similarly, mid-to-Late Cretaceous mountain building took place, accompanied by the greatest and most widespread granitic invasions of California's history. Intermittent and local crustal disturbances occurred throughout the Tertiary, culminating in the Pliocene and Pleistocene Coast Range orogeny. This involved the most profound deformation in the history of the Coast Ranges.

Basement rocks of the Coast Ranges consist of two groups: (1) Upper Jurassic to Upper Cretaceous rocks of the Franciscan Formation that were deposited in deep offshore troughs, or eugeosynclines, and (2) the Upper Paleozoic (?) gneisses and schists of the Sur Series intruded by Upper Jurassic(?) and Upper Cretaceous granitic rocks. Older rocks have not been found beneath either of these major groups.

67-164 O - 66 - pt. I (Face p. 36)

	PRECAMBRIAN	PALEOZOIC	MESOZOIC	CENOZOIC



[Names in Roman type are formally named rock units. Terms in italics refer to informally named rock-stratigraphic units. Rock units of continental (nonmarine) origin are designated by *]
Vertical pattern indicates periods of apparent nondeposition; diagonal pattern designates parts of section that are older but unexposed or not identified.

* The stratigraphic nomenclature and age designations used in this chart do not necessarily follow the usage of the U.S. Geological Survey but follow the usage of authors who have described stratigraphy in the several parts of the State.

FIGURE 3. Generalized stratigraphic correlation chart for California.

67-164 O - 66 - pt. I (Face p. 36)

The Sur Series consists of gneisses, schists, and marble—formed from thick sedimentary and volcanic formations that were affected by high-grade metamorphism. They crop out most extensively in the Santa Lucia and Santa Cruz Mountains. Rocks of the Sur Series, and the granitic rocks that intrude them, yield extremely valuable crushed and broken stone, and limestone for the manufacture of cement. The Sur Series is also a major source of dolomite.

The Franciscan Formation consists of at least 20,000 feet of graywacke, dark shale, metavolcanic rocks, chert, minor limestone, and metamorphic rocks of the blue-schist and green-schist facies. The Franciscan is intruded by peridotite and serpentine, which perhaps also constitute the material of the upper mantle on which the Franciscan was deposited. These masses of ultramafic rock in places contain deposits of chromite, and are also the parent rocks of the nickel-bearing laterites. These rocks are also the source of extensive asbestos deposits being mined in San Benito and adjacent Fresno counties. The Franciscan Formation supplies crushed and broken stone and riprap, and has been a major source of manganese in the past. Franciscan rocks are found in all parts of the Coast Ranges except in the 20- to 40-mile-wide strip between the San Andreas and Nacimiento fault zones.

A major group of rocks with an aggregate thickness on the order of 30,000 feet represents all epochs from Late Jurassic to Late Cretaceous time. These unmetamorphosed shelf-facies rocks—sandstone, shale, siltstone, and minor conglomerate and limestone—lie on the Sur Series and Franciscan Formation and are also contemporaneous (at least, in part) with the Franciscan Formation and the granitic rocks. The thickest, most continuous sections of the shelf-facies sedimentary rocks dip under the Great Valley from the east flanks of the Diablo and Mendocino Ranges. Lower and Upper Cretaceous rocks are predominantly dark sandstone (graywacke) and arkose (granitic sandstone) with minor shale and conglomerate. They contain larger proportions of K-feldspar grains than does the Franciscan.

Cenozoic formations comprise a great variety of sedimentary and volcanic rocks but all are apparently of shallow marine (shelf and slope) and continental origin. Rapid lateral changes in facies and thicknesses reflect intermittent localized folding, faulting, and volcanism. Those changes are most marked at the margins of the basins and ranges. Paleocene marine sedimentary rocks are quite similar to those in Upper Cretaceous formations, but are not as thick or as widespread. Progressively more restricted seaways from Paleocene to late Eocene time limited the deposition of Eocene sands, muds, and clays to narrow basins in the area of the Coast Ranges.

From late Eocene to middle Miocene time, seaways in the Coast Range region were severely restricted and climates became markedly seasonal and locally semi-arid. Conglomerate, sandstone, shale, and mudstone of these epochs include shallow-marine materials and extensively distributed, and locally thick continental red beds. Oligocene formations crop out only in the southern Coast Range; probably the northern Coast Range area was above sea level during Oligocene time. In the Santa Cruz, Santa Lucia, and Diablo Ranges, shallow-water marine sandstone, shale, some conglomerate, and local tuff beds repre-

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Lower and middle Miocene formations consist of marine, shelf-facies sandstone, conglomerate, shale, and mudstone which were deposited in rather narrow basins extensively in the southern Coast Ranges and in a narrow trough as far north as the central Mendocino Range in the northern Coast Ranges. Middle Miocene seas were more widespread than those of the early Miocene. Great volumes of volcanic materials were extruded during middle Miocene time—tuff, breccia, agglomerate, rhyolitic to andesitic flows, and plugs.

Shallow seas reached a maximum extent in early late Miocene time. The most widespread Tertiary formation is the Monterey Formation of middle to late Miocene age which is found throughout the Coast Ranges as far north as Point Arena. All common lithologic types are represented, but most characteristic are siliceous shale, chert, and diatomaceous shale. The Miocene Epoch closed with deposition of coarser sandy marine sedimentary facies, such as the San Pablo, Santa Margarita, and Sisquoc Formations in more restricted basins between the rising Coast Ranges.

In Pliocene time, sands, muds, and some tuff were deposited in narrow, shallow marine embayments throughout the Coast Ranges as far north as the Eureka Basin. Most of the formations appear too thin, or were not deposited, in the anticlinal-crest areas, reflecting uplift and folding of many of the individual Coast Ranges. Late Pliocene and early Pleistocene time were marked by very restricted and thin local marine beds in narrow basins, and a remarkably widespread and locally thick series of conglomerate and gravel. Floods of gravel and coarse sand deposited in the channels, deltas, and floodplains of streams almost covered the site of the southern Coast Ranges and extended locally along the margins of the northern Coast Ranges. Volcanism was locally important, but did not compare with the great middle Miocene volcanic epoch. Late Quaternary formations include some coastal marine terrace deposits, bay muds, and beach sands, but most are flat-lying alluvium and local lake deposits.

Formations of Tertiary age are the principal source and reservoir rocks for petroleum and natural gas. Most of the petroleum products have come from the southern Coast Ranges. Principal production is from Miocene and Pliocene formations in the Santa Maria, Cuyama, and Salinas basins, and from the eastern flanks of the Diablo and Temblor ranges. Upper Miocene and lower Pliocene marine sedimentary rocks provide nearly all of California's diatomite. Quaternary deposits are supplying most of the State's needs for sand and gravel. Salt (sodium chloride), bromine, and magnesium compounds are now obtained in large quantities from the waters of San Francisco Bay and the Pacific Ocean at Moss Landing.

Three great north-northwest-trending fault zones dominate the structural pattern of the Coast Ranges. The most westerly of these is the Nacimiento-Sur fault zone which separates the western coastal block of Franciscan basement rocks from the granitic block east of that fault zone. This fault is probably essentially normal, with perhaps some strike-slip in a right lateral sense, but in its northerly projection extends into the Sur Thrust zone. No earthquakes of historic record seem to have originated in the Nacimiento-Sur fault zone.

The great San Andreas fault, striking obliquely across the Coast Ranges and Coast Range structures from the coast at Point Arena to the Tehachapi Mountains 400 miles southeast is California's best-known structural feature. South of the Tehachapi Mountains, the fault zone extends along the east side of the Salton Sea. It extends northward, offshore, probably at least as far as the Mendocino Escarpment. Like the Nacimiento fault zone, the San Andreas separates Franciscan basement on the east from the granitic basement. Movements on the San Andreas fault during the Quaternary have been right slip and normal; older displacements, probably beginning in Late Jurassic time, which formed the Franciscan-granitic rock contact, were perhaps predominantly vertical. Geologists are strongly divided on this latter point, however; some maintain that there has been a cumulative right slip of several hundred miles. The San Andreas fault dips very steeply east and is essentially straight in strike except at its southerly end and where it turns eastward as it enters the Transverse Ranges province. Prominent branches of the San Andreas fault are the Pilarcitos, Hayward, and Calaveras faults in the San Francisco Bay area. The Pilarcitos is an older, inactive fault, but the others have been the sources of a great many of California's earthquakes.

A third great fault zone, possibly related to the Nacimiento and San Andreas in origin, is the South Fork Mountain fault which separates the Franciscan block on the west from the Mesozoic granitic (and older crystalline rock) block on the east. This great fault zone constitutes the geologic and structural boundary between the Coast Ranges and the Klamath Mountains provinces. The major contact between Sierran granitic "basement" and Franciscan Formation of the Coast Ranges, which lies buried beneath sediments of the west side of the Great Valley, may be a southward continuation of the South Fork Mountain fault. This is an old, inactive fault.

Apparently of major importance in the structural picture are elongate masses of peridotite and the serpentine derived from it; they are essentially sill-like bodies which seem to have intruded rocks as young as Late Cretaceous in age. Because of the extreme mobility of serpentine, such bodies are almost everywhere in fault contact with other rock formations and are most commonly aligned along fault zones. They commonly appear as "cold intrusions" faulted against later rocks. Together with rocks of the Franciscan Formation, they form a series of diapiric structures or piercements along the anticlinal crest of the Diablo Range.

Folding of the Coast Ranges, like the accompanying faulting, has been complex, and individual fold axes can seldom be traced more than a few miles. Axial trends are generally parallel to the major faults and thus tend to strike a little more westerly than the trend of the Coast Ranges as a whole. Very little is known of structures within the complex Sur Series and of how these rocks responded to the forces which built the Coast Ranges. History of deformation within the Franciscan Formation is also little known because of the complex lithology, the discontinuity of individual lithologic units, and the massive character of the graywacke which comprises such a large part of the Franciscan. General heterogeneity of structure within the Franciscan Formation is in striking contrast to the more open folding of the shelf-and-slope sedimentary facies of approximately equivalent ages. Major faults in the Coast Ranges are much more continuous than the folded structures. Fold axes do not commonly continue from one range into the next.

The Coast Ranges are flanked on the east by many thousands of feet of Upper Jurassic, Cretaceous, and Cenozoic shelf-facies sedimentary rocks which dip homoclinally toward the Great Valley from the north end of the Sacramento Valley to the south end of the Diablo Range. This thick group of shelf-facies rocks is separated from the heterogeneously structured, eugeosynclinal Franciscan rocks on the west by a major fault zone marked by sill-like bodies of serpentine.

The Coast Ranges were formed essentially by contemporaneous folding, faulting, and uplift, probably beginning in Late Jurassic time, and occurring again and again with increasing intensity to culminate in the mid-Pleistocene. Local uplift and depression, fault movements, and mild folding have continued to the present.

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GEOLOGY OF THE KLAMATH MOUNTAINS

(By W. P. Irwin, U.S. Geological Survey, Menlo Park, Calif.)

The Klamath Mountains are made up of rocks that for the most part are older and more highly deformed than those of surrounding provinces. These older rocks, some of which are metamorphosed, are sedimentary and volcanic in origin. Their principal deformation was during the Nevadan (Jurassic) orogeny, during which they were intruded by ultramafic and granitic rocks. These rocks, including the intrusives, form a complex foundation, or subjacent terrane, on which younger less deformed sedimentary and volcanic rocks are deposited. The subjacent terrane of the Klamath Mountains is comparable to that of the Sierra Nevada, and the two doubtless join beneath a cover of superjacent rocks at the northern end of the Great Valley (pl. 1).

The sedimentary subjacent rocks are chiefly slaty shales, sandstones, and conglomerate, but locally include discontinuous lenses of limestone and thin-bedded chert. Volcanic rocks, most of which are basaltic or andesitic, but some of which are rhyolitic, occur at irregular intervals throughout the stratigraphic section of subjacent rocks. The most complete succession of subjacent strata is in the eastern part of the Klamath Mountains, where the stratigraphic section is 40,000 to 50,000 feet thick and ranges from Late Ordovician to Middle Jurassic in age (fig. 3). The economically most important of these are the Balaklala Rhyolite (Devonian) and Bully Hill Rhyolite (Triassic) for their copper deposits, the Bragdon Formation (Mississippian) for its gold-bearing quartz veins, and the McCloud Limestone (Permian) quarried for the manufacture of cement. In the western Klamaths, where the geology is more complex and not as thoroughly studied, the strata range from Devonian(?) to Late Jurassic in age. These are separated from the better known strata in the eastern Klamaths by an arcuate belt of metamorphic rocks that is concave to the east (pl. 1). The metamorphic belt includes hornblendic and micaceous schists that were formed from volcanic and sedimentary rocks during the Carboniferous or earlier.

The subjacent strata were deposited mainly in the ocean along the border of the ancient continent; perhaps some of the volcanics formed small islands and the limestones formed shallow reefs. This general environment of deposition likely existed essentially until the Nevadan orogeny, although there are gaps in the stratigraphic record as well as evidence of tectonic activity earlier, but perhaps less intense than the Nevadan. During the Nevadan orogeny, the thick, orderly succession of strata were folded, faulted, and intruded by ultramafic and granitic rocks. This orogeny culminated in the Late Jurassic with regional emergence of the subjacent terrane above sea level.

The overall structure of the subjacent terrane, which presumably developed chiefly during the Nevadan orogeny, is not clearly known. Most of the principal folds and faults trend parallel to the arcuate lithic belts, as do many linear ultramafic bodies and certain of the granitic intrusives (pl. 1). The arcuate pattern is interpreted to result from westward thrusting along low-angle faults; ultramafic rock has been intruded along some of the thrust faults. The ultramafic rocks are important as a source of chrome ore.

With emergence of the Klamath Mountains, near the close of the Jurassic, great quantities of debris were shed from the newly made land into the bordering seas. Erosion proceeded so vigorously that, by the Early Cretaceous, the cover was stripped from the once deeply buried Nevadan batholithic rocks. The detritus from the eroded cover was deposited as a thick section of strata in the bordering seas on the upturned edges of the deformed subjacent strata and on the eroded batholithic rocks.

Deposition of the marine superjacent strata continued during most of the Cretaceous as the land area shrank owing to erosion and slow submergence. Near the end of the Cretaceous, the Klamath region again rose above sea level, and although it is clear that the Cretaceous superjacent deposits once covered much of the Klamath region, only a few small patches now remain to be seen. The end of the Cretaceous marked the last significant marine invasion of the Klamath region.

During the Tertiary, the Klamath Mountains province continued to undergo erosion and was the source of detritus for marine and continental strata now exposed around much of its perimeter in Oregon and along its eastern side in California. Within the province, the Tertiary is represented chiefly by the continental Weaverville Formation of probable Oligocene age (fig. 3). The Weaverville Formation crops out in several structurally controlled, northeast-trending patches in the southern part of the province, and lies unconformably on Cretaceous and older rocks. It consists of beds of locally derived sandstone, mudstone, conglomerate, tuff, and lignite that probably were deposited on flood plains and in swampy lakes. In the extreme western part of the province a few small, thin patches of essentially horizontal beds of friable detrital rocks are found on the crests of ridges. These rocks, called the Wimer Beds, contain marine fossils of late Miocene age.

The crests of the ridges, on which the remnants of the Wimer Beds are found, are similar in altitude to the crests of other ridges nearby. This accordance of crestlines led to the idea that many of these broad-topped ridges are remnants of an ancient land surface of low relief, named the Klamath peneplain. Crestlines equated with this hypothetical erosion surface are widespread in the Klamath Mountains and increase in altitude from about 2,500 feet in central Del Norte County to more than 6,000 feet in southern Trinity County. A succeeding cycle of erosion, the Sherwood stage, destroyed much of the so-called Klamath peneplain and developed broad land surfaces at lower altitudes between the remnants. The Sherwood surface has in turn been dissected deeply by modern streams, giving rise to a second set of accordant ridges.

Volcanic rocks that range from basalt to rhyolite in composition erupted extensively along the eastern edge of the Klamath Mountains during the Cenozoic Era. They are the principal rocks of the Cascades province and are prominent in the northern part of the Great Valley. Within the limits of the Klamath Mountains these volcanic rocks occur as thin erosional outliers that at some places have overlapped the boundary between the subjacent terrane and the Cretaceous superjacent rocks. The oldest of these is the Tuscan Formation of Pliocene age, which consists of clastic volcanic rocks interlayered with sands and gravels.

Weakly consolidated Pleistocene gravels of the Red Bluff Formation are widespread in the northern part of the Great Valley and lap onto the southeastern edge of the Klamath Mountains. Within the Klamath Mountains, sands and gravels are found on terraces at many levels along the courses of the major streams, and some of the higher of these may be equivalents of the Red Bluff Formation. Many of these terrace deposits, as well as the sands and gravels in the present drainage channels, have been an important source of placer gold.

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GEOLOGY OF THE SOUTHERN CASCADE RANGE, MODOC PLATEAU, AND GREAT BASIN AREAS IN NORTHEASTERN CALIFORNIA

(By G. A. Macdonald, U.S. Geological Survey, Hawaii Institute of Geophysics, Honolulu, Hawaii; and T. E. Gay, Jr., California Division of Mines and Geology, San Francisco, Calif.)

The Cascade Range, Modoc Plateau, and Great Basin geomorphic provinces in northeastern California are discussed together in this section because their general lithologic and structural continuities are more notable than their dissimilarities.

Southern Cascade Range

The Cascade Range is a volcanic mountain range that extends southward into California from Oregon and Washington. In Oregon and northernmost California, the oldest rocks of the range—the Western Cascade series—are Miocene in age and rest on marine and nonmarine sedimentary rocks of Eocene and Oligocene age. The Western Cascade rocks consists of lava flows of basaltic, andesitic, and dacitic composition, with intercalated pyroclastic rocks, some of which are rhyolitic. They are characterized by a general alteration of ferromagnesian minerals to chlorite and related minerals, which gives a slight greenish coloration to the rocks. The alteration is probably the result of a general permeation by hydrothermal solutions near the end of the Miocene Epoch, when the rocks were somewhat uplifted by mountain-building movements. In Oregon, the rocks were invaded by small Tertiary granitoid intrusions which brought some deposition of metallic ores. In California, however, these intrusions are not exposed, and no economic metallization has yet been found in the Western Cascade rocks of this State.

As their name implies, the Western Cascade rocks are exposed in a north-south belt along the western side of the Cascade Range. In California, this belt is about 5 to 15 miles wide and extends about 50 miles south of the Oregon border. The southernmost exposures of the rocks are just southwest of the town of Mount Shasta.

After the Western Cascade rocks were eroded for an interval in late Miocene to early Pliocene time, volcanic activity resumed in the early Pliocene. A new series of rocks, the High Cascade series, was erupted to form a ridge overlapping and parallel to the Western Cascade series but slightly farther east—a belt about 30 to 40 miles wide and 150 miles long in California.

The High Cascade rocks range from basalt to rhyolite, with pyroxene andesite predominating. The High Cascade volcanism resulted in an extension of the Cascade Range some 80 miles southeast of the Western Cascade belt, beyond Mount Lassen, to Lake Almanor. At the southeast end of the High Cascade belt, its lavas overlap the metamorphic and granitic rocks of the Sierra Nevada along an irregular line that runs in general southwestward from near Susanville past Lake Almanor toward Oroville. The oldest of the Pliocene High Cascade rocks in California are near the southeast end of the range. In the region just southwest of Lassen National Park, High Cascade andesite flows are overlain by the late Pliocene Tuscan Formation. The latter consists largely of volcanic breccias deposited as mudflows, grading westward into volcanic conglomerates and sandstones, and spreading far southward over the western edge of the Sierra Nevada. Interbedded with the Tuscan breccias near their base is the rhyodacitic Nomlaki Tuff Member, formed by incandescent flows of volcanic ash that were still so hot when they came to rest that the particles of glass became welded together in the middle and lower parts of the layer.

In the area east of Redding, Cascade lavas are absent beneath the Tuscan Formation, which there rests directly on sedimentary rocks of Eocene and Late Cretaceous age. The Eocene rocks consist of conglomerate and sandstone of the nonmarine Montgomery Creek Formation, containing fossil leaves, petrified wood, and some beds of low-grade coal. The Late Cretaceous rocks are sandstones and shales, which elsewhere contain some petroleum, but so far none has been found in this area.

The early High Cascade lavas were very fluid basalt and basaltic andesite that erupted quietly, with very little explosion. They erupted from fissures and built a broad ridge of overlapping, low shield volcanoes and lava flows. As time passed, some of the erupting lava became more silicic, and the amount of explosive activity increased. Big composite cones of interbedded andesitic lava flows and pyroclastic debris were built along the crest of the ridge, with associated domes and flows of dacite, and, toward its southern end, rhyolite. The big cones included Mount Shasta; Burney Mountain; Crater (Magee) Peak; a mountain known as Mount Tehama, or Brokeoff Volcano, that once occupied the vicinity of the present Lassen Peak; and another that once stood just to the southwest, in the area of Mineral. On the flanks of the latter, huge flows of rhyolite lava and ash were erupted, and probably as a result of the draining of this magma from beneath, the top of the mountain collapsed to form a caldera like the well-known caldera of Crater Lake in Oregon. The summit of Brokeoff Volcano also caved in to form a caldera, within which continued volcanism built a series of dacite domes, including Lassen Peak.

Just north of the great dome of Lassen Peak a row of similar domes, the Chaos Crags, grew in very recent time. Explosions at their base undermined the north edge of the domes, which collapsed in a series of avalanches to form the Chaos Jumbles. About the same time a flow of incandescent ash swept down the valley of Manzanita Creek from the northwest side of Lassen Peak. The last of the avalanches and the ash flows occurred only about 200 years ago. Mount Lassen erupted most recently during the summers of 1914–1917, with a small flow of lava at the summit of the dome, and mudflows and a glowing avalanche to the northeast, down the valleys of Lost and Hat Creeks.

Mount Shasta, the largest of the Cascade Range volcanoes, rises 10,000 feet above its base and has a volume of about 80 cubic miles. The main cone consists at the base largely of flows of basaltic andesite, and in its upper part predominantly of flows of pyroxene andesite with a smaller proportion of dacite. Pyroclastic materials and mudflow deposits are sparse. After the main cone had formed, a north-south fissure across it controlled the emplacement of a later series of domes, cinder cones, and associated lava flows, ranging from basalt to dacite. During late Pleistocene time, flows of basaltic andesite extended more than 40 miles southward along the Sacramento River Canyon from Everitt Hill, a small shield volcano on the southwest flank of Mount Shasta. At Shasta Springs a large volume of water issues from the base of these flows. Also in the waning stages of the volcano, an east-west fissure on its western flank resulted in the lateral cone of Shastina, and the dome of Black Butte at the western base of the mountain. Postglacial lava flows from vents below Shastina, and two small domes that grew in the crater of Shastina, escaped erosion by the glaciers that covered most of Mount Shasta and Shastina during the Pleistocene epoch.

The latest eruptions of Shasta, possibly as recent as 1786, formed a blanket of pumice and cinder over the top of the mountain. A small acid hot spring still exists at the edge of the snowfield that fills the summit crater. Although there is no sign that they are imminent, future eruptions of Shasta, Lassen, and other Cascade volcanoes, are not only possible, but probable.

The Medicine Lake Highland, some 35 miles east of Mount Shasta, is generally regarded as an outlier of the Cascade Range. The region is underlain by the Oligocene to Miocene Cedarville Series and the Pliocene Warner Basalt, both of which are widespread in the Modoc Plateau, to the east. The building of the Highland was preceded, in early Pliocene time, by eruption of flows and domes of rhyolite and rhyolitic obsidian and a flow of incandescent ash, and farther west by the building of a series of cones of massive basalt flows. Then, in late Pliocene and early Pleistocene time, a shield volcano 20 miles across was formed, of pyroxene andesite. After reaching a height of about 2,500 feet, the top of the shield collapsed to form a caldera 6 miles long, 4 miles wide, and 500 feet deep. Lava rising along the circular fractures that bounded the caldera formed flows that poured into it, building cones that eventually overtopped its rim and sent new flows down the outside of the shield. The resulting eight small volcanoes completely hide the caldera boundaries, forming between them the basin that holds Medicine Lake. Later Pliocene and Pleistocene eruptions of andesite, dacite, and rhyolite built broad ridges north and south of the lake basin, including the perlitic rhyolite mass of Mount Hoffmann, flows of glassy dacite just north of Medicine Lake and on the south side of Mount Hoffman, and finally—about 1700 years ago—the obsidian masses of Little Glass Mountain and Glass Mountain. Transition of the Medicine Lake Highland to the Modoc Plateau is marked by Recent basalt flows and cinder cones of types widespread in the Plateau, on the flanks of the Highland.

Modoc Plateau

The Modoc Plateau is a highland region capped by vast late Tertiary and Quaternary basalt plains and numerous volcanic shield cones that largely overlap older basin-range structures. These structures are typified by fault-block mountains of Tertiary volcanic rock, with intervening basin-like grabens that commonly contain sedimentary rocks deposited in large Pliocene and Quaternary lakes that had resulted from interruption of the drainage by faulting or volcanism. To the east and southeast the Modoc Plateau merges with the Great Basin, across an arbitrary boundary. The Warner Range, which borders the Modoc Plateau on the east, is generally regarded as a part of the Great Basin, but its rocks and general structure are continuous with those of the Modoc region. On the west, the border of the Modoc Plateau with the Cascade Range is also indefinite; the faulting characteristic of the Modoc region extends into the edge of the Cascade Range, and some types of rocks are common to both provinces.

The oldest rocks of the Modoc region are a series of interbedded lava flows, pyroclastic rocks, and lake deposits forming some of the block-faulted ranges, and generally tilted at an angle greater than 20°. Through similar lithology and structural relationships, they are correlated with the Cedarville Series, which is best exposed in the Warner Range, where it ranges in age from late Oligocene to late Miocene. The Cedarville Series is mainly andestitic, but ranges from basalt to rhyolite. Several small gold, copper, and mercury deposits have been found in rocks associated with it.

Rocks of Pliocene age include both volcanic and lake deposits. The latter include the Alturas Formation, which occupies the basin west of the Warner Range in the vicinity of Alturas, and similar rocks in the basin of Lake Britton and the valley of Willow Creek west of Tulelake. The lake sediments are tuffaceous siltstones and ashy sandstones—the latter commonly ranging to current-bedded, water-laid tuffs—and thick, extensive deposits of diatomite with variable ash content. The Pliocene volcanic rocks include basalt and andesite lava flows and mud flows, and dacitic to rhyolitic pyroclastic rocks. Southwest and west of Alturas, the Alturas Formation is locally associated with beds of pumiceous welded tuff, formed by incandescent flows of ash; the tuff has been quarried to a minor extent for building stone. Similar but less-welded Pliocene ash-flow deposits are also present in the mountains between Canby and Adin, where they are interbedded with lava flows and mud-flow deposits, as well as stream- and lake-deposited sediments.

The older Pliocene rocks, like those of Miocene age, are found in block-faulted mountain ranges. Later volcanic rocks, also tentatively assigned to the Pliocene, are much less faulted and retain to a much greater degree their original constructional land forms. These include a series of small shield volcanoes between Honey Lake and the Madeline Plains.

Throughout much of the Modoc Plateau region the basins between the fault-block ranges were flooded by wide-spreading, very fluid flows of basalt, erupted mostly from fissure vents, that formed flat plain surfaces rather than volcanic cones. These "plateau" basalts have generally been referred to as "Warner Basalt," but because of uncertainty of the correlation with the basalt farther northeast, the basalt in the region just north of Lassen National Park has been called the Burney Basalt. At the north edge of Lake Britton, pillow lavas at the base of the Warner Basalt are intermingled with Pliocene diatomaceous lake sediments, and are almost surely of Pliocene age; but near Lassen Park the Burney Basalt overlaps folded and eroded andesites that cannot be older than latest Pliocene, and it is therefore unlikely that the basalt is older than earliest Pleistocene. In the Modoc Plateau region as a whole, the rocks called Warner Basalt probably range from late Pliocene to Pleistocene in age.

Younger than the Warner Basalt is a series of lower Pleistocene to Recent basalt flows and associated cinder cones; small shield volcanoes, many of them capped with cinder cones; and lake beds. The lake sediments resemble those of Pliocene age. The shield volcanoes are mostly basalt, but partly andesite. Chemically, mineralogically, and texturally, many of these flow basalts resemble the Warner Basalt. Many of them are of pahoehoe type, like most of the Warner flows, and in places contain many lava tubes such as those of the Lava Beds National Monument and Hat Creek Valley, where the lavas are probably less than 2000 years old.

Other very recent flows are of the aa or block lava type. These include the Callahan and Burnt Lava flows on the flanks of the Medicine Lake Highland, and the quartz basalt flows at Cinder Cone in the northeastern part of Lassen National Park, which last erupted in 1851.

The faults of the Modoc region trend in a northwesterly to northerly direction. The Likely fault is believed to have had appreciable right-lateral movement, but most of the faults are normal, with primarily vertical displacement. The normal faulting reached a maximum near the end of the Miocene, but has continued into Recent time. Occasional earthquakes suggest that some of the faults, such as that along the east side of Hat Creek Valley, are still active.

Large volumes of water issue from the Warner and later basalts at several places, including Big Spring, near Old Station on Hat Creek; Rising River, farther north in the same valley; the springs at Burney Falls and along Burney Creek just above the falls; and those at the headwaters of Fall River. The latter, with a flow of about 900 million gallons daily, are among the largest springs in the United States.

GREAT BASIN

Two minor projections of the Great Basin province—the Warner Range-Surprise Valley area, and Honey Lake Valley—adjoin the Modoc Plateau and the Sierra Nevada provinces in northeastern California. Their dominant northeast-trending block-faulted structure is characteristic of the Great Basin province, but their rocks are related to adjacent provinces rather than to those of the Great Basin. The Warner Range is uplifted at least 5,500 feet vertically, west of the Surprise Valley normal fault, and consists mainly of andesitic to basaltic flows and pyroclastic rocks of the Oligocene to Miocene Cedarville series. Flows of Pliocene to Pleistocene "Warner Basalt" cover the gentler sloping southwest flank of the range, and with the coalescing Miocene and Pliocene shield volcanoes that form its southern end, are transitional from the Great Basin to the Modoc Plateau. Toward the Oregon border, the range has a steeper, faulted western front, lapped with Quaternary gravels that probably represent accelerated erosion and transport in glacial times. Intrusive masses of post-Cedarville rhyolitic rocks in the northern part of the range include the gold veins of the High Grade district, the quicksilver showings along the Goose Lake front of the range, and notable deposits of obsidian and perlite.

Surprise Valley, the near-desiccated site of Pleistocene Lake Surprise—contemporary of Lake Lahontan, which was only 35 miles to the south—is a graben east of the spectacular Surprise Valley fault scarp. Numerous hot springs and the eruption of a mud volcano in 1955 suggest recency of fault movement and continued connection with underlying thermal zones.

Honey Lake Valley is a graben wedged between the northern end of the Sierra Nevada granitic mountains, and the southern end of the Modoc Plateau volcanic terrane. Spectacular faults form the Sierra front and bound the Fort Sage Mountains block at the southeast end of the Valley. Steeply tilted and folded Tertiary lake sediments at the southeast end of Honey Lake are almost concealed by Recent lake and alluvial cover. Tufa-building hot springs along the northeast edge of the valley, some with traces of quicksilver, suggest hidden extensions of province-bounding faults.

GEOLOGY OF THE GREAT VALLEY

(By C. A. Repenning, D. L. Jones, and W. O. Addicott, U.S. Geological Survey, Menlo Park, Calif.)

The Great Valley of California is an elongate northwest-trending structural trough formed by the westward tilting of the Sierra Nevada block against the eastern flank of the Coast Ranges. In general, sediments deposited in this trough dip uniformly westward away from the Sierra Nevada except in a belt along the southern and western sides of the Great Valley where deposition was greatest and where deposits generally dip to the east. The Coast Ranges have not developed in as structurally uniform a way as has the Sierra Nevada and the western limit of the Great Valley depositional basin was poorly defined in pre-Tertiary time. In early Tertiary time, however, evolution of the Coast Ranges progressed to the point where the western limits of the Great Valley depositional basin were in large part coincident with those of the modern geomorphic province.

In this great trench the accumulation of sediments may locally have reached a thickness of 6 miles in the San Joaquin Valley and 10 miles in the Sacramento Valley. Most of the deposits in the Sacramento Valley are composed of Upper Jurassic and Cretaceous sandstone and siltstone of marine origin. The deposits in the San Joaquin Valley by contrast, are largely Cretaceous and Tertiary marine sandstone, siltstone, and claystone with an increasing proportion of continental deposits in younger strata. The consequent facies variations in the Tertiary deposits of the San Joaquin Valley have led to a complex stratigraphic nomenclature and have provided a wide variety of stratigraphic traps for the accumulation of petroleum.

Pre-Tertiary Rocks

Clastic upper Mesozoic rocks, ranging in age from Late Jurassic to Late Cretaceous, form an enormously thick wedge that thickens from a few hundred feet on the east to over 40,000 feet on the west. The rocks on the eastern side are dominantly shallow water marine, with perhaps some minor brackish water or nonmarine beds present, and on the western side are dominantly deep water, marine turbidites. The present western margin of these rocks is a major fault marked by extensive intrusion of serpentine that separates the structurally simple, eastward-dipping rocks of the Great Valley from the structurally complex and partly metamorphosed upper Mesozoic rocks of the Coast Ranges.

Upper Jurassic rocks are thickest along the western edge of the Sacramento Valley where they comprise about 15,000 feet of dominantly dark gray fine- to coarse-grained clastic sediments. Marine volcanic rocks are locally present in the lower part of the sequence.

In the San Joaquin Valley, Upper Jurassic rocks are much thinner than in the Sacramento Valley, and range in thickness from a few hundred feet to perhaps several thousand feet. The dominant rock type is bluish-gray siltstone and shale with fossiliferous, light gray-weathering limestone concretions.

Lower Cretaceous rocks are thickest and most widespread on the western side of the Sacramento Valley where they comprise 15 to 20 thousand feet of alternating thick units of mudstone, sandstone, and conglomerate. Facies changes along strike are common, and there is complex intertonguing and lensing-out of sandstone and conglomerate beds.

In the San Joaquin Valley, a very thin sequence of lowermost Cretaceous rocks apparently rests conformably on Upper Jurassic rocks, and this, in turn, is overlain directly in many places by thick Upper Cretaceous rocks. In a few places, beds of late Early Cretaceous (Albian) age crop out, but their distribution and relationship are poorly understood. Apparently much of the San Joaquin Valley region either received little or no sediment during most of Early Cretaceous time, or the rocks were removed by erosion prior to deposition of Upper Cretaceous beds.

Upper Cretaceous rocks are widespread on both the east and west sides of the Great Valley and consist of alternating thick units of sandstone, mudstone, and locally thick conglomerate lenses. In the southern and central part of the western Sacramento Valley, each sandstone and mudstone unit has received a formational name as shown on the correlation chart, but these units become unrecognizable to the north. On the east side of the Sacramento Valley, a few thousand feet of fossiliferous sandstone, shale, and conglomerate are exposed in the valleys of the major rivers. Near Chico these deposits have been named the Chico Formation.

Uppermost Cretaceous rocks which occur only in the subsurface in the southern and central parts of the Sacramento Valley contain large reserves of gas. The principal Cretaceous producing horizons are the Forbes Formation, Kione Formation or Sand, and Starkey Sand.

Upper Cretaceous rocks of the San Joaquin Valley are generally subdivided into the Panoche Group or Formation and the overlying Moreno Formation or shale. The Panoche Group comprises over 20,000 feet of alternating thick units of shale, sandstone, and conglomerate that exhibit rapid facies changes along strike.

The Moreno Formation consists of about 3,000 feet of purple and maroon claystone with minor beds of sandstone and white porcellanite. Organic remains, mainly fish scales, foraminifera, and diatomite, are common, as is pyrite in the subsurface and gypsum at the surface. Deposition probably took place in a restricted basin with stagnant conditions near the bottom. The uppermost part of the Moreno Formation is of earliest Tertiary age.

Significant natural gas production from sandstone reservoirs in the Panoche and Moreno is developed in several fields in the northern part of the San Joaquin Valley, principally in the vicinity of Stockton.

Tertiary Rocks

In contrast to pre-Tertiary deposition, Tertiary deposition took place in more limited basins which more nearly approximate the modern boundaries of the province. Three structural developments restricted the Tertiary depositional basins: evolution of the Coast Ranges progressively limited the westward continuity of depositional basins with the Pacific; proportionately greater westward tilting of the southern part of the Sierra Nevada block accentuated basining in the San Joaquin Valley area so that marine basins gradually withdrew southward from the Sacramento Valley; and a prominent arch, the Stockton arch, united the Sierra Nevada with the Coast Ranges and disintegrated the continuity of the marine depositional basins within the Great Valley province (fig. 4).

Paleocene and early Eocene marine deposits were formed in the southern part of the Sacramento Valley. This sequence includes the Martinez and Meganos Formations, important gas producing units. The overlying Capay Formation is a widespread transgressive unit that unconformably oversteps lower Tertiary and Upper Cretaceous rocks towards the north and the east in the subsurface. These formations are composed of dark gray, green, and brown siltstone, sandstone, and conglomerate with locally abundant glauconite. Scattered continental deposits of probable Paleocene or Eocene age occur in the northern end and along the eastern side of the Sacramento Valley.

Two unusual subsurface features of early Eocene age are the Princeton and Meganos Gorges of the central and southern parts of the

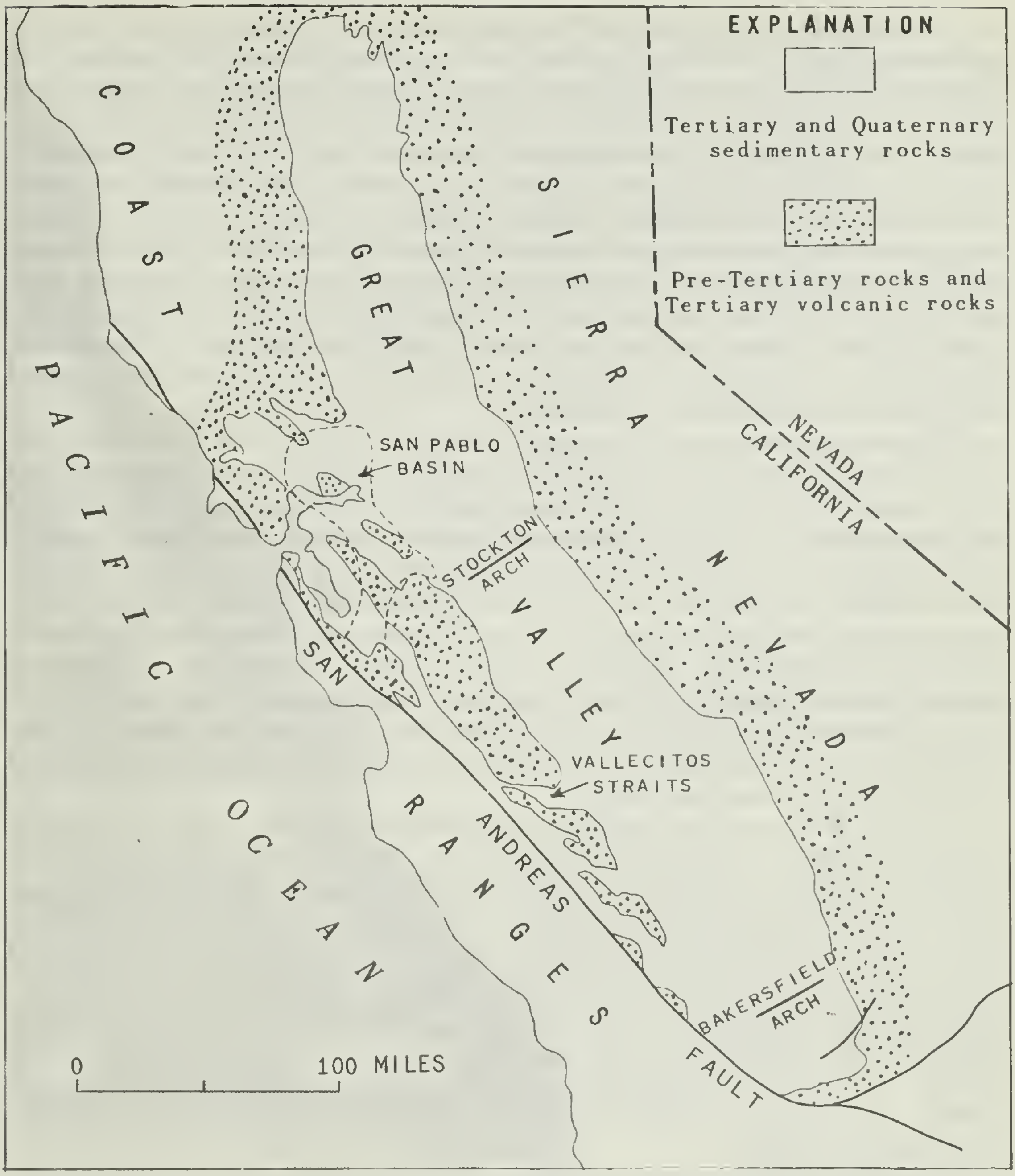

FIGURE 4. Index map of Great Valley locating selected palegeographic features.

Sacramento Valley. These south- to southwest-trending submarine erosional channels and their sedimentary fill are important in the entrapment of gas in west-dipping Cretaceous and lower Tertiary sandstones.

Marine early Tertiary shale and minor sandstone included in the Lodo Formation were deposited in a basin lying between the Stockton arch and Bakersfield. One of several prominent Paleocene to middle Eocene sandstone units along the western side of the basin, the Tesla Formation, may have been deposited in a strait that crossed the western end of the Stockton arch and united the Paleocene to middle Eocene basins on either side. Part of the early Tertiary continental deposits along the east side of the San Joaquin Valley may be equivalent in age to the Lodo.

A widespread unconformity separates early Eocene from late Eocene rocks south of the Stockton arch. On this erosion surface the Domengine Sandstone and the Kreyenhagen Shale were deposited. North of the arch a relatively thin blanket of sandstone, the Ione Formation, covers the east side of the south half of the Sacramento Valley. Thick late Eocene deposits consisting of interbedded shale and sandstone (Domengine?, Nortonville, and Markley Formations) are present only in the southwestern part of the valley. Late Eocene deposits are missing on the Stockton arch. In the San Joaquin Valley the late Eocene marine basin extended southward to deposit the thick Tejon Formation at the foot of the San Emigdio Mountains. Continental sediments of apparent late Eocene age were deposited along the foot of the Sierra Nevada.

Oligocene deposits were formed in essentially the same basins as the late Eocene deposits. North of the Stockton arch a pronounced period of erosion followed late Eocene deposition. In the southern part of the Sacramento Valley a prominent south- to southwest-trending submarine channel of late Eocene to Oligocene age, the Markley Gorge, was eroded into lower Tertiary strata and subsequently filled with marine sand and siltstone. South of the arch, however, Eocene to Oligocene deposition appears to have been continuous. Oligocene sediments are dominantly shale and are often included with the underlying Kreyenhagen Shale. In the southern part of the San Joaquin Valley, however, sandstone, partly of continental origin, is a prominent part of the Oligocene section.

In early Miocene time no marine deposits were formed north of the Stockton arch. South of the arch lower Miocene marine deposits in the south half of the San Joaquin Valley consist of sandstones and sandy shales including the Temblor Formation and the Vedder Sand. Continental formations border these marine deposits on the south and the southeast. A fairly thick sheet of continental deposits interfingers with the marine section in the central part of the San Joaquin basin and extends northward across the Stockton arch into the Sacramento Valley. Extensive rhyolitic tuffs and other volcanic materials are present in the continental lower and middle Miocene deposits of the Sacramento Valley.

In middle Miocene time the areas of deposition remained essentially the same but less marine sandstone was formed. Sand content increased again during the late Miocene as the basin shoaled and the shoreline began retreating towards the west. The Santa Margarita Sandstone of the eastern part of the marine basin was overlain by nonmarine Miocene- and Pliocene deposits including the Chanac Formation. To the west, in the deeper part of the basin from Coalinga to the southern end of the valley, dominantly fine-grained diatomaceous, cherty and siliceous sediments were deposited. Discontinuous offshore sandstones in the southern part of the basin, such as the Stevens Sand, form many oil-producing stratigraphic traps.

North of the Stockton arch, the sea gradually transgressed eastward from the San Pablo basin west of the Great Valley and by late Miocene time extended into the western part of the Sacramento Valley.

During the late Miocene and the Pliocene volcanic sediments being deposited in the southeastern quarter of the Sacramento Valley changed composition from rhyolitic (Valley Springs Formation) to andesitic (Mehrten Formation). The change from rhyolitic to andesitic debris is also found in the marine conglomerates of the San Pablo Group near the southwestern edge of the Sacramento Valley.

Tectonic activity in the Great Valley at the beginning of Pliocene time resulted in erosion in many areas, particularly along the western edge of the San Joaquin Valley. Many of the oil fields in this area produce either from structural traps caused by the early Pliocene warping or from truncated Miocene reservoir beds sealed by Pliocene deposits. With few exceptions, the present boundaries of the Great Valley were developed during the early Pliocene orogeny, and Pliocene deposition, largely continental, took place in all parts of the valley.

Pliocene marine deposition in the Great Valley was restricted to the south half of the San Joaquin Valley. In the western part of the area shallow water conglomerate, sandstone, and sandy shale of the Jacalitos, Etchegoin, and San Joaquin Formations were deposited. The basal Pliocene units unconformably overlie the upturned edges of older rocks along the western and southern margins of the valley. As Pliocene deposition continued the sea gradually retreated and the thick wedge of continental deposits of the southeastern part of the valley spread basinward. The nonmarine Chanac and Kern River Formations of the southeastern San Joaquin Valley are continuous with Pliocene continental deposits that cross the Stockton arch and extend throughout the Sacramento Valley.

Pleistocene Rocks

Deposition in most parts of the Great Valley was continuous from Pliocene to Pleistocene time. In the area of marine Pliocene deposition fresh-water lakes were formed at about the beginning of Pleistocene time due to disintegration of the seaway between the Great Valley and the Pacific by rising blocks of the Coast Ranges. Lacustrine sandy shale and sandstone of the Tulare Formation unconformably overlie marine Pliocene rocks along the west side of the Valley. These grade marginally into continental deposits.

Summary

During the later Mesozoic the Great Valley was the site of deposition of a great wedge of marine sedimentary rocks that reached thicknesses of more than 40,000 feet along the west side. As deposition continued the locus of maximum sedimentation gradually was displaced southward from the northern part of the Great Valley to the extreme south end by latest Tertiary time. Widespread Mesozoic deposits of Late Cretaceous age gave way to much restricted depositional basins in the early Tertiary when the Great Valley became separated by the cross-valley Stockton arch. Tertiary marine deposition in the southern part of the Sacramento Valley north of the Stockton arch continued into the Oligocene after which the seas retreated to the San Pablo Basin, a small marginal basin to the southwest. The initial locus of marine Tertiary deposition in the San Joaquin Valley was centrally located adjacent to the Vallecitos Straits, a persistent Paleocene to middle Miocene connection to the sea. Beginning in late Eocene time, the locus of deposition shifted toward the south end of the Valley and an additional marine connection opened along the southwest side of the Valley. Upper Eocene and later sedimentary deposits were localized in sub-basins created by a cross-valley submarine ridge, the Bakersfield arch. Marine deposition ceased at the close of the Pliocene.

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GEOLOGY OF THE SIERRA NEVADA

(By P. C. Bateman, U.S. Geological Survey, Menlo Park, Calif.)

The Sierra Nevada is a strongly asymmetric mountain range—it has a long gentle western slope and a short steep eastern escarpment that culminates in its highest peaks. It is 50 to 80 miles wide and runs west of north through eastern California for more than 400 miles—from the Mojave Desert on the south to the Cascade Range and Modoc Plateau on the north. Mount Whitney, in the southeastern part of the range, attains a height of 14,495 feet and is the highest point in the conterminous 48 States. The "High Sierra," a spectacular span of the crest, which extends north from Mount Whitney for about a hundred miles, is characterized by a procession of 13,000- and 14,000-foot peaks.

The Sierra Nevada is a tremendous physical barrier and a highly effective trap for capturing moisture from air moving eastward from the Pacific. Warm moist air from the ocean is forced upward into colder regions; and because cool air can hold less moisture than warm air, precipitation across the Sierra Nevada is heavy. The small precipitation in the arid Great Basin to the east, in the rain shadow of the Sierra Nevada, is evidence of the effectiveness of the Sierra Nevada as a trap for moisture.

General Geologic Relations

The Sierra Nevada is a huge block of the earth's crust that has broken free on the east along the Sierra Nevada fault system and been tilted westward. It is overlapped on the west by sedimentary rocks of the Great Valley and on the north by volcanic sheets extending south from the Cascade Range. Volcanic sheets cap large areas in the north part of the range.

Most of the south half of the Sierra Nevada and the east half of the north part is composed of plutonic (chiefly granitic) rocks of Mesozoic age. These rocks constitute the Sierra Nevada batholith, which is part of a belt of plutonic rocks that runs southward into Baja California and northward into western Nevada, Idaho, and British Columbia. In the north half of the range the batholith is flanked on the west by the western metamorphic belt, a terrane of strongly deformed and metamorphosed sedimentary and volcanic rocks of Paleozoic and Mesozoic age. The famed Mother Lode passes through the heart of the western metamorphic belt. Farther south, scattered remnants of metamorphic rock are found within the batholith, especially in the western foothills and along the crest in the east-central Sierra Nevada. Sedimentary strata of Paleozoic and late Precambrian age predominate east of the Sierra Nevada in the White and Inyo Mountains.

Paleozoic and Mesozoic Stratified Rocks

The Paleozoic strata in the metamorphic remnants of the eastern Sierra Nevada are chiefly metamorphosed sandstone, shale, and limestone, whereas those in the western part of the range contain abundant volcanic rocks and sedimentary rocks that were derived from volcanic rocks. The materials in the eastern strata were derived chiefly from the erosion of older terranes and accumulated in shallow seas where limestone reefs flourished (miogeosynclinal environment) ; on the other hand, much of the materials in the western strata were derived from volcanic outpourings and accumulated to great thickness in deeper parts of the ocean (eugeosynclinal environment).

The most complete section of Paleozoic rocks in the eastern Sierra Nevada is in the Mount Morrison roof pendant, where more than 30,000 feet of strata of Ordovician to Permian (?) age are exposed. There the oldest rocks, chiefly slate and chert, are overlain by sandy limestone and calcareous sandstone; these strata are overlain, in turn, by thin-bedded hornfels that was derived from siltstone, mudstone, and shale.

In the western metamorphic belt, most of the Paleozoic strata have been referred to the Calaveras Formation, which contains sparse fossils of Permian age in its upper part, but which is very thick and for the most part unfossiliferous. However, strata of Mississippian and Silurian (?) ages are present in the Taylorsville area, at the north end of the belt. In the southern part of the western metamorphic belt, the most extensive Paleozoic rocks are carbonaceous phyllite and schist with thinly interbedded chert, but lenses of mafic volcanic rocks and carbonate are widespread and locally attain thicknesses of several thousand feet. In the northern part, mafic volcanic rocks, slate, and sandstone constitute about equal parts of the Paleozoic section.

Strata of Mesozoic age crop out in several northwest-trending belts that parallel the long axis of the Sierra Nevada. In the eastern part of the range, a belt of metamorphic remnants that contains Mesozoic strata extends for more than 150 miles. The rocks in this belt are chiefly volcanic rocks of intermediate composition and graywacke-type sandstone derived chiefly from volcanic rocks. These rocks weather gray and contrast strongly with nearby strata of Paleozoic age which weather reddish brown. The thickest section of Mesozoic strata is exposed in the Ritter Range roof pendant and is about 30,000 feet thick. Early Jurassic fossils have been collected from a locality about 10,000 feet above the base of this section.

In the western metamorphic belt, the Paleozoic strata are flanked by Mesozoic strata on the west and, in the north part, also on the east. In addition, at least part of the strata in a group of roof pendants that extends for about 65 miles southeast through the heart of the batholith from lat 37° N. is of Mesozoic age.

These strata of the western metamorphic belt have yielded both Triassic and Jurassic fossils, but Triassic strata are of small extent and most of the strata are Upper Jurassic. The Upper Jurassic rocks include sequences of slate, graywacke, conglomerate, and volcanic rocks. These rocks commonly are interbedded and in places intertongue with volcanic rocks.

The Paleozoic and Mesozoic strata of the Sierra Nevada have been complexly folded and faulted, and steep or vertical beds, cleavage, and lineations, including fold axes, are common. A predominance of opposing, inward-facing top directions in the strata on the two sides of the range define a complex faulted synclinorium, the axial part of which is occupied by the granitic rocks of the batholith. The axis of the synclinorium trends about N. 40° W. in the central part of the range but trends northward in the northern part.

The eastern limit of the synclinorium is marked by a belt of Precambrian and Cambrian rocks that extends from the White Mountains southeastward into the Death Valley region. The western limit presumably lies beneath the Cretaceous and Tertiary strata of the Great Valley. The range-front faults that bound Owens Valley and the east side of the Sierra Nevada strike obliquely across the major structures in the Paleozoic and Mesozoic strata. In the White and Inyo Mountains and in many remnants within the Sierra Nevada batholith the strata are strongly folded and faulted, causing many repetitions of formations, but in the Mount Morrison and Ritter Range pendants of the eastern Sierra Nevada the gross structure is homoclinal, and tops of beds face west across more than 50,000 feet of vertical or steeply dipping strata ranging from Ordovician to Jurassic in age.

In the western metamorphic belt the gross distribution of strata resulting from the development of the synclinorium has been reversed by movement along steeply dipping fault zones of large displacement, and the Paleozoic strata lie between two belts of Mesozoic strata. The internal structure of the individual fault blocks is, in general, homoclinal, and most tops are to the east; beds dip eastward steeper than 60°. The homoclinal structure is interrupted in parts of the belt by both isoclinal and open folds, but even in such places the older strata of a fault block generally are exposed near its west side and the younger strata near its east side.

The Sierra Nevada lies within the mobile belt of the western Cordillera and represents part of the extended deformation within that region. The steep dips of thick stratigraphic sequences within the Sierra Nevada indicate that the amplitude of the synclinorium was very great and that the sialic upper crust was depressed deeply into the region of the lower crust or mantle. This circumstance and the localization of the granitic rocks in the axial region of the synclinorium suggests that the magmas that rose from depth and crystallized to granitic rock were formed by partial fusion of sialic rocks that had been depressed into regions of high temperature.

THE BATHOLITH

The batholith is composed chiefly of quartz-bearing granitic rocks ranging in composition from quartz diorite to alaskite, but includes scattered smaller masses of darker and older plutonic rocks as well as remnants of Paleozoic and Mesozoic metamorphic rocks. In general, granodiorite and quartz diorite predominate in the western Sierra Nevada and quartz monzonite in the eastern Sierra Nevada, but some felsic plutons are found in the west and some mafic ones in the east.

The granitic rocks are in discrete masses or plutons that are in sharp contrast with one another or are separated by thin septa of metamorphic or mafic igneous rocks or by late aplitic dikes. Individual plutons range in area from less than a square mile to several hundred square miles—the limits of many large plutons have not been delineated. On the whole, the batholith appears to consist of a few large plutons and a great many smaller ones. All of the larger and some of the smaller plutons are elongate in a northwesterly direction, parallel with the long direction of the batholith, but many of the smaller ones are elongate in other directions or are irregularly shaped or rounded.

Isotopic dates of minerals by the potassium-argon method and of whole rocks by the rubidium-strontium method suggest at least three age groups of granitic rocks. In the eastern Sierra Nevada several granodiorites are at least 180 million years old (Late Triassic or Early Jurassic); in the western Sierra Nevada the plutons appear to be 140 to 150 million years old; and along and just west of the crest the plutons appear to be 80 to 90 million years old (early Late Cretaceous).

The batholith is almost devoid of mineral deposits except for contact-metasomatic deposits of tungsten. Nevertheless, the batholith is generally thought to be the source of the many deposits of gold, copper, lead, zinc, and silver peripheral to it. Major tungsten deposits occur in the eastern Sierra Nevada where Paleozoic carbonate rocks are in contact with silicic intrusives, and in the western Sierra Nevada in a migmatite zone in granodiorite. Rich deposits of gold, copper, chrome, limestone, and building stone are present in the western metamorphic belt.

During the Early Cretaceous the Sierra Nevada was part of a narrow north-trending highland that lay between the Pacific region and the Rocky Mountain geosyncline. The enormous quantities of material that were deposited in those areas suggest deep erosion of the Sierra Nevada region, amounting to several miles, between the emplacement of the Late Jurassic and the early Late Cretaceous plutons. The amount of material eroded from the Sierra Nevada since the end of the Cretaceous has been much less—perhaps only a mile or two on the average. Thus it seems probable that the present level of exposure is much deeper into the Jurassic intrusives than into the Cretaceous intrusives.

UPLIFT AND SCULPTURING OF THE SIERRA NEVADA

The sedimentary deposits in the Great Valley were deposited across the downslope continuation of the tilted Sierra Nevada block. During the Tertiary, a deep basin formed in the southern part of the Great Valley while only a shallow basin formed in the north part, suggesting much greater tilting and uplift of the southern than of the northern Sierra Nevada. A deep Cretaceous basin in the north part of the Great Valley suggests precisely opposite conditions during the Cretaceous—that is, greater tilting and uplift of the northern Sierra Nevada.

The volumes of sedimentary rocks that have collected in the Great Valley during different epochs indicate that the rate of sedimentation increased progressively during the Tertiary. This suggests, in turn, that the average rate of uplift of the Sierra Nevada also increased progressively during the Tertiary although there is evidence to indicate that tilting and uplift occurred at irregular intervals. The details of uplift have been studied from records of erosion surfaces, from the profiles of ancient and modern streams, and from the sedimentary history in the Great Valley. The minimum ages of landforms have been determined from animal and plant remains collected from sedimentary deposits that rest on the landforms and by potassium-argon dating of volcanic rocks.

During the first part of the Tertiary the Sierra Nevada was a broad, gently sloping upland. Gold-bearing gravels were deposited in broad graded streams during the Eocene and Oligocene. In late Miocene time extensive bodies of rhyolite tuff and associated gravel (Valley Springs Formation) were deposited across the old landscape of the northern Sierra Nevada. Somewhat later, during the Pliocene, andesitic mudflows together with conglomerate and sandstone (Mehrten Formation) buried the northern Sierra Nevada under a volcanic blanket that ranged from 1,500 feet thick at the west foot of the range to more than 4,000 feet along the crest. These eruptions buried the old drainages, and new drainages were then developed upon the constructional surface of the volcanic rocks. Apparently, the southern Sierra Nevada was not affected by widespread volcanism, although volcanic outpourings took place locally.

During the later part of the Tertiary, sporadic westward tilting resulted in the uplift of erosion surfaces to different levels. The most recent major uplift occurred after volcanic rocks, with a potassium-argon age of about 3 million years, were erupted, and as a result streams were entrenched in narrow, steep-sided canyons.

During the early stages of uplift, the southern Sierra Nevada was the west flank of a broad arch that extended across the region east of the Sierra Nevada to Death Valley, and it seems likely that some such structure also existed for the northern Sierra Nevada. As the curvature of the arch increased, faults began to form and eventually the crest and east flank of the arch broke up to form Owens Valley and the basins and ranges eastward to Death Valley.

During the Pleistocene, after the crest of the Sierra Nevada had been uplifted to near its present height, glaciers formed and swept down canyons both to the east and to the west. These glaciers sharpened peaks, rounded canyons to U-shapes, and formed myriad other forms that add so much to the interest and beauty of the Sierran landscape.

The last uplifts and glaciations took place so recently that we cannot say they are of the past. Continued earth movements are indicated by earthquakes and minor seismic activity along the east side and near the south end of the range and by geodetic measurements. Only a slight increase in average winter precipitation, especially if accompanied by lowering of the average summer temperature, would initiate a new epoch of glaciation.

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GEOLOGY OF THE GREAT BASIN SOUTH OF THE 39TH PARALLEL

(By J. H. Stewart and D. C. Ross, U.S. Geological Survey, Menlo Park, Calif.)

The Great Basin in California south of the 39th parallel is a triangular-shaped area lying east of the Sierra Nevada, north of the Mojave Desert, and west of the continuation of the Great Basin into Nevada. The region consists of high mountain blocks trending generally north-northwest separated by deep basins. The contrast in elevation between the mountains and basins is great. The lowest part of Death Valley is 282 feet below sea level, the lowest point on the North American continent, and the Panamint Range west of Death Valley rises to over 11,000 feet. Owens Valley, a prominent trough along the western side of the region, lies generally about 4,000 feet above sea level, and the White-Inyo Mountains on the east and the Sierra Nevada on the west both rise to over 14,000 feet.

The decipherable geologic history of the region has been long and complex. The preserved record indicates long periods of marine deposition, shorter periods of orogeny (mountain building) and granitic intrusion, and both ancient and fairly recent volcanic activity. Inasmuch as the Great Basin geology of California is so closely related to that of Nevada, readers are also referred to the geologic summary (p. 11–39) in the report on the mineral and water resources of Nevada (Nevada Bureau of Mines Bull. 65, 1964).

The ranges of the Great Basin are characterized by complex structure—tight folds, high-angle faults, and low-angle thrust faults are common. Vertical movement on the numerous high-angle faults has been a major factor in outlining the basins and ranges, which give the region its desolate scenic beauty. Major high-angle faults essentially bound the region on the west (Sierra Nevada frontal fault) and on the south (Garlock fault). Other major high-angle faults lie along one or both sides of Panamint Valley, Saline Valley, and Owens Valley, and along Death Valley. In addition to vertical movement, the Death Valley-Furnace Creek fault system may have as much as 50 miles of right-lateral offset. A major low-angle thrust fault system is found in the southern Death Valley area (Amargosa thrust), and an as yet unnamed thrust, segments of which have been identified in the Inyo, Last Chance, and Saline Ranges, may have moved late Precambrian and Cambrian strata more than 20 miles over upper Paleozoic rocks.

The tectonic forces that cracked the earth's crust in these tremendous movements are still being felt. In 1872 one of the largest historic earthquakes in the United States shook Owens Valley; the zone of visible faults associated with this earthquake extends for more than 100 miles along the valley.

The oldest rocks exposed in this part of the Great Basin consist largely of gneiss, schist, and granitic rock that crop out mostly in the ranges around Death Valley and locally elsewhere in the southernmost part of the region. On the basis of radiometric ages of zircon (Lanphere and others, 1963), these rocks are about 1,800 m.y. old. These rocks were probably originally clastic sediments which were later involved in orogenic movements, metamorphosed, and intruded by granitic rocks. They form the basement of the thick section of upper Precambrian, Paleozoic, and Mesozoic sedimentary rocks.

During late Precambrian time a marine trough developed in the region and many thousands of feet of sediment were deposited. The oldest of these deposits belongs to the Pahrump Series which consists of phyllitic siltstone, quartzite, conglomerate, limestone, and dolomite, and is as thick as 7,000 feet. These strata were intruded by diabase during the Precambrian, and talc deposits formed near the contacts of the diabase and carbonate rocks. Locally, uplifts occurred within the basin of deposition during and immediately after the time the Pahrump Series was being deposited.

Following deposition of the Pahrump Series, a clastic section composed dominantly of marine sand and silt was laid down during the remainder of the late Precambrian and during the Early Cambrian. This section is over 10,000 feet thick. These strata were derived from source areas to the east and southeast of the region and were deposited in a northeast-trending trough that deepened to the west. The basal formation of this section, the Noonday Dolomite, contains large deposits of lead, silver, and zinc.

Above the clastic section of late Precambrian and Early Cambrian age is a section of marine carbonate rocks ranging in age from Middle Cambrian to Devonian. These strata are locally about 12,000 feet thick. In Nevada, strata of this age are divided into three assemblages, an eastern carbonate assemblage of nearshore to offshore, shallow-water deposits; a transitional assemblage of offshore, mostly shallow-water deposits of shale, limestone, and chert; and a western siliceous and volcanic assemblage of offshore, mostly deep-water deposits (Roberts, *in* Nevada Bur. Mines Bull. 65, 1964, p. 22–25). The deposits of this age in California are mostly part of the eastern carbonate assemblage, although some deposits in the Inyo Mountains probably belong to the transitional assemblage. Deposits in the Sierra Nevada west of the Great Basin definitely belong to the transitional assemblage.

During the Mississippian a mountain chain rose in about the same area as the present southern Sierra Nevada, and coarse detrital material derived from this highland was deposited in the southern Great Basin. This mountain chain extended into central Nevada where the orogenic event that produced the chain is referred to as the Antler orogeny (Roberts and others, 1958). The mountain building in Nevada was accompanied by large-scale thrusting of lower Paleozoic strata to the east. Thrusting of this age, however, has not been recognized in the southern Great Basin in California, but a mid-Paleozoic unconformity in the Inyo Mountains may reflect the marginal effects of this orogeny. The amount of coarse detrital material derived from the Antler orogenic belt decreases rapidly during the Mississippian. Later in the Mississippian and also in the Pennsylvanian, fine silt and minor amounts of carbonate were deposited in the western part of the Great Basin in California. Deposits of these periods become more limy to the east and are dominantly carbonate rock near the California-Nevada state line. The Mississippian and Pennsylvanian strata are over 6,000 feet thick in the Great Basin in California.

Coarse detrital material was again introduced into the basin during the Permian, apparently from a source area to the west in the site of the present Sierra Nevada. This orogenic event is referred to as the Sonoma orogeny in Nevada (Silberling and Roberts, 1962). Deposits of Permian age are about 3,000 feet thick.

At the start of the Triassic, fine marine muds were deposited in a north-south trough in the Great Basin in California. The highlands that existed in the site of the Sierra Nevada during Permian time apparently sank below the sea before Triassic time, as the Triassic strata do not contain coarse debris that would indicate the presence of a highland. The marine Triassic deposits, which are about 2,000 feet thick, are overlain by at least 7,000 feet of volcanic rocks of Triassic and Jurassic age.

During the Jurassic and Cretaceous in the Great Basin in California, orogenic movements took place and great granitic batholiths were emplaced. Most of the structural features in the region, except for Cenozoic high-angle faulting, were probably produced during these periods. The dates of emplacement of the granitic bodies is established on the basis of radiometric K-Ar dating. The contacts of these granitic rocks with Paleozoic limestone and dolomite are the site of many tungsten, talc, and silver-lead-zinc deposits. Gold-silver-quartz veins are probably also related to this period of granitic intrusion.

During the Tertiary, thick continental deposits were laid down in local basins and volcanic activity was widespread. The thickest

Tertiary sedimentary sections are in the Death Valley region, and some of these strata contain deposits of borate minerals. Volcanic activity was prominent a short distance east of Death Valley (the Greenwater Volcanics) and also along the western side of the Great Basin in California. Large caldera-like features (volcano-tectonic structures) formed in Long Valley and at Mono Lake. These volcanic centers were the source for thick deposits of ash-fall and ash-flow tuffs, and lava flows. At the Mono Craters volcanic center, among the latest formed features are domes of obsidian within shallow craters in pumice. The last volcanic event in much of the Great Basin in California was the extrusion of basalt and the formation of cinder cones. Ubehebe Crater, an explosion vent in basaltic rocks in the northern part of Death Valley, and the many cones in the Coso Mountains, are examples of this episode.

In the latter part of the Tertiary, the physiographic features—the basins and ranges—began to take the shape we see today. High-angle faulting was dominant, outlining mountain blocks and defining the depressed basin areas. This basin-range faulting is still continuing—as late as the 1950's, tens of feet of vertical movement along such faults resulted in strong earthquakes in the Great Basin in neighboring Nevada.

The increased precipitation that accompanied Pleistocene glaciation developed a system of large lakes in the Great Basin. Lake Manly, one of the better known lakes, filled Death Valley to a depth of about 600 feet. The return of the arid conditions we know today dried out these lakes to form the saline lakes and barren playas so characteristic of this region. Borates, potassium and sodium compounds, lithium, phosphate, and bromine are recovered commercially at Searles Lake and Owens Lake from these lake deposits and their associated brines. During the latest history of the region, and continuing today, erosion of the mountain ranges and deposition of the debris has formed conspicuous alluvial fans along the flanks of the ranges.

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GEOLOGY OF THE MOJAVE DESERT REGION

(By T. W. Dibblee, Jr., and D. F. Hewett, U.S. Geological Survey, Menlo Park, Calif.)

The Mojave Desert is an area of low mountain ranges that separate many undrained alluviated basins or valleys. In the western part these have no definite pattern, but in the central and eastern parts many of them trend northwest and north. Relief increases eastward as altitudes of the alluviated valleys decrease from 4,000 feet at the western margins of the desert to near sea level at the Colorado River.

The rocks of the Mojave Desert province are separable into two major divisions, (a) pre-Cenozoic rocks, and (b) Cenozoic sedimentary and volcanic rocks. The pre-Cenozoic rocks are composed of (1) metamorphic and old sedimentary rocks, and (2) igneous rocks.

The metamorphic rocks are gneisses and schists of known and probable Precambrian age. They were recrystallized at great depth from rocks that were mostly sedimentary and which formed enormously thick sections. The gneisses are coarsely crystalline banded rocks composed mostly of quartz, feldspar, and biotite mica. They are exposed east and south of Baker, near Barstow and Randsburg, and near the southwestern border of the Mojave Desert. In a few places the gneisses contain deposits of rare-earth and radioactive minerals. The schists are foliated micaceous rocks. They are exposed only near Randsburg and in the Orocopia and Chocolate Mountains in the southern part of the desert.

Old sedimentary rocks, mapped as the Pahrump Series of late Precambrian age, are found in only two areas in the extreme northeastern part of the Mojave Desert; one in the Silurian Hills north of Baker and the other farther east in the Kingston Mountains. This unit rests unconformably on gneiss, is many thousands of feet thick, and consists mostly of quartzite, shale or hornfels, and dolomite.

The Precambrian rocks are overlain unconformably by a great thickness of old marine sedimentary strata of Paleozoic age, divided into formations as shown on the columnar section (fig. 3). They are most extensive in the northeastern Mojave Desert near the Nevada state line, notably in the Kingston, Ivanpah, and Providence Mountains. The lower half of this stratigraphic section is of Cambrian age; in the Kingston and Ivanpah Mountains this section is mostly quartzite and shale (the basal unit, the Noonday Dolomite, has recently been assigned to the Precambrian). In the Providence Mountains the basal part of the Cambrian section is quartzite, the remainder is mostly limestone and dolomite. The rest of the Paleozoic (Devonian to Permian) section in these areas is mostly limestone and dolomite. Remnants of similar rocks of known and probable Paleozoic age engulfed in granitic intrusive rocks occur in many other parts of the desert, notably in the mountains southwest of Needles, in areas southeast of Twentynine Palms, in areas near Victorville, and in the Tehachapi Mountains west of Mojave.

Two nonmarine sedimentary formations of Triassic and Jurassic ages have been mapped in several places near the Nevada state line. Marine formations of these ages were recognized at one place near Baker, and possibly at another near Barstow. The thick section of slate (pre-Cenozoic rocks of unknown age) in the southeastern Mojave Desert near Blythe may be of this age.

The pre-Cenozoic igneous rocks are of two types, metavolcanic and plutonic. The metavolcanic (and hypabyssal) rocks are mostly andesitic porphyry of Mesozoic age that form a complex of extrusive and shallow intrusive masses and dike swarms in the central Mojave Desert.

The plutonic igneous rocks are coarsely crystalline and were emplaced at great depth. Most are granitic, are widespread, and make up the major part of the pre-Cenozoic rocks of the Mojave Desert. The oldest of these are granitic rocks (quartz monzonite) exposed in the northeastern part (Hewett, 1956), and anorthosite and syenite in the Orocopia Mountains east of Salton Sea (Crowell and Walker, 1962). All are of Precambrian age and intrude gneiss. Gray granitic rock (quartz monzonite) of Jurassic(?) age is widespread in the east-central Mojave Desert. Gray to black diorites and gabbros of Mesozoic age crop out locally in many parts of the desert. All these Mesozoic plutonic rocks are intrusive into the metamorphic and old sedimentary rocks. Nearly all the above-mentioned pre-Cenozoic rocks are intruded by gray-white granitic rock (quartz monzonite to granite) of Cretaceous age that is very extensive in almost all parts of this province, especially in the western and central parts.

Metallic mineral deposits containing sulfides of iron, copper, lead, zinc, and silver, and commonly containing disseminated gold and silver, form veins in pre-Cenozoic rocks in many parts of the desert region. Most are found in metamorphic and old sedimentary rocks near intrusive contacts with granitic rocks; many occur in the granitic rocks. Tungsten ores occur under similar conditions. Other deposits containing these minerals except tungsten are found in fault or shear zones in these rocks. Deposits of iron ores are found in old sedimentary rocks along or near contacts with the intrusive granitic rocks of Jurassic(?) age. In the southwestern Mojave Desert, limestone is being quarried extensively for industrial uses, mainly for cement manufacture.

The Cenozoic sedimentary and volcanic rocks lie unconformably upon the pre-Cenozoic rocks which were deeply eroded during Cretaceous time. Those of early Tertiary age are sedimentary and are known in only one area strictly within the province, namely in the Orocopia Mountains east of Salton Sea where about 2,500 feet of marine sandstone (Maniobra Formation of Crowell and Susuki, 1959) of Eocene age are exposed.

Elsewhere on the Mojave Desert the Tertiary volcanic and sedimentary rocks are nonmarine, of middle and late Tertiary age, and are widespread. The most extensive Tertiary unit is an assemblage, as thick as 10,000 feet, of volcanic lava flows, breccias, tuffs, and some sedimentary rocks, of probable Oligocene to early Miocene age. It is exposed in many areas in all but the southwestern part of the province. The volcanic rocks, which range from rhyolite through andesite to basalt, were erupted from groups of vents and fissures, later filled with volcanic plugs, in many areas within these parts. Near Mojave in the western Mojave Desert, this assemblage was named the Gem Hill Formation of the Tropico Group; in areas north of Barstow, as the Pickhandle Formation. Elsewhere it is not named. Ores of gold and silver, some very rich, were mined from veins in the volcanic plugs associated with this unit, notably near Mojave, Randsburg, Barstow, and Ludlow. These plugs contain veins of barite near Barstow and Ludlow and manganese ore near Ludlow. The volcanic rocks also contain perlite, pumicite, and tuff, of commercial grades.

The above-described volcanic and sedimentary unit is overlain, in places unconformably, by a predominantly sedimentary unit as thick as 5,000 feet of middle Miocene to early Pliocene age. In the western Mojave Desert it is known as the Barstow Formation near Barstow; Punchbowl Formation at Cajon Pass; and Fiss Fanglomerate near Rosamond. At the west end of the Mojave Desert this unit grades westward into marine beds. Commercial minerals in this unit include the world's largest deposit of borate minerals that are being mined from lake-bed shale near the base of this unit at Boron. Similar lake-bed shales of this unit contain deposits of borate and strontium minerals and of absorptive tuff or bentonite, near Barstow, Yermo, and Ludlow.

Stratigraphic sections of middle and late Pliocene age are exposed in the northern part of the province, notably west of Mojave and east of Randsburg. In the Randsburg area the section includes andesite flows and tuffs associated with andesitic intrusions. In other parts of the province much of the dissected alluvial sediments may be of this age.

Deposits of Quaternary age that fill the desert valleys are mainly alluvial sediments, some lake-bed clays, and dune sand. In a few places they include local basalt flows and cinder cones. The cinder cones are composed of basaltic pumice which is quarried for industrial uses. The clays of Bristol Lake near Amboy in the central Mojave Desert contain enormous deposits of salt with calcium chloride which are being quarried for industrial uses.

The pre-Cenozoic metamorphic and old sedimentary rocks of the Mojave Desert province are complexly folded, faulted, and intruded by plutonic igneous rocks. These igneous rocks, mostly granitic, which extend southeastward from the Sierra Nevada province, assimilated most of the pre-existing rocks. All this happened during the Mesozoic Era.

The Tertiary stratified rocks which rest on the deeply eroded surface of the pre-Cenozoic rocks are themselves tilted, faulted, and deformed into folds with axes that trend mostly west to northwest. They were deformed during late Tertiary and early Quaternary time. In many places Quaternary alluvial sediments and basalt flows are slightly deformed in the same manner.

The Mojave Desert Region is in large part bounded geologically on the southwest by the San Andreas fault and on the northwest by the Garlock fault, or physiographically by mountain ranges uplifted along these master faults. Both are vertical, active faults along which movement was mainly horizontal; the area southwest of the San Andreas fault has moved northwest, and that northwest of the Garlock fault has moved southwest, relative to the wedge-shaped block that forms the major part of the Mojave Desert province. The southwest half of the Mojave block itself is broken by a number of vertical faults parallel to the San Andreas fault. Along many of these faults the terrain has slipped horizontally as on the San Andreas. South of the Garlock fault, and north of Salton Sea, the Mojave block is broken by some vertical faults that trend east, along which the terrain has slipped in part horizontally as on the Garlock fault. All or most of these faults within the Mojave block involve Quarternary formations and are therefore active. The Garlock fault becomes a southwest-dipping thrust fault at its east end as it curves southeastward around the Avawatz Mountains.

The structural pattern of the eastern part of the Mojave Desert province differs from that of the western and central parts and is more like that of the Basin and Range province to the north. In this part the old sedimentary rocks are compressed into folds with axes that trend mostly north; some are broken by low-dipping thrust faults that are themselves folded. Most of this deformation occurred before or during the invasion of the Mesozoic granitic rocks, but some of the thrust faults involve lower Pliocene formations. Some of these show no topographic expression and therefore have long been inactive.

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GEOLOGY OF THE TRANSVERSE RANGES

(By T. W. Dibblee, Jr., U.S. Geological Survey, Menlo Park, Calif.)

The Transverse Range region is one of eastward-trending mountain ranges and valleys. It is so named because this trend is transverse to the generally northwesterly trending features of southern California.

The lowlands of the San Bernardino and Los Angeles plains of the eastern part of this region rise abruptly northward to the San Bernardino and San Gabriel Mountains, respectively, two of the most rugged and highest ranges in southern California. Westward the San Gabriel Mountains split into two mountain chains, including the Santa Ynez Range on the north and the Santa Susana Range on the south, separated by the Santa Clara River Valley. Westward from Los Angeles stretch the Santa Monica Mountains, and their westward projection into the sea is formed by the four channel islands, north of which lies the Santa Barbara channel.

The rock units of the Transverse Range region may be divided into two main groups, (a) crystalline basement complex of metamorphic and plutonic rocks, and (b) sedimentary and volcanic rocks.

The basement complex, exposed mostly in the eastern part of the province, is composed of hard crystalline metamorphic rocks and plutonic igneous rocks. It forms the old terrane upon which the sedimentary and volcanic rocks were deposited. The metamorphic rocks crystallized at great depth from rocks of mostly sedimentary origin. The plutonic igneous rocks intruded the metamorphic rocks also at great depth in the form of molten magmas that crystallized into coarse-grained, mostly granitic, rocks.

The metamorphic rocks of this complex are described below, from supposedly oldest to youngest, together with their economic aspects. (1) Gneiss, Precambrian(?). This rock is coarsely crystalline, layered; formed by severe metamorphism probably from rocks that were mostly sedimentary. The gneiss is exposed mainly in the San Bernardino and San Gabriel Mountains. In some areas it contains layers of coarse, white marble. In a few places the gneiss contains small deposits of graphite and (or) radioactive minerals. The marble has been quarried for roofing aggregate. (2) Pelona Schist, Precambrian(?). This is a highly foliated micaceous rock, recrystallized from mostly sedimentary rocks. It is exposed in the San Gabriel and San Bernardino Mountains. In places it contains a little soapstone (steatite) and manganese ore. The schist is quarried for use as slab rock. (3) Metasedimentary rocks, Paleozoic. These rocks are exposed mostly in the San Bernardino Mountains where they rest unconformably on gneiss, and consist of the Saragossa Quartzite overlain by the Furnace Limestone. Gold was mined from shear zones in both these formations. The Furnace Limestone is quarried for industrial uses, including cement manufacture. (4) Santa Monica Slate, pre-Cenozoic (Triassic (?) and Jurassic). This rock, crystallized from shale, is exposed only in the Santa Monica Mountains. It has been quarried for slab rock. (5) Unnamed schist, pre-Cenozoic. This fine-grained foliated rock crops out only on Santa Cruz Island.

The plutonic igneous rocks of the basement complex include anorthosite and syenite, Precambrian, exposed only in the western San Gabriel Mountains and which contain small deposits of titaniferous iron ore; small masses of quartz diorite, diorite, and gabbro, Mesozoic or older; and large masses of granitic rocks, mostly quartz monzonite, late Mesozoic.

The sedimentary and volcanic rocks rest unconformably on the basement complex in the eastern part of the province. They underlie almost all the western part where they form an assemblage as thick as 40,000 feet. The stratigraphic formations that make up this assemblage are as shown on the columnar section (fig. 3).

Formations of late Mesozoic age are marine sandstone, shale, and conglomerate, as in the Coast Range province. They include the Franciscan Formation, thickness unknown, Espada Formation, at least 7,000 feet thick, and Jalama Formation, about 3,500 feet thick, all in the Santa Ynez Range, and "Chico" sandstone as thick as 3,000 feet in the Santa Susana Range. The Franciscan Formation contains mafic volcanic flows and serpentine intrusions, in addition to sandstone, shale, and conglomerate, and is the host formation for deposits of mercury.

The formations of Paleocene and Eocene age also are nearly all marine sandstone, shale, and some conglomerate. The total thickness is 8,000 feet or more. They are overlain by the mostly Oligocene Sespe Formation composed of about 3,000 feet of nonmarine sediments. In the western Santa Ynez Range the Sespe grades laterally westward into the marine Alegria Formation. All of these formations contain oil-producing sands. At the east end of Santa Clara River Valley, the equivalent of the Sespe, or the Vasquez Formation, contains volcanic flows, also small deposits of borate minerals at one place.

The lower Miocene section, about 2,000 feet thick, is marine and consists of the Rincon Shale with Vaqueros Sandstone at the base. This sandstone is an important petroleum producer along the Santa Barbara coastal area. In the Santa Monica Mountains and eastward this section consists of sandstone and shale of the Topanga Formation.

The marine middle Miocene to lower Pliocene section ranges from 2,000 to 7,000 feet thick. The basal part locally is composed of volcanic flows that are thickest in the Santa Monica Mountains and Channel Islands. The rest of the section is mostly siliceous and diatomaceous shale of the Monterey (or Modelo), Puente, and Sisquoc Formations, which locally contain sandstone. Diatomite is quarried from the Monterey Shale and Sisquoc Formation in the western Santa Ynez Mountains near Lompoc. In Ventura County, sandstones in the Monterey (or Modelo) Shale produce large amounts of petroleum. On the north side of the San Gabriel Mountains the section is composed of the nonmarine Mint Canyon and Punchbowl Formations.

The Pliocene section underlies the Santa Clara River Valley and Santa Barbara Channel where it consists of some 15,000 feet of marine sandstone and shale of the Pico Formation. This formation is the largest producer of petroleum in the province. Eastward the Pico thins and in part grades laterally into the nonmarine Saugus Formation. The Pico Formation is overlain by about 2,000 feet of marine Pleistocene sands of the Mudpit Shale and Santa Barbara Formation. These grade laterally eastward into the nonmarine Saugus Formation.

The basement complex of the Transverse Range province, as in adjacent provinces, is complex structurally as well as in rock distribution. It is composed of severely folded metamorphic rocks, complexly intruded by the various plutonic igneous rocks.

This province has no definite geologic boundaries, but it is in large part bounded on the north and south by major east-trending faults. It is partly bounded by the southeast-trending San Andreas fault but this and the San Gabriel fault to the southwest also transect it diagonally.

Movement on the highly active San Andreas fault is horizontal. The northeast block has shifted southeastward relative to the southwest block, but simultaneously these blocks have been pushing against each other with terrific force. As a result of this force the terrane of basement complex that forms the San Bernardino Mountains was squeezed up like a wedge between the San Andreas fault and thrust faults to the northeast. Similarly, the terrane of basement complex that forms the San Gabriel Mountains and those to the northwest was squeezed up between the San Andreas and the San Gabriel faults, but the western part of this block was downwarped to form the Ridge basin, which is filled with Tertiary sedimentary rocks. As a result of these movements, the basement complex of all these ranges is severely shattered, and the overlying Tertiary stratified rocks are severely compressed into folds with east-trending axes.

The enormously thick stratigraphic section of mostly marine formations of Cretaceous and Cenozoic ages that underlies the western part of the Transverse Range province accumulated in a great crustal downwarp, or trough, that geologists call the Ventura basin. It was submerged during Cretaceous and most of Cenozoic time when it subsided continuously until more than 40,000 feet of sediments accumulated in it. The axis of this trough followed the area now occupied by the Santa Clara River Valley and westward into the Santa Barbara Channel, which is the still-submerged part of this downwarp.

The strata along the flanks or margins of the Ventura basin have been squeezed up by tremendous compressive forces to form the western Transverse Ranges. On the north flank, the Santa Ynez-Topatopa Range was formed mainly by uplift and southward tilt of the strata along the Santa Ynez fault at the north base of this range, and in part by arching and thrust faulting of these strata. On the south flank, the Channel Islands and Santa Monica Mountains were formed largely by uplift and arching of the strata along a zone of east-trending faults. Farther north on this flank the Santa Susana Range was formed by arching of the strata, partly on two thrust faults. Within or adjacent to these major upheavals, the strata are compressed into numerous folds of east-trending axes. Many of these folds near the axial part of the Ventura basin have entrapped the petroleum and gas of this basin to form the oil fields of this province.

In summary it may be said that the physiographic features of the Transverse Range province are the effect of an enormous amount of north-south crustal shortening that resulted from tremendous compressive forces. Part of this shortening is between the marginal Santa Ynez Fault and the zone of faults through or adjacent to the Channel Islands and Santa Monica Mountains. These are steep faults transverse to the great San Andreas fault. Movements on these are in part horizontal, in which the terrane north of the Santa Ynez fault has been pushed westward, and the submerged terrane south of the Channel Islands-Santa Monica fault has been pushed eastward, relative to the intervening transverse block.

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GEOLOGY OF THE PENINSULAR RANGES

(By G. L. Peterson, R. G. Gastil, and E. C. Allison, Department of Geology, San Diego State College, San Diego, Calif.)

The Peninsular Ranges, bounded on the east by the Gulf of California and Salton Trough and on the north by the Transverse Ranges, constitute a distinctive physiographic and geologic province. Baja (Lower) California, Mexico, the 800-mile-long peninsula that separates the eastern Pacific from the Gulf of California, constitutes the bulk of the province, but only that relatively small portion north of the international border is discussed here.

In general aspect, the province most closely resembles the Sierra Nevada province and has had a somewhat similar geologic history. Apparently the development of the province began with a thick accumulation of predominantly marine sedimentary and volcanic rocks. Ages of these oldest rocks are as yet poorly documented, but late Paleozoic and early Mesozoic fossils have been reported, and Jurassic fossils are locally present in the western part of the province. Following this accumulation, in mid-Cretaceous time, the province underwent a pronounced episode of mountain building. The thick accumulation of sedimentary and volcanic rocks was complexly metamorphosed and invaded by igneous intrusions. These intrusive rocks, the Southern California batholith, now constitute the dominant terrain of the province. A period of erosion followed the mountain-building episode, and during Late Cretaceous and Cenozoic time, sedimentary and subordinate volcanic rocks were deposited upon the eroded surface of the batholithic and pre-batholithic rocks. These post-batholithic rocks occur principally along the western and northern margins of the province. Thus, in terms of geologic history, rocks of the province can be subdivided into three general units: 1) pre-batholithic rocks, 2) the Southern California batholith, and 3) post-batholithic rocks. Each of these gross rock units and its economic significance is outlined below. Cenozoic faulting and changes of sea level relative to land level added distinctive topographic features which are discussed on a later page.

Pre-batholithic Rocks

Pre-batholithic rocks occur principally in the highlands or centrally located part of the province. They occur on the western flank of the batholith and as remnants in numerous areas within the batholith. These metamorphic rocks are further divisible into two broadly differing types. The first and probably oldest type is more common in the central and eastern parts of the province. In general, this group of rocks is a highly metamorphosed assemblage of schists, amphibolites, quartzites, gneisses, and crystalline limestones. Evidence for the age of this complex is scanty, but most investigators regard it as late Paleozoic and early Mesozoic. Crushed and broken stone, dimension stone, and crystalline limestone (used in the manufacture of cement) are important economic commodities. Other economic deposits derived from these rocks are also associated with the batholithic rocks and are discussed below.

A second assemblage of pre-batholithic rocks occurs on the western side of the province, and principally occupies a narrow belt extending down the coast from the Santa Ana Mountains to San Diego. In contrast to the first, this belt of rocks consists of the mildly metamorphosed slates and argillites of the Bedford Canyon Formation and a thick succession of volcanic and related rocks designated the Santiago Peak Volcanics. Offshore, on Santa Catalina Island, there is a small exposure resembling the Franciscan Formation, a unit more characteristic of the Coast Ranges. The entire western belt of metamorphic rocks is apparently of Jurassic and Early Cretaceous age, as is indicated by several recent fossil discoveries. Crushed stone, decorative building stone, and pyrophyllite (used principally as an insecticide base) are apparently the only commodities now being obtained from this belt of rocks.

The structural details of the pre-batholithic rocks are highly complex, but individual rock units have a predominant northwesterly trend and are generally inclined steeply to the southwest or northeast. This persistent grain is disrupted in many areas, however, by igneous intrusions associated with the batholith.

Batholithic Rocks

The Southern California batholith constitutes the backbone and dominant portion of the province, extending from near Los Angeles southeastward approximately 1,000 miles to the southern extremity of Baja California. Average width of outcrop in southern California is approximately 70 miles. The batholith is by no means a single homogeneous rock unit, but a complex series of intrusions and related metamorphic rocks. Various investigators have described, mapped, and named numerous smaller rock divisions within the batholith. These smaller divisions range widely in rock type including gabbros, tonalites, granodiorites, and granites. Radiometric age determinations date the final consolidation of the batholith at 90 to 100 million years ago, in mid-Cretaceous time.

A variety of mineral resources are associated with the batholithic and pre-batholithic rocks. Ores of copper, gold, molybdenum, nickel, silver, and tungsten have been mined sporadically. The deposits are mostly low grade, however, and mining activity was greatest during times of exceptional demand, such as during the world wars. Far more important in recent years has been the production of crushed and broken stone and dimension stone. Of the latter, several varieties such as "black granite" (gabbro) and "gray granite" (quartz diorite or granodiorite) are quarried at several localities and marketed for industrial purposes and as decorative building or monument stone.

Numerous pegmatite dikes cut across the earlier igneous and metamorphic rocks of the batholithic complex. The gem- and lithium mica-bearing pegmatites of Riverside and San Diego Counties are particularly well known. These deposits have yielded numerous minerals including pink and green tourmaline, garnet, quartz crystals, lepidolite, beryl, spodumene, topaz, and feldspar. These dikes have constituted one of the most important sources of gem and lithium minerals in the United States.

Post-Batholithic Rocks

Sedimentary and subordinate volcanic rocks deposited on the eroded surface of the batholithic and pre-batholithic rocks are confined principally to the coastal area of the province. In this report they are further subdivided into two areas of outcrop for purpose of description. The first, and southernmost area consists of a narrow strip extending from Oceanside south to the International border. Post-batholithic rocks of this area are almost entirely sedimentary and consist of poorly consolidated, richly fossiliferous, and generally flat-lying units of sandstone, shale, and conglomerate. Formations include, in ascending order, Rosario (Cretaceous), La Jolla and Poway (Eocene), San Diego (Pliocene), and Sweitzer, Lindavista, and Bay Point (Pleistocene). Materials used chiefly in the construction industry (sand and gravel, clay, expansible shale, and specialty sands) are extracted from these units and constitute some of the most important economic commodities of San Diego County at the present time. In the past, minor amounts of placer gold have been obtained from some of the Eocene gravels of this area.

North of Oceanside, the width of area covered by post-batholithic rocks increases markedly and extends inland to the vicinity of Pomona and northward to the Transverse Ranges. In this area, the Los Angeles basin, sedimentary rock units are both more numerous and individually thicker, and are more deformed than farther south. Apparently this area was persistently downwarped and occupied by the sea throughout much of Cenozoic time, and tectonically was more comparable to the Transverse Ranges than to the remainder of the Peninsular Ranges. As with the post-batholithic rocks to the south, materials used in the construction industries are important economic commodities, but in contrast, the Los Angeles basin is also well known as one of the most important petroleum provinces on the western shore of North America.

Post-batholithic volcanic rocks occur as minor units in the Los Angeles basin, in areas south of Elsinore, and near Jacumba. Volcanic rocks also occur on Santa Catalina Island and constitute the dominant rock type of San Clemente Island. Economic significance of these volcanic rocks is negligible at present.

Structure and Topography

Structurally, the province appears to be an uplifted and westward-tilted block. The eastern flank is the highest and most rugged part, with altitudes gradually decreasing toward the ocean. Cutting across this large-scale pattern are numerous, large, northwest-trending faults.

These faults subdivide the province into several subparallel blocks which are topographically expressed as northwest-trending ranges and intervening valleys. The largest faults parallel the San Andreas fault system and are probably closely related. A much smaller northeast-trending set of faults appears to be associated with the major set. Apparently the faults were active throughout much of Cenozoic time. Activity to the present is indicated by recent warping and displacements, by hot springs along the fault traces, and by seismic unrest in the vicinity of many of the larger faults.

Distinctive topographic features of the coastal part of the province include numerous bench-like surfaces developed when the sea was at higher levels. These marine terraces are abundant in certain tectonically active areas, such as near Palos Verdes. In other areas only three main terraces have been developed. Many of the coastal cities of southern California such as San Diego, Del Mar, and Oceanside are located largely on these terraces.

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GEOLOGY OF THE SALTON TROUGH

(By W. B. Hamilton, U.S. Geological Survey, Denver, Colo.)

The Salton Trough is a desert basin extending northwestward into southern California from the Gulf of California. The trough is bounded by mountains of Precambrian, Paleozoic, Mesozoic, and Tertiary rocks, but is itself mostly a plain of low relief floored by surficial deposits. A region 85 miles long and up to 30 miles wide, which is most of the surface of the trough, is below sea level, dammed from the Gulf by the delta of the Colorado River. The fluctuating surface of the 30-mile-long Salton Sea is more than 200 feet below sea level.

The Salton Trough is filled by late Cenozoic sediments whose maximum thickness, about 21,000 feet, is just south of the Mexican border (Biehler and others, 1964). The stratigraphy of the valley fill, as exposed in the deformed areas about the basin and as known from well records, was described by Dibblee (1954). The sediments represent continuous deposition from late(?) Miocene time to the present and, except for the marine Imperial Formation low in the section, are continental clastic strata. Fanglomerates, alluvial sands and silts, and lacustrine silts and clays, interfinger complexly and have been given various formation names by Dibblee (Borrego, Brawley, Canebrake, Mecca, Ocotillo, Palm Spring, Split Mountain). The lacustrine Borrego Formation contains thin strata of thenardite (sodium sulfate) east of Salton Sea. Large deposits of gypsum occur just below the Imperial Formation in Fish Creek Mountain west of El Centro. Silicic and intermediate volcanic rocks are present locally in the upper Cenozoic section.

Pre-Cenozoic crystalline rocks are exposed throughout the mountains that border the trough and similar rocks presumably underlie the Cenozoic sediments that fill it, but are exposed in the trough only in several low uplifts along strike-slip faults. In the Mecca Hills, north of the Salton Sea, anorthosite and gneiss of Precambrian age and schist of probable Paleozoic age underlie Pliocene and Quaternary sandstone and fanglomerate (Crowell, 1962, p. 26–29). Jurassic (about 155 million years old) quartz diorite forms Superstition Mountain, northwest of El Centro (Bushee and others, 1963). Undated granitic and metamorphic rocks crop out in a small mass at the Mexican border near the east edge of the trough (Strand, 1962).

Five small extrusive rhyolite domes of Quaternary age protrude through the sediments of the trough at the southeast end of the Salton Sea (Kelley and Soske, 1936). The northeast line of the domes is crossed by a northwest-trending line of hot springs, mud pots, and mud volcanoes (White, 1955). Carbon dioxide at high pressure and temperature is plentiful here in shallow subsurface reservoirs and is produced commercially where it is found with a low water content (White, 1955). A mile-deep well drilled nearby for geothermal power encountered very hot (about 600° F) brine containing about 33 percent by weight of sodium, calcium, and potassium chlorides, and in addition lithium, barium, lead, silver, copper, and other metals in amounts far higher than those known elsewhere in subsurface brines (White and others, 1963). Commercial use of the brine and its geothermal heat is to be expected once waste-disposal problems are solved.

The present Salton Sea has been maintained by irrigation water since it formed in 1905–1906 when the Colorado River broke into the Salton Trough during floods. A higher stand of the Salton Sea, ending only a few centuries ago, left wave-cut shorelines, lacustrine shells, and locally travertine, about the basin to an altitude generally a little above present sea level (e.g., Dibblee, 1954, pl. 2).

Wind-blown sand forms deposits throughout much of the Salton Trough. By far the largest are the Sand Hills, a belt about 5 miles wide of dunes trending northwestward for 40 miles from the Mexican border in the eastern part of the trough.

The Salton Trough is the northern extension of the structural depression of the Gulf of California. Continental crust, lacking beneath the deep southern part of the Gulf, thickens gradually northward along the northern part; it is about 20 miles thick at the International border, and 25 miles thick at the north end of the Salton Trough (Biehler and others, 1964). The structure of the Salton Trough is dominated by the several right-lateral strike-slip faults of the San Andreas system—San Jacinto, Imperial, San Andreas proper, etc.—which trend obliquely into it from the northwest. The faults present an en echelon array, stepping to the right; individual faults strike more westerly than does the fault system as a whole, or than does the gulf depression into which the system trends. Right-lateral surface offsets within the Salton Trough occurred during earthquakes of 1857 (San Andreas fault; the offset sector was mostly northwest of the trough, but probably extended into it), 1934 (San Jacinto fault, in Mexico; Biehler and others, 1964), and 1940 (Imperial fault). Deformation of the region is continuing at a very rapid rate, and the southwest margin of the trough moved several feet northwestward, relative to the northeast margin, within the short period 1941–1954, without further surface faulting (Whitten, 1956, fig. 3). Future severe earthquakes accompanying surface faulting are to be expected.

Previous late Quaternary right-lateral offsets along the San Andreas fault in the trough are indicated by displaced drainage lines and by the tight, locally isoclinal folds with steeply plunging axes of Pleistocene and alluvial sediments adjacent to the fault. Total Cenozoic displacement has been enormous: distinctive middle Eocene strata are displaced 180 miles along it, from the Orocopia Mountains at the northeast edge of the Salton Trough to the Tejon region (Crowell, 1962); displacement of mid-Cretaceous granitic rocks has been 300 miles (c.f. Hill and Dibblee, 1953). The Gulf of California apparently opened as the Peninsula of Baja California pulled obliquely away from the mainland during Cenozoic time, and the Salton Trough probably formed by tensional thinning of the continental crust accompanying this motion (Hamilton, 1961).

The folding and minor faulting, like the major strike-slip faulting, demonstrate clockwise torsion within the trough throughout late Cenozoic time (Dibblee, 1954, p. 28). The primary right-lateral faults trend northwestward. Minor left-lateral faults trend northeastward, and probably represent adjustments between blocks dragged by the major faults. Folds in the Cenozoic sediments trend mostly eastward and are en echelon, along or near both the major and minor fault zones.

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MINERAL RESOURCES

INTRODUCTION

(By J. P. Albers, U.S. Geological Survey, Menlo Park, Calif.)

The economic value of a mineral resource is determined by the cost of mining and processing, cost of marketing, including transportation to market, and by the demand for the commodity. Costs and demand vary with fluctuations in local or national economy, advances in the technological fields of exploration and exploitation, and increases in requirements by industry and the expanding population. A resource that cannot be developed profitably today may become the basis for a profitable enterprise in the future because of these constantly changing sociologic, technologic, and economic factors.

A distinctive characteristic of mineral economics is that once a mineral resource is exhausted it cannot be replaced. This creates problems both in concepts of conservation and execution of resource development. For this reason, efficient development, intelligent use, and continuing search for new or substitute mineral resources are of importance to economic growth. Advances in the techniques of exploration and processing of mineral resources have been successful in meeting the most fundamental needs of the nation's economy to date. However, with depletion of high-grade deposits, it will become necessary to locate and develop deposits that are lower grade, particularly those that give promise of yielding more than one mineral commodity, others that are deeply buried, and still others that are farther from established markets.

The accumulation of a mineral or rock to form an economic deposit is the result of one or more specific geologic processes, and therefore each type of mineral resource is limited in distribution to certain geologic environments. Thus, the occurrence of many individual mineral commodities in California is more or less restricted to specific geologic-geomorphic provinces. Deposits of many metals, particularly base and precious metals, are concentrated in deposits by aqueous solutions emanating from large deep-seated bodies of magma. Deposits of this origin commonly occur as veins that fill fractures in the host rock, or occur as a metasomatic replacement of the host rock. The primary deposits of gold, copper, silver, tungsten, and molybdenum in the Sierra Nevada region originated as emanations of solutions from the more silicic, lighter-colored facies of granitic rocks of the Sierra Nevada batholith. However, it is important to note that these metalliferous deposits are restricted to the sedimentary and volcanic rocks that were invaded by the batholith, and that the batholith itself is barren. Similar conditions prevail in the Klamath Mountains where deposits of base and precious metals are found in rocks invaded by granitic plutons, and in the Mojave Desert and Great Basin where iron, rare-earths, and base-metal deposits are found principally as a replacement of carbonate rocks near igneous contacts. Such commodities as talc, pyrophyllite, kyanite, and andalusite, are also closely related to igneous rocks, being the product of the metamorphism of invaded country rock by the heat and emanations from the igneous intrusion.

Other mineral commodities found in close association with deep-seated igneous rocks include mica, feldspar, gemstones, chromite, asbestos, and nickel. These are commonly in the igneous rocks themselves rather than in the invaded country rock. Mica, feldspar, beryl, and many gemstones are most commonly extracted from pegmatites, irregular dike-like bodies of very coarsely crystalline igneous rock intruded into igneous rock of finer grain size. However, mica and feldspar also are extremely abundant in many ordinary igneous and metamorphic rocks and in some localities are produced commercially from the bulk mining of these rocks. Chromite, asbestos, and nickel are associated with dark mafic and ultramafic igneous rocks—the first two commodities with peridotite and serpentinite, and the latter with peridotite, serpentinite, and gabbro. Chromite crystallized contemporaneously with the ultramafic rock, and deposits of this mineral formed by a process called magmatic segregation. Asbestos occurs as small vein-like fracture fillings mostly in ultramafic rock that have been serpentinized, and nickel is present in sulfide minerals and also indigenously in very small amounts in ultramafic rocks.

Mercury deposits are found chiefly in regions of extensive Cenozoic volcanic and tectonic activity. The most important deposits in California, however, are found in silica-carbonate rock, a hydrothermal alteration of serpentine found mainly in the Franciscan Formation of the Coast Ranges. Nevertheless, cinnabar, which replaces the silica-carbonate rock, is thought to be a product of volcanic activity. In places in California, the mercury mineral cinnabar is being deposited around presently active hot springs.

Mineral fuels such as petroleum, natural gas, peat, and asphalt, are products of organic decay and recomposition in a sedimentary environment, and these resources are therefore in sedimentary rocks. In California, mineral fuels are best preserved in thick sedimentary deposits of late Mesozoic and Tertiary age found in the San Joaquin, Los Angeles, and other sedimentary basins. Diatomaceous earth results from accumulation of the siliceous shells of microscopic plants in either a marine or continental sedimentary environment; commonly it is in sedimentary deposits that are in close association with volcanic rocks. Hence deposits of diatomaceous earth occur not only in upper Mesozoic and Tertiary sedimentary terranes such as the southern Coast Ranges but also in volcanic terranes such as the Modoc Plateau.

Some of California's most important mineral commodities are the saline minerals—boron and borax, bromine, calcium chloride, potash, salt, sodium carbonate, and sodium sulfate. Deposits of these commodities were formed in two large saline lakes that developed during late Cenozoic time mainly in closed basins in the Great Basin province. They are the product of evaporation of waters richly charged with mineral constituents. Gypsum and anhydrite are more widely distributed but somewhat less soluble products of evaporation that formed in many marine and continental basins in the State.

The purpose of this generalized and incomplete review of California's mineral resources is to demonstrate how the occurrence of individual resources or groups of resources is restricted to certain geologic environments within the State. A more detailed summary of the resources on a commodity-by-commodity basis is given in the succeeding pages.

California's production of the various mineral commodities during 1963 and 1964, the latest years for which figures are available, is given in table 3.

TABLE 3.—*Mineral production in California,*[1] *1963 and 1964*

Mineral	1963		1964	
	Short tons (unless otherwise stated)	Value (thousands)	Short tons (unless otherwise stated)	Value (thousands)
Asbestos	19,591	$1,547	55,041	$4,419
Barite (crude)	5,082	31	5,604	45
Boron minerals	700,183	54,981	776,000	60,871
Calcite (optical grade) pounds	----------	----------	4	2
Cement [2] 376-pound barrels	46,278,000	147,656	47,204,000	149,933
Clays [3]	3,395,000	8,031	3,651,000	8,196
Copper (recoverable content of ores, etc.)	916	564	1,035	675
Feldspar long tons	75,516	(4)	102,264	(4)
Gem stones	(5)	200	(5)	200
Gold (recoverable content of ores, etc.) troy ounces	86,867	3,040	71,026	2,486
Gypsum	1,756,000	4,222	1,893,000	4,539
Lead (recoverable content of ores, etc.)	823	178	1,546	405
Lime	487,000	8,932	577,000	10,312
Magnesian compounds from sea water and bitterns (partly estimated) MgO equivalent	82,397	6,135	94,739	7,143
Mercury 76-pound flasks	13,592	2,575	10,291	3,240
Mica, scrap	977	14	(4)	(4)
Natural gas million cubic feet	646,486	189,420	664,051	198,551
Natural gas liquids:				
Natural gasoline and cycle products thousand gallons	715,303	54,188	720,373	54,088
Lp gases do	393,503	17,329	352,614	15,893
Peat	39,873	450	35,391	443
Petroleum (crude) thousand 42-gallon barrels	300,908	746,232	300,009	729,022
Pumice, pumicite and volcanic cinder	460,000	2,017	443,000	1,937
Salt (common)	1,716,000	(4)	1,525,000	(4)
Sand and gravel	112,185,000	128,178	112,995,000	129,333
Silver (recoverable content of ores, etc.) troy ounces	157,000	200	172,000	222
Stone [6]	37,977,000	58,253	45,805,000	63,566
Sulfur ore long tons	785	4	520	3
Talc, pyrophyllite, and soapstone	120,452	1,427	132,601	1,631
Wollastonite	3,000	28	3,625	36
Zinc (recoverable content of ores, etc.)	101	23	143	39
Value of items that cannot be disclosed: Bromine, calcium chloride, carbon dioxide, masonry cement (1963), clays (ball and fuller's earth) 1964, coal (lignite), diatomite, iodine, iron ore, lithium minerals, molybdenum, perlite, platinum-group metals, potassium salts, rare-earth metals, sodium carbonate, sodium sulfate, steam (natural), tin, tungsten concentrate, uranium, and values indicated by footnote [1]	----------	90,366	----------	113,280
Total	----------	1,526,241	----------	1,561,033

---

[1] Production as measured by mine shipments, sales, or marketable production (including consumption by producers).

[2] Excludes masonry cement included with "Value of items that cannot be disclosed."

[3] Incomplete figure. Ball clay and fuller's earth included with items that cannot be disclosed.

[4] Withheld to avoid disclosing company confidential data.

[5] Weight not recorded.

[6] Includes slate.

Source: U.S. Bureau of Mines.

ALUMINUM

(By G. B. Cleveland, California Division of Mines and Geology, Los Angeles, Calif.)

Aluminum, the second most abundant metal in the earth's crust, is found in nearly all rocks. Only under special geologic conditions, however, does it occur in large high-grade deposits that can be economically worked as a source of the metal. At present, the only important ore of aluminum is bauxite. The principal domestic deposits of bauxite are in Arkansas, Georgia, Alabama, and Mississippi. These contain less than one percent of the world's reserves, and many cannot compete either in quality or price with foreign imports. In 1963, the domestic deposits supplied only about 12 percent (1,525,000 long tons) of the bauxite consumed in the United States. The balance (about 11,318,000 long tons) was drawn principally from the Caribbean islands of Jamaica, Haiti, and the Dominican Republic, and from the Guianas. The United States ranks first in the production of primary aluminum metal, supplying about 2,313,000 tons of the world total of about 6,095,000 tons in 1963.

Aluminum has an extremely wide variety of uses. Most of them are in products where light weight or resistance to corrosion are important—military equipment, industrial, farm and residential building materials, automobiles, home appliances, and materials and containers It is also used in industrial chemicals, and electrical wire.

Bauxite is a colloidal mixture composed of various proportions of the minerals gibbsite ($Al(OH)_3$) and the dimorphic forms boehmite and diaspore, both ($AlO(OH)$). Common impurities are rutile, siliceous minerals such as kaolinite and quartz, as well as the iron oxides—limonite, hematite, and goethite—and the carbonate minerals calcite, magnesite, and siderite. Bauxite is gray, cream, yellow, dark red, or earthy brown, is normally pisolitic or oolitic and generally has a mottled appearance. Bauxite is a residual product formed by the deep weathering of aluminous rocks under tropical conditions, and is commonly a constituent of lateritic soils. All domestic deposits are Eocene in age.

The known occurrences of bauxite in California are limited to small deposits which are associated with fire clay. None of these deposits has proved large enough to have been developed as a commercial source of aluminum; nor has this metal been recovered from any raw material mined in California. However, other alumina-rich deposits, principally the large anorthosite bodies in the southern part of the State and the alumina-rich clays, constitute potential resources that may eventually yield aluminum on a commercial basis.

The only large anorthosite bodies known in California are exposed in the western San Gabriel Mountains of southern California and have a combined outcrop area of about 50 square miles. The San Gabriel Mountain anorthosite is composed of calcic andesine (97 percent) with small amounts of apatite and zircon.

Although California contains no known deposits of clay that compare in alumina content with the high-alumina (40 percent and above) or diasporic clays (50 percent or more alumina), some of the State's fire clay can be classified as alumina-rich clay. The alumina-rich fire clays from California deposits range from about 30 to 40 percent alumina. These deposits are in the Eocene Ione Formation which occurs along the western foothills of the Sierra Nevada, the Paleocene Silverado Formation exposed in the Alberhill-Corona area of Riverside County, and in the Eocene Tesla Formation in eastern Alameda County. These clay beds vary in their alumina content, and the higher grade material would have to be selectively mined.

Aluminum has been produced experimentally or on a small-scale commercial basis from anorthosite, high-alumina clays, alunite, nepheline syenite, leucite, andalusite, and aluminous shales. When bauxite reserves become depleted, one or more of these materials may be developed on an economic basis.

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ANTIMONY

(By Q. A. Aune, California Division of Mines and Geology, Redding, Calif.)

Antimony is a brittle, silver-white metal with a melting point of 630.5°C. Antimony metal has the property of expanding when cooled and of hardening certain other metals when alloyed with them. The effect of antimony in lead alloys is to add stiffness and physical strength, to resist chemical action, and to make sharp, accurate castings. In nonmetallic compounds, it may be used as an opacifying agent or as a pigment. Certain antimonial compounds have fire-extinguishing characteristics which account for the bulk of antimony consumption during wartime. The nearly complete dependence of the United States on foreign supply as shown in figure 5, and the diversity of its major uses earn antimony's classification as a strategic mineral.

A substantial portion of metallic antimony produced in the United States is secondary antimony reclaimed from scrap metal (fig. 5). In recent years, production of antimonial lead has consumed roughly 18,000 tons of antimony annually, over two-thirds of this from secondary antimony, and most of it used in auto batteries. Production of bearing metal, cable covering, sheet and pipe, solder, and type metal has also relied heavily on secondary antimony.

Antimony deposits may be classified in two types. The mineralogically simple type consists dominantly of antimony minerals in a siliceous gangue, commonly with a little pyrite and in places small quantities of other metal sulfides. The original antimony mineral is stibnite (antimony sulfide) or, rarely, native antimony. Where exposed to oxidation, the original minerals are converted to antimony oxide. Although most of the world's production is from deposits of the simple type, most of the antimony mined in the United States is, for economic reasons, from deposits of the complex type: ores mined primarily for lead, gold, silver, quicksilver, zinc, or tungsten, with antimony as a by-product.

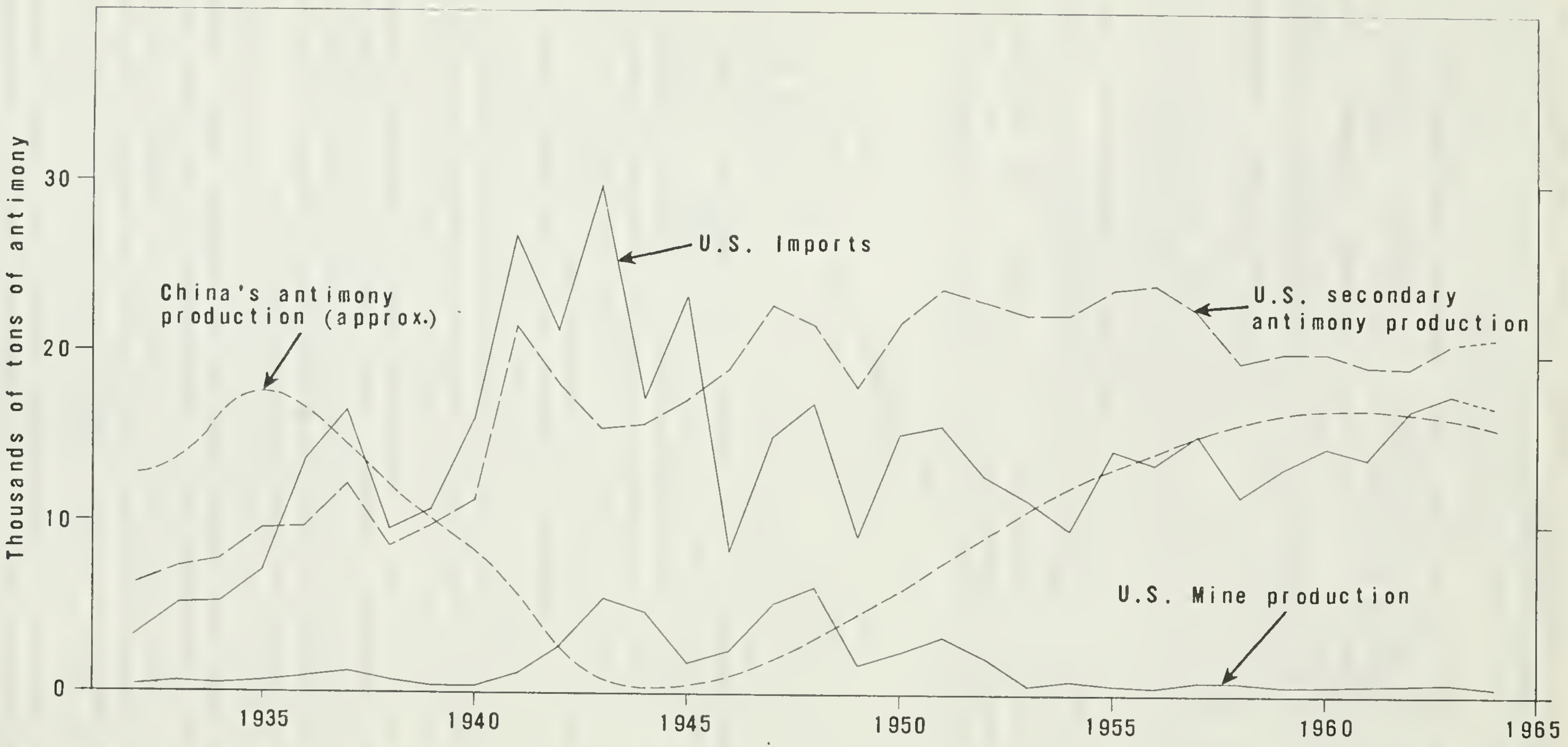

FIGURE 5. Trends in U.S. production and imports of antimony. The antimony production of China, the principal world producer, is also shown. (Data from U.S. Bureau of Mines Minerals Yearbook, 1963.)

Most of the antimony deposits of California, as shown on figure 6, are of the simple type—small ore bodies that commonly show structures characteristic of epithermal deposits—fissure fillings, irregular disseminations in vugs or "pockets" and breccia, and haphazard fracture control.

The Stayton district in San Benito and Merced Counties is the largest antimony mining district in California, although production has been small, limited to perhaps 500 tons of antimony metal, none since World War II. Antimony occurs as stringers and cavity fillings of tarnished stibnite which are localized in numerous north-northwest-trending fault zones in Tertiary basalts and tuffs. In late 1949 and throughout 1950, the Cordero Mining Co. of Palo Alto and the U.S. Bureau of Mines prospected the Quien Sabe mine, a principal deposit of this district, and revealed a moderate tonnage of ore averaging three percent antimony.

The Wildrose Canyon deposit in the Panamint Range, Inyo County, has been the principal past producer in California. Antimony oxides and stibnite occur in blanket-type breccia deposits in schists, and as fissure fillings in quartz veins.

At the Transportation (Old Dependable) deposit, near the base of the Panamint Range a few miles east of the Wildrose Canyon deposit, stibnite and antimony oxides occur in small, scattered masses in shale overlying limestone. Other deposits in Inyo County occur at the Hilltop, Rocket, and Darwin mines on the west slope of the Argus Range, and the Bishop mine on the east slope of the Sierra Nevada near Bishop.

A number of deposits have been worked for antimony in Kern County. Most of these deposits consist of stibnite and quartz in veins along shear zones in granodiorite or quartz diorite. The largest deposit of this type is the San Emigdio (Antimony Peak) deposit in southeastern Kern County. Calcite, pyrite, and antimony oxides are also present. The deposit was mined intermittently from 1882 to 1892, during World War I, and most recently in 1940–1941.

Deposits at Antimony Flat, eastern Kern County, consist of small nodules and clusters of radiating stibnite blades disseminated along poorly exposed steeply dipping quartz veins in granodiorite. Stibnite occurs in quartz veins in silicified andesitic rock at the Mammoth Eureka mine 17 miles east of Caliente in east-central Kern County; this mine was the source of an undetermined quantity of antimony ore during World War I. At the Tom Moore mine, aggregates of bladed and massive stibnite and native antimony occupy a quartz vein in a shear zone in metamorphic rocks. At the Jenette-Grant mine, stibnite occurs with quartz along a limestone-schist contact.

In the Atolia district, near the west border of San Bernardino County, stibnite is locally present in subordinate proportions in veins in quartz monzonite. Mineralogy is complex. Chalcedony, quartz, scheelite, and carbonates of calcium, iron, and magnesium are principal minerals, with cinnabar also locally present. At the Desert Antimony (Wade) deposit in the Mountain Pass area, eastern San Bernardino County, quartz-stibnite-barite-calcite veins occur in granitic gneiss.

Total inferred California reserves of antimony metal from ore estimated to contain greater than one percent antimony, assuming such "ore" could be economically worked, would be on the order of only 15 to 20 thousand tons, a small amount compared to America's annual

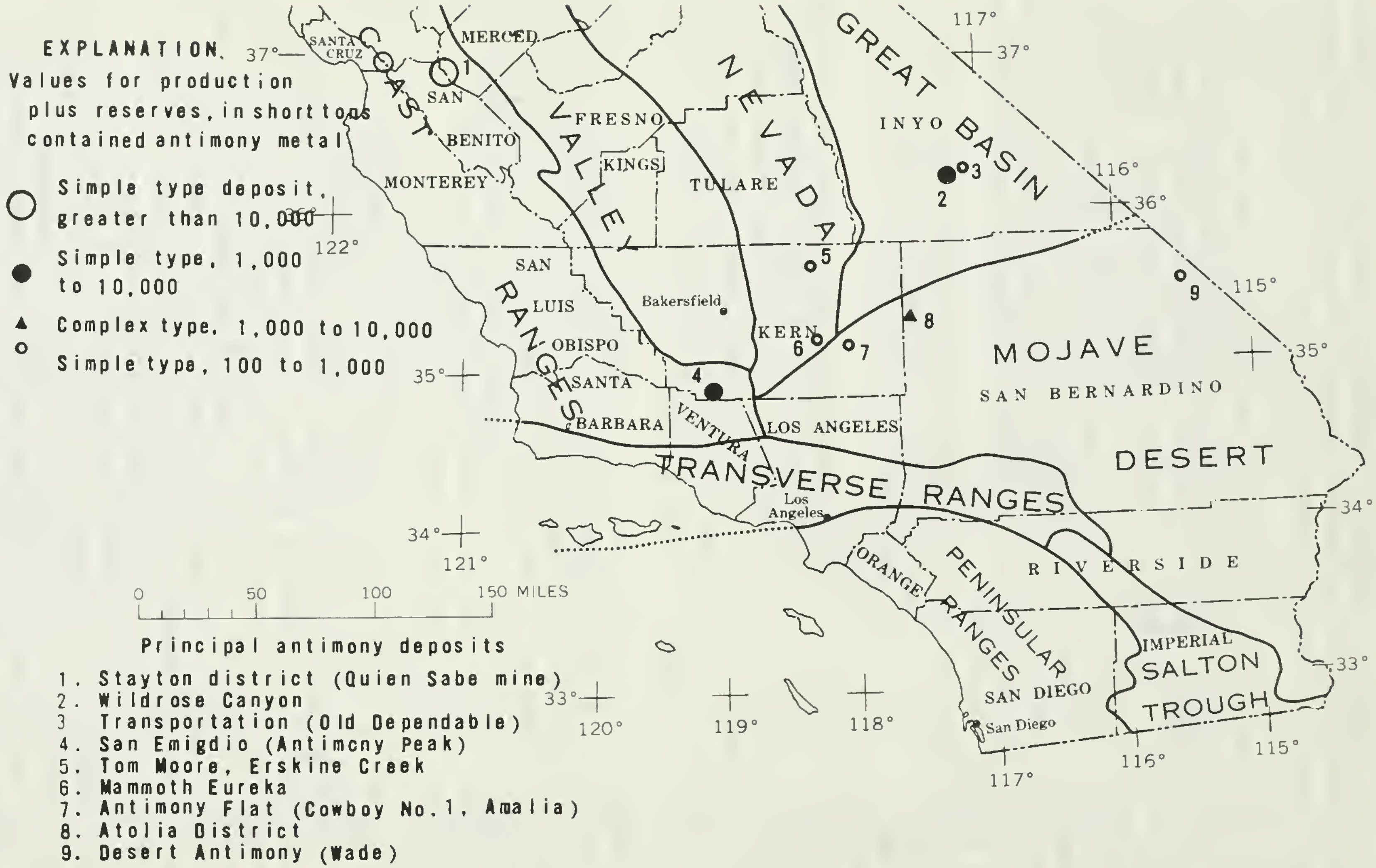

Figure 6. Antimony in California.

needs, and most of this tonnage is in the Stayton district. Many of the deposits are largely "high-graded" or worked out. Any large tonnage developments probably must come from new deposits. Such new deposits, if present, would seem most likely to occur in areas favorable to epithermal deposition. Such areas are most likely to occur in the Great Basin province and the eastern margin of the Sierra Nevada. Somewhat lesser possibilities are in the central Coast Range and eastern Klamath Mountain areas.

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ARSENIC

(By Q. A. Aune, California Division of Mines and Geology, Redding, Calif.)

Arsenic is produced as a by-product of copper and lead smelting and in the recovery of gold and silver. It is recovered only in the form of arsenious oxide (white arsenic), as no metallic arsenic has been produced in the United States since about 1950. The United States ranked as a major producer and consumer of arsenical products in 1964. Other important producing countries in the free world include Sweden, Mexico, and France. No domestic ores are mined exclusively for arsenic. The first recorded production of white arsenic in the United States was in 1901. Arsenic is used for manufacturing calcium and lead arsenate insecticides and herbicides, in chemicals for wood preservation, and is added to lead shot and glass. A small amount is used in the recently developed solid state masers and lasers.

The most common occurring arsenic-bearing minerals are the sulfides arsenopyrite, realgar, and orpiment. Arsenopyrite is commonly associated in hypothermal vein deposits with the ores of tin, nickel, cobalt, silver, and gold, and with pyrite, chalcopyrite, galena, and sphalerite in mesothermal deposits. Realgar and orpiment occur in epithermal deposits with the ores of silver and antimony and in deposits formed by sublimation from hot springs.

In the early 1920's, California deposits were mined principally for their arsenic content at Grass Valley, Nevada County; at the Contact mine in Kern County; and at the Black Mountain prospect in San Diego County.

Arsenic, principally in the mineral arsenopyrite, has a widespread occurrence in the ore deposits of California, but at present is of doubtful commercial interest in any California deposit. It is especially abundant in the arsenopyrite-bearing silver ores of the Randsburg district in Kern and San Bernardino Counties, and in the arsenopyrite-bearing gold ores of the Alleghany district in Sierra County and the Mother Lode of the Sierra Nevada. Arsenopyrite and sulfarsenides are also present in the base-metal ores of the Mojave Desert, the Sierra Nevada foothills, and the Shasta mining district.

Since 1924, large quantities of byproduct arsenic available for import from Mexico have held prices down. More recently many uses of arsenic as a toxic agent have fallen off with the advent of organic compounds such as DDT. These competitive conditions have rendered California arsenic mining unprofitable, and the closing of nonferrous metal mines, from which arsenic might be recovered as a by-product, has terminated production in the State.

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ASBESTOS

(By S. J. Rice, California Division of Mines and Geology, San Francisco, Calif.)

Uses and Economic Importance

Asbestos is one of the few important nonmetallic minerals that is largely imported from foreign sources. Of the 790,000 tons of asbestos used in the United States in 1964, only about 100,000 tons were produced from domestic deposits. Most of the remainder was imported from Canada.

Certain grades of asbestos are indispensable to the construction and transportation industries, and all grades occupy important places in the general industrial economy. Most of the important uses of asbestos are based on the fact that it has physical characteristics similar to those of organic fibers, yet it is both noncombustible and noncorrosive. These physical properties are summarized in table 4. As used in the manufacture of numerous products, asbestos acts as a reinforcing agent or as a friction or insulation material. The principal use is in the manufacture of asbestos-cement products such as pipe,

TABLE 4.—*Properties of asbestos minerals*

[Modified from Badollet, 1951]

	Chrysotile	Tremolite	Crocidolite	Amosite	Anthophyllite
Color	Green, greenish-yellow, gray, or white.	White, grayish-white, greenish-yellow, or bluish-gray.	Lavender, blue, or greenish	Ash-gray, greenish, or brown.	Grayish-white brownish-gray or green.
Texture	Soft to harsh, silky	Generally harsh, some soft	Soft to harsh	Coarse, but somewhat pliable.	Harsh.
Geologic occurrence	In serpentine	In serpentine and various metamorphic rocks.	Iron-rich siliceous argillite and quartzose schists.	Same as crocidolite	In crystalline schists, serpentine, or meta-serpentine.
Veining and fiber length	Cross and slip fibers; short to long.	Slip or mass fiber; rarely cross fiber; short to long.	Cross fiber; short to long	Cross fiber; mostly long	Mass or slip fiber; rarely cross fiber; mostly short.
Tensile strength, pounds per square inch.	80,000 to 100,000	8,000 or less	100,000 to 300,000	16,000 to 90,000	4,000 or less.
Flexibility	Very flexible	Fairly flexible to brittle	Flexible	Flexible	Fairly flexible to brittle.
Spinnability	Very good	Generally poor; rarely spinnable.	Fair	Fair	Very poor.
Fusibility	Fusible at 6	Fusible at 4	Fusible at 3	Fusible at 6	Infusible or difficultly fusible.
Acid resistance	Poor	Good	Good	Good	Very good.

shingles, wallboard, and corrugated sheets. Large quantities also are used in the manufacture of vinyl and asphalt floor tiles, friction materials such as clutch facings and brake bands, insulation materials, and gaskets. Small amounts of the spinning grades of strong-fiber varieties are woven into asbestos fabrics for various special uses.

Mineralogy and Geologic Occurrences

The word asbestos is not a mineral name, but a term applied to several naturally fibrous minerals that are used primarily because of their fibrous characteristics. These minerals include chrysotile, crocidolite, amosite, anthophyllite, and tremolite.

Chrysotile

Chrysotile is the most important asbestos mineral, accounting for more than 90 percent of the world's asbestos production. Chrysotile fibers of good quality are silky, highly flexible, and have a tensile strength somewhat greater than that of silk.

Chrysotile occurs only in serpentine, a fine-grained rock composed almost entirely of hydrous magnesium silicate minerals similar to chrysotile in composition. Almost all masses of serpentine contain chrysotile, most commonly in cross-fiber veins that rarely are more than half an inch thick. In places, however, the fibers lie along faults or shear planes and are not so apparent. Only rarely is chrysotile sufficiently abundant in the rock to constitute an asbestos ore body. Most of the chrysotile fibers in any deposit are very short (less than one-sixteenth of an inch long), and clean extraction of the asbestos requires complicated and expensive milling equipment, so a large volume of fiber-rich rock is required for a commercially valuable ore body.

About 40 percent of the world production of chrysotile comes from cross-fiber deposits in a relatively small district in the province of Quebec, Canada. The discovery of these rich deposits in 1877 laid the foundation of the modern asbestos industry. Substantial amounts of chrysotile are produced from similar deposits in the U.S.S.R. and Africa.

Amphibole asbestos

Amphibole asbestos is a general term for all varieties other than chrysotile. These are all members of an exceedingly common group of rock-forming silicate minerals characterized by perfect prismatic cleavage. Only a few of the amphibole minerals, principally those that are aluminum-poor, become sufficiently fibrous to be used as asbestos. In approximate order of economic importance, these are crocidolite, amosite, anthophyllite, and tremolite.

The principal source of crocidolite—blue asbestos—is the Union of South Africa, but lesser quantities are produced in Australia and Bolivia. Commercial deposits of this variety have not been found in California. Amosite, a yellowish-gray, long-fiber variety, is produced in Africa, and has not been found elsewhere. Both of these varieties occur as cross-fiber veins in metamorphosed sedimentary rocks rich in silica and iron, and both have strong fibers.

Most anthophyllite asbestos occurs in massive deposits derived by metamorphism of peridotite. The fibers have no preferred orientation, but are arranged in bundles of varying sizes oriented at random.

Deposits of this type are mined in Finland and North Carolina. In California, long-fiber anthophyllite occurs as veins along faults in serpentine; the fibers are oriented roughly parallel to the walls of the veins. The latter mode of occurrence is characteristic also of tremolite asbestos deposits in the State, and, in this environment, the two varieties cannot easily be differentiated. The fibers of both are white and very weak.

HISTORY OF DEVELOPMENT OF CALIFORNIA ASBESTOS DEPOSITS

Although asbestos has been mined sporadically in California since 1887, a full-fledged asbestos industry did not emerge in the State until 1960. This dramatic emergence is demonstrated by the production figures, table 5. Prior to 1960, only 9,049 tons, valued at $331,454 had been produced, whereas production during the interval 1960–1964 was 87,782 tons, valued at $6,412,764. Much of the earlier production was of amphibole asbestos, long-fiber tremolite and anthophyllite, mined and hand sorted from small deposits. It was sold primarily for use as filter fiber. Current production is entirely chrysotile.

TABLE 5.—*Asbestos production in California, 1887–1964*

Year	Short tons	Value	Year	Short tons	Value	Year	Short tons	Value
1887	30	$1,800	1913	47	$1,175	1941	16	$2,867
1888	30	1,800	1914	51	1,530	1942	4	836
1889	30	1,800	1915	143	2,860	1943	723	15,000
1890	71	4,260	1916	145	2,380	1944		
1891	66	3,960	1917	136	10,225	1945	37	3,605
1892	30	1,830	1918	229	9,903	1946		
1893	50	2,500	1919	131	6,240	1947	165	12,100
1894	50	2,250	1920			1950		
1895	25	1,000	1921	140	19,275	1951		
1898	10	200	1922	50	1,800	1953	224	16,779
1899	30	750	1923	20	200	1954		
1900	50	1,250	1924	70	4,750	1955	1,205	21,401
1901	110	4,400	1925	25	1,650	1956	858	28,832
1904	10	162	1926			1957		
1905	112	2,625	1927	13	1,160	1958	2,695	84,050
1906	70	3,500	1928			1959		
1907	70	3,500	1929	219	6,175	1960	7,280	125,115
1908	70	6,100	1930			1961		
1909	65	6,500	1932	309	3,274	1962	5,870	321,719
1910	200	20,000	1933			1963	19,591	1,546,890
1911	125	500	1934			1964	55,041	4,419,040
1912	90	2,700						

NOTE.—Where necessary in order to conceal output of individual producers, production figures are combined to cover a 2- or 3-year period. During years omitted there was no recorded production.

During and immediately after World War I, when asbestos prices were high, attempts were made to develop chrysotile deposits in California, particularly those near Copperopolis, Calaveras County, and Washington, Nevada County. These operations failed, largely because there was only a very limited market for asbestos on the Pacific Coast at that time. Transportation rates made fiber from this area noncompetitive on the eastern market with that from Quebec.

The recent surge of development of California deposits was stimulated by the post-World War II population and industrial boom on the West Coast. Several new plants that manufacture asbestos products were constructed in California, and older ones were enlarged. The principal asbestos products manufactured here utilize the shorter grades of chrysotile that can be produced in abundance in California.

This growing demand resulted in extensive exploration of deposits in Calaveras, Fresno, and San Benito Counties in 1959 and 1960, and by 1964 four asbestos mills had been constructed to process ores from these deposits.

Occurrences In California

Serpentine, the principal host rock for asbestos deposits, is abundant in California, and asbestos has been found at numerous localities in the State (fig. 7). Most of the deposits that have been worked have been described by Wiebelt and Smith (1959), but only four areas contain deposits of chrysotile asbestos that are presently being mined.

Copperopolis area

The first chrysotile asbestos deposit worked in California is located 7 miles southeast of Copperopolis, Calaveras County (Rice, 1963). This deposit is similar to those in Quebec in that the chrysotile occurs as stockworks of cross-fiber veins in massive serpentinized peridotite.

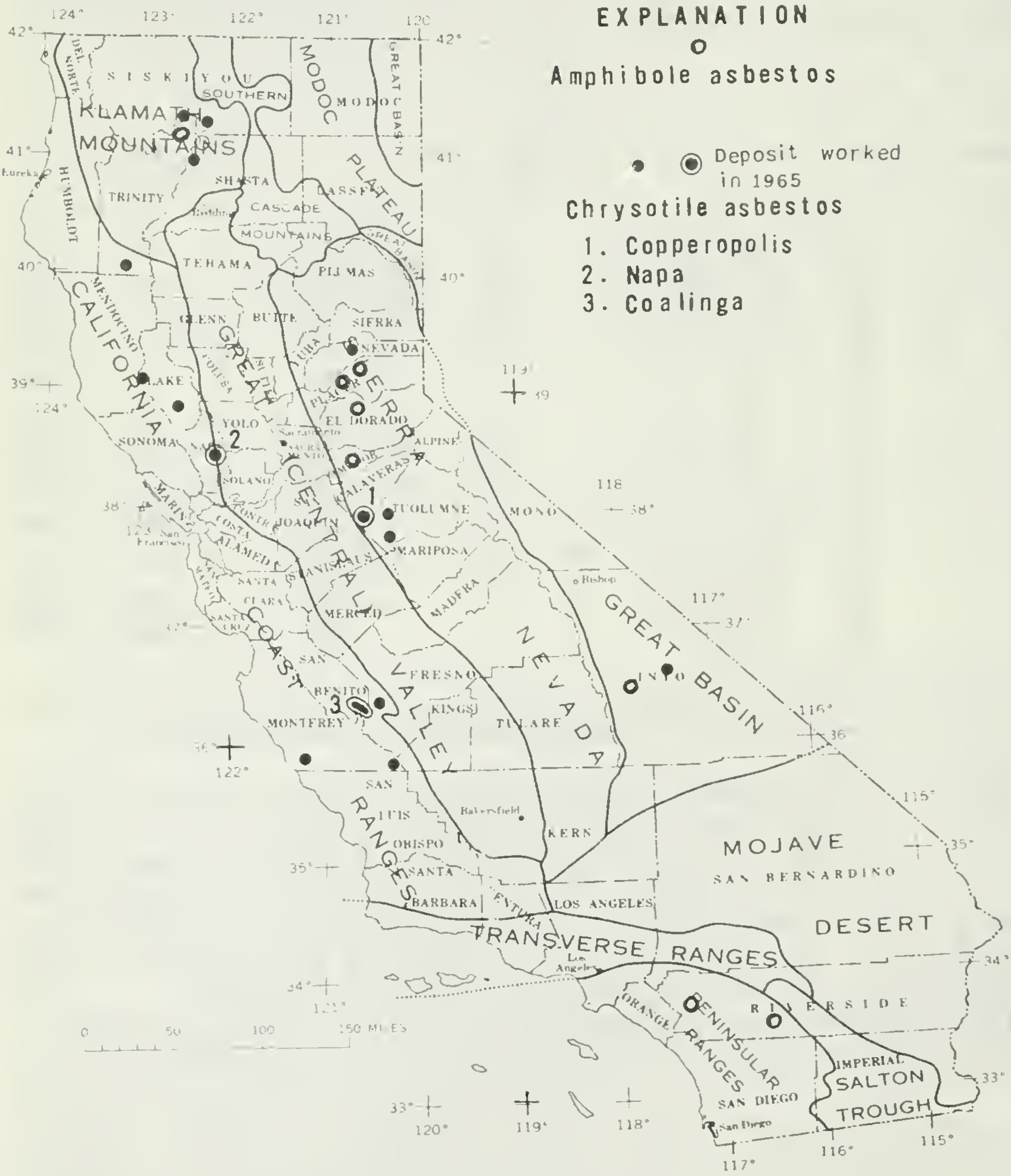

Figure 7. Principal asbestos deposits in California.

Width of the veins is highly variable, from less than one-thirty-second of an inch to about an inch, but only a small percentage of them will yield fibers more than one-fourth inch long. The ore body apparently occupies the crest of an anticline in a large sill of serpentine.

Although several unsuccessful attempts were made to develop this deposit in the early 1900's, not until 1959 was it thoroughly explored by trenching and core drilling. This work indicated an elliptical-shaped ore body, some 1,800 feet long and 375 feet in average width. Sufficient tonnage was proved—more than 20,000,000 tons of ore containing about 6½ percent asbestos—to indicate a commercial deposit (Merritt, 1962, p. 58). In 1962, a mill was constructed at the deposit capable of processing 2,500 tons of ore per day and of recovering any grade of milled fiber. The mine is now operated by Pacific Asbestos Corp.

Napa area

A deposit of cross-fiber chrysotile asbestos in sheared serpentine, about 18 miles northeast of Napa, was the site of a small asbestos operation during World War II and during the middle 1950's. The veins are narrow, ordinarily yielding fibers less than one-sixteenth of an inch long, so that only the shorter fiber grades can be recovered from the rock.

A 40-ton mill installed on the property in the early 1940's was inadequate for modern operations, so it was replaced in 1959 by a new mill having a capacity to process about 125 tons of ore per day. It is operated by Asbestos Bonding Co.

Coalinga area

A large serpentine mass in the southern Coast Ranges, some 20 miles northwest of Coalinga, Fresno County, constitutes one of the largest asbestos deposits in the world. The bulk of this mass, altogether some 14 miles long and 4 miles wide, has been highly sheared and much of the serpentine recrystallized to flaky, matted chrysotile along the closely spaced shear planes (Rice, 1963). Cross-fiber veins are rare in this deposit, and the recoverable fiber is all short, but the chrysotile content is very high, exceeding 50 percent in places. Fiber produced from this deposit has attributes that promise an interesting future for the district. Among these, Coalinga fiber is superior to Canadian short fiber in whiteness and in its ability to absorb hydrocarbons (Munro and Reim, 1962).

The commercial asbestos potential of this enormous deposit, which probably contains more than 100 million tons of ore, was not recognized by the industry until 1959, when Union Carbide Nuclear Co. began filing mineral claims in the area, then largely open Federal land. Other companies soon were attracted to the area, and by 1965. three mills having an aggregate productive capacity of about 50,000 tons of fiber per year were in operation. Companies active there in 1965 were Coalinga Asbestos Co., Atlas Corp., and Union Carbide Nuclear Co.

Recent discoveries and commercial development of California asbestos deposits indicate that the potential for new discoveries in the

State is high. The total outcrop area of serpentine in the Coast Ranges, Sierra Nevada, and Klamath Mountains is on the order of 2,000 square miles, and significant portions of this have not been prospected for asbestos. It seems probable that more discoveries will be made of Coalinga-type deposits in the southern Coast Ranges. Also, many interesting chrysotile prospects in the serpentine masses in Shasta, Trinity, and Siskiyou Counties (Wiebelt and Smith, 1959) suggest that this relatively remote area is a promising one.

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ASPHALT AND BITUMINOUS ROCK

(By M. B. Smith, U.S. Geological Survey, Los Angeles, Calif.)

The primary use of native asphalt and bituminous rock in California in the past has been for road-paving material. However, crude oil has been recovered from these rocks at several localities. These latter operations were not commercially successful, but it seems likely that the future use of bituminous rock will be for its oil content.

Asphalt (brea) in California occurs at the surface where it is usually mixed with soil, and in vein-like fracture fillings in rocks. Some veins are nearly pure asphalt. Bituminous rocks, mainly sandstones or finer grained rocks impregnated with viscous asphaltic material, crop out at the surface in many places, and in some places they extend to depths of several hundred feet where they contain less viscous fluid and will yield oil to wells.

Nearly all the deposits in the State are in sedimentary rocks of Miocene to Recent age in the California Coast Ranges, Transverse Ranges, and Peninsular Ranges provinces (fig. 8). Most of the deposits are at the surface near the margins of the sedimentary basins. They also occur in the basins where some rocks are near the surface as a result of folding or faulting, or where oil has migrated along faults.

The present production of bituminous sandstone in the United States is very small, only 1,800 tons valued at $15,000 in 1963. Past production in California has been about 1.5 million tons of bituminous sandstone with a value of $4.75 million, 219,000 tons of asphalt with a value of $2 million, and 24,500 barrels of crude oil with a value of $100,000.

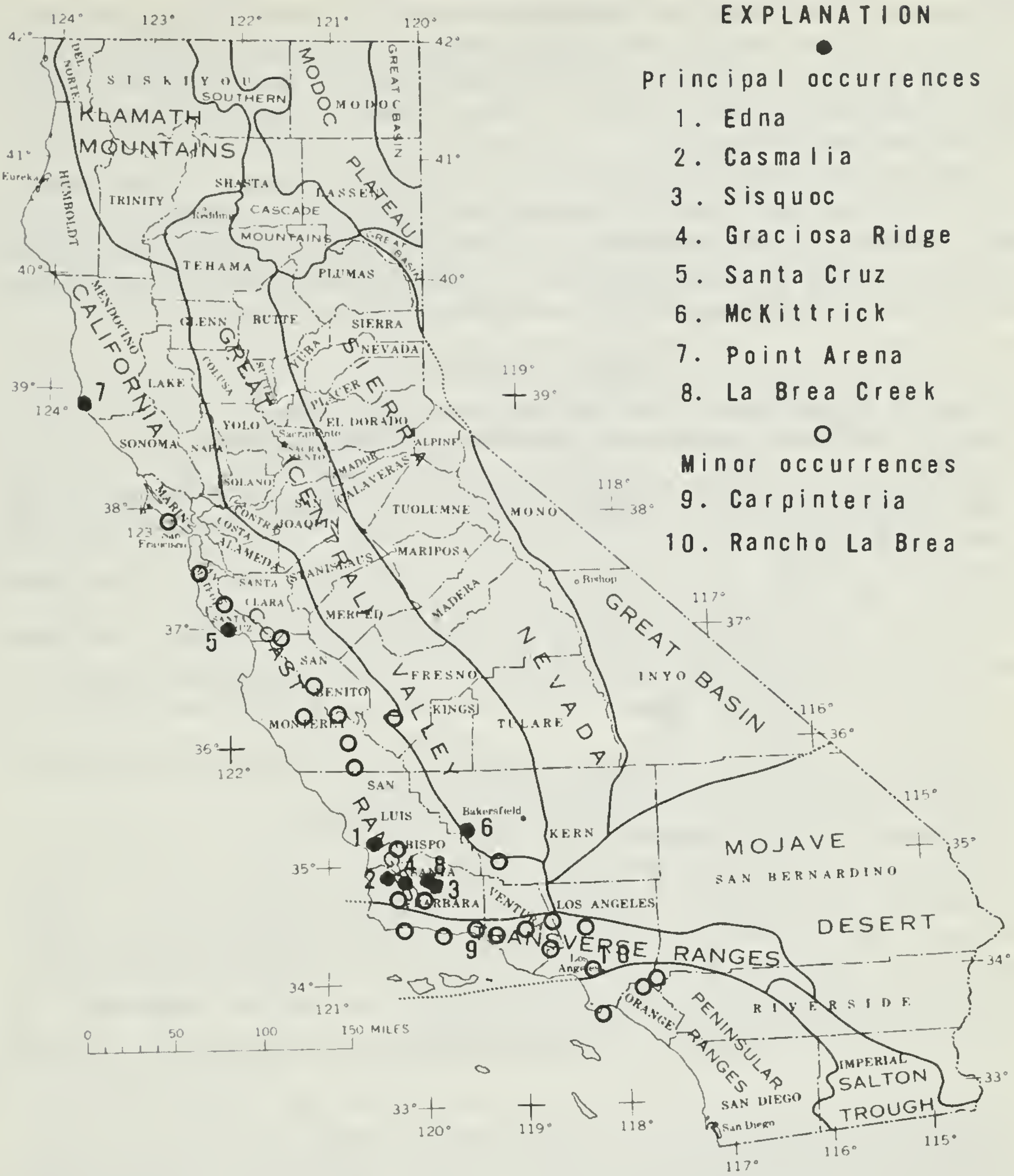

FIGURE 8. Asphalt and bituminous rock in California.

The production of native asphalt ceased long ago. The production of bituminous sandstone reached a peak in 1910, but then decreased rapidly as petroleum asphalt from refineries captured the market for road paving material. It was discontinued in 1949, and the only operation since that time has been the quarrying of a bituminous rock which is then burned to obtain lightweight concrete aggregate and pozzolan. Crude oil has not been recovered from such deposits since 1959.

The resources of oil recoverable by known methods from bituminous rocks in California are believed to be large. Estimated reserves are about 300 million barrels that could be recovered from only those deposits that have been quite well examined and worked in places.

However, this oil can not be recovered at a cost now competitive with crude oils from wells. As the recovery of this oil by quarrying or mining would require moving about 400 million tons of rock, it seems that some method of recovering the oil from the rocks in the ground offers the best prospect.

Also it has been estimated (Duncan, D.C., written communication) that 1 billion barrels of oil-equivalent could be recovered from the higher grade bituminous shale of late Miocene and Pliocene age in the State, and that as much as 70 billion barrels of oil-equivalent is present in widespread Miocene shales (Rubel, 1955).

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BARITE

(By F. H. Weber, Jr., California Division of Mines and Geology, Los Angles, Calif.)

Barite, naturally occurring barium sulfate, is the heaviest of the nonmetallic industrial minerals; its specific gravity is 4.5. It is used principally as a weighting agent in oil and gas well drilling fluids, and to manufacture barium chemicals; lesser amounts are used in paints, rubber, and glass, as high-density aggregate in concrete for nuclear shielding, and for other purposes. The United States is the leading world producer, importer, and consumer of crude barite, with a consumption in 1963 of 1,400,000 tons, valued at about $14,000,000. Of this amount, 824,000 tons, valued at $9,447,000 was mined domestically, principally in Missouri, Arkansas, Georgia, and Nevada, with smaller quantities in California and several other states.

The total recorded output of barite mined in California, from 1910 to 1963, is 735,000 tons, with a value of $5,440,000. The annual consumption of the crude mineral from 1959 to 1963 by California industry fluctuated between 100,000 and 130,000 tons, but only about 5,000 to 15,000 tons were mined annually in the State. Most of the crude barite rock consumed in California is mined in Nevada, where deposits are numerous and commonly large and relatively high in grade; they yield barite rock of at least 4.2 in specific gravity, the minimum weight suitable when crushed and ground, for use in drilling fluids. Thus the resultant low cost of the crude mineral compensates for the relatively high transportation cost to California processing facilities. Crude barite for use in drilling fluids is processed in California principally by Baroid Division of National Lead Co., Macco Corp., Calada Materials Co., Industrial Minerals and Chemical Co., and Yuba Minerals and Milling, Inc.; barium chemicals are manufactured by FMC Corp. The value per short ton of crude barite delivered to these facilities, ranges from about $13 or $14 to about $22 or $23 per ton, the value generally being higher in southern California. Fluctuations in the amount of barite consumed in the State generally reflect the activity in drilling, with less activity in mid-1965 reflected in lesser tonnages of barite being consumed.

Though California furnishes only a small proportion of the crude barite rock that it consumes, the State contains more than 150 known barite localities, including 7 deposits that have yielded more than 15,000 tons, and about 15 deposits which have yielded from 100 to 10,000 tons as shown on fig. 9 and on table 6. Deposits mined since 1960 that have yielded at least several hundred tons are the Ninemile Canyon (1961–1963) and Bald Mountain (1963–1965) in the Sierra Nevada; the Glidden Co. (1962–1964) and Alwood (1962) in the Klamath Mountains; the Gunter Canyon (1962–1965) in the White Mountains; and the Leviathan (1961) and Silver Bow (1961) in the Calico Mountains.

Slightly more than 90 percent of the total barite mined in California has come from 5 deposits that are part of a crude belt which extends at least from the southern to the northern Sierra Nevada; and may extend, interrupted by the Cascade Mountains, into the Klamath Mountains. The deposits occur in metamorphic rocks of the Calaveras Formation and similar units. Of these 5 deposits, 2 lie in the southern part (El Portal, Ninemile Canyon) and 3 in the northern part (Almanor, Democrat, Spanish). The deposits of the southern part consist of long, steeply dipping vein-like bodies of quartz-barite rock which averages about 3.9 to 4.1 in specific gravity. These bodies occur within north- to northwest-trending linear zones which are at least 3 miles in length, but commonly are offset by minor faults; individual fault segments of the barite bodies are at least 3,000 feet in length, and range in thickness from 1 to 40 feet and perhaps average 3 to 8 feet. Nearly all barite rock mined has been upgraded by jigging (Ninemile Canyon, Bald Mountain) or by a combination of jigging and sink-float (El Portal, mined from 1910 to 1948, and the source of almost 60 percent of the total barite mined in California). The most

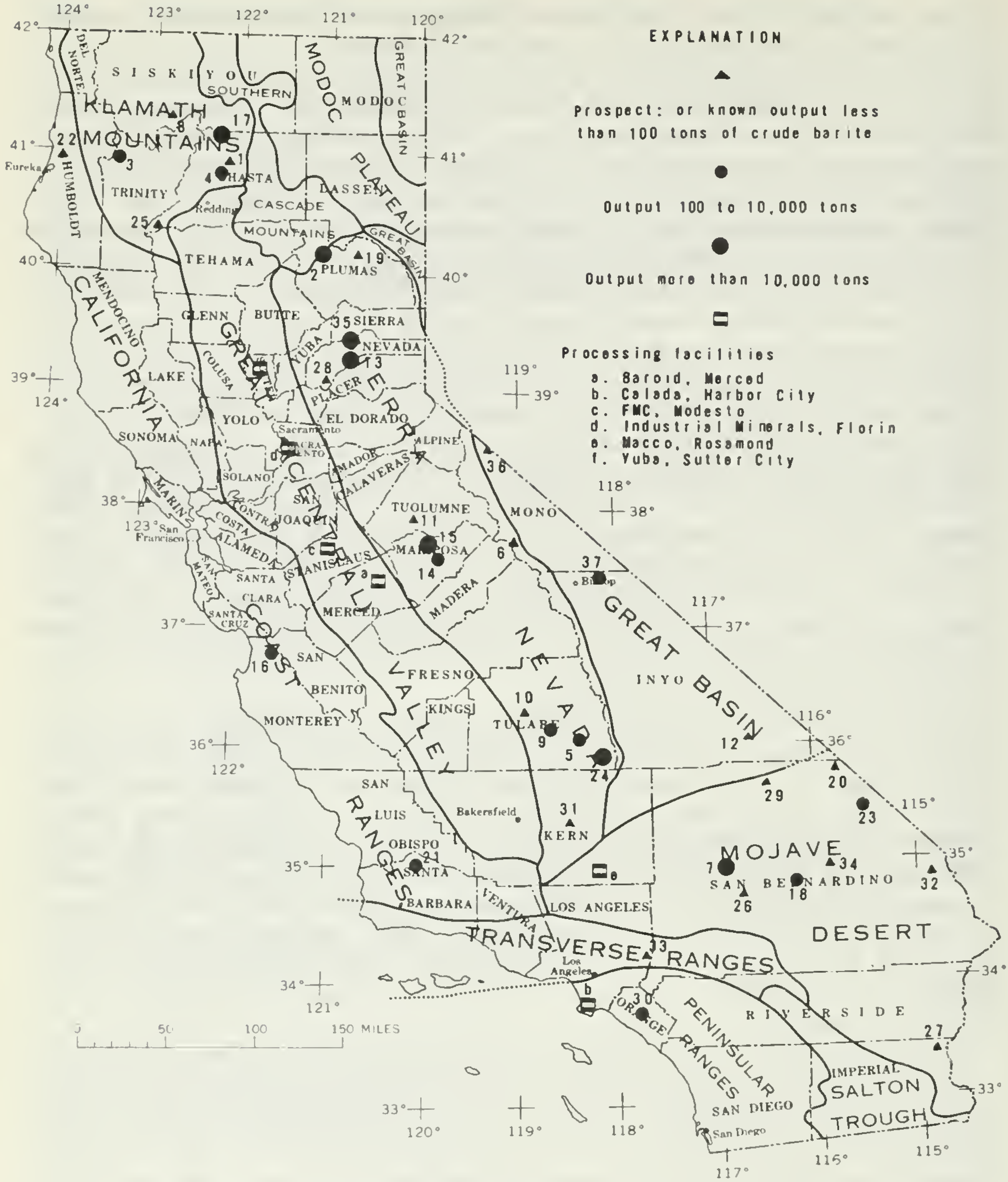

FIGURE 9. Barite in California (numbers refer to table 6).

recently developed deposit is the Bald Mountain; this deposit and the Devils Gulch together probably contain at least several hundreds of thousands of tons of barite rock to a depth of 50 feet or less. Deposits in the northern part of the belt consist of dark-gray barite, from 3 to 10 feet thick, which is interlayered with phyllite and related rocks; the three productive deposits now are mostly worked out at the surface. Projections of linear zones within this belt, utilizing known geology, would make excellent targets for future prospecting.

In recent years, the Glidden Co. deposit, on Girard Ridge in the Klamath Mountains, has been the principal State source of barite rock of greater than 4.2 specific gravity. This deposit consists chiefly of dark-gray barite from 3 to 10 feet thick which is interlayered with

Table 6.—Barite deposits of California

[Numbers refer to localities shown in fig. 9]

1. Afterthought and others (including Hirz Mount. Greenwood, Exposed Treasure, Bidwell, Ranch) (a).
2. Almanor (includes Cameron, Synthetic Iron Color mines) (c).
3. Alwood (a).
4. Austin (e).
5. Bald Mountain (two properties: Baro, Paloma) (b).
6. Buckhorn (b).
7. Calico Mountains and vicinity deposits (include Barium Queen, Big Medicine, Burcham-Waterloo, La Mountain, Lead Mountain, Leviathan, Mount General, Penny, Silver Bow, Silverado, Waterman) (b, d).
8. Callahan Ranch lead-barite (e).
9. Camp Nelson (a).
10. Chickencoop Canyon barite-witherite-sanbornite (a).
11. Clavey River (e).
12. Death Valley region (Bradbury Well, Miller Spring, Greenwater, Warm Spring Canyon (a).
13. Democrat (c).
14. Devils Gulch (Egenhoff) (b, c).
15. El Portal (b, c).
16. Fremont Peak (Gabilan Peak) (a).
17. Glidden Company (Loftus) (C).
18. Hansen and others (including Ludlow Belle) (b).
19. Indian Valley (Dawn) silver-barite (d).
20. Kingston (e).
21. Labrea Canyon (c).
22. Liscom Hill (a).
23. Mountain Pass (Molybdenum Corp. of America) rare-earth minerals (d).
24. Ninemile Canyon (Paso Baryta; includes Barite King mine) (b, c).
25. Noble (e).
26. Ord Mountain copper-gold (d).
27. Palo Verde (includes Palo Verde, White Swan properties) managanese-barite (a).
28. Pine Hill gold (d).
29. Pipeline Canyon (a).
30. Red Hill mercury (a).
31. Ritter Ranch (a).
32. Sacramento Mountains barite-fluorite, etc., deposits (a).
33. San Dimas (a).
34. Sands (a).
35. Spanish (c).
36. Topaz (a).
37. White Mountains deposits (including Gunter Canyon, White Mountains, Ritch, Starr, Last Chance, and Smith) (c).

EXPLANATION OF LETTERS IN PARENTHESES, ACCOMPANYING NAMES OF DEPOSITS

(a) Relatively small deposits, large tonnages of barite rock not apparent at surface. Potential seems limited.
(b) Large or possible large tonnages of lower grade rock of less than 4.2 specific gravity, as indicated in text.
(c) Small to large tonnages of rock may exist beneath present surface workings. Largely mined out at surface.
(d) Barite might be recovered as a by-product.
(e) Potential undetermined.

gently dipping, mildly metamorphosed siltstone and shale of Devonian age. The barite occurs stratigraphically at an interval of about 15 to perhaps several hundred feet beneath several large, adjacent bodies of limestone. This limestone occurs in a north-northeast-trending belt 11 miles long which should be prospected for additional barite.

The Calico Mountains and vicinity, on the Mojave Desert, is the site of a famous old silver district which was active mainly from 1882 to 1896. Barite occurs principally as an important gangue mineral in northwest-trending silver-bearing veins which consist mostly of jasper. Barite seems to be most abundant in the northwest part of the Calico district itself, and at the Waterman and Lead Mountain mines. The most important barite recovery operation has been at the former Leviathan silver mine, where the mineral was recovered from 1957 to 1961 by air separation from rock of about 3.5 in specific gravity. Barite once was recovered briefly from the tailings of the Waterman mine; and small tonnages of barite of 4.0 to 4.2 grade have been shipped from the Silver Bow and other properties. Recently active prospects include the Penny and Big Medicine, which may contain large tonnages of low-grade rock. Deposits similar to the Calico Mountain deposits are the Hansen and others, which lie to the east.

At Mountain Pass, on the Mojave Desert, the Molybdenum Corp. of America recovers rare-earth minerals from large carbonate bodies which consist also of 20 to 25 percent barite; barite might be recovered as a by-product at the recently expanded operation. The Gunter Canyon and other deposits in the White Mountains consist of generally thin veins of commonly high grade barite. Also of possible significance is the Labrea Canyon deposit, mined out at the surface, but possibly containing additional white barite bodies below the surface. A recently located deposit is the Buckhorn, in the eastern Sierra Nevada, which consists principally of two adjacent, north-northwest-trending, irregular zones which are about 150 feet long and 35 to 75 feet wide; the zones consist of white, granular barite which is very thinly interlayered with silicified mudstone ("chert"). Small quantities of white barite occur in the Afterthought and several similar deposits in the Klamath Mountains, and in the Palo Verde deposit on the Mojave Desert. Additional deposits that have been prospected in recent years are the Sands, Kingston, and Topaz.

The greatest potential resources of barite in California consist of the larger, lower grade deposits which mostly today cannot compete with rock shipped into California from Nevada. A factor that might lead to greater exploitation of these deposits is the use, in recent years, of some lower grade barite for drilling; one company, for example, markets a product of 4.0 specific gravity. In addition, greater amounts might be produced competitively by beneficiation, or as a by-product, especially if the higher grade Nevada deposits become depleted.

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BERYLLIUM

(By E. B. Gross, California Division of Mines and Geology, San Francisco, Calif.)

Beryllium is one of the less common lightweight metals which has become a more significant commodity as new uses for it have developed. Since 1945, beryllium and beryllium oxide have been fabricated into rods used in nuclear reactors to moderate the speed of fission neutrons and to control the reflection of neutrons to the reactor core. It has been used also in neutron generators as a neutron source.

Metallurgical uses of beryllium consume most of the metal produced. Small amounts of beryllium added to steel increase its tensile strength. However, its ability to add strength and hardness to soft and ductile metals such as copper, aluminum, and magnesium increases its usefulness in alloys of the lighter metals. More than half of the total beryllium is used in a beryllium-copper alloy which is hard, resistant to fatigue, and non-magnetic. Uses for this alloy include springs, special tools, and other non-magnetic devices. A lightweight beryllium-aluminum alloy has found limited applications in air-frames and structures of aircraft and missiles and for guidance mechanisms. Beryllium oxide has been used in refractory materials, where its high electrical resistivity and melting point of 4,658°F is advantageous.

Increasing uses for beryllium have necessitated more intense exploration for source materials. Research equipment such as beryllometers (neutron activation detectors) and a fluorescent method for detecting small amounts of beryllium in rocks have evolved. In 1964, beryllium ores were processed only in Pennsylvania and Ohio.

The primary occurrence of beryllium is within pegmatite dikes associated with granitic and syenitic intrusive bodies; deposits have been found in quartz-rich veins associated with fluorite and in veins within quartz monzonite. Lately, the most promising source of ore has been the disseminations of beryllium-bearing minerals in granites and rhyolitic tuffs. Beryllium-rich tactites contain helvite or beryllium dispersed within the contact minerals of the replacement deposit. Alluvial occurrences, derived from primary intrusive igneous rocks, have been the source of only limited production. Beryllium has been found in about 43 minerals, of which only three contain sufficient beryllium to be of interest as source materials. Beryl ($Be_3Al_2Si_6O_{18}$) is the principal ore mineral and is obtained chiefly from zoned granitic pegmatite bodies, most commonly within the inner zones. Because of this sparse distribution, conventional mining and concentration processes are not followed, and most of the ore has to be concentrated by hand-cobbing. Recently deposits of lower grade containing the beryllium minerals phenacite (Be_2SiO_4) and bertrandite ($Be_4Si_2O_7(OH)_2$) have been found disseminated in rhyolitic tuffs.

The element, beryllium, was discovered by the French chemist Louis Vaugelin, in 1797. An appreciable amount of beryllium was produced by F. Wohler of Germany in 1828. In 1916, the first ingot of beryllium metal was obtained in the United States, but interest in uses of beryllium did not develop until 1926, when it was alloyed with copper. The beryllium industry grew from this and similar metallurgical uses.

Production of beryllium ore in the United States has declined since 1957 (see table 7). In 1963, only one ton of ore was produced following the removal of government price support. World production in 1957 was 11,300 short tons of 11 percent BeO, compared to about 6,500 tons in 1964. Brazil yielded most of the foreign production. In the United States, 14 states produced beryllium ore, but no deposits in California have been exploited.

TABLE 7.—*World production and U.S. consumption of beryllium*

[In short tons]

	World production	U.S. production	U.S. consumption
1956	12,900	445	4,341
1957	11,300	521	4,309
1958	7,450	463	6,002
1959	11,200	326	8,173
1960	12,300	244	9,692
1961	12,900	317	9,392
1962	10,900	218	7,758
1963	7,400	1	7,934
1964	6,500	[1] 17	[1] 5,800

[1] Estimated.

Beryl has been found in many pegmatites in California, primarily in the Peninsular Ranges of San Diego and Riverside Counties (see fig. 10). Two beryllium discoveries include one near Lone Pine, Inyo County, in the Great Basin province and the other in pegmatites near Jacumba, San Diego County (Weber, 1962). No commercial production has come from either of these deposits. A list of beryllium-bearing deposits, chiefly containing beryl, are given by county in table 8. Other rare beryllium-bearing minerals are mentioned in the table.

TABLE 8.—*Beryllium deposits in California*

Index No. on fig. 10	Pegmatite deposits	County	References
1	Near Academy	Fresno	California Division of Mines Bulletin 173.
2	East of Lone Pine	Inyo	Do.
3	Mount Lowe area	Los Angeles	Do.
4	Thompson Gem mine, Mount Thompson	Lassen	Do.
5	Fano mine, Coahuila Mountains	Riverside	Do.
6	Near Hemet	do	Do.
7	Jensen quarry, near Riverside	do	Do.
8	Mears, base of Box Spring Mountain	do	Do.
9	Southern Pacific silica quarry, near Nuevo	do	Do.
10	Aguange Mountain, near Oak Grove	San Diego	Do.
11	Katrina deposit, near Pala (helvite, phenacite, bertrandite).	do	Do.
12	Himalaya and Esmeralda mines, Mesa Grande	do	Do.
13	Mac mine, near Rincon (helvite)	do	Do.
14	Mines near Ramona (hambergite)	do	Do.
15	Crystal mines, near Jacumba	do	Do.
16	Near Jamestown	Toulumne	Do.
	CONTACT METAMORPHIC DEPOSIT		
17	West of Lone Pine (mineral not identified)	Inyo	U.S.G.S. Map MR-35.

FIGURE 10. Beryllium in California (numbers refer to table 8).

Future appraisal of beryllium deposits in California will depend on improved exploration techniques, applying new research instruments for detecting large, low-grade disseminated deposits. Large tonnages of low-grade beryllium ore perhaps may be present in some of the Mojave Desert and Great Basin provinces of California, analogous to the deposits already delineated in Utah, Colorado, and Nevada. However, exploitation of these low-grade deposits will be delayed until adequate processing procedures are resolved. Only minor quantities of beryl have been obtained from contact metamorphic rocks and alluvial deposits.

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BISMUTH

(By Q. A. Aune, California Division of Mines and Geology, Redding, Calif.)

Bismuth is a brittle, silver-white metal with a reddish hue, and has a low melting point of 271.3°C. Its principal uses depend on its ability to impart desirable qualities of fusability, castability, and machinability to a wide variety of industrial alloys; and on its value as an ingredient in pharmaceutical compounds, salts, and mixtures used for indigestion remedies, antacids, burn and wound dressings, antisyphilitics, dusting powder, and cosmetics.

Bismuth is obtained mainly as a by-product in the metallurgical treatment of silver, lead, zinc, copper, gold, tungsten, tin, and molybdenum ores. Native bismuth, bismuthenite, and a number of other bismuth-bearing minerals are commonly found in stringers and pockets in hydrothermal veins with the above ores. Bismuth minerals also occur in contact metamorphic deposits and in pegmatites.

Twenty tons of bismuth ore were mined at the Lost Horse mine, Riverside County, in 1909; concentrates containing up to 14 percent bismuth were obtained from the Garnet Dike tungsten mine, Fresno County, but no attempt was made to recover bismuth from the concentrates.

Bismuth occurrences are relatively widespread, as shown in figure 11. The paucity of recorded California production is not an indication of the lack of production, but signifies that the source of the bismuth was not reported. The by-product relationship of bismuth to other metals coupled with the small domestic supply places a major reliance on foreign sources and marketing of bismuth material.

Native bismuth and several oxidized bismuth minerals have been reported with arsenopyrite and gold in quartz veins at the Big Blue group of mines in Kern County. The Darwin and other mines of the Darwin district, Inyo County, contain bismuth in association with lead-silver-zinc-tungsten ores. Mineralization is in replacement and vein deposits in limestone and calc-silicate rocks. Bismuth is associated with gold-copper vein deposits between Tertiary monzonite and rhyolite at the Bagdad-Chase mine, San Bernardino County; it also occurs in the form of a bismuth sulfide associated with copper

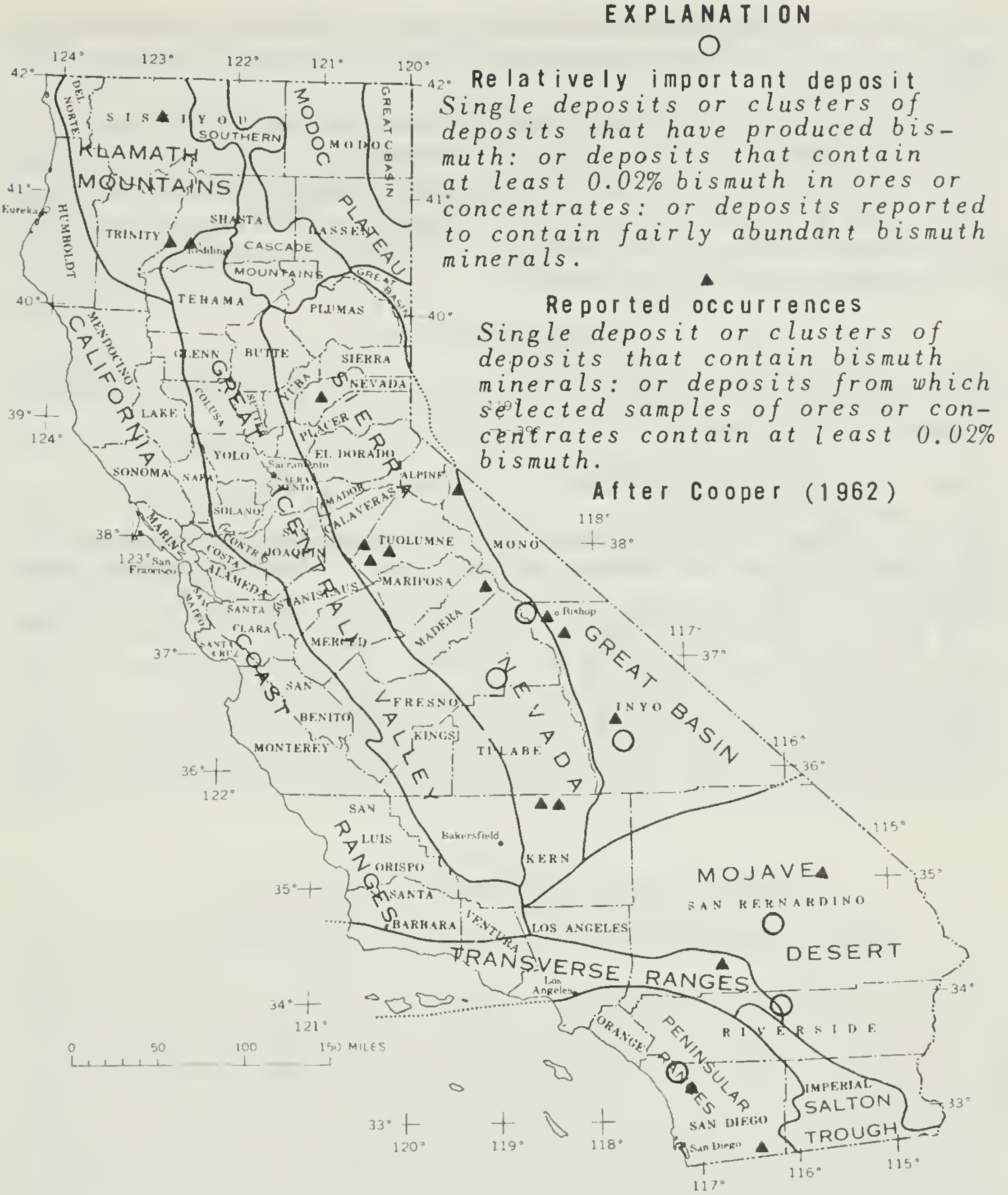

FIGURE 11. Bismuth in California.

minerals in a quartz vein that cuts a foliated micaceous quartzite at the Lost Horse mine in the Pinon Mountain district, Riverside County.

At the Garnet Dike tungsten mine, a contact metamorphic deposit in Fresno County, bismuthinite occurs with scheelite in a tactite zone having the form of a vertical chimney with a maximum diameter of about 60 feet. Bismuth occurs in association with tungsten-molybdenum-copper ores in tactite near a quartz monzonite contact at the Pine Creek mine, Inyo County. Oxidized bismuth minerals occur with garnet, epidote, clinozoisite, and other contact metamorphic minerals in a highly metamorphosed limestone at the United Tungsten copper mine in San Bernardino County. Native bismuth, bismuthinite and bismutite occur with tourmaline, lepidolite, and other pegmatite minerals in the gem mines at Pala, Rincon, and Jacumba, San Diego County.

There are numerous other bismuth occurrences in California that are unappraised or are regarded as having no potential importance as sources of the metal. Since between 80 and 90 percent of the annual total United States consumption (roughly 1,000 tons) is in the northern and eastern United States, California ore has little marketing advantage over foreign ores.

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BORAX AND OTHER BORON COMPOUNDS

(By W. C. Smith, U.S. Geological Survey, Menlo Park, Calif.)

About 100 years ago California became the first domestic producer of borax, and about 40 years ago it became the largest supplier of boron raw materials to the world market (Ver Planck, 1956 and 1957; W. C. Smith, 1960 and 1962). California's share of world production has been 90 percent in many years, and probably will be nearly as large in the future, although Turkey has been increasing its production and Argentina and Chile have large deposits that are potentially more productive than they have been in the past. California's leadership of the world's borax industry has been based upon large-scale, economical operations at two major boron deposits, Searles Lake and Kramer, each established in the late 1920's and repeatedly expanded as consumption required. The known reserves in these two major deposits and in potentially workable colemanite deposits are estimated to be large enough to sustain California's production at recent rates for the next hundred years.

In the following description of use, production, and geologic occurrence of borax and other boron compounds, it will be convenient to refer by name to the principal compounds and boron minerals of California, so these are listed on table 9, with chemical composition and boron content. Borax is chemically the same, whether mineral, industrial compound, or the familiar household pharmaceutical.

TABLE 9.—*Principal boron compounds and minerals of California*

Name	Chemical composition	Boron content (calculated weight percent)	
		B	B_2O_3
Chemical compounds:			
Borax	$Na_2B_4O_7 \cdot 10H_2O$	11.3	36.5
Anhydrous borax	$Na_2B_4O_7$	21.4	69.1
Boric acid	H_3BO_3	17.5	56.4
Minerals:			
Borax	$Na_2B_4O_7 \cdot 10H_2O$	11.3	36.5
Kernite	$Na_2B_4O_7 \cdot 4H_2O$	15.8	51.0
Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	13.3	42.9
Probertite	$NaCaB_5O_9 \cdot 5H_2O$	15.4	49.6
Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$	15.7	50.8

USES OF BORON COMPOUNDS

The use of boron compounds has increased over the years, and this trend is expected to continue. Among the scores of industrial, agricultural, and consumer uses, the largest is that of borax in glass and glazes. About a fourth of production goes into glass, notably fiberglass, heat-resistant glass, and optical glass. The many uses in the chemical and allied industries are summarized by Johnstone and Johnstone (1961), and recent research in boron compounds is reviewed each year in the Minerals Yearbook of the U.S. Bureau of Mines (Miller, 1964; Stipp and Schreck, 1963, etc.).

PRODUCTION

Borax mining began in 1864. In the five-year period 1959 to 1963, inclusive, California's production of borax and other boron compounds was equivalent to 331,941 tons of B_2O_3 per year, with a value near $49,000,000 per year (Miller, 1964). Boron is exceeded in value of products only by oil, gas, and construction materials. Figures for production combine all products and are in terms of equivalent tons of B_2O_3. Most of the raw material is processed in elaborate plants at the deposits, and the principal bulk commodities shipped are refined borax, anhydrous borax, and boric acid. The California producers ship only minor tonnages of crushed or otherwise partly treated borate minerals. A trend toward higher values per ton should be recognized; among the reasons for it are the increase in shipments of anhydrous forms (to save on freight costs) and the increase in number of refined boron compounds prepared at the primary plants.

California supplies essentially all the boron products consumed in the United States, although small quantities of special boron-bearing materials are imported. About half the production is exported. Distribution abroad is mainly to the highly developed industrial areas of the free world. For other regions, accurate statistics are not available, but we believe that only the U.S.S.R. and China are producing and that their output is less than that of the free world (Sokoloff, 1964).

GEOLOGIC OCCURRENCE

In California, the principal boron deposits are in the Mojave Desert and adjacent parts of the Great Basin in the eastern and southeastern

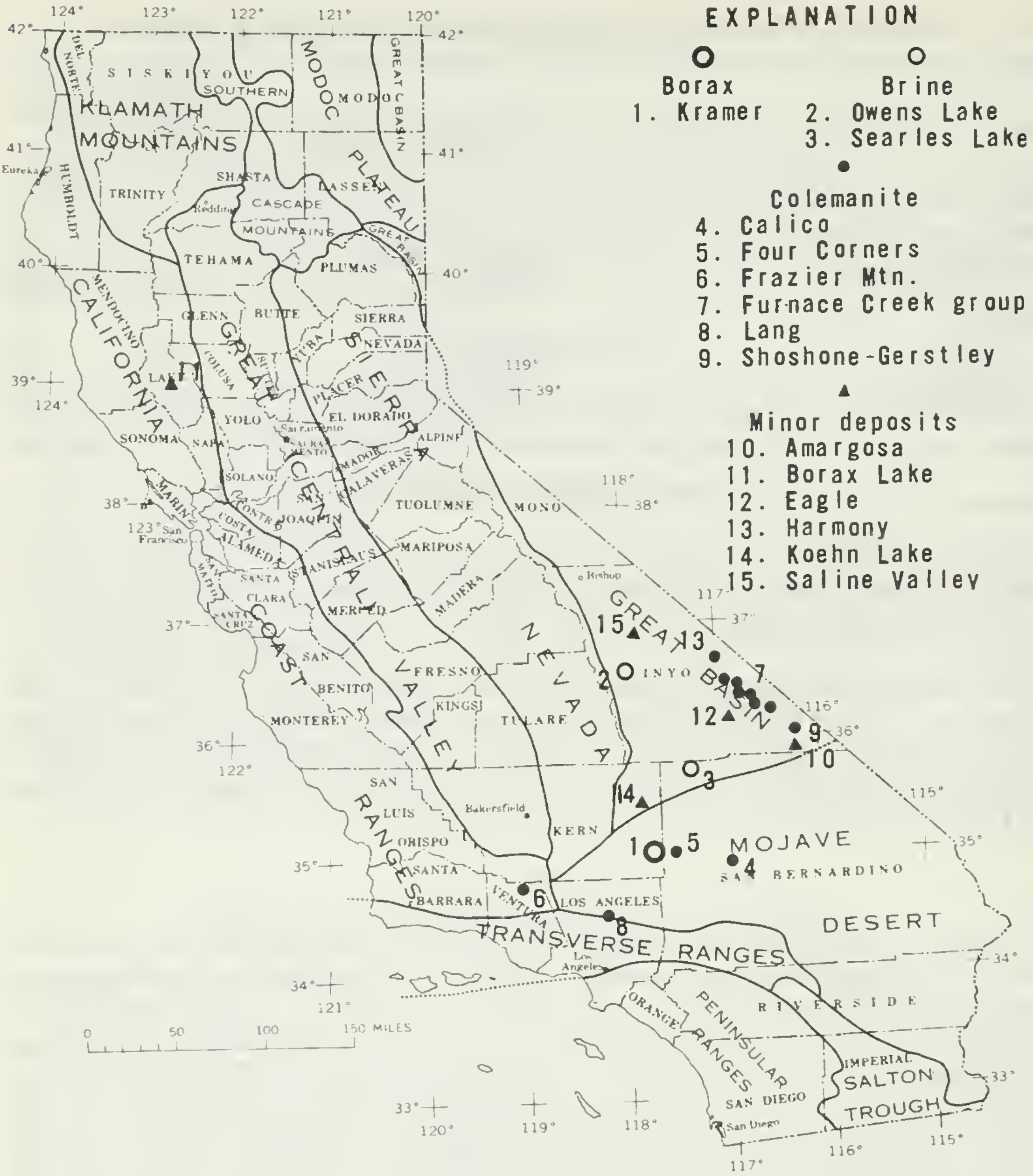

FIGURE 12. Boron in California.

parts of the State (fig. 12). Boron is not known to occur in nature as the element. And here, as elsewhere, the boron is in solution in water or combined with other elements in hydrated sodium and calcium borate minerals, among which the best known is borax (see table 9). All the deposits in California are geologically young (Cenozoic) and of continental origin. They are classed as evaporites, with the deposits of common salt, sodium carbonate, and sodium sulfate that originate as saline residues where surface water dries up in arid inland basins. Evaporation is almost the whole story of origin for many of these salines, with the important qualification that during the crucial final stages when minerals come out of solution the dominant process—sometimes the only process that can be identified later from the existing mineral assemblage—may be temperature change (for borax, cooling), or chemical reaction as waters mix, or replacement of susceptible minerals. Equally important for the origin of boron deposits in arid basins is location within one of the world's Cenozoic volcanic-tectonic belts, where waters contain significantly more boron than average. Many California and western Nevada waters are boron-bearing, presumably because of some fundamental relationship to the well-known belt that follows the Pacific Ocean margin. Where this volcanic-tectonic belt passes through areas long dominated by inland basins and arid climate, as in western South America between latitudes 15° and 30° S. as well as in California, the accumulated salines include major borate deposits.

Searles Lake brine

At Searles Lake borax is recovered from brine that also yields potash, sodium carbonate, and several minor coproducts. Two large chemical plants, operated by American Potash & Chemical Corp. and Stauffer Chemical Co., treat brines pumped from groups of shallow wells that penetrate saturated layers of crystalline saline minerals in a section of lake beds underlying the Searles Lake playa (Teeple, 1929). Halite of the uppermost saline layer is exposed in the center of the playa, where it forms a hard salt pan 10 or 12 square miles in area. The layers containing the commercially valuable brines also underlie the mud flats that encircle the central salt, so their total extent is about 40 square miles. In the stratigraphic section, the productive saline layers are in two zones, separated by a "parting mud" that is 12 or 14 feet thick, and underlain by a "bottom mud." The upper saline zone generally is 70 to 80 feet thick, the lower zone 30 to 40 feet. In these zones, it is estimated, about 40 percent of the volume is brine. The subsurface layers of saline minerals are more or less coarsely crystallized and have a porous, vuggy structure, so they yield brines freely. The brine stands essentially at the surface of the playa, the brine level evidently being maintained there by subsurface flow.

Reserves at Searles Lake have been estimated as adequate for 50 years production (Dyer, 1950), and an estimate in these terms is more appropriate than separate figures for tonnage and grade of the several coproducts, all of which must be produced and marketed.

As the lake beds of this saline deposit lie where they accumulated, evidence of their origin is obtainable not only from study of the stratigraphy and mineralogy of the sediments but also from study of the topography of the basin and the region. The slopes above the playa are marked with many ancient shorelines, the highest at 640 feet above the salt flat at a position fixed by the altitude of an overflow channel leading eastward to Panamint Valley. These show that the basin has contained a succession of lakes. Regional surveys have shown that the lakes received water mostly from the west, and mainly from a long section of the eastern slope of the Sierra Nevada that drains via the Owens River into Owens Lake (Gale, 1915). In cool moist periods of the past, Owens Lake would overflow and the runoff would go through China Lake into Searles Lake and, at maximum flow, beyond. In the commercially drilled sediments of Searles Lake, then, one major climatic swing from cool-moist to warm-dry is represented by the bottom mud and lower saline zone, another by the parting mud and upper saline zone (Flint and Gale, 1958; Smith, G. I., 1962; Smith and Haines, 1964).

The quantities of chemicals concentrated in Searles Lake required evaporation of enormous amounts of Owens River water, which presumably had a composition about the same in the Pleistocene as it is now (339 ppm total dissolved solids and 1 ppm boron; Clarke, 1924).

Chemical analyses of Owens River water show that the principal source of its boron is a group of thermal springs in the headwaters region, nearly 150 miles from Searles Lake. The Searles Lake brines contain about 34.5 percent total dissolved solids, including 0.35 percent boron (commonly reported as 1.6 or 1.7 percent of $Na_2B_4O_7$; see analyses in table 44). The "solid" minerals of the saline layers were also once in solution; they are halite, trona, hanksite, and several less abundant sodium chloride, sulfate and carbonate minerals. Additional chemical precipitate is in the main mud layers and the thin mud layers within the saline zones; they contain much calcium carbonate in gaylussite, aragonite, calcite, and dolomite (Smith and Haines, 1964). Boron is distributed through the section. In addition to the boron in brine, the deposit contains crystalline borax, the amount ranging from a few crystals in the bottom mud and at several other horizons to a borax lens 5 feet thick in the upper salt.

Kramer borax deposit

At Kramer, bedded borax interlayered with shale and siltstone is mined from a large open pit and processed in an adjacent refinery by the U.S. Borax & Chemical Corp. (Barnard and Kistler, 1965). The lake beds that contain the borax have no known outcrops—the ore was found by drilling—and they lie at depths of 150 to 1,000 feet, beneath younger beds recently found to be middle Miocene in age (R. H. Tedford, written communication, 1965). The ore contains, on average, nearly 25 percent B_2O_3. It is as much as 200 feet thick and extends under about 500 acres. Reserves are estimated to be about 100 million tons. Even at recent high rates of extraction, this is about 100 years' reserve.

The lithology and mineralogy of the Kramer ore body require classing the borax as a lake deposit, and as an evaporite only in a qualified sense. The associated sediments lack structural features attributable to desiccation, and the array of saline minerals that typically result from extensive evaporation is absent. The shale and siltstone beds are thin and banded, and, like the occasional layers of tuffaceous sandstone, they persist laterally with uniform thickness and composition. Along beds, the initial borax content seems to vary little, but in vertical section, the ore ranges from lean to rich, some layers being shale containing scattered borax crystals and others nearly solid borax enclosing scattered lumps of shale, with gradations between. Apparently the 200-foot section of borax and accompanying sediments accumulated in a quiet, continuous lake in which conditions varied from time to time, but only in a narrow range. That the precipitation of borax probably was caused by cooling seems likely, and overflow to carry away other saline components seems required (Gale, 1946; Bowser, 1964).

Among other borate minerals at Kramer, colemanite and kernite occur in quantity. Colemanite was the first borate found in the district (1913) and, with associated ulexite, was the first borate mined (1924 to 1927). Colemanite occurs in a thin zone which is above the borax ore body, and which also underlies a much larger area, about a mile by 4 miles in extent (Gale, 1946). Kernite, which was mined for several years after 1927 but is not processed in the present operations, extensively replaces borax in the deeper parts of the ore body (Christ and Garrels, 1959; Schaller, 1929).

Colemanite deposits

Colemanite and ulexite are produced in the Death Valley region, where the U.S. Borax & Chemical Corp. operates one mine near Shoshone and one in Corkscrew Canyon, and the Kern County Land Co. operates one mine in Furnace Creek wash. A few hundred tons per year of the calcium-bearing borates are shipped as crushed mineral for special uses. Other colemanite deposits, now idle but mined between 1900 and 1927, are near Death Valley, in the Calico Mountains of the Mojave Desert, and at Lang in Los Angeles County, and Frazier Mountain in the northwest corner of Ventura County (Noble, 1916; Foshag, 1921; Gale 1914b). One major deposit, discovered by drilling done for the Geological Survey during 1957 but not opened for mining, lies subsurface about 8 miles east of Kramer (Benda, Erd, and Smith, 1960). This deposit, estimated to contain between 15 and 40 million tons, averages about 14 percent B_2O_3 (Griswold, 1959). Borate-bearing horizons in the Death Valley area, if drilled, probably would be found to contain a comparable tonnage and grade (California Div. Mines and Geology, 1963). The colemanite deposits offer a substantial resource for the future.

The colemanite deposits are in lake beds of Tertiary age. The deposits along Furnace Creek, studied by McAllister (1964), are typical. The largest deposits are in the lower part of the (Pliocene) Furnace Creek Formation, and are lenses or groups of lenses enclosed in calcareous mudstone, sandstone, conglomerate and calcareous chipstone. The section also contains gypsiferous beds, some limestone, and intrusive basalt in sheets and fragmental masses. Calling the ore "colemanite," as customary, is misleading, because ulexite and probertite are major constituents, each occurring as minable masses of one mineral and also intimately mixed with other borates. Colemanite, in many places if not everywhere in these deposits, is a replacement mineral. Most conspicuously, it replaces ulexite, but it also replaces limestone, forming cross-cutting masses and veins. The ulexite is a dense, massive variety, unlike the "cottonball" ulexite of recent playa deposits, and apparently recrystallized. Probertite may also be a replacement of ulexite; it is of lower water content. Mining has exposed a zonal structure in some of the ore, in which colemanite is nearest the surface or envelops ulexite, and probertite is deepest, within ulexite. The lenticular form of the deposits and their spread along the outcrop of the lower part of the Furnace Creek Formation suggests accumulation from place to place in an extensive lake, or in a group of shallow intermittent lakes in an extensive basin. The evidence that the lake waters were persistently calcareous suggests that water containing sodium borate entered locally, and that ulexite was precipitated where waters mixed.

Minor deposits

California has several minor deposits which contain no reserves of significance but do present features of historic and scientific interest. The first borax mined in the United States (1864–1868) was dug from the bottom mud of Borax Lake, Lake County (Vonsen and Hanna, 1936). The occurrence of coarse borax crystals grown in bottom mud suggests some similarity to the Kramer deposit; also, the precipitation of trona, halite, northupite, and gaylussite in a year when the lake desiccated (1934) suggests similarity to Searles Lake. The lake has a small drainage basin, within which there are springs that presumably supplied borax-bearing water like that of much-studied springs at Sulphur Bank, 9 miles to the west, which contain 720 ppm of boron (White, 1957).

From 1874 to 1907 borax was produced from "marsh" deposits in Death Valley, Saline Valley (Gale, 1914a), Koehn Lake, and at the margin of Searles Lake. Such deposits are salt crusts, or efflorescences, accumulated on top of the muddy surfaces of wet playas. Both borax and ulexite occur in this environment, accompanied by sodium carbonate, sulfate, and chloride saline minerals. The Death Valley floor obviously receives boron weathered from outcrops of the colemanite deposits in the adjacent hills. This relationship points to the conclusion that similar solution, transport, and redeposition has been occurring in southeastern California at least since the middle Miocene, with changes in the pattern of basins and ranges causing boron to move from one sedimentary section to a new one.

Summary of Boron Resources

Searles Lake and Kramer, the major sources, have reserves large enough to sustain production at recent rates for 50 to 100 years. Colemanite deposits, now little worked, contain additional large resources potentially workable under favorable economic conditions. Geologic studies indicate that the borate deposits of California occur in sections of arid-basin sediments that range in age from Miocene to Recent. Past drilling has demonstrated that the major borate deposits lie concealed beneath alluvial deposits that cover extensive areas in the southeastern part of the State, and it is probable that future drilling will discover additional deposits.

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BROMINE

(By G. I. Smith, U.S. Geological Survey, Menlo Park, Calif.)

Most of the bromine produced in the United States comes from plants in Texas and Michigan which extract it from sea water and well brines. Production also comes from oil-well brines in Arkansas, and from two plants in California. One of these California plants utilizes sea-water bitterns left over from the solar evaporation of salt, and the other uses saline brines pumped from Searles Lake.

Bromine is used most extensively in additive compounds for gasoline. Smaller quantities are used in the manufacture of fireretarding and fireproofing materials, fire extinguishers, fumigating mixtures, sanitizing additives for swimming-pool water, bleaches, photographic emulsions, laboratory reagents, and medicinal and pharmaceutical preparations (Miller, 1964).

Production of bromine in the United States began in the mid-1800's. Output was somewhat limited because of competition with the Stassfurt deposits in Germany, but at the time of World War I, domestic production rose to 1.7 million pounds per year. By 1929, the widespread use of bromine in gasoline antiknock compounds resulted in an increase of domestic production to about 6.5 million pounds per year, and by 1939, production had risen to 37.9 million pounds. During World War II, national production rose to 102.1 million pounds. By 1963, domestic annual output had reached 203.3 million pounds, and was valued at $48.5 million (Keiser, 1960).

Production of bromine in California began in 1926 when plants were built at Chula Vista and San Mateo to extract bromine from the bitterns produced during solar salt evaporation along the edges of San Diego and San Francisco Bays. The San Mateo plant closed about 1930, and the Chula Vista plant closed in 1945. In 1931, a new plant was constructed at Newark, on the southeast shore of San Francisco Bay, by the California Chemical Corp.; it is now operated by the Inorganic Chemical Division of the FMC Corp. and uses bittern produced by the Leslie Salt Co. The bittern contains 0.175 percent bromine, and the bromine is recovered during the first step of a process that also produces magnesia. Since 1940, bromine has also been extracted from Searles Lake by the American Potash & Chemical Corp. In that operation, bromine, along with several other products, is extracted from a complex brine that contains about 0.085 percent bromine. Current production data from these California plants are not published, but in 1957, their combined output was estimated to be about 2 million pounds of bromine and bromine compounds a year, which would have been a little over 1 percent of the Nation's total (Ver Planck, 1957).

In May 1965, bromine was selling for 22½ cents per pound in tank-car lots; other bromine-bearing chemicals were higher priced (quoted by the Oil, Paint, and Drug Reporter, May 31, 1965). With prices in this range, transportation costs are not a large part of the total price, and producers in most parts of the country and world are able to compete for available markets.

Future resources of bromine are essentially unlimited because of the use of sea water as one of the raw materials. California's production, however, comes from plants that extract bromine from brines that may someday become unavailable. The resources in Searles Lake are presumably large, but bromine production will cease if extraction of the several other components becomes unprofitable. The plant using bitterns at Newark is dependent upon the continued production of salt, and, as noted in the chapter on Salt, that industry is jeopardized by the population expansion which tends to encourage the conversion of evaporating pond areas into real estate or other types of developments.

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CADMIUM

(By P. K. Morton, California Division of Mines and Geology, Los Angeles, Calif.)

Only in comparatively recent years has cadmium been recognized as an important metal to man. During the first 60 years after its discovery in 1817 by F. Strohmeyer, little use was found for the metal. Most of the important use-development of the metal came after 1919 with the advent of an electroplating process developed by M. J. Udy.

The primary uses of cadmium are listed below in the approximate order of consumption:

1. Plating—55 to 60 percent. Cadmium is used as a corrosion-resistant coating on a wide variety of iron and steel products by electroplating, hot dip, spray, or vacuum plating methods.
2. Cadmium sulfide, sulfoselenide, and lithopone—15 percent. Utilized as yellow, orange, and red pigments.
3. Other cadmium compounds—15 to 20 percent. This category includes stearate for vinyl plastics, phosphors for television tubes, and nitrate for nickel-cadmium batteries.
4. Low melting point fusible alloys such as solders, automatic fire-sprinkler systems, etc.

A small but important use of cadmium is in cadmium sulfide crystals which are used in the aerospace industry for solar energy conversion, in radiation detection devices, and photosensitive elements.

The only known primary sources of cadmium are zinc ores, and zinc-bearing lead and copper ores. Greenockite (cadmium sulfide) is the principal ore mineral of cadmium, but it rarely occurs except in close association with sphalerite, a zinc sulfide. Most of the cadmium recovered, however, does not occur as greenockite but as a constituent of zinc minerals—principally sphalerite. Sphalerite has been shown to contain as much as 4.5 percent cadmium (Rankama and Sahama, 1950, p. 708). Zinc concentrates processed in the United States contain an average of from 0.1 to 1.4 percent cadmium (Schroeder, 1965, p. 4). California zinc concentrates have yielded an average of 0.22 to 0.28 percent cadmium (Goodwin, 1964, p. 97).

World production in 1919 was about 200,000 pounds; in 1963 it was 26,300,000 pounds. United States production rose from 131,000 pounds in 1919 to 503,000 pounds in 1925, and increased rapidly to an average annual production of about 10 million pounds for the five-year period from 1959 through 1963. Shipments by United States producers in 1963 totaled 10,124,000 pounds valued at $21,880,000.

Total California production figures are not available, but during the five-year period ending in 1963 the estimated California cadmium production was about 5,600 pounds. In terms of the United States production during the same period this amounts to about 0.01 percent.

The close association of cadmium to zinc results in the unfortunate circumstance wherein cadmium reserves and production are a function of zinc reserves and production. In California, cadmium is found in the lead-zinc ores of the Great Basin province in Inyo and San Bernardino Counties; the copper-zinc ores of the foothill belt in the western Sierra foothills; and the Shasta County copper-zinc district.

(The reader is referred to the zinc section of this volume for further discussion of these areas.)

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CALCITE, OPTICAL GRADE

(By S. J. Rice, California Division of Mines and Geology, San Francisco, Calif.)

Use and Economic Importance

Transparent and unflawed calcite (Iceland spar) is made into polarizing prisms for use in several types of optical instruments. These prisms yield very high quality polarized light for such instruments as polarizing microscopes, metalographs, saccharimeters, dichroscopes, photometers, colorimeters, and polariscopes. Although the unit price is high, calcite suitable for these purposes is rare, and only a few hundred pounds at most are used annually. Artificial materials such as polaroid have been used increasingly as a substitute for calcite polarizing prisms since World War II, but expanding demand for research-quality instruments should guarantee a ready market for optical-grade calcite, which is superior to known substitutes for some uses.

Calcite suitable for optical purposes must be transparent, water-clear, and free from microscopic inclusions, cleavage cracks, or twinning. It must also occur in masses large enough to yield crystals or cleavage rhombohedra at least about one cubic inch in volume. In any deposit, the percentage of optical-grade material recoverable is very low compared to the amount of clear calcite present.

Mineralogy and Geological Occurrence

Calcite ($CaCO_3$) is one of the most common minerals, but only rarely does it occur in the form of the large transparent crystals called Iceland spar. It is characterized by highly perfect rhombohedral cleavage and a hardness of 3, and it effervesces vigorously in dilute hydrochloric acid. Its value as an optical material is based on its strong double refraction. This is a property whereby light passing through a cleavage rhomb is resolved into two separate rays that are polarized at right angles to each other, and which are refracted at different angles. The latter phenomenon can be demonstrated by placing a cleavage fragment of clear calcite over a dot on a piece of paper and observing that two dots appear.

Iceland spar is found lining cavities within discontinuous calcite veins and pockets that rarely can be traced laterally or downward for more than a few tens of feet. Although calcite veins occur in many kinds of rocks, most of the productive deposits in the world are enclosed in volcanic rocks, and appear to have formed during the last stages of volcanism. Since the late 1930's most of the domestic requirements for Iceland spar have been supplied from such deposits in the states of Sonora and Chihuahua, Mexico (King, 1946 and 1947; Fries, 1948). Domestic production has been largely from California, Montana, and New Mexico.

Occurrences in California

Iceland spar has been mined at three localities in California (see fig. 13). The only one being worked in 1965 is on the western side of Mount Baldwin, near the head of Convict Creek in Mono County. The

FIGURE 13. Calcite (optical grade) in California.

deposits here occur as numerous lenses or huge druses in marble (Mayo, 1934). The druses are ellipsoidal to irregular in shape, up to about 40 feet in length, and bordered by very coarsely crystalline white calcite. They are lined with large crystals, some up to several cubic feet in volume, of clear calcite from which the optical-grade material is obtained. Sand and clay fills most of the cavities found, and large crystals that have fallen from the roofs of the cavities are found embedded in this fill. Optical-grade calcite was discovered in this area prior to 1934, but systematic exploitation was first undertaken by the U.S. Calcite Co. in 1963.

An Iceland spar deposit in Modoc County, about 10 miles south of Cedarville, was mined intermittently in the period 1920–1925 (Hughes, 1931), but has since been idle. The calcite occurs in veins as much as three feet thick that are in andesite. Individual crystals recovered from this deposit were relatively small, up to about 12 ounces. About 1,000 ounces of Iceland spar were sold from this deposit in 1920–1921, probably the mine's most active period.

During World War II, Iceland spar was produced from deposits on the east side of the Santa Rosa Mountains in San Diego County and used to manufacture optical ring gunsights (Weber, 1963). Here the crystals occur with common calcite and gypsum as veins which filled joints in conglomerate, the largest deposits being at the intersections of joints. The calcite crystals are unusual in that they are thin and tabular, being flattened perpendicular to the c axis. Those mined were as much as 18 inches in diameter and 3 inches thick, but as trimmed to useable plates they averaged between 2 and 3 inches in diameter and ¼ to ⅜ inches thick. Some 6,000 pounds of Iceland spar were shipped from this deposit from late 1942 to early 1944, but not all of it was useable (Wright, 1957).

The wide geographic distribution of known deposits in California, as well as the diversity of geological environments in which they are found, suggest that possibilities are good for finding additional deposits in the State. Present marketing conditions, and those of the foreseeable future, appear to be good for this commodity.

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CALCIUM CHLORIDE

(By G. I. Smith, U.S. Geological Survey, Menlo Park, Calif.)

About a third of the calcium chloride used in the United States is a by-product of the Solvay sodium carbonate process. The other two-thirds comes from natural brines. Of this, Michigan produces 95 percent; California, 4 percent; and West Virginia, 1 percent (Babcock, 1964).

The natural brines from which calcium chloride is produced are generally neutral to slightly acid, and are high in calcium, sodium, and chloride, but low in carbonate and sulfate as shown in table 10. The brines used for calcium chloride production in Michigan (table 10, analysis 8) and West Virginia come from wells sunk into Paleozoic formations. California production comes entirely from late Quaternary deposits in Bristol Lake.

TABLE 10.—*Analysis of waters containing high concentrations of calcium chloride*

[Analyses in parts per million; n.d., not determined or not reported]

	1	2	3	4	5	6	7	8
	Bristol Lake solar concentrated brine	Bristol Lake well brine	Cadiz Lake, San Bernardino County	Salton Sea area artesian well, Imperial County	Salton Sea geothermal well, Imperial County	Oil field brine, Raisin City, Fresno County	Oil field brine, South Mountain, Ventura County	Brine well, source of calcium chloride, Michigan
Ca	43,000	17,190	4,500	14,400	40,000	2,190	5,890	74,800
Mg	1,074	598	410	3,600	730	832	69	9,960
Na	57,370	46,070	22,600	18,400	51,000	14,800	4,140	22,500
K	3,303	1,479	1,040		25,000	251	117	9,120
Cl	172,900	104,600	44,760	61,200	185,000	29,000	17,000	208,000
Br	n.d.	n.d.	n.d.	n.d.	146	108	91	2,910
SO_4	210	1,048	280	200	56	0	18	40
CO_3	n.d.	n.d.	0	----------	n.d.	0	0	n.d.
HCO_3	n.d.	n.d.	0	300	n.d.	193	17	n.d.
B_4O_7	30	88	n.d.	n.d.	1,870	30	trace	1,365
NO_3	n.d.	n.d.	n.d.	990	35	44	n.d.	n.d.
pH	n.d.	n.d.	n.d.	n.d.	ca. 5–6	6.4	n.d.	n.d.
Total dissolved solids (percent)	27.9	17.1	7.36	9.91	30.99	4.76	2.74	33.1

1. Durrell, 1953, p. 13, analysis II; brine from drainage canal in salt body. Analysis by W. W. Brannock.
2. Durrell, 1953, p. 13; analysis I; brine from shallow well. Analysis by W. W. Brannock.
3. Gale, H. S., and Hicks, W. B., 1920. Brine from depth of 36 feet. Analysis by Smith, Emery & Co.
4. Recalculated to actual concentrations from data of Coleman, 1929, quoted by Ver Planck, 1957. Well on Mullet Island.
5. White, D. E. (1965). Analysis by J. D. Hem and others.
6. White, Hem, and Waring, 1963, table 13, analysis 1. Analysis by D. O. Watson.
7. White, Hem, and Waring, 1963, table 13, analysis 2.
8. White, Hem, and Waring, 1963, table 13, analysis 8.

Bristol Lake lies in the east-central part of the Mojave Desert province (see fig. 67, chapter on Salt). The fill beneath the floor of this closed depression consists of more than a thousand feet of salt and clay (Bassett and others, 1959), but the brines abnormally rich in calcium chloride (table 10, analysis 2) are restricted to the top 32 feet (Gale, 1951, p. 10). Cadiz Lake, in an adjacent basin, contains a similar but less rich calcium chloride brine (table 10, analysis 3). Similar brines have also been found in springs and in a geothermal well in the Imperial Valley of California (table 10, analyses 4 and 5).

Geologic explanations for the origin of Bristol Lake brine are not satisfactory. The brine's characteristics are quite different from those in most dry lakes, though somewhat similar to those obtained from some oil fields. Examples of such brines are found in a few California fields (table 10, analyses 6 and 7), but better and more common examples are found in oil field brines of other states that come from older rocks.

Consumers of calcium chloride in the United States mostly utilize the tendencies of its solid form to absorb water and its solutions to freeze at low temperatures. About 30 percent of the solid calcium chloride produced is used for deicing road surfaces, 25 percent is for dust control, 13 percent is for inhibiting the loss of moisture in concrete during setting and curing, and 5 percent is for refrigeration. The rest is used chiefly for freezeproofing bulk shipments of fragmental materials, for dustproofing mines and roads, and for dehumidifying. Because of the high density of calcium chloride solutions, it is also used in oil-well drilling and as a ballast for tractor tires (Ver Planck, 1957; Keiser, 1960; Babcock, 1964).

The properties of calcium chloride are uncommon, and for many years the material was regarded as nearly worthless. Over the last 20 years or so, however, consumers have discovered many new uses, and established uses have become widespread. For example, in 1962, production of natural and synthetic calcium chloride in the United States was 672,000 tons, double the amount produced 10 years earlier (Keiser, 1960; Babcock, 1964).

In the period 1959–1963, annual production of 75-percent-equivalent calcium chloride from natural sources averaged about 437,000 tons; this was valued at $8.32 million, or about $19 per ton. California production in 1953 was about 16,000 tons (Ver Planck, 1957), and the State's 1963 share in national production from natural sources shows that this tonnage has remained about the same.

Most of the product marketed in California is used for the treatment of ore and seaweed and by the concrete industry, but smaller quantities are used for dust control, refrigeration, drying operations, and oil-well drilling (Ver Planck, 1957). California markets have not grown as fast as those in the rest of the country because they do not include populous areas affected by winter driving problems.

Producers of calcium chloride from the brines of Bristol Lake are the National Chloride Co. of America and the Leslie Salt Co. (formerly the California Salt Co.). Both companies concentrate the natural brines (table 10, analysis 2) by solar evaporation until most of the salt is precipitated and the more soluble calcium chloride is concentrated in the solution. Much of the brine is sold in that form; the rest is sold to the Hill Bros. Chemical Co., located nearby, where it is converted to solid flake form (Ver Planck, 1957).

Future production and consumption of calcium chloride are likely to increase rapidly because new uses are being consistently developed. Natural resources are large. Although not all of it could be recovered economically, the total amount of calcium chloride in Bristol Lake is estimated to be enough to last hundreds of years at present production rates. Additional sources of calcium chloride in California might lie in Cadiz Lake, in the geothermal brines of the Salton Sea area, and in oil field brines.

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CARBON DIOXIDE

(By C. D. Edgerton, Jr., U.S. Bureau of Mines, Pittsburgh, Pa.)

Carbon dioxide is a colorless, odorless, nonflammable, heavier-than-air gas commonly found in association with natural gas in subsurface reservoirs. The concentration of carbon dioxide here may range from a fraction of 1 percent to nearly 100 percent. It is also found in many volcanic gases, in mineral springs, and in emissions from other phenomena related to geothermal activity. Carbon dioxide occurs in the earth's atmosphere in concentrations of less than 1 percent.

Carbon dioxide can be readily liquified and solidified. In the latter state it is known as dry ice, and is an excellent refrigerant. In the solid state, its temperature is minus 109° F. It passes from the solid to the gaseous state without going through a liquid phase.

Industry uses carbon dioxide principally in the manufacture of carbonated soft beverages and as a refrigerant. It also is used in the preservation of food and other products that would deteriorate if exposed to air, in fire extinguishers, and as an explosive.

In California, carbon dioxide formerly was produced commercially from three fields, one in Imperial County and two in Mendocino County. These fields, however, have not produced for several years. In 1965, the State's only production of naturally occurring carbon dioxide came from a plant near Taft, in Kern County, operated by Tidewater Oil Co. which extracted the product from natural gas from nearby oil fields. Tidewater sold the carbon dioxide to aircraft companies for use in freezing rivets, and to bottlers of carbonated beverages. Another plant in the same area, operated by Standard Oil Co. of California, extracted carbon dioxide from natural gas, but the product was not marketed. The latter plant was operated to upgrade the natural gas by removing the carbon dioxide in order that the natural gas would meet pipeline specifications.

Although the State's production of naturally occurring carbon dioxide is, at present, limited to the above, various analyses by the Bureau of Mines indicate the presence of carbon dioxide in the natural gas from a number of the State's fields. Table II gives the percentage of natural gas from representative California fields.

TABLE 11.—*Percentage of carbon dioxide in natural gas from representative California fields*

Field	County	Percent of carbon dioxide
Ten Section	Kern	0.8
Santa Maria	Santa Barbara	15.5
Torrey	Ventura	6.8
Coalinga	Fresno	11.1
McKittrick	Kings	30.4
West Los Angeles	Los Angeles	1.0
Midway Sunset	Kings	10.5
Fullerton	Orange	1.7
Kern River	Kern	6.5

Only a small percentage of the carbon dioxide produced in California comes from natural sources. Most of it is produced by calcining limestone, during the fermentation of alcohol, and as a by-product of other industrial processes.

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CHROMITE

(By T. P. Thayer, U.S. Geological Survey, Washington, D.C.)

Chromite, as the only economic source of chromium, is an essential commodity for modern industry, and over the last 10 years the United States has used about 1,200,000 long tons of it annually. About 60 percent of the total is reduced to ferrochromium and used metallurgically in steel alloys for strength and resistance to corrosion, and approximately 28 percent is used in high-temperature furnace linings, especially in the steel industry. The chemical industry consumes the remaining 12 percent to make dichromate as a basis for dyes, tanning, and chromium plating. Although magnesite can be substituted for much of the chromite in refractories, there are no satisfactory substitutes for chromium in the metallurgical and chemical industries.

The United States has depended on imported chromite since about 1880 (see fig. 14), and even when imports were interrupted by war

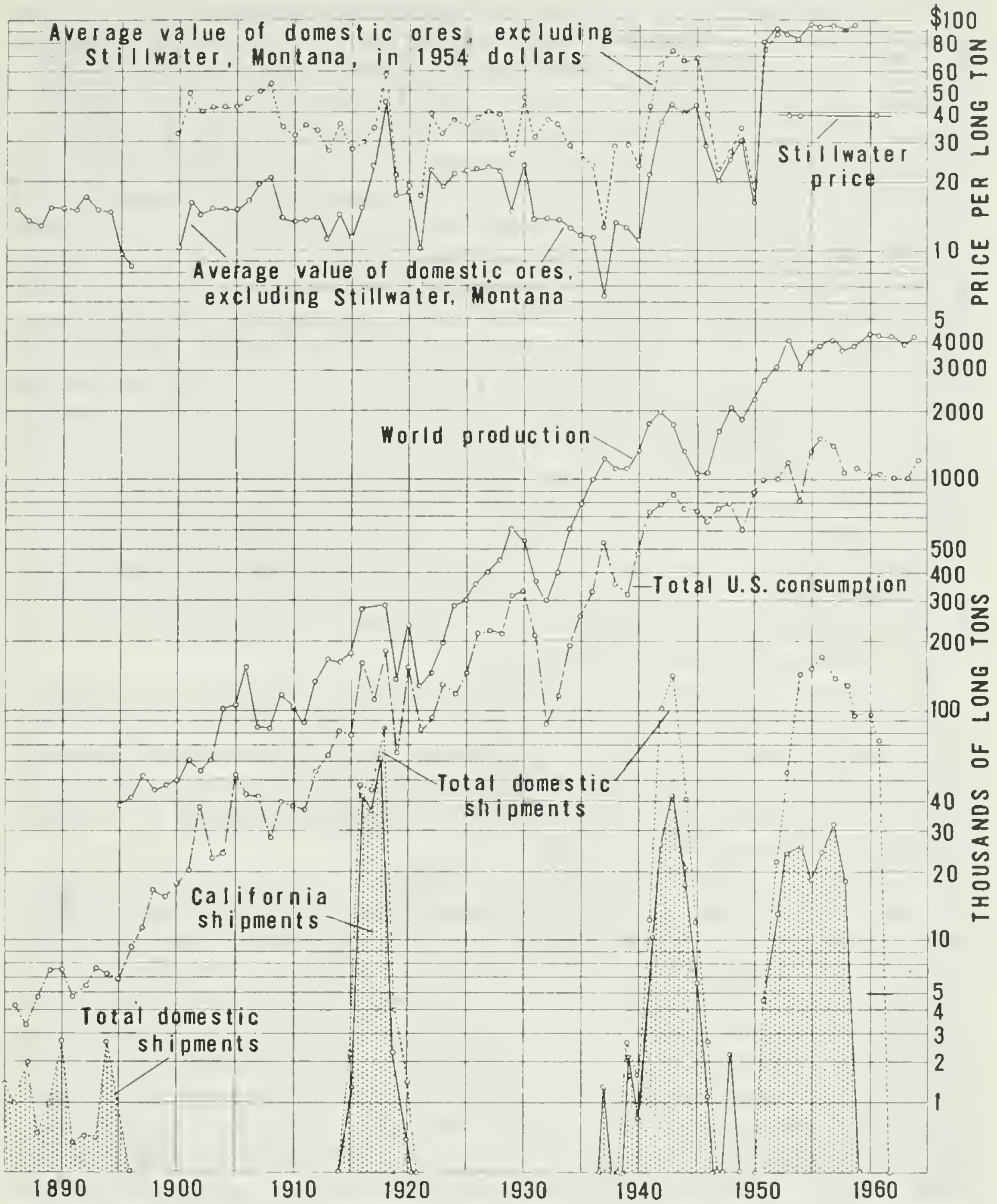

FIGURE 14.—Production of chromite in California since 1885 in relation to total United States production and consumption, world production, and domestic price. Note increase in proportion of concentrates in the United States as a whole, and decreasing peaks in California production during the last three war periods despite successively higher prices (most data from U.S. Bureau of Mines Minerals Yearbooks).

has been unable to obtain as much as half of its needs from domestic deposits. Total domestic production of 1.9 million long tons is equivalent to about 18 months consumption at recent rates, and California's production of 543,000 long tons would last about 5½ months. Between about 1875 and 1940, before development of large deposits in Montana, California was the principal domestic source of chromite.

Chromium ores are mixtures of the mineral chromite with gangue minerals, mostly serpentine and magnetite, in various proportions. The chromite contains all the chromium in the ore, but in addition contains variable amount of iron oxide, MgO, and Al_2O_3 as essential constituents. The chromium content of an ore depends, then, on two factors: the ratio of chromite to gangue and the composition of the chromite mineral. Ores that contain too much gangue can be raised to usable grade by grinding the ore and separating the chromite from the gangue by several physical processes, but if the chromite itself is too low in chromium, commercial grade cannot be attained. Most California chromite is of the metallurgical type, for which conventional specifications require 48 percent Cr_2O_3, a Cr:Fe ratio of 3:1, and SiO_2 not more than about 5 percent; lower grade ores can be used metallurgically, however, with some loss in efficiency. Before 1940, most ore mined was high enough in grade to ship as lumpy ore directly or after sorting by hand, but since then most mine-run ores have been concentrated. Although the High Plateau mine in Del Norte County has yielded relatively large amounts of lumpy ore averaging more than 48 percent Cr_2O_3 with Cr:Fe ratio exceeding 3:1, it is exceptional. Shipments from California between 1950 and 1958 were mostly concentrates which averaged 43 to 44 percent Cr_2O_3 with Cr:Fe between 2.6:1 and 2.7:1.

The chromite deposits in California are of two types: irregular lenticular to tabular bodies of the podiform type (Thayer, 1964) that occur only in peridotite and serpentinite, and placer or sand deposits. Beach sands south of Crescent City are known to contain chromite, but have not been fully explored; they are not believed to be large (Wells and others, 1946, p. 74).

The known podiform deposits in California range in size from a few pounds to about 135,000 long tons of ore, the size of the ore body that was mined out at the Grey Eagle mine in Glenn County. Many deposits are of massive ore, with sharp boundaries, but the larger ones are of disseminated ore and commonly grade into barren rock. The ore bodies occur individually or in clusters distributed more or less at random in the peridotite or serpentinite. Most deposits have been found by surface exposures or by drilling and mining in the vicinity of exposed ore bodies. In a few places, as in the San Luis Obispo district (Walker and Griggs, 1953, p. 50), ore bodies are alined along shear zones. Despite much research, however, no economic method has been devised as yet for finding the numerous chromite deposits that must lie just below the ground surface in many parts of the world.

The principal chromite districts of the State (fig. 15) are in the Klamath Mountains, in the northern Sierra Nevada, and in the southern Coast Ranges. Two relatively small areas, Del Norte County and the San Luis Obispo district, have yielded 215,600 long tons of chromite, nearly 40 percent of the recorded State total, and the 13 largest mines produced 244,700 tons, slightly more than 45 percent of the State total. Several hundred small mines and prospects are known. The random distribution of deposits is emphasized by production of 10 percent of the State total from two essentially isolated mines (see fig. 15), the Grey Eagle in Glenn County (Rynearson and Wells, 1944), and the Butler Estate in western Fresno County (Matthews, 1961).

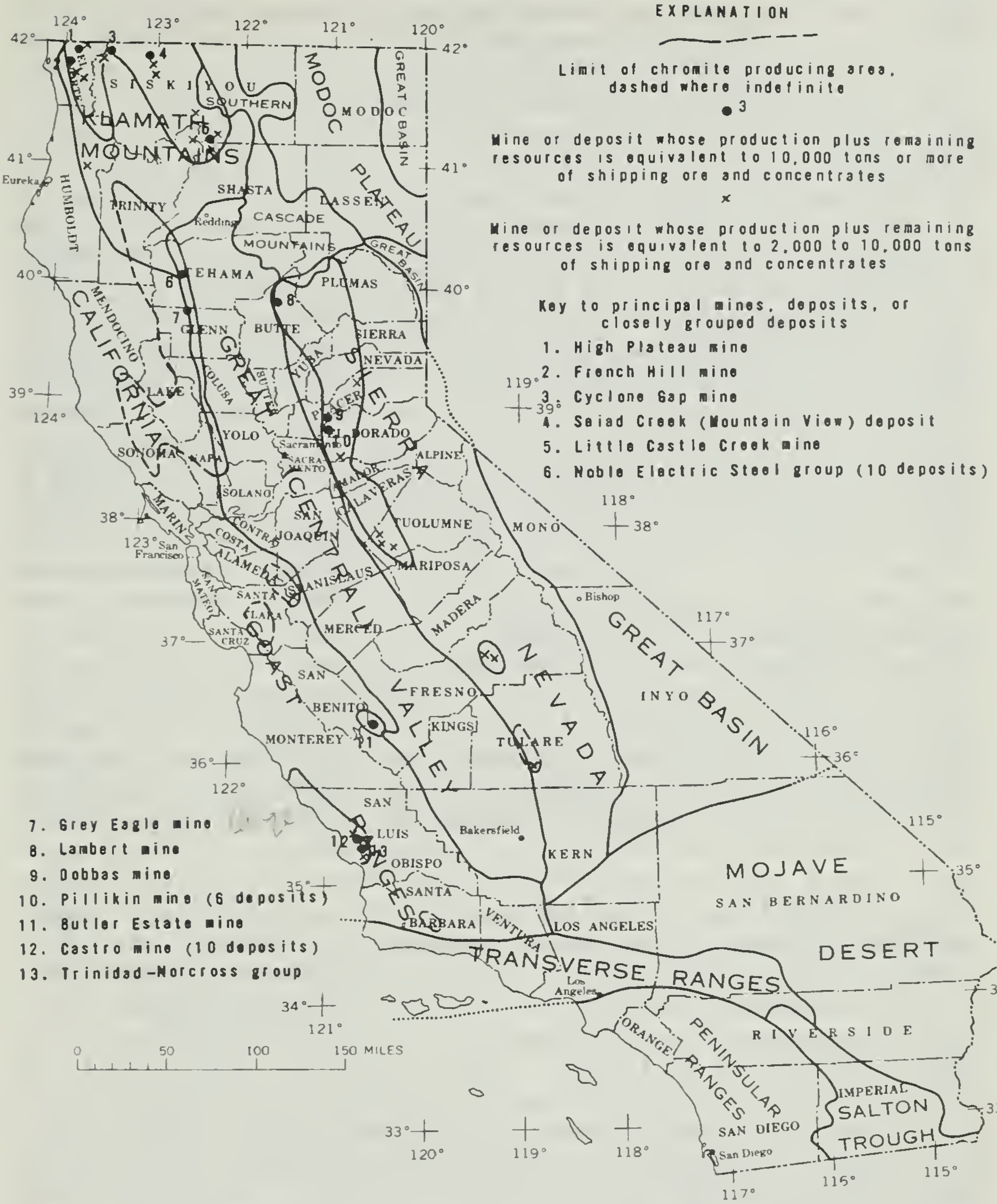

FIGURE 15. Chromite districts and principal deposits in California.

The record of chromite production in California since World War I (fig. 14) clearly shows the impact of declining reserves and increased difficulties in mining. Although many deposits and districts were then relatively inaccessible, 143,700 long tons was shipped from the State in the 3 years 1916–1918; the peak year was 1918 when 63,145 tons was produced. In 3 years during World War II (1942–1944) 124,347 tons was produced, with a maximum of 54,420 tons in 1943; but during the Korean War it took 5 years (1953–1957) to produce 124,342 tons with 31,162 tons as the annual peak. In 1918 the price or ore exceeded $45 for only a short time; in terms of

1954 dollars, peak realized prices during the three periods 1916–1918, 1942–1944, and 1953–1957 averaged \$60, \$65 to \$75, and \$80 to \$90, respectively. During the last two periods, moreover, a market was assured by Government purchase programs (U.S. Commerce Dept., 1962, p. 82); this was not the case during World War I. During World War I most of the ore was of the lumpy type desired by industry, and required only hand sorting. The outstanding chromite mine during World War II was the Grey Eagle, where the Rustless Mining Co. obtained 30,806 tons of concentrates averaging 46 percent Cr_2O_3 and a Cr:Fe ratio of 2.67:1 from ore averaging 13 percent Cr_2O_3; 33 tons of rock was mined for every ton of concentrates obtained (Dow and Thayer, 1946, p. 9). Comparisons of the sizes of open pits with production from San Luis Obispo district during the chromite purchase program of the 1950's indicates comparable ratios of waste rock to concentrates. The average price of about \$90 per long ton received for ore averaging 42 to 43 percent Cr_2O_3 and a Cr:Fe ratio of 2.6 to 2.7:1 was equivalent, quality considered, to twice the highest world prices in 1956 and 1957, and 3 or 4 times the world price in the first half of 1965. When the Government purchase program ended May 30, 1958, California shipments were at a rate of about 35,000 tons a year.

The chromite resources of California were estimated by the U.S. Geological Survey [1] as equivalent to 100,000 long tons of Cr_2O_3 in the ground or about 210,000 tons of standard metallurgical-grade ore, as of 1956. No overall figures are available on ore reserves when mining stopped in 1958, but it is unlikely that they equalled a year of production. Because of the long-term uncertainty of the Government subsidy, ore was mined as fast as it was found; future mining will, therefore, depend on discoveries. The only known moderately large chromite deposits are in El Dorado, Siskiyou, and Tehama Counties. Low-grade disseminated deposits, largely in the Pillikin and Dobbas mines, in El Dorado County, were estimated (Cater and others, 1951, p. 108) to contain about 600,000 tons of rock averaging 5 percent Cr_2O_3; concentrates, however, average only about 43 percent Cr_2O_3 with Cr:Fe ratio of 1.3 to 2.3:1 (Cater and others, 1951, p. 137). In Siskiyou County some 275,000 tons of disseminated ore is known, most of it in the Seiad Creek (Mountain View) deposit; although the total Cr_2O_3 content is equivalent to nearly 40,000 tons of 48 percent concentrates, milling tests have not achieved satisfactory recoveries (Engel and others, 1956, p. 6). Deposits in the vicinity of North Elder Creek, Tehama County, were estimated in 1943 (Rynearson, 1943, p. 204) to contain the equivalent of 24,000 tons of standard ore, but all of Tehama County shipped only 3,350 tons in the period 1952–1958.

The California potential for production of usable chromite might be summarized by applying a factor of 75 or 80 percent to the tonnages given in the following statement of the Materials Advisory Board (1959, p. 44) regarding the United States:

> Although many miners may disagree, the Government purchase programs for chromite during World War II and from 1951–1958 give a reliable measure

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[1] Estimate by T. P. Thayer, Department of the Interior Information Service, press release, June 5, 1957.

of the production potential of the pod deposits. The production record of high-grade ores from the pod deposits may be summarized as follows:

“Period	Base price (in 1954 dollars)	Annual production of ores and concentrates (+ 45 percent Cr_2O_3 in thousands of long tons)
		Average
1942–44	$87	13.6–25.7
1952–57	113	12.8–29.0

This shows that a base price 32 percent higher and major improvements in mining technology managed to increase production of high-grade ore by only 10 percent. The depletion of reserves is illustrated by the San Luis Obispo district in California, where plans were being made late in 1957 to handle 80 tons of rock for every ton of concentrates from an operation expected to produce about 10,000 tons of concentrates. Although a higher base price might increase production of the +45 percent ores above the 20,000 tons annually for a very few years, progressive depletion is inevitable. Lowering specifications below the last purchase program cutoff (42% Cr_2O_3, Cr : Fe ratio of 2 : 1) might double the tonnage, but with high-silica concentrates.

In conclusion, neither the history of chromite mining nor known chromite reserves indicate that California could provide more than a small part of our national requirements for chromium. Over the long term the United States and the free world have little choice but to depend increasingly on major sources of supply in Southern Rhodesia, the Republic of South Africa, Turkey, and the Philippines. Furthermore, the outlook for developing large sources of chromite in the Western Hemisphere is not encouraging.

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CLAY

(By F. R. Kelley, California Division of Mines and Geology, San Francisco, Calif.)

The term "clay" is a broad one, and has been used to include many diverse materials. In general, it "implies a natural, earthy, fine-grained material which develops plasticity when mixed with a limited amount of water" (Grim, 1953). The term commonly is used both in referring to a definite group of silicate minerals, and as a rock term to indicate detrital rocks of the smallest grain size (less than about four microns), regardless of the composition of the particles. Grim distinguishes between "clay minerals" and "clay materials", and the latter is a useful term under which many of our industrial clays would fall.

Wet mud can be molded and shaped, and will dry to a hard mass that will have considerable strength, as long as it is not again subjected to moisture. Developing plasticity in a clay by the addition of water is a reversible process, which can be repeated at will. But if the clay body is subjected to prolonged and intense heating its character is changed, and it becomes hard and immune to further attack by moisture. These are the characteristics of clay which account for much of its usefulness.

The clay minerals characteristically are hydrous aluminum silicates, with other elements such as magnesium, iron, potassium, sodium, and calcium in some of them. Most of them are "layer-silicates", with sheet-like lattice structures resembling the micas. Based on chemical composition and crystalline structure, three main groups are differentiated, as follows:

kaolinite group
montmorillonite group
hydrous mica or illite group

Various other minerals, such as attapulgite, sepiolite and the mixed-layer clays have clay-like properties, but do not fit into the three groups mentioned.

Classification

Because clays have been utilized for so many purposes over a long period and are such a diverse group of materials, many other classifications have been used in their description. Geologically, clays may be classified on the basis of their origin as residual, i.e., formed in place, and sedimentary, i.e., transported from their place of origin. The terms high-alumina clay and ferruginous clay refer to chemical composition; refractory clay and semiplastic clay refer to physical properties; brick clay and bleaching clay refer to use. No single classification will serve all purposes.

For gathering statistical information, the U.S. Bureau of Mines employs a classification based on industrial use, as follows:

kaolin or china clay
ball clay
fire clay, including stoneware clay
bentonite
fuller's earth
miscellaneous clay

Much information is cataloged under this classification, and it affords a convenient standard.

Kaolin or china clay

These clays are composed largely of kaolinite, but may have much quartz, mica, feldspar, or other material from the parent rock still present. White kaolins are used in whiteware bodies and other high-grade ceramic uses, and as fillers and coating materials in papermaking. Kaolins also are used as fillers in rubber and linoleum, and in various chemical, medicinal, and cosmetic applications.

Ball clay

The important characteristic of the ball clays is their high plasticity and bonding power. They are composed largely of poorly crystalline kaolinite and are very fine grained. They are used in blending with other clays to enhance their workability in manufacturing ceramic products such as sanitary ware, wall tile, and the like.

Fire and stoneware clay

These are made up primarily of kaolinite-group minerals, but vary widely in composition. Their most important property is refractoriness (high resistance to heat), and they are subdivided into several classes on the basis of a test known as the pyrometric cone equivalent. Clays above cone 19 (P.C.E. 19, about 1,520°C or 2,768°F) on this scale are regarded as fire clays. They are further designated as low duty, ranging from 19 to 28; medium duty, from 29 to 30; high duty, from 31 to 32; and super duty 33 (about 1,745°C or 3,173°F) or above. Fire clays vary widely in plasticity, and the fired color may vary from near-white to red. They are used in a variety of ceramic products, ranging from common brick to art pottery, sewer pipe, and ornamental tile. Some of the best grades go into refractory brick for use in the steel industry. Some low-grade fire clay is used in the manufacture of stoneware.

Bentonite

The term "bentonite" is a rock name, originally applied to a highly swelling clay material in Wyoming and other Rocky Mountain states. This clay is derived from the alteration of volcanic ash and is composed principally of montmorillonite. Many bentonites are nonswelling, and it has been established that only montmorillonites holding sodium as an exchangeable ion will swell conspicuously, but if this ion is replaced by calcium, the material loses its swelling properties.

The bentonites are the most reactive of the clays, and are useful as plasticizers, absorbents, binders, pelletizers, filtration and clarification aids, ion exchange media, reservoir sealers, and drilling muds.

Fuller's earth

Fuller's earth is a nonswelling bentonitic material also composed principally of montmorillonite. It is a highly absorptive clay, and owes its usefulness to its ability to absorb various organic molecules in the purification of mineral and vegetable oils, and a variety of other uses.

Miscellaneous clay, including shale

This group takes in a variety of clay materials, including the low-grade alluvial clays, shales, many soil materials, and any argillaceous material that does not fit into one of the other groups. Natural clay materials are usually mixtures, and the less pure clays of any of the groups may be classified as miscellaneous clays. Any of the clay minerals may be present, plus other detrital minerals, including quartz, mica, the feldspars and others, as well as rock fragments and organic matter. The miscellanous clays have a variety of uses. For specific purposes, they are upgraded by blending with higher quality clays to develop certain properties. Large quantities of miscellaneous clays go into the manufacture of heavy clay products, such as common brick, structural tile, and sewer pipe. For this purpose, the clay must develop some plasticity but must not shrink excessively, and must fire to a suitable color and strong texture at reasonably low temperatures. Organic matter in a clay material may cause bloating, and large amounts of bloating clays are used in the manufacture of expanded shale lightweight aggregate. Large tonnages of common clays of suitable bulk composition go into the production of portland cement, as a source of alumina and silica. Smaller amounts are used as fillers for various purposes, rotary drilling muds, and a variety of other uses.

Geologic Occurrence of Clays

The clay materials are secondary, forming as alteration products of pre-existing rock materials by weathering processes or hydrothermal alteration, or in some cases by diagenetic processes. The more soluble constituents of the original rocks are leached out, leaving behind the relatively stable aluminum silicates which are reformed as clay minerals. If the alkalis and alkaline earths are not completely removed, the clay minerals formed may be montmorillonites or illites. Kaolinite appears to represent a more advanced stage of clay formation. Under severe chemical weathering, the kaolinite itself may break down, leaving only a residue of aluminum and iron oxides, such as in the lateritic soils of the tropics.

Clay deposits may be residual or transported, according to their relationship with neighboring rock bodies. Residual clays are formed when chemical weathering alters the surface rocks to appreciable depths. Such weathering is most active under warm, moist climatic conditions, and if removal of the weathered residues by mechanical erosion is slow, a weathered zone of considerable depth may be developed.

If the clay, once formed, is removed and transported elsewhere, it may be laid down as a sedimentary clay deposit. These are usually interbedded with other sediments, but the clays tend to stay in suspension until finally they settle out in sheltered basins of relatively quiet water. Sedimentary clays commonly are associated with lignite, derived from the thick vegetation of marshy areas bordering the basins.

In California, the fire clays of the Ione and Alberhill areas are sedimentary clays associated with white sands and lignite. Warm, moist, semitropical climates prevailed in these areas during parts of the Paleocene and Eocene Epochs, and mantles of residual clay were developed on the alumina-rich bedrock of the low-lying land areas. Much material was eroded from these residual zones, and deposited in lagoons, swamps, and along the shallow margins of the adjacent seas to form these sedimentary clay deposits.

Hydrothermal clays are formed when hot, chemically active waters rise through fissures and leach the soluble constituents out of the surrounding rocks, leaving a residue of kaolinized wallrock. The altered zone will be of limited lateral extent and will grade outward into fresh rock, but it may extend to considerable depth.

Bentonite deposits appear to have formed by the alteration of volcanic ash beds. Volcanic glass is unstable, and the transformation to montmorillonite takes place as carbonate- and acid-rich groundwater percolates through the fine-grained mass. Similar changes occur during the diagenesis of many sediments, as the action of ground water causes the formation of authigenic clay minerals within the sedimentary material.

History of Discovery and Development

As the early gold seekers spread through central California, they also found other mineral materials of potential value, including coal and clay, but the beginnings of clay mining are not well documented. At first, the recovery of useful clays was incidental to early coal-mining operations, which were carried on at several localities, including Mount Diablo, Corral Hollow and Carbondale, in the Ione area. One of the earliest potteries in the State was at Antioch, using clay from the Black Diamond Coal mine.

At Corral Hollow, coal mining had started by 1858, and high-grade clays of the district became the basis for a thriving clay industry which operated until 1912, when it was discontinued due to high mining costs. The Dosch pit north of Ione was opened up in 1864 and is the oldest continuously operating clay pit in the State. In 1865, the clays of the Ione district were mentioned in the reports of the State Geological Survey. The Gladding, McBean mine and plant at Lincoln began operations in 1875 and has operated continuously since that date. In southern California, coal mining at Alberhill dates from 1882, and clay production from 1895.

In the early days of the State, destructive fires had resulted in a demand for bricks, and local brickyards were established in many of the towns throughout the State. In the last few decades, as transportation improved, many of these small operations became uneconomic and have passed out of existence; now, most of the brick manufacturing is done near the larger population centers.

The demand for a variety of clays and clay products continues, and clay production in California is at an all-time high.

CALIFORNIA CLAY PRODUCTION

Clay materials are common and widespread, and are utilized in many countries of the world, but no overall, world-wide production figures are available. During 1963, the United States produced over 50 million tons of clay of all types, valued at about $181 million (see table 12). In general, clay production is largest in the more industrialized nations. Considering kaolin and china clay production alone, the United States is the source of about 36 percent of the world production of over 8,757,000 tons, followed by the United Kingdom and U.S.S.R.

TABLE 12.—*U.S. and California clay production, 1963*

	Kaolin and china clay	Ball clay	Fire clay	Bentonite	Fuller's earth	Miscellaneous clays
U.S. production (tons)	3, 163, 573	547, 668	8, 390, 174	1, 584, 516	481, 817	36, 031, 254
U.S. production (dollar value)	59, 770, 274	7, 541, 471	39, 557, 870	18, 536, 229	11, 210, 618	44, 257, 364
California production (tons)	18, 941	(1)	531, 390	14, 444	(1)	2, 800, 900
California production (dollar value)	297, 989	(1)	1, 920, 589	[2] 282, 928	(1)	5, 165, 419
California percent of U.S. total	0. 5		4. 9	[2] 1. 7		11. 7
California rank among States (dollar value)	[3] 5(?)	[4] (?)	[5] 5	[6] 4	[7] (?)	1
Price per ton (average U.S.)	$11–$68	$8–$22	$4. 71	$11. 70	$23. 27	$1. 20

[1] Unapportioned. Combined production of ball clay and fuller's earth for California was 29,606 tons, valued at $363,910.
[2] 1962.
[3] Georgia 1st.
[4] Tennessee 1st.
[5] Ohio 1st.
[6] Wyoming 1st.
[7] Florida 1st.

In 1963, California's production of all clays totalled 3,395,281 tons, valued at $8,030,830, and based on dollar value, it ranked fifth among the states, as follows:

Percent of total value U.S. production

Georgia	30. 0
Pennsylvania	8. 1
Ohio	7. 7
Wyoming	6. 3
California	4. 4

Of California's mineral commodities in 1963, clay was ninth in dollar value at 0.5 percent of the total, or if mineral fuels are excluded it ranked sixth, at 1.6 percent, behind cement, sand and gravel, stone, boron and lime. Production of clay was reported by 65 companies, from about 100 properties, in 34 different counties. About one-quarter of this production was fire clay, and nearly two-thirds was miscellaneous clay, of which 41 percent went into portland cement, 29 percent into expanded shale aggregate, and 30 percent into heavy clay products and other uses.

California Deposits

Fire clay deposits

Fire clays of good quality have been mined in several districts in California (see fig. 16). Along the western foothill belt of the Sierra Nevada, the sedimentary formations of the Great Valley overlap on the gently sloping Mesozoic bedrock surface. In many places, the oldest rocks of the Great Valley sedimentary sequence are light-colored sandstones and clays of Eocene age, known as the Ione Formation. These sediments are well exposed over a 2 by 12 mile area near Ione, in Amador County, where they are made up of clayey sandstones, clays, siliceous gravels, conglomerates and lignite, of variable thickness and lithology. The clays are kaolinitic, and occur in lenses up to 30 feet thick. The formation dips gently westward and is overlain by tuffaceous sediments of Miocene age. The fire clays of this district have been used in refractories and heavy clay products for many years, and recently high-grade clays and glass sand have been recovered from the clayey sandstones.

Elsewhere along the foothill belt, to the northwest and southeast, there are occasional exposures of the Ione Formation, as at Lincoln, in Placer County, a major source of fire clays for 90 years. Other localities include Michigan Bar, Folsom, Valley Springs, Knight's Ferry, and Cooperstown, where some of the recent production has been ball clay, usable as a blending material in the manufacture of wall tile and other products.

The Ione beds dip into the synclinal trough of the Great Valley, and, west of the valley, beds of comparable age and lithology are exposed at several places. At Tesla, in Alameda County, coal and clay were mined from these beds for many years, but the beds dip steeply, and large-scale open-pit mining is not possible. For this reason, mining operations were stopped many years ago, although some of the clays were of excellent quality.

In southern California, a major zone of high-grade fire clays occurs in western Riverside County, from the Alberhill area northwest to Corona, and around the northern end of the Santa Ana Mountains into Orange County. During Paleocene time, the Mesozoic crystalline bedrock of the area was deeply weathered, with the development of residual clays, and some of these were removed and deposited with Paleocene beds of the Silverado Formation. Sandy beds are interstratified with the sedimentary clays, and in many places the Silverado is overlain by several feet of Quaternary conglomerate.

Alberhill and the Corona area have been major sources of clays for refractories and heavy clay products for many years. In the Claymount area west of Corona, mining of highly refractory clays began in 1925. A new major clay deposit was opened up south of Corona in 1954.

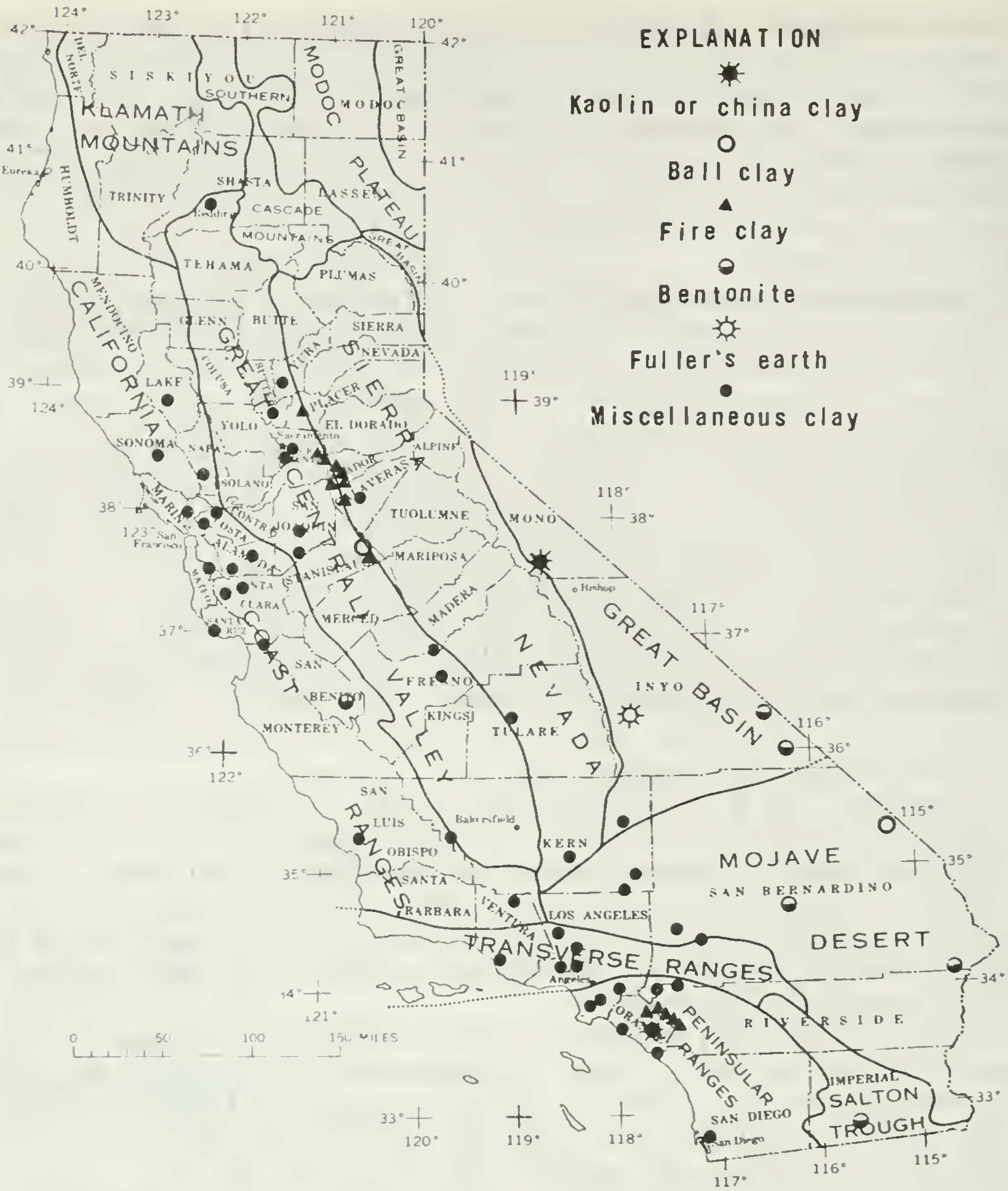

FIGURE 16. Clays produced in California.

In southern Orange County, near El Toro, small amounts of high-grade kaolins are recovered by washing a clay-sand mixture from the Silverado Formation.

Bentonitic clay deposits

Many deposits of bentonitic clay material are scattered over the southern part of California. They occur in rocks of various ages, but the majority are Tertiary.

South of Owens Lake, near Olancha, is an important source of non-swelling bentonite. This clay is derived from a tuff, altered by hydrothermal solutions, and occurs as a low-dipping bed about 16 feet thick, beneath a layer of basalt. It is classed as a fuller's earth, and is used as a filtering and decolorizing agent.

In San Benito County, bentonitic beds occur near the base of the Kreyenhagen Shale, exposed in the steeply dipping south flank of the

Vallecitos syncline. This material has been used as a reservoir and canal sealer, and some has been used as an insecticide carrier.

Near Hector, in San Bernardino County, a unique swelling bentonitic material is mined. It is high in magnesia, low in silica, and has a small lithium content, and is derived from an altered basic tuff or flow in a lake bed sequence. It resembles Wyoming bentonite in its swelling properties, and has been extensively used in rotary drilling mud. After beneficiation, some is used in pharmaceuticals and beverage clarification.

Bentonite is being mined at several other localities, including Death Valley Junction, Tecopa, Brawley, and Vidal.

Other deposits

Clay deposits in the Hart area, eastern San Bernardino County, have been mined for more than 40 years. These clays were formed by hydrothermal alteration of Tertiary rhyolites. Some of them are classed as kaolins and others as ball clays, and they are used in pottery, sanitary ware, and wall tile.

In southeastern Mono County, high-grade kaolin is produced from a deposit near Casa Diablo. This clay is a hydrothermally altered tuff, occurring in a horizontal deposit up to 25 feet in thickness. Some of this clay is sold as a filler in papermaking.

Common clay deposits

Common clays are abundant in California, and large tonnages of alluvial clays and shales are mined annually near population centers, for use in heavy clay products such as building brick. Often the common clays are blended with others to make higher grade ceramic products. Large quantities are also used in making portland cement and expanded shale aggregate. Nearly every county in the State has produced common clay in the past.

Resource Potential and Future Prospects

No detailed information on California's clay reserve and potential resources is available, and only rather broad estimates can be made. Each of the several types of clay is a separate entity, and, furthermore, the use of a given clay material may depend more on relatively obscure and subtle physical properties than on its general classification; so there would be many special cases to consider in any detailed estimate.

Kaolin.—California's resources are small, and large amounts are brought in from outside sources. There is some chance for discovery of new deposits, but perhaps the best means to improve the California position is research to find new ways of using some of the lower grade kaolinitic clays.

Ball clay.—This follows the pattern of kaolinite, with small California production and large imports brought in from Kentucky and Tennessee. However, there appear to be moderate resources of ball clay available and, as time goes on, the local material should find wider acceptance and use as additional testing on its properties is done.

Fire clay.—Reserves appear to be satisfactory, except for the most refractory grades of fire clay. Additional fire clay can probably be found by drilling programs, based on careful studies of sedimentary trends. The State's known small deposits of super-duty refractory clay have been depleted, and this clay is now imported. Careful exploration and drilling might find new small deposits of super-duty clay, but probably far short of enough to meet needs.

Bentonite and fuller's earth.—Intensive prospecting and testing probably would bring to light more deposits of usable bentonite of many diverse types. However, the outlook appears to be unfavorable for finding large resources of Wyoming-type swelling bentonite.

Common clay.—Large resources appear to be available. However, urbanization around the population centers will restrict the use of some deposits, and recovery operations will be forced further away as the cities expand.

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COAL

(By E. R. Landis, U.S. Geological Survey, Denver, Colo.)

Of the total energy consumed in the United States in 1963, 22 percent was furnished by coal. Only oil, with 41 percent, and gas, with 33 percent, outpaced coal (U.S. Bureau of Mines, 1964a, p. 50). Over half of the coal produced in 1963 in the United States was burned to generate electricity, almost 19 percent was used to produce coke, about 24 percent was used industrially, and about 6 percent went for retail deliveries (U.S. Bureau of Mines, 1964a, fig. 14). Only a very small amount of coal is mined in California but 1,690,000 tons were shipped into the State from Utah and New Mexico in 1963 to make coke for smelting steel and for other industrial uses (U.S. Bureau of Mines, 1964b).

Coal is an organic sedimentary rock composed of metamorphosed plant material admixed with a subordinate amount of inorganic constituents. The plant material may have accumulated at its growing site or may have been transported by water and wind to its depositional site. Peat is excluded by definition because it is not metamorphosed, but it is the material from which coal is derived. Coal results when peat is buried and progressive changes in physical and chemical properties take place, mainly related to time and weight of overlying sediments. In places the changes are speeded by pressure from structural deformation or heat from igneous intrusive rocks. The progressive metamorphism increases the carbon content and heat value while decreasing the moisture and volatile matter contents. Coals are classed by rank, according to the degree of metamorphism, from lignitic to subbituminous, bituminous, and anthracitic, and the rank is generally an index to the usability and value of the coal (table 13). Anthracitic coal is largely used for domestic and other space heating, but some is blended with bituminous coal to make coke. Bituminous and subbituminous coal range widely in properties but in general the higher rank coal is likely to be used for special purposes, such as making metallurgical coke, and the lower rank coal is likely to be used solely for heat energy, as in steam-electric utility plants. Lignitic coal is largely used as a source of heat energy but carbon, industrial gases, humic acid compounds with a great variety of uses, and montan wax are also derived from lignite.

Coal deposits range in shape from thin beds of wide extent, to thick nearly equidimensional bodies. As with other stratified rocks, the shape and attitude of coal beds are affected by the deforming forces, folding, faulting, and igneous intrusion. For profitable development under present-day conditions with a high degree of mechanization, coal beds mined underground should be 3½ feet or more thick with a small range in thickness, flat-lying, not broken by faults, and at depths of less than 1,000 feet. In surface, or strip, mining the additional important factors are thickness and character of the material overlying the coal bed—the coal should be less than 100 feet below the surface and the overburden should be easily removable.

In 1963, the United States mined 16 percent of the world coal output, about 477 million tons, and ranked third in production behind the U.S.S.R. with 584 million tons and Germany (East and West) with 559 million tons (U.S. Bureau of Mines, 1964a, p. 168–170). First recorded production of coal in California was in 1855, and the annual coal production exceeded 100,000 tons during most years between 1867 and 1903 (Jennings, 1957, p. 153). The coal was used for steam generation by the railroads and steamships, and for industrial and domestic heating. Oil and gas began to displace coal as a heat source shortly after 1900 and by 1914 annual coal production was a few thousand tons. In recent years the amount of coal produced annually in California has probably been a few thousand tons, almost all of which is used as a raw material from which montan wax and a few by-products are derived. Montan wax is used in shoe polishes, floor waxes, electrical insulation, leather dressings, inks, carbon paper, protective coatings and waterproofing compounds, greases, phonograph records, rubber, investment castings, and many other allied products (Jennings, 1957, p. 162). Almost all of the coal imported into California is carbonized to make coke and by-product chemicals. Only 37,000 tons of the total 1,690,000 tons that were shipped from Utah and New Mexico went to retail deliveries and other uses (U.S. Bureau of Mines, 1964b).

Small, scattered deposits of coal are reportedly present in 43 counties of the State but have been mined or intensively prospected at less than a dozen localities in 11 counties (Jennings, 1957, p. 153) (fig. 17).

TABLE 13.—*Classification of coals by rank* [1]

[American Society for Testing Materials (1964)]

Class	Group	Fixed carbon limits, percent (dry, mineral-matter-free basis)		Volatile matter limits, percent (dry, mineral-matter-free basis)		Calorific value limits, Btu per pound (moist,[2] mineral-matter-free basis)		Agglomerating character
		Equal or greater than—	Less than—	Equal or greater than—	Less than—	Equal or greater than—	Less than—	
I. Anthracite	1. Meta-anthracite	98			2			Nonagglomerating.[3]
	2. Anthracite	92	98	2	8			
	3. Semianthracite	86	92	8	14			
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22			Commonly agglomerating.[5]
	2. Medium volatile bituminous coal	69	78	22	31			
	3. High volatile A bituminous coal		69	31		[4] 14,000		
	4. High volatile B bituminous coal					[4] 13,000	14,000	
	5. High volatile C bituminous coal					11,500 10,500	13,000 11,500	Agglomerating.
III. Subbituminous	1. Subbituminous A coal					10,500	11,500	Nonagglomerating.
	2. Subbituminous B coal					9,500	10,500	
	3. Subbituminous C coal					8,300	9,500	
IV. Lignite	1. Lignite A					6,300	8,300	
	2. Lignite B						6,300	

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[1] This classification does not include a few coals, principally nonbanded varieties, which have unusual physical and chemical properties and which come within the limits of fixed carbon or calorific value of the high-volatile bituminous and subbituminous ranks. All of these coals either contain less than 48 percent dry, mineral-matter-free fixed carbon or have more than 15,500 moist, mineral-matter-free British thermal units per pound.

[2] Moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal.

[3] If agglomerating, classify in low-volatile group of the bituminous class.

[4] Coals having 69 percent or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of calorific value.

[5] It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class, and there are notable exceptions in high-volatile C bituminous group.

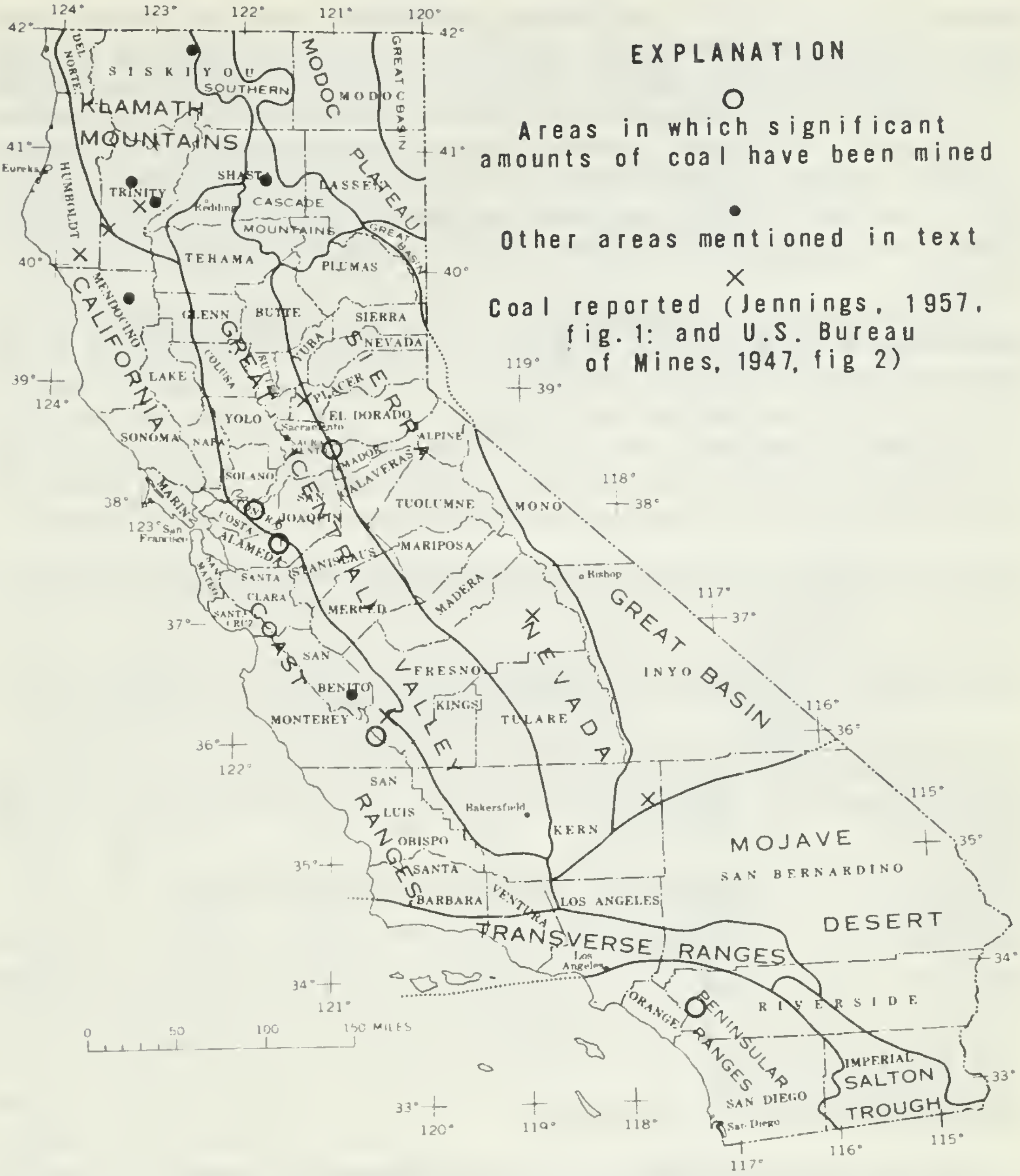

Figure 17. Coal in California.

The following brief discussion is derived largely from Jennings (1957) and the U.S. Bureau of Mines (1947).

High-volatile bituminous coal is present in the Temblor (?) Formation of early and middle Miocene age in the Stone Canyon district of southeastern Monterey County, and some bituminous coal occurs in rocks of Eocene age in southern San Benito County. The bituminous coal in the Stone Canyon district may be of the variety known as cannel coal, which characteristically has as much or more volatile matter as carbon and is noncoking (U.S. Bureau of Mines, 1947, p. 4). Subbituminous coal and lignite occur in the Montgomery Creek Formation in Shasta County, in the Tesla Formation in Alameda County, and in the Domengine Formation in Contra Costa County. These three rock units are all Eocene in age and are probably partially or completely equivalent to each other. Subbituminous coal is also present in the Temblor Formation of Miocene age in Mendocino County and in rocks of Eocene age in Siskiyou County. Lignitic coal occurs in rocks of Early Cretaceous age, and in the Weaverville Formation of Oligocene (?) age in Trinity County; in the Silverado Formation of Paleocene age in Riverside and Orange Counties, though the available incomplete analysis suggests that some or all of this coal may be subbituminous; and in the Ione Formation of Eocene age in Amador County.

The coal beds of California do not range widely in age, and the differences in rank are due largely to differences in amount of structural deformation that the deposits have undergone. The coal-bearing rocks in the Coast Ranges have been folded and faulted and the coal has commonly been metamorphosed to higher ranks than the coal in the foothills of the Sierra Nevada and in the Peninsular Ranges where the strata dip gently or are horizontal (Jennings, 1957, p. 153) (table 14).

TABLE 14.—*Range of analyses of representative California coals, as-received basis*

Sample source	Number of samples	Rank (table 13)	Moisture (percent)	Volatile matter (percent)	Fixed carbon (percent)	Ash (percent)	Sulfur (percent)	Calorific value (B.t.u. per pound)
Stone Canyon,[1] Monterey County.	3	High volatile B bituminous.	4.4- 8.0	44.8-50.0	30.3-36.0	7.5-15.9	4.1-4.6	11,420-12,130
Mount Diablo,[1] Contra Costa County.	1	Subbituminous A.	15.0	38.4	34.5	12.1	5.6	9,240
Corral Hollow,[1] Alameda County.	2	Subbituminous B.	17.6-18.0	39.2-41.1	23.3-26.4	16.4-18.0	2.9-3.1	[2] 8,110
Alberhill,[3] Riverside County.	1	Lignite A [4] or subbituminous C.	19.0	46.5	21.9	12.6	-------	------------
Ione, Amador [1] County.	2	Lignite A-------	40.3-45.8	30.9-31.3	13.2-15.7	7.6-15.2	1.0-1.3	5,640- 6,060

[1] U.S. Bureau of Mines (1947).
[2] Only 1 calorific value reported.
[3] Jennings (1957).
[4] Reported to be lignite; but may be subbituminous.

Significant quantities of coal have been mined in only five areas—Mount Diablo in Contra Costa County, Corral Hollow in Alameda County, Stone Canyon in Monterey County, Alberhill in Riverside County, and Ione in Amador County (fig. 17). Total recorded production to date is about 5,310,000 tons, of which about 3,500,000 tons was mined in the Mount Diablo district between 1855 and 1902 (Jennings, 1957, p. 153). Of the remainder, at least 350,000 tons were mined in the Corral Hollow district between 1897 and 1902 (Jennings, 1957, p. 157).

According to Karp (1949, p. 341), the known coal resources of California are estimated to be more than 100 million tons, of which Averitt 1961, p. 85) estimates about 50 percent is lignitic coal, 40 percent subbituminous, and 10 percent bituminous. The general assumption that for every ton of coal actually produced another ton has been lost in mining or is unrecoverable is probably valid for areas such as California where precise information is unavailable.

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COBALT

(By J. T. Alfors, California Division of Mines and Geology, San Francisco, Calif.)

Cobalt compounds have long been used to give a beautiful blue color to pottery and to glass. This ancient use still persists, but the remarkable ability of cobalt metal to impart great strength to alloys at high temperatures, and magnetic qualities to certain alloys, has led to increased use of cobalt in the past 20 years. Recently, other refractive metals have partially replaced cobalt for high-temperature superalloys and the amount of cobalt used for permanent-magnet alloys also has declined on account of substitutes (U.S. Bureau of Mines, 1965, p. 39).

The domestic consumption of cobalt in 1963 was 10.5 million pounds, 7 percent less than 1962. The major uses of cobalt were for high-temperature, high-strength alloys (23 percent) and for permanent-magnet alloys (22 percent). Uses in steel (12 percent) and other products brought the total consumption of metallic cobalt to 75 percent. Nonmetallic (exclusive of salts and driers) consumption, mainly in pigments and as ground-coat frit, was 13 percent of the total. Sales and driers account for 12 percent of the domestic consumption (Ware, 1964, p. 2–3).

Cobalt is generally recovered as a by-product of copper or nickel ores. Some cobalt is obtained during the processing of iron, gold, lead, and silver ores. Other metals associated with cobalt include zinc, manganese, uranium, platinum, and chromium (Vhay, 1952, p. VI–5, 6; Centre d'Information du Cobalt, 1960, p. 8–29).

The important primary ore minerals of cobalt are skutterudite ($(Co,Ni,Fe)As_3$), carrollite (Co_2CuS_4), linnaeite (Co_3S_4), and cobaltite ($CoAsS$). The principal cobalt minerals in the oxidized zone of mineralization are asbolite (a cobalt-bearing mixture of hydrous manganese and iron oxides), heterogenite (a hydrous oxide of cobalt and copper), sphaerocobaltite ($CoCO_3$), and erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$) (Bilbrey, 1960, p. 216; Centre d'Information du Cobalt, 1960, p. 8–10).

Cobalt deposits commonly are associated with mafic or ultramafic igneous rocks as magmatic segregations of sulfides or as vein or replacement deposits formed by hydrothermal activity. Cobalt-bearing vein deposits are less commonly associated with granitic rocks. Cobalt is concentrated to economic grade in some lateritic soils developed on serpentinized peridotite and other ultramafic rocks. A good summary of the geology of a large number of cobalt deposits is given by Vhay (1952, p. VI-5 to VI–54).

The Centre d'Information du Cobalt (1960, p. 1–7) has summarized the history of cobalt since its use in ancient Persia and Egypt. From the 16th century until 1874, cobalt was produced chiefly in Norway, Sweden, Saxony, and Hungary. The lateritic cobalt ores from New Caledonia were the main source of cobalt from 1874 until 1904 and thereafter the silver-cobalt-arsenic veins of Ontario, Canada, provided virtually all of the world's supply. Extraction of cobalt from the copper ore deposits of Katanga, Belgian Congo (now Republic of the Congo) began in 1924 and since 1940 Union Miniére du Haut-Katanga has been the largest producer of cobalt in the world. Other major cobalt producers are Canada, Morocco, and Northern Rhodesia.

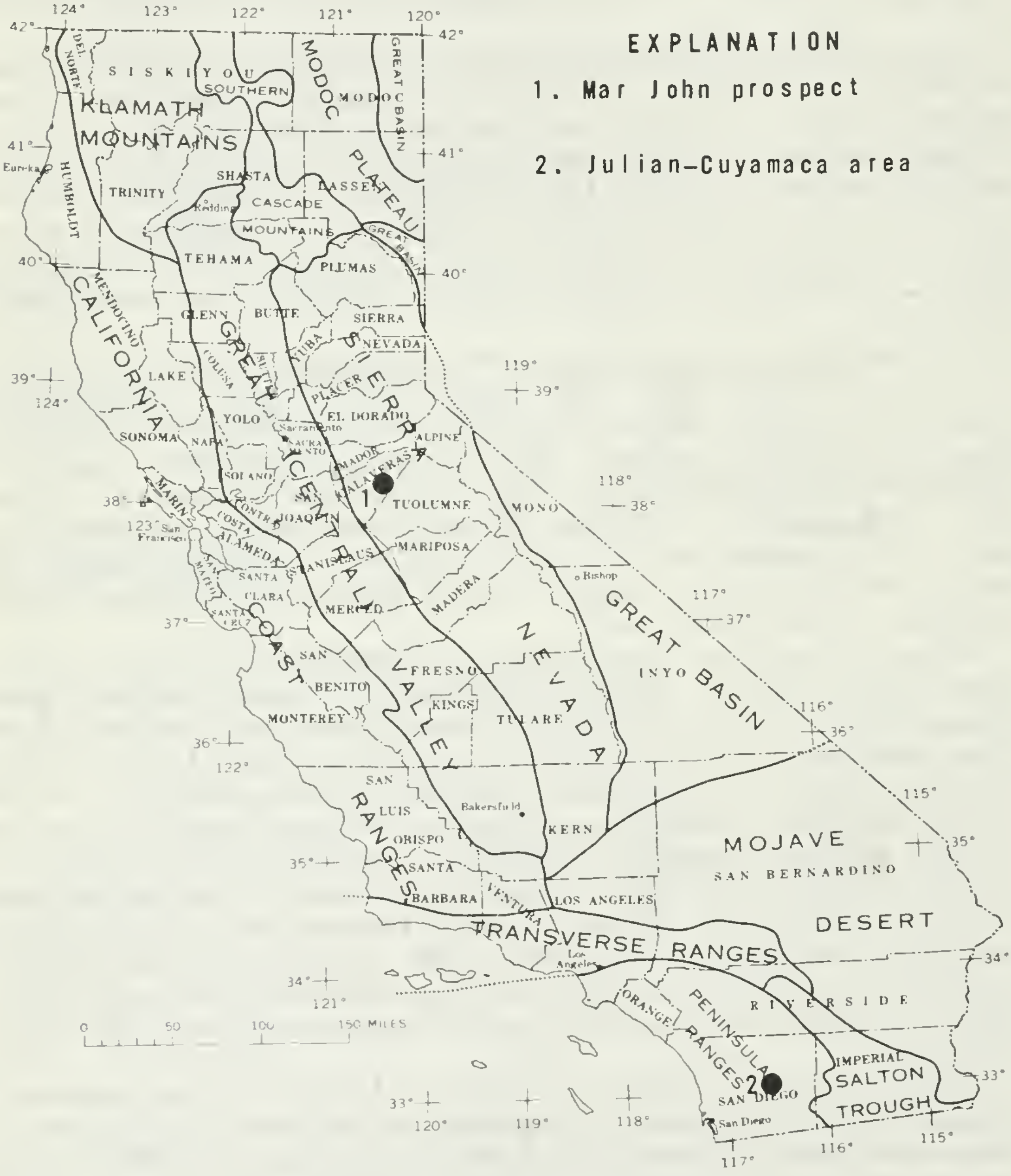

FIGURE 18. Cobalt in California.

The Bethlehem Cornwall Corp. has recovered cobalt from pyrite associated with the Cornwall, Pennsylvania, magnetite ore since 1940, and in 1963 was the only domestic producer mining cobalt (Ware, 1964, p. 1). From 1952 to 1959, the Calera Mining Co. produced cobalt from the Blackbird district of Idaho. The National Lead Co. recovered cobalt at Fredericktown, Missouri, from 1955 to 1961.

Minor occurrences of cobalt-bearing minerals have been reported from numerous localities in California (Murdoch and Webb, 1956, p. 52, 60–61, 76, 123, 146, 260–262, 301; 1960, p. 11, 13–14, 19), but there has been no commercial production of cobalt in the State. A few tons of cobalt ore were mined at the Mar John property (fig. 18) in Calaveras County in 1924 but were not marketed (Chesterman, 1956, p. 165). A list of California occurrences of cobalt is given by Vhay (1952, p. VI–38, VI–39, VI–54) but most of them are very small deposits. Any future production of cobalt in California would undoubtedly be as a by-product in the mining of copper, nickel, or iron ore. The areas with most potential are the copper deposits of the Foothill Copper Belt of the Sierra Nevada and the Friday nickel deposit, Julian-Cuyamaca area, San Diego County.

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COPPER

(By A. Robert Kinkel, U.S. Bureau of Mines, San Francisco, Calif., and Arthur R. Kinkel, Jr., U.S. Geological Survey, Washington, D.C.)

Copper is one of the most versatile and widely used metals. Its superior electrical conductivity and alloying characteristics are responsible for its importance in the industrial economy. About half of all copper consumed is for electrical applications and about 40 percent is used for alloy manufacture, largely brass. The automotive industry uses 30 to 40 pounds per vehicle and accounts for about 9 percent of the copper consumed in the United States. In addition to its role in copper-base alloys (brass and bronze), copper is an important constituent of a large number of alloys having a metal other than copper as the principal component (McMahon, 1965).

The world is adequately endowed with sources of copper. New discoveries and extensions of mines in many copper provinces of the world during the 1950's greatly increased the known world copper resources. In addition to the primary sources of copper metal, a large reserve of secondary copper (scrap) has been accumulated and is continually being augmented. The collection and processing of this scrap into secondary metal constitutes an important segment of the copper industry in all major consuming countries.

Since World War II there has been considerable change in copper mining technique. In 1939, when the average copper ore mined contained 1.29 percent copper, 59 percent of the copper output came from open-pit mines. In 1963, when the average ore mined contained 0.74 percent copper, 81 percent of the ore was from open-pit mines. The trend is toward very large, but low-grade deposits that can be mined by highly mechanized methods, and thus at low cost. Most California copper deposits have been medium sized to small deposits that require underground mining, and thus are less favorable for mining unless the grade of the ore is high.

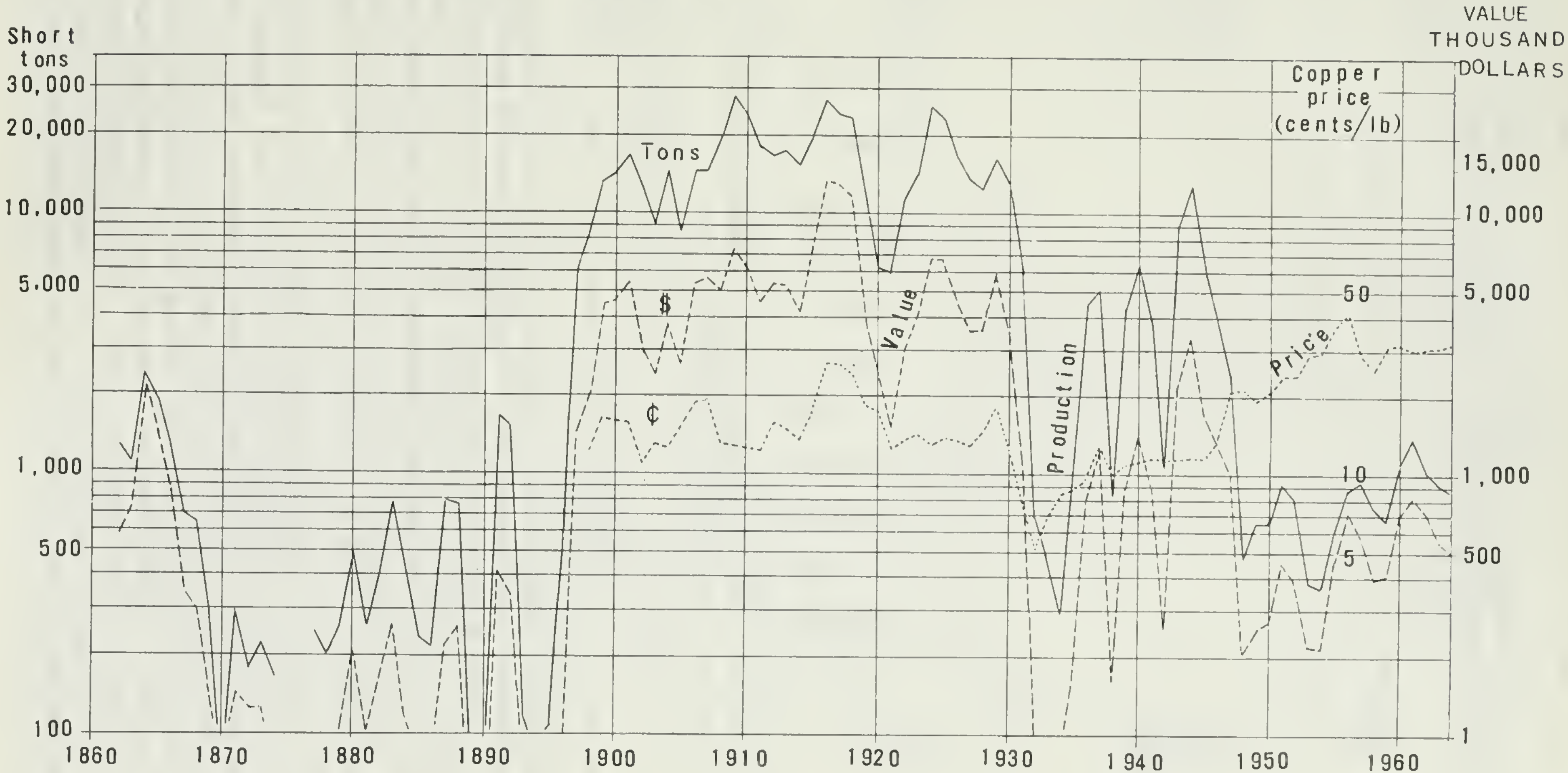
California's copper production has been an important economic asset in the past, although it was moderate by national standards. California accounted for over 15 percent of the national total, from 1862 to 1866, and for over 5 percent in 1867–1868, 1901 and 1909. During years of peak copper production (1909, 1916, and 1924), the State accounted for about 3 percent of the national total. During 1906–1918 the value of the State's copper output exceeded $10 million annually (see fig. 19).

The principal copper deposits of California occur in five areas. These are: 1) the counties of the northern Coast Ranges; 2) Shasta County; 3) Plumas County; 4) the Foothill copper belt, which extends from Butte County south to Fresno County; and 5) the southern counties of Inyo, San Bernardino, San Diego, and Imperial. By far the largest part of the copper produced in California has been from massive pyrite-type ores. Silver and gold are the major byproducts of California copper ores. Sulfur and iron from pyritic copper ores could be produced if economic conditions were favorable.

History and Production

The mining history of California began with the discovery of gold in 1848, although copper had been produced previously from a few small deposits in Los Angeles County. Exploration following the discovery of gold resulted in the discovery of many base-metal deposits, and copper production began in Calaveras County in 1862, and soon after in Amador County. Mines of Calaveras County eventually became the largest producers in the 250-mile-long Foothill copper belt. Production from this belt virtually ceased during 1868–1881, for the gold and silver content of the surface-enriched ores decreased on reaching the primary sulfide zone and would no longer support the cost of shipping the ore to smelters in Wales. During the early 1880's production was revived in the Foothill belt for a short period, and between 1902 and 1960 there was almost continual, although small, production from one or more mines along the belt. Foothill belt production was 4,700 tons of copper in 1917, a level not approached in later years (see fig. 20).

Copper was discovered in Plumas County shortly after production began in the Foothill belt and small amounts were produced inter-



Source: U.S. Bureau of Mines, San Francisco 5/65

FIGURE 19. Copper production in California, 1862–1964.

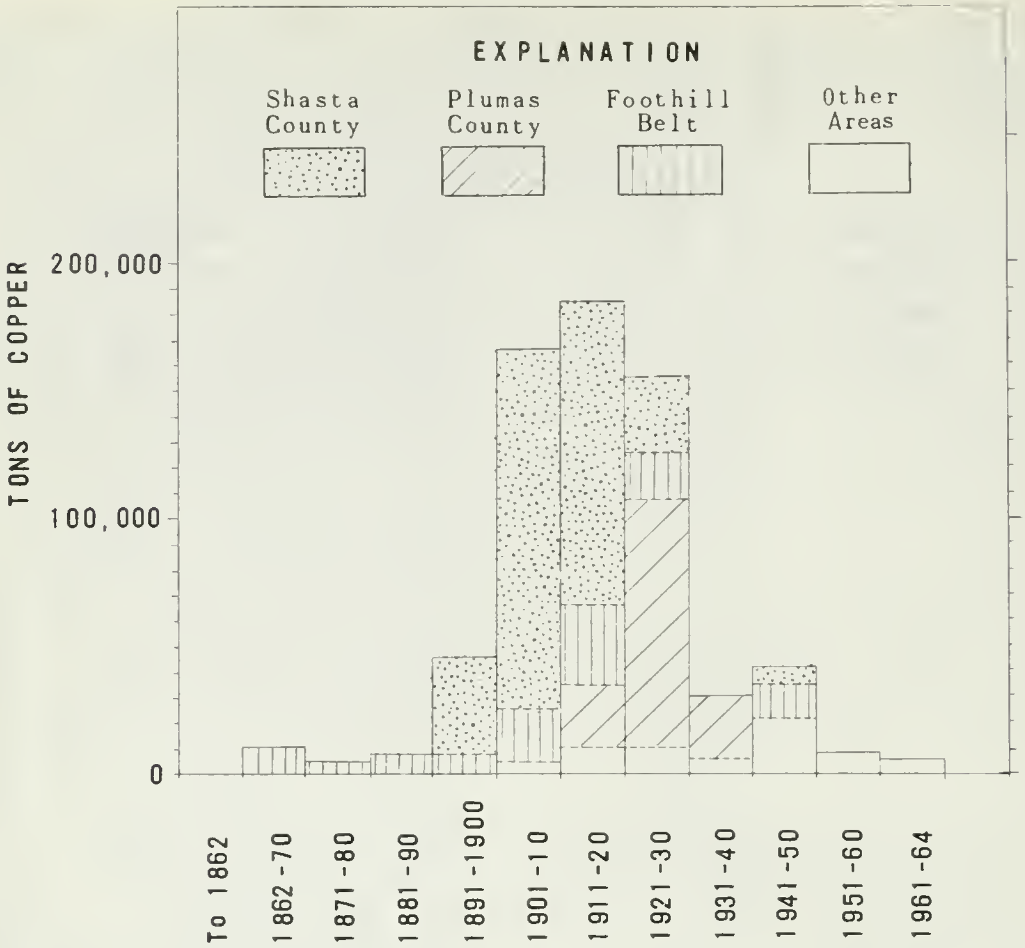


FIGURE 20. California copper production by decades, 1862–1964, showing production of major districts.

mittently from 1865 to 1869. The first significant production began in 1914, and by 1925 output reached 13,500 tons of copper. Copper mining virtually ceased in Plumas County after 1941 when the Walker mine (No. 21, fig. 21) was closed.

The East and West Shasta districts (Nos. 10 and 11) did not begin copper production until about 1894 but by 1896 were the principal source of copper. A peak production of 25,000 tons was attained in 1909. Mines of the East and West Shasta districts produced a total of slightly over 10,000 tons annually between 1906 and 1918 from local smelters. With the exception of the period 1924–1929 and a short period during World War II, production rates have not since been significant.

Copper production in other areas of the State has been relatively small. Minor copper was produced in the northern Coast Ranges (in Del Norte, Humboldt, Siskiyou, and Trinity Counties) in the 1860's and 1870's, but reached significant proportions from Siskiyou and Trinity Counties from 1915 and 1930 and again in Siskiyou County from 1943 to 1945. Small tonnages were produced periodically from central and southern Coast Range counties. Pyrite mines in Alameda County (No. 60) have a reported output of 284,000 tons of copper-bearing pyrite from 1901 to 1925; this ore was mined mainly for sulfur but it probably contained about 4,000 tons of copper, part of which was recovered.

The bulk of the copper in California was produced during 1891–1930 as shown in table 15 and figure 20. The significance of Shasta, Plumas, and the Foothill belt counties production is shown on figure 20 and table 15.

TABLE 15.—*Copper production in California, 1862–1964*

BY YEARS

Years	Short tons	Thousands of dollars
1862–90	15, 700	8, 900
1891–1930	542, 600	176, 300
1931–60	78, 700	22, 400
1961–64	4, 400	2, 600
Total	641, 300	210, 100

BY COUNTIES

County	Short tons	Percent of State total
Shasta	335, 500	53
Plumas	162, 700	25
Foothill belt counties	81, 000	13
Northern Coast Range counties	21, 800	3
Others	40. 300	6
Total	641, 300	

Since the mid-1950's the bulk of the copper produced has been obtained as a by-product in processing tungsten ore at the Pine Creek mine (No. 62), Inyo County and from numerous polymetallic mines in Inyo and San Bernardino Counties. The principal localities are listed in table 16.

SHASTA DISTRICT

The East and West Shasta districts account for about 53 percent of the copper produced in California. Nine mines produced copper in the West Shasta district and three in the East Shasta district. In both districts the large copper- and zinc-bearing massive pyrite deposits contain minor gold and silver. Ore bodies in the West Shasta district are generally large flat-lying lenses essentially concordant with bedding in felsic volcanic flows and pyroclastic rocks of Devonian age (Kinkel, Hall and Albers, 1956). Ore bodies in the East Shasta district are smaller, steeply dipping, and are lenticular to vein-like or tabular (Albers and Robertson, 1961). They are also essentially concordant with foliation and generally with bedding in felsic volcanic flows and pyroclastic rocks of Triassic age. In both areas the ores are in the uppermost parts of thick piles of submarine volcanic rocks which are overlain by argillic marine sediments. The rocks in both areas are moderately folded and metamorphosed, and locally they are strongly sheared.

Ore in the West Shasta area is mainly massive pyrite that contains several percent copper in parts of the ore but less than half of one percent copper in other parts. Some of the ore was mined mainly for its sulfur content. Zinc is erratically distributed, but some of the ore contains more than 10 percent zinc. The ores generally have a zinc: copper ratio of about 2:1, but most of the zinc was not recovered. Cadmium occurs in appreciable quantities but was not recovered. Insoluble material, mainly quartz and sericite, ranges from 3 to 5 percent in most of the ore. Ore in the East Shasta district is also a massive pyritic zinc-copper ore that contains minor gold, silver, galena, and tetrahedrite, and has a gangue of barite, quartz, sericite, and anhydrite. Ore bodies of the East Shasta district are generally smaller than those of the West Shasta district but are of higher grade.

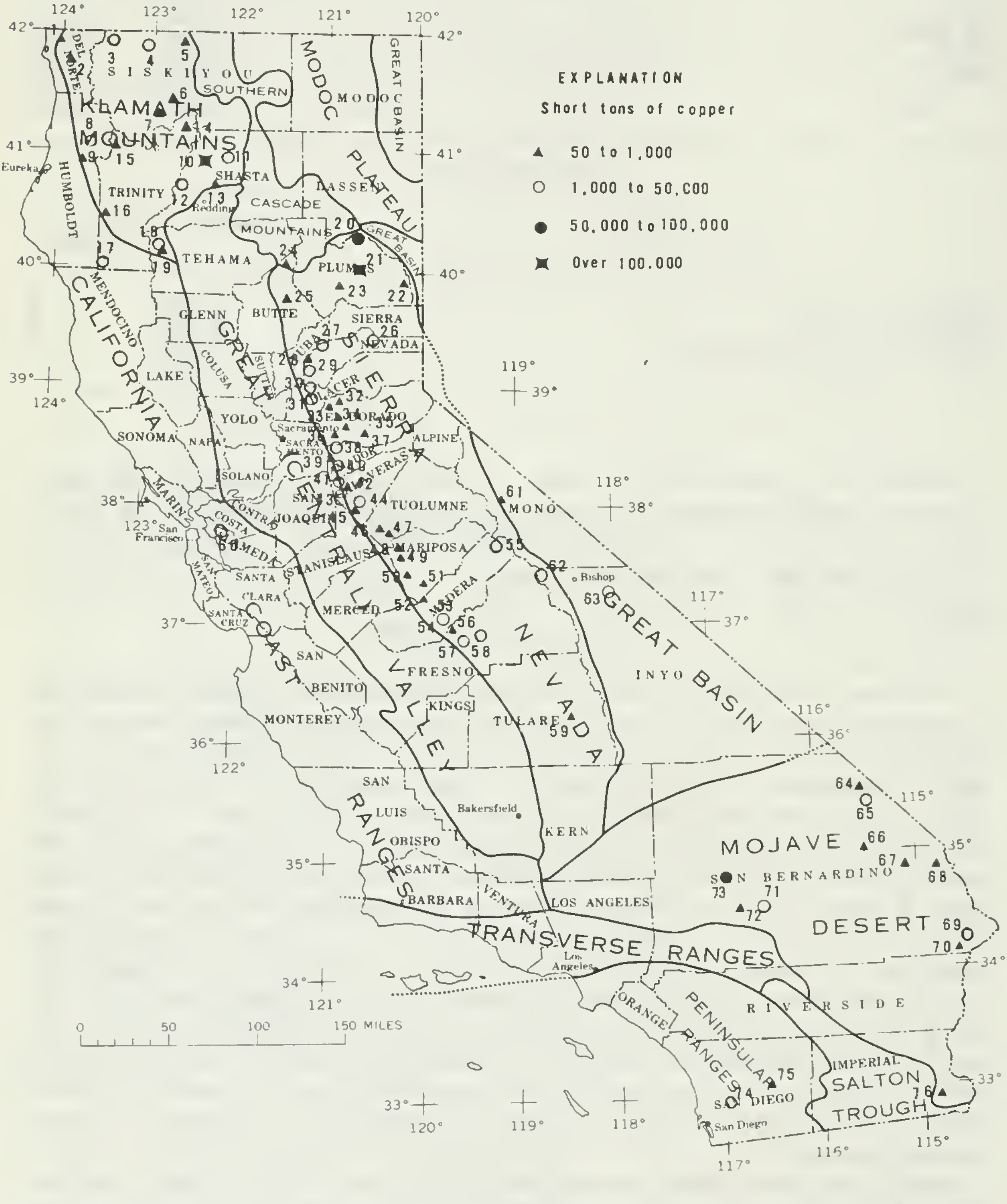


FIGURE 21. Principal copper localities in California by size categories based on production plus metal remaining in the deposits (numbers refer to table 16).

TABLE 16.—*Principal copper localities in California*

County	Index No.	District or mine
Del Norte	1	Wimer District.
	2	French Hill District.
Siskiyou	3	Gray Eagle Mine.
	4	Blue Ledge Mine.
	5	Klamath River District.
	6	Scott River District.
	7	Do.
Humboldt	8	Copper Bluff Mine.
	9	Horse Mountain District.
Shasta	10	West Shasta District.
	11	East Shasta District.
	12	French Gulch District.
	13	Redding District.
Trinity	14	Minersville District.
	15	New River District.
	16	Mad River District.
	17	Island Mountain Mine.
Tehama	18	Tom Head District.
	19	Colyear Springs District.
Plumas	20	Lights Creek District.
	21	Genesee District.
	22	Red Rock District.
	23	Saw Pit Flat District.
Butte	24	Inskip District.
	25	Big Bend Mine.
Nevada	26	Meadow Lake District.
	27	Foothill Belt, Boss-San Juan Mine.
	28	Foothill Belt, Mineral Hill Group.
	29	Foothill Belt, Spenceville Mine.
Placer	30	Foothill Belt, Dairy Farm Mine.
	31	Foothill Belt, Valley View Mine.
El Dorado	32	Foothill Belt, El Dorado Copper Mine.
	33	Foothill Belt, Lilyama Mine.
	34	Foothill Belt, Funnybug Mine.
	35	Foothill Belt, Noonday Mine.
	36	Foothill Belt, Cosumnes Copper Mine.
	37	Foothill Belt, Big Canyon Mine.
Amador	38	Foothill Belt, Copper Hill Mine.
	39	Foothill Belt, Ione Copper Mine.
	40	Foothill Belt, Newton Mine.
Calaveras	41	Foothill Belt, Penn Mine.
	42	Foothill Belt, Nassau Mine.
	43	Foothill Belt, Quail Hill Mine.
	44	Foothill Belt, Copperopolis Group.
	45	Foothill Belt, Napoleon, Collier Mines.
Tuolumne	46	Foothill Belt, Oak Hill Mine.
	47	Foothill Belt, Salambo Mine.
Mariposa	48	Foothill Belt, La Victoria Mine.
	49	Foothill Belt, Blue Moon Mine.
	50	Foothill Belt, Pocahontas.
	51	Foothill Belt, Green Mountain Group.
Madera	52	Foothill Belt, Buchanan Mine.
	53	Foothill Belt, Jesse Belle, Daulton Mines.
	54	Foothill Belt, Krohn Mine.
	55	Minarets District.
Fresno	56	Foothill Belt, Painter Mine.
	57	Foothill Belt, Fresno Copper Mine.
	58	Foothill Belt, Copper King Mine.
Tulare	59	Camp Wishon District.
Alameda	60	Alma, Leona Mines.
Mono	61	Lundy District.
Inyo	62	Pine Creek Mine.
	63	Loretto Mine.
San Bernardino	64	Clark Mountains District.
	65	Ivanpah Mountains District.
	66	Providence District.
	67	Signal District.
	68	Needles District.
	69	Whipple Mountains District.
	70	Turtle Mountains District.
	71	Buckeye District.
	72	Fry Mountains District.
	73	Ord Mountain District.
San Diego	74	Ramona District.
	75	Julian District.
Imperial	76	Ogilby District.

Lights Creek and Genesee districts

Plumas County contains three major deposits and numerous small deposits. At the Engels and the Superior mines in Lights Creek district (No. 20) the ore occurs as steeply dipping replacement veins and stockworks in granitic rock. Sulfides are mainly bornite and chalcocite (Anderson, 1931). At the Walker mine in the Genesee district the ore occurs as seams, stockworks, and disseminations of chalcopyrite, chalcocite, and pyrrhotite in schistose rocks (Knopf, 1935). The Engels and Superior mines were closed in 1930 and the Walker mine in 1941.

Foothill copper belt

The Foothill copper belt extends along the west flank of the Sierra Nevada batholith. At least 40 copper-zinc mines have been operated along this narrow 250-mile-long belt but only a few have produced large amounts of copper and zinc. The Foothill belt contains folded and metamorphosed sedimentary and volcanic rocks of Paleozoic and Jurassic age (Heyl, 1948). Along the ore zone the rocks are interbedded felsic and mafic volcanics and related pyroclastic rocks and intrusives, and marine shales that are in part altered to slate. The degree of metamorphism is variable but generally increases toward the south along the belt. Most ore bodies appear to be in the upper part of a thick, partly submarine, volcanic pile, the Amador Group of Middle and Late Jurassic age, which is overlain by the Mariposa Slate of Late Jurassic age.

In the Foothill copper belt the ores are massive sulfide made up mainly of pyrite; they contain chalcopyrite and sphalerite and small amounts of gold and silver. The sparse gangue minerals are quartz, barite, sericite, and chlorite. Ore occurs as steeply dipping lenticular or tabular bodies in siliceous, sericitic, and pyritic zones, and ore bodies are peneconcordant with both schistosity and bedding. In the southern part of the belt where the metamorphism is of higher grade along the ore zone as in Madera and Fresno Counties, pyrrhotite is more common and in places exceeds pyrite in abundance. Some deposits contain minor galena, tetrahedrite, bornite, and cobalt. At the Jesse Belle mine (No. 53) in Madera County part of the ore contained up to 0.3 percent cobalt.

The Penn mine (No. 41) is the largest copper-zinc deposit in the Foothill belt. Individual ore lenses at this mine have a steep pitch-length of as much as 1,000 feet, a breadth from 100 to 400 feet, and a thickness of as much as 30 feet. This mine has produced about 40,000 tons of copper and over 6,000 tons of zinc. Zinc exceeds copper in the ore but was not recovered during most of the period of operation (Heyl, Cox, and Eric, 1948).

The eastern part of the Foothill belt (locally known as the East belt) contains many small but rich vein and replacement deposits of bornite and chalcocite in metamorphic and igneous rocks, generally in a quartz gangue.

Other districts

The southernmost copper districts are in Inyo, San Bernardino, San Diego, and Imperial Counties, which lie within the Basin and Range province. This province is characterized by a thick accumulation of Paleozoic carbonate rocks with interbedded slates and quartzites; these are block faulted. The mineral deposits occur as veins and replacement deposits of complex lead-zinc-copper ores in carbonate rocks. In the western and southern parts of the area, intrusive and metamorphic rocks become increasingly common with little change in the mineralization apart from increasing gold content in the western deposits and copper in the southern deposits.

Several copper deposits in the northern Coast Ranges have been important producers in the past. Deposits occur largely as vein, replacement, and disseminated deposits in folded and faulted sedimentary rocks and in felsic and mafic volcanic rocks. Chalcopyrite, chalcocite, or bornite, with variable amounts of sphalerite, are the common minerals. The deposit of massive cupriferous pyrite at Island Mountain (No. 17), Trinity County, has been one of the largest producers of copper in the area (Averill, 1941). Native copper is reported in small amounts throughout the Coast Ranges. The only significant sulfide producers in the southern part of the Coast Ranges have been the Alma and Leona deposits of copper-bearing massive pyrite in Alameda County (Davis, 1950).

Reserves and Potential Resources

A number of inactive copper deposits in California are known to contain sufficient ore to support moderate production rates for several years. These resources are small by national standards, and many deposits would be difficult to mine under present economic conditions because of the cost of mine rehabilitation, transportation, and other factors. The resource potential of copper in California lies in undiscovered ore bodies in a number of areas that are favorable for exploration with modern techniques.

Known or reasonably assured copper resources are mainly in five areas. These are: 1) Shasta County; 2) Foothill copper belt; 3) Plumas County; 4) northern Coast Ranges; and 5) Minarets district. The known copper resources of California total about 470,000 tons of copper.

Practically all of the copper mined in California has come from deposits that were exposed at the surface. There are geologic reasons for believing that undiscovered ore bodies should be present in a number of areas, and based on past production, these should be of sufficiently high grade to warrant mining. Ore bodies in two of the most productive areas, the Shasta district and the Foothill belt, are not marked by broad alteration halos or other features that give surface clues to the presence of ore that may exist a short distance beneath the surface. Exploration for subsurface ore bodies can be limited to certain zones or horizons by geologic study that will give information on the processes of ore deposition, but this must be followed by the geophysical and geochemical techniques that have been developed so rapidly in the past decade but have not yet been applied in most of these areas. Past production and geology of the Shasta, Foothill, and other promising areas suggest that many copper ore bodies will still be discovered in California.

Technical and Marketing Problems

Almost all of California's copper has come from underground mines. Those in the Shasta area are in rocks that generally allow open unsupported stopes, but some support of the walls is generally required in the steep ore bodies in schistose rock along the Foothill belt. Principal deterrents to mining are the generally small size of the ore bodies except for a few in the West Shasta district, the fine grinding required by many of the massive pyritic ores, and high transportation costs to smelters. Discovery of adequate reserves would encourage the establishment of centrally located mills, although antipollution requirements discourage local smelting.

Many treatment and marketing problems are encountered by prospective copper producers in California. Although California is a major consumer of copper products, the market for rolled, shaped, or alloyed products is now supplied by imports or from secondary sources. The nearest copper smelters treating non-company ores and concentrates are at Tacoma (Washington), Anaconda (Montana), Hayden, Superior, and Douglas (Arizona). The freight rates to any of these plants from California deposits are prohibitive for all but the higher grade ores.

An increasingly serious problem confronting all mining enterprises is the reluctance of State and Federal agencies to look favorably on any enterprise which might impair the esthetic value of possible recreational and scenic areas. Antipollution legislation will continue to be important economically in California mining. These factors all increase the cost of mining, but none would be prohibitive if reserves of adequate size and grade could be found.

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DIATOMITE

(By G. B. Cleveland, California Division of Mines and Geology, Los Angeles, Calif.)

Diatomite (Kieselguhr) is the commercial name for a unique sedimentary rock called diatomaceous earth. This rock consists almost wholly of fine-grained particles of an inert form of silica, similar chemically to the mineral opal. The particles range in size generally from a few to a few hundred microns; each particle is essentially flat, commonly perforated, and all the particles are loosely packed to yield a highly porous and permeable material. This combination of properties makes diatomite an efficient medium for the rapid filtration of industrial solutions. Filtration has been the principal use of diatomite, and, in 1965, this use accounted for about half of the United States production; about one-fourth was consumed as fillers, one-twentieth for heat and sound insulation, and the balance distributed among some of the three hundred known uses, such as absorbents, lightweight aggregate, pozzolan, abrasives, pesticide carriers, and ceramics.

GEOLOGY

Diatomaceous earth is an accumulation of fossils. The fossils are mainly of diatoms, a class of minute plants that live in water; unlike most terrestrial plants, they are simple, one-celled form of largely floating (plankton) organisms. The shape and ornamentation of the diatom shell (frustule), which is the most diverse imaginable, is the main basis for separating the many thousands of species known. Being aquatic, diatoms occur in waters throughout the world, but their remains accumulate as diatomaceous earth only in ocean or lake basins where ecologic conditions support enormous numbers of individuals. Cool, clear, well-lighted water promotes the growth of diatoms, but more important is a constant source of chemical nutrients to replenish those taken out of solution during the growth of the diatom community.

The principal lacustrine deposits of the State all lie in volcanic terranes, and the common association of volcanic ash with diatomaceous earth in both marine and lacustrine strata is well established. Volcanic processes appear to play a significant part in the formation of diatomaceous earth, and this relationship can best be demonstrated for deposits of lacustrine origin and near-shore deposits of marine origin. During volcanic episodes, established drainage systems commonly are dammed by lava flows, and new basins may be created atop the flows themselves; these may ultimately fill with water and form lakes. Lakes, being infinitely smaller systems than oceans, are much more sensitive to slight chemical and physical changes. Chemical nutrients essential to diatom growth are not readily supplied to streams feeding lake waters during normal weathering and erosion. However, solutions, and emanations accompanying volcanism, and ranging widely in chemical composition and concentration, may be introduced into lake waters, enriching them in those elements necessary for diatom growth. Chief among these elements is silica which the diatom uses in building its shell. Silica is presumed to be supplied both by silica-rich hydrothermal solutions and by the chemical breakdown of volcanic ash. Ash deposited directly into a lake breaks down chemically and provides a ready source of silica, while a long-term supply is derived from subaerially deposited ash, which is carried by streams into the lake basin during subsequent erosion of adjacent highlands. Among the several other elements required by diatoms, the concentration of nitrogen and phosphorus is considered a limiting factor in diatom growth because of the relative paucity of these elements in lake and ocean water.

Recent work has shown that the volcanic environment is not a requisite for the formation of thick marine diatomaceous sediments. Studies indicate that, in the Gulf of California, the concentration of silica, and presumably other nutrients, is replenished periodically and diatoms flourish. The subsequently formed sediments are of purity comparable to those of California's principal commercial diatomite deposits. The nature of diatomaceous earth formed in a marine environment differs somewhat from that formed in a lacustrine environment. Generally, each habitat supports a diatom flora indigenous to it, and relatively few diatoms flourish in both marine and lacustrine waters. Moreover, marine deposits generally comprise a wider variety of species. An individual deposit of either marine or lacustrine origin may have an advantage over the other type in certain commercial applications, but suitable material from both kinds of deposits has been successfully processed for all the principal uses. Generally, the marine deposits have proven to be a more abundant and versatile source of material for a wider range of applications than have those of lacustrine origin.

Diatomaceous earth is light colored, generally gray to white, but commonly ivory, pale pink, pale green, yellowish-brown, or dark brown. Diatomaceous earth, being composed principally of opaline-like silica ($SiO_2 \cdot nH_2O$), is a relatively inert rock soluble only in strong acids or alkalies. Commonly clay and volcanic ash are main impurities, with some silica sand, calcium or magnesium carbonates, and iron oxides or iron carbonates present. The pH ranges from about 4.5 to 8. The natural moisture content is generally high, ranging commonly above 50 percent in commercial deposits. The specific gravity of opal ranges from 1.8 to .25. However, because of the porosity of the individual diatom shell and the degree of compaction, the apparent specific gravity of dry unconsolidated diatomaceous earth ranges from 0.12 to 0.25, and dry consolidated material has a specific gravity of about 0.4. The porosity of commercial diatomaceous earth ranges from 75 to 85 percent. The combined water (about 6 percent) is driven off between 500° and 800°C and the melting point is reached between 1,400° and 1,600°C; however, earths containing certain impurities may melt well below 1,400°C. Specifications for commercial diatomite (largely filter use) emphasize particle-size distribution and species of diatoms (shapes and sizes), as well as density and physical state, with chemical purity generally a secondary consideration.

History of Development

The commercial value of diatomite was not recognized until the late 1880's, when a small amount was mined from the deposits at Lompoc for building stone; in 1889, production records show that 39 tons of diatomite were mined from deposits near Calistoga in Napa County. During the early 1900's, only a few hundred tons were mined annually in California, but the material was being tested for several uses, such as heat insulation and refining of beet sugar. The latter use bacame the foundation of the modern diatomite industry, and filter application has been a prime consideration in the evaluation of any diatomaceous earth deposit planned for large scale exploitation. The Lompoc deposits were being actively developed at the turn of the century, and, beginning in 1904, the deposits in Monterey County were developed. At the time of World War I, California's annual production had reached about 13,000 tons.

The diatomite industry developed rapidly after World War I, from an important statewide industry to one of national and even international significance. The Johns-Manville Corp. gained control of a large part of the Lompoc deposits in 1928, and, in 1930, the Dicalite Co. opened the extensive deposits in the Palos Verdes Hills in Los Angeles County. The industry was consolidated by a few large corporations during the 1940's, and, with the stimulus of World War II and industrial expansion since then, a steady rise in both tonnage and average price has been recorded. The Dicalite Co. acquired deposits near Lompoc in 1942, and in 1944, the company was purchased by the Great Lakes Carbon Corp. Mining of diatomite in Monterey County ceased in 1942 after nearly $500,000 worth of material had been produced. The Palos Verdes Hills deposits were abandoned in 1958, when the Great Lakes Carbon Corp. centered all of its production at Lompoc. The Lompoc area since has retained and re-enforced its position as the main world source of diatomite.

PRODUCTION FACTORS

For over 50 years, the United States has been pre-eminent among the countries of the world in the mining and processing of diatomite, and California yields about 80 percent of the approximately 500,000 tons mined annually in the United States. About one-quarter of this tonnage is exported to over 60 countries. Exports go mainly to Europe, but important markets are in the Orient, Australia, and Latin America. Diatomaceous earth deposits occur throughout the world, but only the largest, best suited and best situated deposits can compete in the world market. In recent years this market has expanded and undeveloped deposits near the European, Asian and Latin American consuming centers have taken on new significance. Deposits have been developed or new plants built in France, Mexico, and Yugoslavia, and some interest has been shown in developing deposits in Iceland. Established sources in Brazil, Denmark, France, Germany, Italy, and elsewhere are all contributing a larger share as well. Most significant is the development of the Russian diatomite industry which is estimated to yield nearly 350,000 tons annually, making it second only to the United States.

The United States is the largest consumer of diatomite, and California supplies the major part of this market, with the balance coming from domestic sources, mainly from deposits in Nevada. California production during the last several years has maintained a steady increase in volume and dollar value to meet the increasing demand through industrial growth of both the United States and foreign countries. The value of diatomite production places this commodity among the most important industrial minerals mined in the State.

The annual value in recent years has equaled that of the combined annual values of clay, gold, gypsum, mercury, pumice, and talc. A significant demand exists for diatomite in the manufacturing and agricultural industries of California, but the principal markets lie in central and eastern United States. Although the State possesses large and varied resources, several thousand tons of mainly filler grade material is brought annually into California from deposits in adjacent states.

Occurrences in California

Although diatomaceous strata are accumulating in modern basins, the principal commercial sources of diatomite are from ancient deposits. In California, the oldest marine formation known to contain

FIGURE 22. Regional distribution of diatomaceous earth in California.

diatomaceous earth is the Moreno Formation of Late Cretaceous and Paleocene age, and the earliest diatom-bearing lacustrine strata are those in the upper part (Miocene) of the Cedarville Series. The thickest and purest commercial deposits known in the State were formed during late Miocene and early Pliocene times.

At various times since the Cretaceous Period, diatomaceous earth contributed a significant part of the stratigraphic record in California, and, although much of the older deposits have been chemically altered to dense cherty rocks and great volumes of material have been eroded away, California still possesses widespread resources (table 17). As shown on figure 22, these occur in five geographic regions: Coastal, Great Valley, Modoc Plateau, Channel Islands, and Desert, and minor occurrences are sparsely scattered elsewhere (fig. 22).

TABLE 17.—*Principal formations containing diatomaceous earth in California*

Geologic age	Formation [1] and distribution (shown on fig. 22)			
	Marine	Region	Lacustrine [2]	Region
Recent	--------	--------	Unnamed strata in local basins eastern Siskiyou County and western Modoc County.	3
Pleistocene	--------	--------	Unnamed strata in Mono basin, Long Valley basin (Mono County) and Owens basin(*) and Indian Wells Valley basin (Inyo County).	5
			Unnamed strata in Knight's Ferry area western Tuolumne County; may be upper Pliocene(*).	2
			Unnamed strata in southwestern part of Imperial County; may be Recent.	
			Mohawk Lake Beds (may be Pliocene in part).	3
			Cache Formation (Pliocene or Pleistocene).	1
Pliocene	Unnamed strata at Point Reyes western Marin County.	1	Alturas	3
	Unnamed strata in south-central Monterey County.	1	Sonoma Volcanics(*)	1
	Purisima	1	Coso (Pliocene or Pleistocene)	5
	Foxen	1		
Miocene	Sisquoc (Miocene and Pliocene) (**).	1	Upper part, Cedarville series	3
	Monterey (**)	1, 2, 4		
	Puente	1		
	Modelo	1		
	Maricopa (of former usage)	2		
	Salinas (of former usage)	1		
	Claremont	1		
	Pismo (Miocene and Pliocene)	1		
	Round Mountain	2		
	Unnamed strata on San Clemente Island.	4		
	Unnamed strata on Santa Catalina Island (*).	4		
	Santa Margarita(?)	2		
	Reef Ridge	2		
Eocene	Kreyenhagen (Eocene and Oligocene) (*).	2		
	Markley (Member of Kreyenhagen).	2		
	Kellogg	2		
Tertiary	--------	--------	Unnamed strata in Long Valley area eastern Lassen County (probably upper Pliocene or Pleistocene).	3
Upper Cretaceous.	Moreno	2		

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[1] Known commercial deposits: major sources (**); minor sources (*). Some formations listed are equivalents of each other, notably the Monterey Formation and its local designations; some formation names are no longer in use but appear in the literature.

[2] Numerous diatomaceous earth deposits of the lacustrine type occur throughout the Modoc Plateau Region (3). These deposits have not been studied and no geologic age or formation assignment has been made; they probably range in age from Miocene to Recent.

Coastal region

The coastal counties, from Lake southward to Orange, form a broad belt from which nearly all of the diatomite has been produced in California. The marine Sisquoc and Monterey Formations have yielded by far the greatest tonnages, with minor production from the lacustrine part of the Sonoma Volcanics. The principal deposits occur near Lompoc, in Santa Barbara County; at Bradley and Monterey, in Monterey County; and on the Palos Verdes Peninsula in Los Angeles County. Other diatomite deposits occur south of Morro Bay in San Luis Obispo County; on the north and south slopes of the Santa Monica Mountains and in the Puente Hills, in Ventura and Los Angeles Counties; near Santa Ana and San Juan Capistrano in Orange County; and in southern Napa and Sonoma Counties.

The Lompoc deposits are believed to be the largest source of diatomite currently being exploited in the world. The diatomite occurs as gently folded strata in isolated patches in the northern hills of the western Santa Ynez Mountains south of Lompoc, and in the Purisima, Casmalia, and Solomon Hills, north of Lompoc. In these areas the diatomaceous earth is in the upper part of the Monterey Formation and lower part of the Sisquoc Formation, and is many hundreds of feet thick. However, most of this contains too much clay and other impurities for industrial use. Only certain selected strata a few feet or few tens of feet thick that meet commercial specifications are quarried for industrial use. The aggregate thickness of the commercial diatomite may be several hundred feet.

The two principal companies operating in this area, the Johns-Manville Products Corp., which with its predecessors pioneered the development of the Lompoc deposits, and the Dicalite Division of Great Lakes Carbon Corp., mine from several extensive quarries in the hills south of Lompoc. On the north side of the Lompoc Valley, Diatomic Chemical Co. mines and processes diatomite, mainly for absorbents. North of the Lompoc Valley, in the Casmalia Hills bituminous diatomaceous shale is mined for lightweight aggregate and pozzolan by the Airox Co. This material is calcined by simple burning, utilizing the natural oil in the rock as a fuel. Numerous other deposits of possible commercial grade occur in the Lompoc area but these have been mined only intermittently. The Basalt Rock Co., Inc. in recent years has mined diatomite from the Sonoma Volcanics of Pliocene age in southern Napa County.

Great Valley region

Thick sequences of diatomaceous earth, that range in age from Late Cretaceous through late Miocene occur along the western edge of the San Joaquin Valley, from the Mount Diablo area in Contra Costa County southeastward into Kern County. The main deposits are in the Moreno Formation of Late Cretaceous and Paleocene age, Kreyenhagen Formation of Eocene and Oligocene age and the probable northern extensions of the Kreyenhagen, the Markley Member. Other sources several hundred feet thick are in the Monterey and Reef Ridge Formations of Miocene age. These diatomaceous strata commonly extend for several miles along the west margin of the valley and dip gently to steeply east. Locally, the material is light colored and nearly pure, but, for the most part, is pale tan to brown and considerably contaminated with clay. Exploitation of these sources has been attempted at various times, but no sustained operations have developed nor has any significant volume of material been mined.

Across the valley in the vicinity of Knight's Ferry in southwestern Tuolumne County, occurs a relatively pure, nearly white deposit of diatomite of lacustrine origin, of Pliocene or Pleistocene age. The diatomite layer is at least 15 feet thick. The Pacific Clay Products Co. has mined several thousand tons from this deposit in recent years.

Modoc Plateau

Numerous deposits of diatomaceous earth are scattered throughout the volcanic terrane of northeastern California. These were formed during part of the long volcanic history of this region, which began in early Tertiary time and has continued to the Recent. Contrary to general belief, the deposits in this region are not all capped by volcanic flows; most of them are exposed at the surface or lie below a thin sedimentary cover; only some of the better known deposits are intercalated with flows. The diatomaceous earth beds range from a few feet to a few hundred feet thick, and some deposits occur over tens of square miles. The material commonly is brilliant white and relatively pure, but many deposits are considerably contaminated with volcanic ash.

The evolution of the diatom flora in the various lake basins of this region bears on the nature of the deposits and on the possible commercial suitability of the material. The earliest known deposits are of Miocene age and are comprised commonly of only one species of diatom, *Melosira granulata.* This is a thick-walled form that is not suitable for filter or many other uses. Subsequently, however, various species of diatoms invaded local basins in this region, and the corresponding deposits comprise a more diverse flora. The early Pliocene and Pleistocene deposits may have many tens of species represented, and this material is better suited for many industrial applications.

Some of the better known deposits are near Alturas, in Modoc County; along Willow Creek near Dorris, in Siskiyou County; around the shores of Lake Britton, and along Hat Creek in Shasta County. Numerous other localities are known, and many more probable occurrences are suggested by geologic maps. The Modoc Plateau region offers the best place for locating new sources of diatomite in California.

Channel Islands region

The rocks of the eight Channel Islands are for the most part similar to those of the adjacent coastal area, and diatomaceous earth is known to occur on Santa Catalina, San Clemente, Santa Cruz, and Santa Rosa Islands. Marine(?) diatomaceous earth occurs with upper Miocene andesite east of Isthmus Cove on Santa Catalina Island; unnamed marine strata of middle Miocene age, in part diatomaceous earth, occur south of Wilson Cove and at other places on San Clemente Island; diatomaceous shales of the Monterey Formation are exposed on Santa Rosa and Santa Cruz Islands. Minor production has been recorded from the deposit on Santa Catalina Island.

Desert region

In the eastern desert of California diatomaceous earth was deposited in lakes along an integrated drainage system during Pleistocene time, and in a similar but less known system during Pliocene time. The diatomaceous earth layers in this region are generally less than 10 feet thick; the material is off-white in color, and nearly all of the deposits are contaminated with volcanic ash. Diatomaceous earth is known to occur in several of the Pleistocene basins, of which the principal sources are in Long Valley, Mono County; Owens Valley, from which minor production has been recorded; and Indian Wells Valley, Inyo County. Diatomaceous earth of Pliocene age is intercalated with lacustrine rocks in the Coso Range, Inyo County.

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FELDSPAR

(By F. G. Lesure, U.S. Geological Survey, Washington, D.C.)

Feldspar has been produced in California nearly continuously since prospecting was first reported in 1909 in Monterey and San Diego Counties. More than 70 deposits in 11 counties have been mined or prospected, but production from most of these has been small. Total production from 1910 through 1963 is probably greater than 600,000 long tons of feldspar worth a little more than $4,000,000. From 1909 to 1951 most of the production came from coarse-grained feldspathic pegmatites and amounted to nearly 170,000 tons. Yearly production ranged from less than 1,000 tons in 1910 and 1911 to nearly 15,000 tons in 1928 (Sampson and Tucker, 1931, p. 407; U.S. Bureau of Mines Minerals Yearbooks). In 1952 the Del Monte Properties Co. began recovering feldspar by flotation methods from beach sand in Monterey County. Soon after this the Owens-Illinois Glass Co. also began producing feldspar from an adjacent deposit. Because of this increased production from beach sands California has ranked second after North Carolina in feldspar production since 1957.

MINERALOGY

Feldspar is the general name for a group of aluminum silicate minerals that contain varying amounts of potassium, sodium, or calcium. The feldspars are important rock-forming minerals and constitute nearly 60 percent of many igneous rocks. The principal potassium feldspars are orthoclase and microcline which have the same chemical composition ($KAlSi_3O_8$) but different crystal form. The sodium-calcium feldspars, called plagioclase, form a complete series of minerals that range in all proportions from pure $NaAlSi_3O_8$ (albite) to pure $CaAl_2Si_3O_8$ (anorthite). Natural orthoclase and microcline generally contain 10 to 24 percent $NaAlSi_3O_8$ and plagioclase generally contains 5 to 15 percent $KAlSi_3O_8$. Intergrowths of orthoclase or microcline with albite are called perthite, a common pegmatite mineral. The potassium feldspars and the more soda-rich forms of plagioclase are the types generally mined, but calcium-rich feldspar has been mined from anorthosite bodies in Los Angeles County (Gay and Hoffman, 1954, p. 666).

GEOLOGIC OCCURRENCE

Commercial deposits of feldspar are found in pegmatites, granites and related igneous rocks, and beach sands.

Pegmatites are generally light-colored coarsely crystalline igneous rocks, found as lenticular or tabular bodies in metamorphic rocks or associated with large granitic intrusions. Individual mineral grains range in length from an inch or less to many feet. Feldspar, quartz, and mica are the most common minerals present, but many rare and unusual minerals are found in some deposits. In many pegmatites the minerals are more or less evenly distributed throughout, but in others the minerals are segregated into certain layers or parts of the body called zones. In some pegmatites these zones can be selectively mined to recover the desired minerals by hand sorting and are, therefore, important economically. Until recently most of the feldspar produced in the United States was perthite which is commonly concentrated as very large crystals in certain zones in pegmatite bodies.

Granite and related igneous rocks are composed of one or two kinds of alkalic feldspar and quartz and minor amounts of various other minerals, mainly muscovite, biotite, hornblende, or rarely pyroxene. Deposits range from small masses measured in feet to very large masses measured in miles. Grain size ranges from less than one-fourth inch to an inch or more. Today, deposits of granite that contain only small amounts of ferro-magnesian minerals are mined in bulk and a mixture of potassium and sodium feldspar is recovered by milling and flotation. Beach sands and alluvial deposits rich in feldspar are composed of loose sand grains generally less than one-fourth inch in diameter. Few deposits are rich enough to be worked and only the deposits of Pacific Grove, Monterey County, California, have been worked extensively.

In 1963 about 57 percent of the feldspar used in the United States was from flotation concentrates, 17 percent was from hand sorting, and 16 percent was from feldspar-rich sand (Cooper, 1964, p. 496). In 1957 these figures were 42, 46, and 12 percent, respectively.

Economics and Uses

The average price of crude feldspar was $10.06 per long ton in 1963 and $9.51 in 1960 (Cooper, 1964, p. 495). The average price of ground feldspar was $12.28 per short ton in 1963 and $13.40 in 1960. From 1956 to 1963 about 55 percent of the feldspar sold in the United States was used in glass, 30 percent in pottery, 5 percent in enamel, and 10 percent in other ceramic uses, scouring soaps, and abrasives. Feldspar is used in glass and ceramics as a flux and to impart strength, toughness, and durability to the end product (Castle and Gillson, 1960, p. 360). The glass industry buys feldspar or one of its substitutes as total units of alumina (Al_2O_3) plus potash (K_2O) plus soda (Na_2O). The iron content must be no more than 0.05 percent Fe_2O_3 for most glass grade feldspar, but amber glass may contain up to 0.50 percent. Potassium feldspar is generally preferred in the ceramic industry.

The United States is self-sufficient in feldspar production capacity. There is an increasing shortage of high-grade potassium feldspar but there is an increase in use of lower grade and finer grained materials through milling and flotation. For the past 70 years the United States has been the leading producer and user of feldspar; production in the last few years has averaged 520,000 long tons a year or about one-third world production (Wells, 1965). The largest production comes from North Carolina, California, and Connecticut. Other important producing states include Colorado, Georgia, Maine, New Hampshire, South Dakota, and Virginia. Much of the high-grade potassium feldspar used in California has come from Kingman, Arizona.

In recent years various materials have been used in the glass and ceramic industries as substitutes for feldspar. Chief among these are nepheline syenite, aplite, talc, pyrophyllite, and blast furnace slag (de Polo, 1960, p. 286). Most nepheline syenites contain too much iron oxide for use in glass, but a deposit in Ontario, Canada, that is low in iron is mined extensively. Talc has largely replaced feldspar in wall tile manufacture in California (Wright, 1957, p. 199).

Occurrences in California

Pegmatites containing deposits of feldspar are widely distributed in the southern part of California (Jahns, 1954, p. 42) but only the famous gem-bearing pegmatites of San Diego County have been studied in detail (Jahns and Wright, 1951; Hanley, 1951). Feldspar deposits are particularly abundant in the Peninsular Range province, parts of the southern Sierra Nevada, and the Transverse Ranges as shown on fig. 23 and listed in table 18.

More scattered occurrences are also found in the Great Basin and Mojave Desert provinces. Larger masses of finer grained, feldspar-rich igneous rock which might be sources of flotation feldspar are present but have not been prospected.

The known deposits or occurrences are listed in table 18 (p. 163). Most of these are described briefly by Sampson and Tucker (1931), and the larger deposits are described in more detail by Wright (1957) and Weber (1963, p. 72–82). The largest production in the past few years has come from the dune sands of Pacific Grove, Monterey County, in an area about 6 miles long and 1 mile wide. The sands are composed of 53 percent quartz, 46 percent feldspar, and less than 1 percent other minerals. The largest pegmatite deposit is the Pacific mine, San Diego County, which produced 87,000 tons of feldspar from 1921 to 1943. The only pegmatite deposit worked extensively in recent years, however, is the White Butte deposit of San Bernardino County, mined by Gladding McBean and Co., 1940–1960.

Another type of feldspar occurrence that might become important has been recently described by Sheppard and Gude (1965), who have found that potash feldspar is the major constituent in a fine-grained friable tuff, 1.5 to 4 feet thick, in the Barstow Formation of Miocene age in the central part of the Mud Hills, 10 miles north of Barstow, San Bernardino County. The tuff underlies an area about 1.5 miles long and ¼ mile wide. The material is composed of 87 to 94 percent potash feldspar, a few percent analcime and quartz, and trace amounts of other minerals. Iron content ranges from 0.1 to 1.76 percent Fe_2O_3. Although no tests have yet been made, the material may be a potential source of potash feldspar for ceramics and glass.

Future Outlook

An increasing market for feldspar in California will develop with the continued growth of local glass and pottery industries. The State has abundant resources of feldspar in zoned pegmatites, feldspar-rich granitic rocks, and beach sands, but the feldspar-rich sands of the Pacific Grove area are the principal reserves at this time. The chief merit of zoned pegmatites lies in the benefits of selective small-scale mining confined to a single zone to take full advantage of the enrichment of that zone. Small capital investments by individuals or partnerships are required to enter pegmatite mining. Although most operations are for one mineral, such as feldspar, it is possible to obtain several products, that is, feldspar, quartz, and mica. Recent studies have increased the general knowledge of the occurrence, origin, and economic importance of pegmatite deposits (Cameron and others, 1949; Jahns, 1955), and studies made during World War II have helped improve techniques of prospecting and exploration (Norton and Page, 1956). Renewal of pegmatite mining is hindered by the low cost of the commodity, the smallness of most known deposits, and the lack of custom mills where small operators can sell crude ore

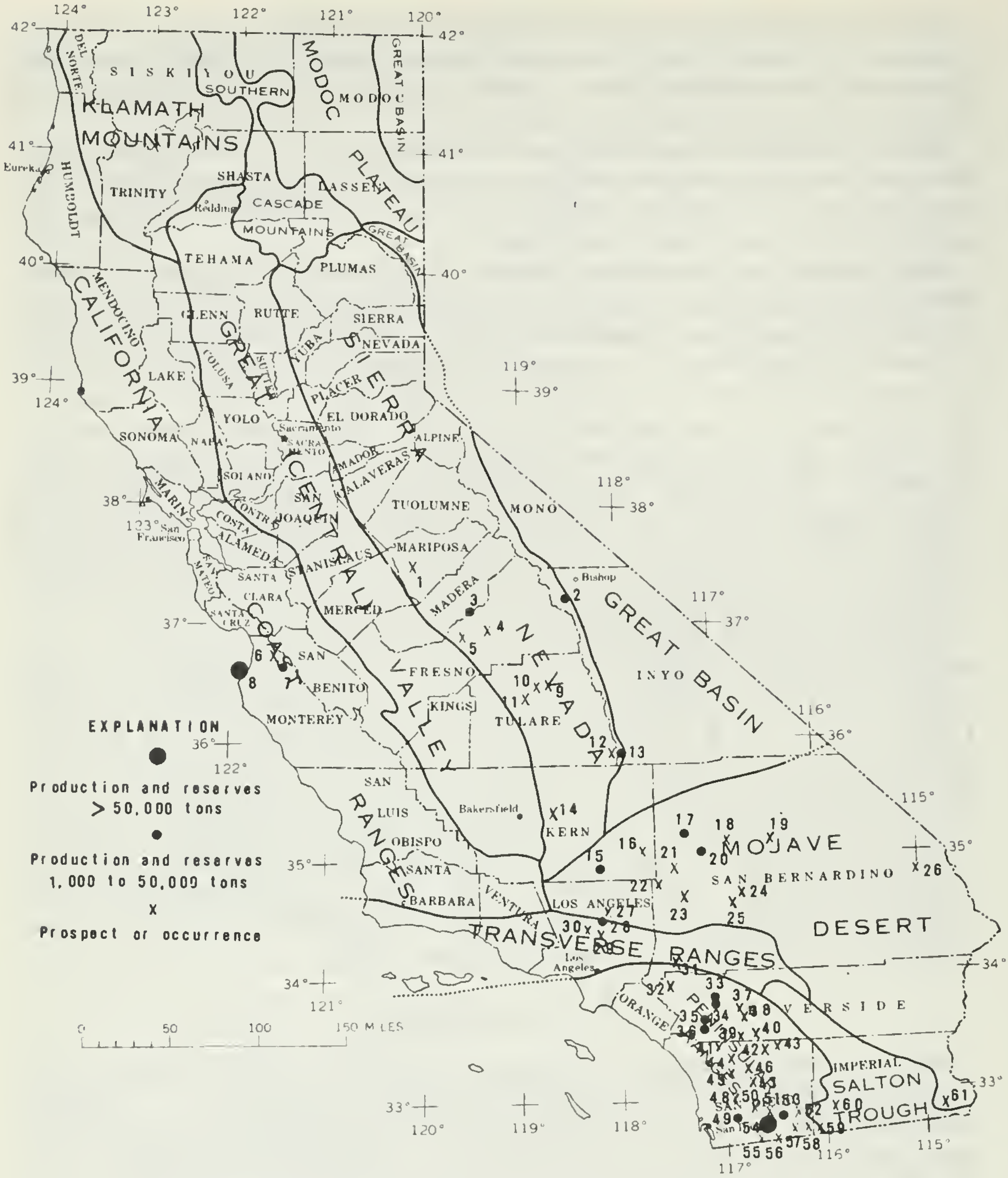

FIGURE 23. Feldspar in California (numbers refer to table 18)

(Wright 1957, p. 199). Recovery of feldspar from granitic rocks is not feasible in California as long as feldspar-rich sands like those at Pacific Grove are available. The recent discovery of potash feldspar in tuff warrants further investigation.

TABLE 18.—*Reported feldspar deposits in California*

Index No. on fig. 23	Deposits	Reference
1	Hamilton	Sampson and Tucker, 1931, pp. 419–420.
2	Nebicite, Sierra White	Norman and Stewart, 1951, pp. 99–100.
3	Childers	Logan and others, 1951, p. 502.
4	Unnamed occurrence	Do.
5	Harrison Stock Farm	Sampson and Tucker, 1931, p. 415.
6	Bardin	Sampson and Tucker, 1931, p. 420.
7	Jens, Johnson Bros	Wright, 1957, p. 197; Sampson and Tucker, 1931, p. 420.
8	Pacific Grove	Messner, 1954, pp. 5–8.
9	Britton Ranch	Sampson and Tucker, 1931, p. 432.
10	Carter, Goodale	Do.
11	Honora Realty Co., Yokohl Valley	Do.
12	White King	Tucker and Sampson, 1938, p. 483.
13	Nine Mile Canyon	Wright, 1957, p. 197.
14	Pegmatite occurrences	Dibblee and Chesterman, 1953, p. 32.
15	Rosamond	Troxel and Morton, 1962, p. 266.
16	Unnamed occurrence	Spurck, 1964, p. 75.
17	White Butte	Wright and others, 1953, p. 165; Wright, 1957, p. 197.
18, 19	Unnamed occurrences	Oesterling and Spurck, 1964, p. 172.
20	Sloan	Sampson and Tucker, 1931, p. 426.
21, 22	Unnamed occurrences	Spurck, 1964, p. 75.
23	Clement and Blackburn	Sampson and Tucker, 1931, p. 426.
24	McKnight Cornishstone	Wright and others, 1953, p. 144.
25	Unnamed occurrence	Oesterling and Spurck, 1964, p. 172.
26	White Rock	Sampson and Tucker, 1931, p. 445.
27	Silica Mining & Products	Gay and Hoffman, 1954, p. 666.
28	Caliproducts, Duncan	Gay and Hoffman, 1954, pp. 525, 665.
29	Gordon	Gay and Hoffman, 1954, p. 665.
30	Chicago-Pacific, Gates Chemical Co., Lambert's Poultry Grits, Stanley Alumina Silicate, Vail.	Gay and Hoffman, 1954, pp. 525, 665–666.
31	Keystone and Lucky Jim	Sampson and Tucker, 1931, p. 426.
32	Stone	Sampson and Tucker, 131, p. 425.
33	Albert Ranch, Brown Ranch, La Borde, Morgan Ranch, Patterson Ranch, Riverside Portland Cement, Tully, Weir Ranch.	Sampson and Tucker, 1931, pp. 420–426.
34	Ensley-Spaulding, K. and K. Ranch, Machado.	Sampson and Tucker, 1931, pp. 422–424.
35	Perris Mining Co	Sampson and Tucker, 1931, pp. 424–425.
36	Murrieta	Sampson and Tucker, 1931, p. 421.
37	Last Chance	Sampson and Tucker, 1931, p. 423.
38	Littlejohn	Do.
39	Lang	Do.
40	Coahuila Brave	Sampson and Tucker, 1931, p. 422.
41	Pala district, Spar King	Jahns and Wright, 1951, p. 51; Tucker and Reed, 1939, p. 37.
42	Lookout, Pearson	Tucker and Reed, 1931, pp. 31, 37.
43	Carlsbad	Weber, 1963, p. 79.
44	Rincon district	Hanley, 1951.
45	Bear, Langer	Weber, 1963, pp. 79, 81.
46	Mesa Grande district, Powers group	Weber, 1963, pp. 82–87.
47	Black Canyon	Weber, 1963, p. 79.
48	Mykrantz	Sampson and Tucker, 1931, p. 430.
49	Hoover, McGinty Mountain	Weber, 1963, pp. 75, 80.
50	Spanish Bayonet	Everhart, 1951, p. 114.
51	Laguna Junction, White Rose	Weber, 1953, p. 80; Sampson and Tucker, 1931, p. 431.
52	Toms Dream	Weber, 1963, p. 83.
53	Buckthorn, Crestline, Gem Spar, Elder	Weber, 1963, p. 79; Wright, 1957, p. 197.
54	Pacific mine	Wright, 1957, pp. 196–198; Weber, 1963, pp. 76–78.
55	Pilz	Sampson and Tucker, 1931, p. 431.
56	Quality	Weber, 1963, p. 84.
57	Marden, Walker, Ward and Williams, White Butte.	Weber, 1963, pp. 81, 83, 217.
58	Dos Cabezas, Moore, Overlook	Sampson and Tucker, 1931, pp. 428–430; Tucker and Reed, 1939, p. 11.
59	Elliot, Red Desert	Weber, 1963, p. 80; Sampson and Tucker, 1942, pl. 1.
60	Superstition Mountains	Sampson and Tucker, 1942, p. 134.
61	Cargo Muchacho Mountains	Henshaw, 1942, p. 159.

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FLUORSPAR

(By C. W. Chesterman, California Division of Mines and Geology,
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Fluorspar is a term applied to a mineral aggregate which is composed principally of fluorite and which contains sufficient fluorine to be useful in the chemical, metallurgical, and ceramic industries.

Fluorite (CaF_2) is the only fluorine-bearing mineral of economic importance. When pure, it contains 48.7 percent fluorine and 51.3 percent calcium. Fluorite has a hardness of 4 on the Mohs' scale, compared with 3 for calcite and 7 for quartz, and a specific gravity of 3.00 to 3.25. It has three perfect cleavages and occurs in many colors ranging through dark purple, blue and yellow to white and colorless. On the basis of these physical properties, fluorite can readily be distinguished from calcite and quartz with which it is commonly associated.

The principal use of fluorspar is in the production of hydrofluoric acid. An exceedingly pure grade of finely ground (80 to 100 mesh) fluorspar, normally containing a minimum of 97 percent CaF_2, is combined with sulfuric acid to form hydrofluoric acid. Hydrofluoric acid is used in the production of plastics, fungicides and pesticides, refrigerants, high octane gasoline, and in the manufacture of artificial cryolite and aluminum fluoride which are used in the production of aluminum.

The metallurgical use of fluorspar in steel production, once the most important, is now second in importance. Metallurgical-grade fluorspar should contain at least 85 percent CaF_2, and materials analyzing below that value are subject to penalties.

Third in consumption of fluorspar is the ceramic industry, which uses finely ground fluorspar in the manufacture of opalescent, opaque and colored glasses, earthenware glazes, and opacified enamels. Ceramic-grade fluorspar must contain at least 85 percent CaF_2, less than 4 percent SiO_2, and less than 0.14 percent Fe_2O_3.

Most fluorspar of commercial interest occurs in veins and irregular bodies enclosed in sedimentary, metamorphic, or igneous rocks. They are replacement deposits and cavity fillings, and have a fluorite content generally ranging from 50 to 95 percent. Fluorite also occurs as a gangue mineral associated with copper, lead and silver ores.

Agricola (1546, p. 109) was the first to use the name fluorite because the mineral became fluid when heated to high temperatures. The fact that fluorite has low viscosity and the ability to form eutectics when in the molten state led to an early use of the mineral in many metallurgical processes, especially in steel manufacture.

The United States production of fluorspar in 1963 was 586,000 short tons, approximately 80 percent of the domestic consumption. Production of fluorspar in the United States has decreased in recent years due to competition of foreign imports, especially those from Mexico, and has resulted in the closing down of many domestic mines. Production of fluorspar in California to date has been less than 1,000 short tons, and is unable to keep pace with the demands of industry.

There are many occurrences of fluorspar in California, but those deposits from which small quantities have been produced are in Inyo, Riverside, and San Bernardino Counties (fig. 24).

Figure 24. Fluorspar in California.

At a deposit on the north slope of Warm Springs Canyon, Panamint Range, Inyo County, fluorspar occurs in veins from 1 foot to 10 feet thick that cut Precambrian granite gneiss (Crosby and Hoffman, 1951, p. 632) The CaF_2 content of representative samples ranges from 29 to 65 percent. A small quantity of fluorspar was produced from one of the veins; the property has been idle since the 1940's. The Palen Mountains, eastern Riverside County, contain many veins of fluorspar. At one locality near the north end of this range, a fluorspar-bearing vein, 5 feet in thickness occurs in monzonite. The vein consists of green, white, and purple fluorite in a matrix of malachite, azurite, calcite, and quartz. A deposit on the east slope of the

Little Maria Mountains, about 14 miles south of Rice, Riverside County, contains several fluorspar-bearing veins from 18 inches to 3 feet in thickness, and as much as 40 feet in length. These veins occur in quartzite and schist. An analysis representative of 130 tons which was shipped from the deposit in 1944, showed 87 percent CaF_2, 4 percent SiO_2, 0.47 percent CaO, 2.25 percent Al_2O_3, and 0.15 percent Fe_2O_3.

The largest number of known fluorspar deposits in California is in San Bernardino County, but only one area has been productive. In the Cave Canyon district near Afton, fluorspar is associated with fine-grained andesitic rocks which occur as intrusive bodies and flows. The volcanic rocks are fractured and form breccias which, in places, contain much coarse crystalline fluorspar. The fluorspar-bearing zones of brecciated andesite are irregular and range from 1 foot to 50 feet in thickness. They are traceable for nearly 2,000 feet on the surface. Some fluorspar occurs in veins that range from a few inches to 4 feet in thickness. The richer parts of the fluorspar-bearing zones locally contain 10 to 40 percent fluorite, but such concentrations are small. Both silica and calcite are present, but metallic sulfides are lacking. Analysis of representative samples shows a range of 35 to 86 percent CaF_2, 8 to 44 percent SiO_2, and 2 to 29 percent $CaCO_3$ (Burchard, 1933, p. 373–374).

In 1955, fluorspar was discovered in the Orocopia Mountains, a few miles south of Shaver Summit, eastern Riverside County. Here, several veins of fluorspar, ranging from a few inches to six feet in width, occur in shear and breccia zones in coarse-grained Mesozoic quartz monzonite. The veins are parallel and pinch and swell along their strike. The largest vein has been prospected intermittently along a strike length of 500 feet. Mine-run fluorspar contains over 91 percent CaF_2, and a hand-picked sample was found to contain 97.83 percent CaF_2. The fluorspar meets all specifications for metallurgical uses, and a small shipment was made early in the spring of 1955 to the Kaiser Co. at Fontana, California, for use in steel manufacture. The prospect has been inactive since 1956.

The potential for a substantial fluorspar production in California is certainly not indicated by its total production in the State. Although there are numerous occurrences of fluorspar in California, they appear to be in small deposits of several thousand tons or less. However, the potential for new discoveries is good, especially in areas where there has been limited production and where prospecting and exploitation have been on a limited basis only.

The copper- and fluorite-bearing siliceous veins in the carbonate rocks of the Tin Mountain area, Inyo County, the fluorite veins in the granitic and metamorphic rocks of the Orocopia and Palen Mountains, Riverside County, and the fluorite-sericite replacement veins in the Goodsprings (Cambrian to Devonian?) Dolomite in Clark Mountain, San Bernardino County, are worthy of further prospecting and exploitation.

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GARNET

(By D. M. Lemmon, U.S. Geological Survey, Menlo Park, Calif.)

Garnet constitutes a mineral group of six main gradational species that are closely related, having the same isometric crystal habit and the same general formula but composed of different combinations of the silicates of magnesium, aluminum, iron, calcium, manganese, chromium, and rarely titanium. They are hard (range from 6.5 to 7.5), tough, moderately heavy (sp. gr. 3.5 to 4.2), and without cleavage but with a sharp fracture.

The principal commercial use is in coated abrasives, formed by cementing closely sized grains to paper or cloth. Garnet-coated papers and cloth are used primarily in woodworking but also in finishing leather, hard rubber, plastics, felt, and the softer metals. Garnet is used extensively in finely sized loose grains to grind glass and lenses; a sludge of 25 micron garnet and water was used in an intermediate finishing operation in grinding the main mirror of the 120-inch telescope at Lick Observatory, Mount Hamilton, Calif. (Hill, 1959). Garnet is also used in sizes between 17 and 45 mesh for sandblasting because it is tougher and heavier than the commonly used silica sand, making it a more efficient impact abrasive, and it can be reused.

Garnet is found in many geologic environments and is geographically widespread. Two species are of principal commercial use: (1) almandite, $Fe_3Al_2(SiO_4)_3$, which occurs in schists and gneisses, and (2) andradite, $Ca_3Fe_2(SiO_4)_3$, found in contact metamorphosed limestone altered to skarn (tactite), in schist, in serpentine, and in some igneous rocks. The chemical compositions given are for pure end members, seldom found, for most natural garnets are mixtures and are named on the basis of the dominant type.

Since World War II, garnet output in the United States has ranged from 6,578 short tons in 1949 to 14,626 tons in 1963, valued at $1,412,000. The principal production in 1963, as in many years past, was almandite pyrope (Levin, 1960) from a small area in the Adirondack Mountains of New York. The remainder of the output came from alluvial deposits in Idaho and was used principally for sandblasting (Ambrose, 1964).

The relatively small United States demand for garnet concentrates is amply met by these two states. New York also exports to foreign markets; its product is superior in the world market as well as in the United States (Vogel, 1960).

Garnet is widely known in California (Troxel, 1957), especially as a gangue mineral in contact metamorphic tungsten deposits. Most of the tungsten ores must be finely ground to recover the scheelite, leaving the garnet in too fine a state to be useful as an impact abrasive. However, some tailings from ores treated in World War I in the Tungsten Hills west of Bishop, California, were fairly coarsely ground to pass 8 to 14 mesh. Some garnet concentrates were derived from these tailings in 1938–40 and marketed for impact abrasives at a price of $18 a ton. Small amounts were produced intermittently through 1955, the last year of recorded output, and several thousand tons were shipped in 1954–55 (Calif. Mining Jour., 1954, v. 23, no. 11, p. 16).

Despite widespread distribution of garnet in California, the outlook for production is poor. Although the abrasive quality of the garnet in many deposits is unknown, most garnet produced would be too fine grained for impact abrasives, and garnet for other uses cannot be produced competitively unless markets are large enough to warrant expensive processing plants to treat deposits less favorably endowed than those of New York.

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GEM STONES

(By E. B. Gross, California Division of Mines and Geology, San Francisco, Calif.)

Gem materials, both precious and semiprecious, include minerals and organic substances that are used for personal adornment, ornamental objects, and decorative and special industrial purposes. Industrial gem materials include inferior grades of diamonds and other hard stones which are used for instrument bearings, and cutting tools and abrasives. Synthetic gems with compositions identical with natural gems are being used in increasing quantities in the industrial applications as substitutes for natural gem materials. Synthetic sapphires are used in needle valves, lasers, dielectric wafers, and optical instruments. Imitation gem materials which attempt to resemble natural or synthetic stones are not considered gem stone commodities. Of 135 different substances that have been used for ornamental purposes, only about 60 mineral species have most of the attributes to qualify as gem stones.

A gem material, to be classified as such, must have certain physical and chemical properties, namely: resistance to abrasion, transparency, usually high refractivity to light, hardness (preferably 7.5 or greater, Mohs' scale), lack of strong parting or cleavage, and absence of internal and external flaws. Besides the above characteristics, a gem stone must have, above all, beauty of form and color, and be rare. Another essential factor for many gem stones is the quality of adaptability to faceting and polishing.

Only certain minerals—diamond, corundum (ruby and sapphire), chrysoberyl (alexandrite), and beryl (emerald) satisfy most of the above characteristics and are customarily considered precious gems.

Semiprecious inorganic gem stones and organic gem materials (jet, amber, and pearl) comprise the bulk of the gem materials. The semiprecious gems do not have all the essential attributes of precious gems, yet many are desired for personal adornment. Most semiprecious gem stones are silicates which include andalusite, benitoite, beryl (aquamarine, morganite) golden cordierite (iolite), diopside, enstatite, epidote, feldspar, garnet, idocrase, jadeite, lazurite (lapis lazuli), nephrite, olivine (peridote), phenacite, rhodonite, scapolite, sodalite, sphene, spodumene (kunzite), topaz, tourmaline, zircon, and zoisite (thulite). Some colored varieties of quartz, such as amethyst, rose, citrine, aventurine and rock crystal, are classed as semiprecious stones. A few oxides, such as hematite and spinel, and phosphates, such as lazulite and turquoise, may be classed as semiprecious, although the phosphates generally are soft. Obsidian, although not strictly a gem stone, is of commercial importance in California.

Many of the semiprecious stones are polished in rounded form, cabochon, or cut into rectangular or square shapes with few facets because of their low refractivity. Gems may be given special treatment, such as heat or X-ray radiations, usually to improve the color; the color change may be permanent or temporary depending on method of treatment.

Most gem stones are faceted or polished to increase their beauty and value. The various cuts include brilliant, baguette, marquise, pear shape, step, emerald, and lens cut. The truly precious gems, after cutting and polishing, bring very high retail prices depending on quality and number of carats (one carat=0.2 grams). Because of high duties applied to cut gems, however, most importers ship gems in the natural state to the United States; these subsequently are faceted in New York or Los Angeles. Also, gems are cut in England, northern European countries, India, and Burma. In 1963, the retail value of a one-carat diamond ranged from $575 to $1,650. Emeralds have the same range of values, because of their rarety. Alexandrites are about $400 per carat, while rubies and sapphires vary considerably in price, depending upon color, adaptability to faceting and polishing, and absence of flaws. Their range is between $200 to $800 per carat, with ruby commanding the higher price. Semiprecious stones and organic gems bring much lower prices, in the range of $5 to $100 per carat.

The sales of synthetic gems have not affected those of natural stones, except for special industrial uses. These include synthetic diamonds, corundum, and spinel. Synthetic rutile (titania) and (fabulite), a strontium titanium oxide, have beauty because of their extreme refractivity, more brilliance than diamonds, but they lack durability. In recent years, emerald has been made in large crystals synthetically by the Chatham process in San Francisco. The synthetic emeralds also command high prices.

The geologic occurrences of gem stones is varied. Many of the most valued gems are primary constituents of igneous rocks. Ultramafic rocks occurring in plugs or dikes contain diamonds disseminated irregularly throughout the rock. Other gems found in mafic rocks are sapphire and ruby, enstatite, olivine, and garnets (pyrope and uvarovite). More acidic igneous rocks contain notably garnet, sphene, rutile, topaz, and zircon. Alkaline igneous rocks occasionally contain gem quality garnet, corundum, zircon, and rutile. Pegmatite dikes associated with granitic and syenitic igneous bodies include the greatest variety of gem stones. They have yielded beryl, chrysoberyl, danburite, cordierite, sphene, tourmaline, spodumene, topaz, lazulite, apatite, and zircon. Many of the best formed gems have been obtained from miarolitic cavities in pegmatites. The world's best known and most productive gem-bearing pegmatites are in Minas Geraes province of Brazil. Most emeralds have come from pegmatites in Columbia, and sapphires and rubies from deposits in India and Ceylon.

Metamorphic rocks have produced gem andalusite, lazurite, and spinels, and contact deposits have yielded apatite, cordierite, corundum, axinite, idocrase, epidote, and garnet. Nephrite and jadeite have formed by hydrothermal processes at the contact of igneous rocks with serpentine. Hydrothermal vein deposits have been the source for datolite, and various types of quartz (such as amethyst, rock crystal, jasper, agate, and citrine), also benitoite, opal, fluorite, and topaz. Many of the above minerals are found in gem-bearing placers, some of which are richer than the primary deposits. Most gem minerals are chemically inert, resistant to abrasion, and thus become concentrated in residual soils and in heavy stream and beach placers.

The value of United States production of gem stones has increased from $1.2 million in 1960 to $1.4 million in 1964, a small value compared to imports of $192.5 million in 1960 and $265 million in 1964. Nearly 88 percent of the total imports are diamonds, chiefly from Africa. Consumption of gems in the United States far exceeds its exports.

More than 60 gem minerals, mostly semiprecious, are produced commercially from domestic sources. At present, California and Oregon rank first in semiprecious gem stone mining in the United States, each producing about 14 percent of the total. For the last few years, the semiprecious gems mined in California included jade, obsidian, tourmaline, turquoise, jasper, opal, and various minor mineral specimens which in value amounted to $200,000 annually.

The earliest gem collecting in California was by Indians who obtained tourmaline and turquoise from Riverside and San Diego Counties. The first recorded discovery was made by Henry Hamilton in 1872 at Thomas Mountain in Riverside County (Wright, 1957). Tourmaline float was noted from a pegmatite dike. In 1892, tourmaline was found in the Pala district followed by a very rich tourmaline-bearing pegmatite discovery in 1898 at Mesa Grande. Commercial gem mining in California was most active in a pegmatite zone, about 25 miles long. This comprised three major districts: Pala, at the northwest end, Rincon, and Mesa Grande, near the southeast end, all within the Peninsular Ranges in San Diego and Riverside Counties (see fig. 25). Most intensive mining in Mesa Grande area was during 1900–1910 and in the Pala area during 1903–1914 (Wright, 1957). Although tourmaline was the chief commodity, other gems such as spodumene (kunzite) and gem quality beryl were mined. Incomplete production statistics for the three areas indicate a total value of $319,200 for Pala, $2,000 for Rincon, and $814,000 for Mesa Grande.

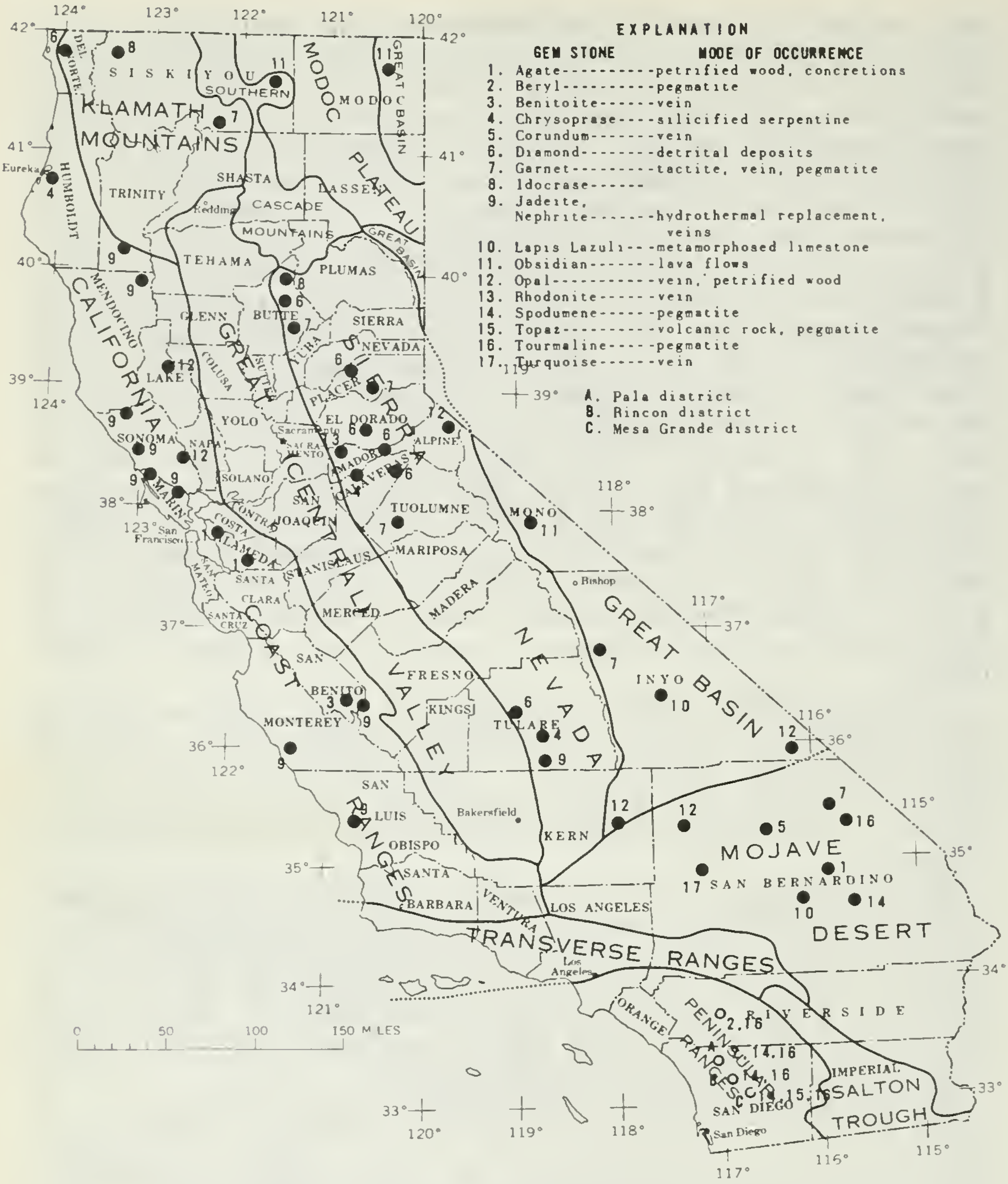

FIGURE 25. Selected gemstone localities in California.

Gem minerals have been recovered also from scattered pegmatites in Coahuila, Red, and Thomas Mountains in Riverside County. Other districts in San Diego County have included Ramona, Julian, and Aguanga Mountains. Since 1925, most of the mines in the above districts have been idle on a full-time commercial basis, but interest of mineral collectors has remained high, so that part-time operators have screened dumps and undertaken sporadic mining in recent years.

Other gem operations within the State have been minor. Prior to 1920, an estimated 500 diamonds have been recovered from placer mining for gold in the western foothills of the Sierra Nevada (Murdoch and Webb, 1956). Few of the diamonds exceeded 2 carats. Benitoite ($BaTiSi_3O_9$), a mineral found in blue crystals, occurs only in San Benito County, California, and was actively mined from 1907–1909.

Since then, few crystals of gem quality have been found. Chrysoprase, a green variety of chalcedony, was found in 1878 near Visalia, Tulare County. Other occurrences of chrysoprase in veins were developed in Tulare County and were exploited between 1878 and 1911. Massive idocrase (californite) was mined near Happy Camp, Siskiyou County, from 1900 to 1911. Since then, mineral collectors have obtained small quantities from the deposits. Jadeite and nephrite have been mined sporadically in many small deposits since 1930 in the Coast Ranges, chiefly in Monterey, Marin, Mendocino, San Benito, and San Luis Obispo Counties (Crippen, 1951; Yoder and Chesterman, 1951; and Chesterman, 1951). More recently, 1963, nephrite-jade has been found in Mariposa County. All occurrences are in veins, lenses, or pods associated with serpentine.

Gem quartz crystal occurrences are known in Amador, Inyo, Lake, Mariposa, and Tulare Counties. Only two turquoise deposits have been developed, these for a brief time (1903–1909) in San Bernardino County. Miscellaneous gem materials such as obsidian, agate, jasper, rhodonite, opal, and other materials useful for lapidary work have been collected in recent years, but large-scale mining of gem stones has been inactive for years.

California will continue to rank high among the States in production of semiprecious gem stones. However, most new discoveries will be found by mineral collectors and prospectors. Possible sources include pegmatites from both the Peninsular Ranges and from scattered dikes along the western foothills of the Sierra Nevada. Contact metamorphic bodies of the Sierras might yield gem quality epidote, garnet, sphene, and spinel. Nephrite-jade, some of good cutting and polishing quality has been found in Mariposa County. Other deposits might be exposed under similar geologic conditions elsewhere in the State. Jade (jadeite and nephrite) potential is still promising in the Sierra Nevada and Coast Ranges, where serpentine is abundant. Desert areas of southeastern California are possible locations for new agate and turquoise occurrences.

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GEOTHERMAL ENERGY

(By D. E. White, U.S. Geological Survey, Menlo Park, Calif., and J. R. McNitt, California Division of Mines and Geology, San Francisco, Calif.)

Introduction

Geothermal energy, or the natural heat of the earth, is useful in generating electricity and for space heating. Total world utilization of geothermal energy is roughly equivalent to 1 million kw, which is small in comparison to the major sources of energy. The first steam well for power was drilled in Larderello, Italy, in 1904; present Italian production capacity is about 350,000 kw. No major interest was shown by other countries until the 1950's when New Zealand first demonstrated that very hot water tapped at depth (rather than steam) can yield steam of adequate quality and quantity to be commercially attractive. As the hot water flows into and up the well and pressure decreases, some water flashes into steam and both water and steam erupt to the surface like a continuously erupting geyser. Production capacity in New Zealand in 1965 is 182,000 kw.

The Geysers steam field in California, the only commercially productive area in the United States (1965), first attracted interest in the 1920's; exploration proved that natural steam without liquid water could be produced from wells drilled a few hundred feet deep. The steam was similar in temperature and pressure to that of Larderello, but the commercial climate was not then sufficiently favorable. In 1955 exploration was again undertaken, eventually resulting in successful generation of power by 1960; a second-stage unit was installed in 1962 and construction of a third stage is underway in 1965; when completed, total capacity will be 51,000 kw. Actual production of power by year is shown in table 20.

Within the United States, California leads all other states in areas explored (15 of total of about 30; see table 19). In addition to The Geysers, two other very promising areas in California are the Salton Sea and Casa Diablo.

Engineering aspects of geothermal energy are summarized by Smith (1964) and economic aspects by Kaufman (1964). The proceedings of the United Nations Conference on New Sources of Energy, Rome, 1961 (see citation for Smith, 1964) contains a large variety of papers on general principles and individual areas of the world.

Geologic Occurrence

The earth is a tremendous reservoir of thermal energy, most of which is too deeply buried or too diffuse to consider as recoverable energy. In general, temperatures increase with depth; the average is approximately 1° C. per 160 feet of depth or 1° F. per 100 feet. Commercial geothermal areas occur where the rate of temperature increase is at least 2 times the "normal" rate, and 5 to 10 times "normal" averaged over hundreds or several thousands of feet in depth is much more favorable. Two important factors determine the economic potential of a geothermal area: temperature, and an adequate supply of water or steam. Except in very porous rocks, most of the energy of a geothermal reservoir is stored in the solid rocks rather than in water or steam in the pore spaces, as commonly supposed (White, 1965). The supply of water or steam must be large enough, either within the reservoir, or by access of water from outside the reservoir, to maintain a necessary rate of production for some minimum time (large enough and long enough to pay a profit for the investment).

Geothermal reservoirs can be classified into two types: (a) those with permeable extensions to the surface, permitting escape of thermal fluids as hot springs and fumaroles; and (b) deep insulated reservoirs with capping rocks of low permeability and little or no surface expression. Gradations exist between extremes of the two types.

Reservoirs related to hot springs are characterized by high near-surface permeabilities, at least locally on faults and fractures, permitting water, steam, and contained heat to escape. Many hot springs discharge heat at rates of ten to hundreds of times the "normal" heat flow of the earth for equal areas. The Upper (Old Faithful) Geyser Basin of Yellowstone Park is a familiar example. Its estimated heat flow from 4 sq. mi. is about 600 times that of an equal area of "normal" crust of the earth (White, 1965). Temperatures near the surface are very high because of the upward transfer of enormous quantities of heat in the escaping water and steam—about 90×10^6 cal per sec. One important consequence of a convection system of circulating fluids, with vigorous leakage of heat, is that the lower part of the system is cooled by inflowing cooler water; temperatures deep in the system are therefore cooler than would otherwise exist.

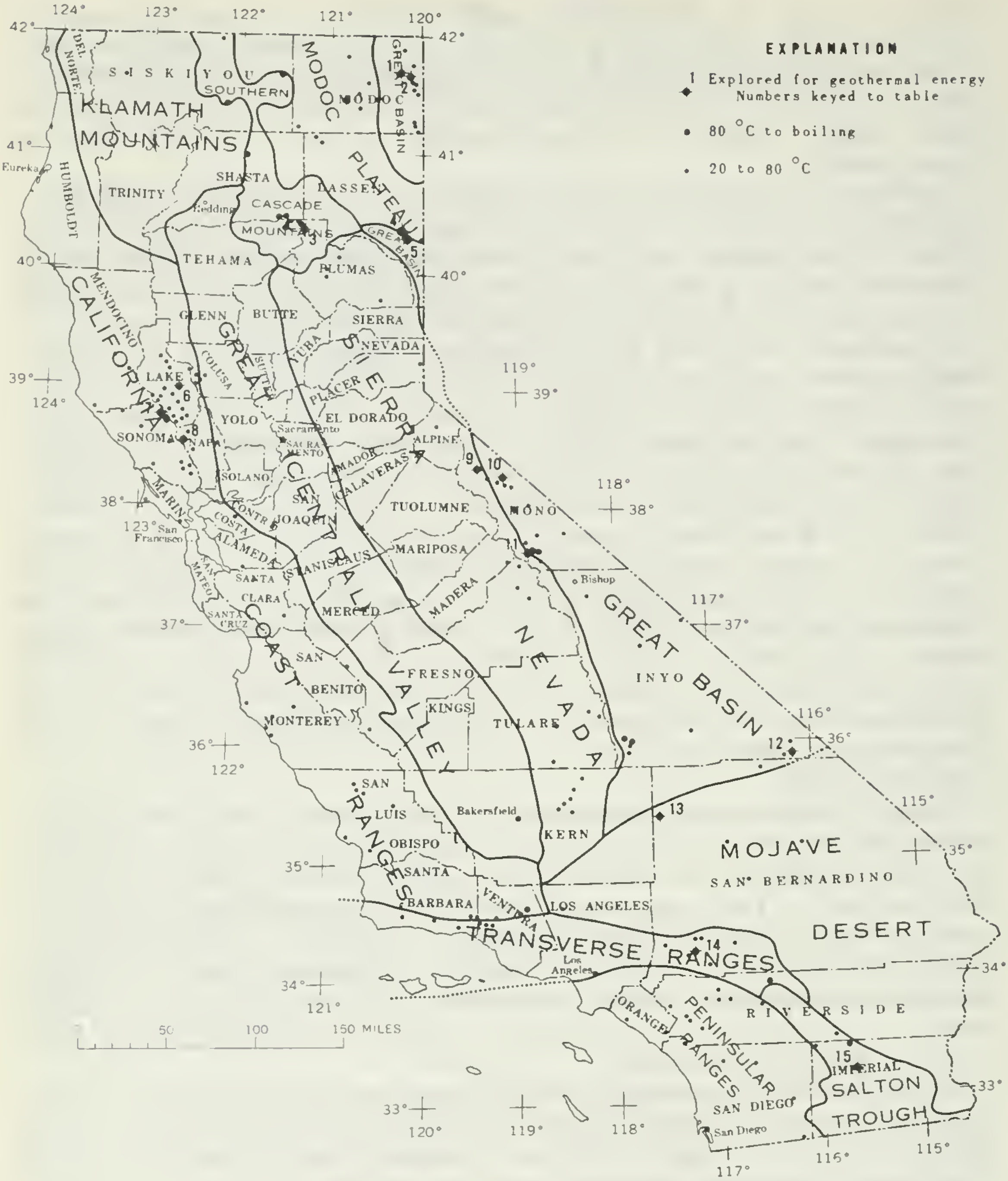
Deep reservoirs with little or no surface expression require a permeable reservoir rock overlain by impermeable rock such as shale that provides insulation and also inhibits convection loss of fluids and heat. At Larderello, Italy, exploration was first focused near feeble natural springs, which were leakages from the system. Other reservoirs have since been found with no surface expression other than high rates of temperature increase with depth. The Salton Sea geothermal area in California is an example of a deep insulated reservoir with very meager natural leakage.

Most geothermal systems are dominated by liquid water, commonly much above 100° C (212° F) because of the high existing pressures. In such systems, steam can form by boiling near the surface, as the hot water rises and pressure decreases sufficiently. In a very few explored systems (Larderello and nearby areas of Italy and The Geysers, California), the heat supply is so high and the rate of flow of fluids through the system so low that the available water is converted to steam, even where pressures exceed 300 pounds per square inch. Experience is showing that these dry steam systems are rare and that extensive utilization of geothermal energy must depend largely upon steam that can be "flashed" from hot water with release of pressure.

Occurrences in California

The known hot spring areas of California are shown in figure 26 (modified from Stearns, Stearns, and Waring, 1937, plate 15).

Fifteen areas have been explored for geothermal energy (table 19 and figure 26). Three areas of particular interest are described briefly below:



Modified from Stearns, Stearns, and Waring, 1937, plate 15

FIGURE 26. Thermal springs of California, showing localities that have been drilled for geothermal energy (numbers refer to table 19).

The Geysers, Sonoma County, California (McNitt, 1963), and related areas (table 19) occur along a five-mile length of a northwest-trending and steeply dipping fault zone. Three areas are being developed, including The Geysers, Sulphur Bank, one mile to the west, and The Little Geysers, four miles to the southeast. Upper Tertiary volcanic rocks lie to the south and east of The Geysers, and the Clear Lake volcanic field of Quaternary age is less than 20 miles to the northeast. However, the geothermal zone is underlain by almost impermeable sandstone, basalt, and serpentinite of the Jurassic and Cretaceous Franciscan Formation.

TABLE 19.—*Areas explored by drilling for geothermal energy in California, with pertinent data*

Index No. on fig. 26	Thermal area	Location	Wells drilled for geothermal energy	Maximum depth (feet)	Maximum temperatures		Dates drilled	Remarks and references
					Subsurface	Surface springs		
1	Lake City	Modoc County, secs. 23 and 24, T. 44 N., R. 15 E.	4	2,150	160	98.0	1959-62	Magma Power Co. (and associates) 1951, and volcano eruption (White, 1955).
2	Cedarville (Surprise Valley)	Modoc County, secs. 1 and 6, T. 42 N., R. 17 E.	1	734	54½	51.5	1962	Magma Power Co. (and associates), ½ mile east of Cedar Plunge resort, 2 shallow wells erupting water and steam, 98° C.
3	Terminal Geyser	Plumas County, sec. 36, T. 30 N., R. 5 E.	1	1,270	129	96.0	1962	Geysers Steam Co.
4	Wendel (Shaffer)	Lassen County, sec. 23, T. 29 N., R. 15 E.	1	630	79	97.8	1962	Magma Power Co. (and associates.)
5	Amedee	Lassen County, secs. 8 and 4, T. 28 N., R. 16 E.	3	1,116	107	97.7	1962	Do.
6	Sulphur Bank	Lake County, sec. 5, T. 13 N., R. 7 W.	4	5,000	>180	80.5	1961-64	Magma Power Co. (and associates), Earth Energy, Inc.; White and Roberson, 1962.
7	The Geysers:	Sonoma County:						
	(*a*) The Big Geysers	Sec. 13, T. 11 N., R. 9 W.; sec. 18, T. 11 N., R. 8 W.	23	5,036	246	99.1	1955-62	Magma and Thermal Power Cos. Steam at depth generally dry, without liquid water. McNitt, 1963.
8	(*b*) Sulphur Bank	Secs. 11, 12, and 13, T. 11 N., R. 9 W.	16	5,127	225	98.0	1962-65	Magma and Thermal Power Cos.
	(*c*) The Little Geysers	Secs. 28 and 33, T. 11 N., R. 8 W.	2	3,476	----------	98.0	1964-65	Do.
8	Calistoga	Napa County, sec. 31, T. 9 N., R. 6 W., and sec. 26, T. 9 N., R. 7 W. (projected).	3	2,000	137	78.0	1960-61	Calistoga and Magma Power Cos.
9	Fales Hot Springs	Mono County, sec. 24, T. 6 N., R. 23 E.	1	413	<38	61.0	1962	Magma Power Co. (and associates).
10	Bridgeport	Mono County, sec. 34, T. 5 N., R. 25 E.	1	982	51	77.0	1962	Do.
11	Casa Diablo-Mammoth	Mono County, secs. 32 and 35, T. 3 S., R. 28 E.	10	1,063	178	90.0	1959-62	Do.
12	Tecopa	Inyo County, sec. 33, T. 21 N., R. 7 E.	1	422	(1)	43.0	1962	Do.
13	Randsburg	San Bernardino County, sec. 25, T. 29 S., R. 41 E.	1	772	115½	(2)	1960	Magma Power Co. (and associates), steam found in old well drilled for water.
14	Arrowhead	San Bernardino County, secs. 11 and 12, T. 1 N., R. 4 W.	2	571	112	86.0	1963	R. A. Rowan & Co.
15	Salton Sea (Niland)	Imperial County, T. 11 S., R. 13 E., and T. 12 S., R. 13 E.	10	8,100	>300	100.2	1961-65	O'Neill Geothermal Co. (2), Earth Energy, Inc. (3), Western Geothermal Co. (2), Shell Oil Co. (2), Imperial Thermal Products (1); White, McNitt, 1963; White, 1965.

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[1] Low.

[2] No springs.

Dry steam is obtained by drilling wells into the fault zone. The wells range from several hundred to 5,000 feet deep. Static wellhead pressures range from 100 to 500 pounds per square inch and seem to reflect the hydrostatic pressure and thickness of a groundwater cover overlying the steam (McNitt, 1963). Measured flow rates from individual wells range from 15,000 lb/hr at 78 psi to 184,000 lb/hr at 120 psi. The heat content of the steam averages about 1,200 Btu per pound (670 cal per gm). Power production since 1960 is listed in table 20.

TABLE 20.—*Production of electricity in kilowatt-hours, The Geysers Power Plant, Pacific Gas & Electric Co., Sonoma County, California (excluding station uses; data from A. W. Bruce, Pacific Gas & Electric Co., 1965)*

Year:	*Production*
1960	33,576,944
1961	94,019,840
1962	100,461,120
1963	167,952,960
1964	203,790,080

In the Salton Sea area, very saline brine was discovered in reservoir rocks below a capping of fine-grained sediments. Details of temperatures and production capacity have not been released for publication. Temperatures of 270°C to 370°C are indicated near 5,000 feet (White, 1965). The exploration wells have all produced at rates that are qualitatively impressive; they are distributed through an area at least 6 miles long and 2 miles wide adjacent to Salton Sea. Published geophysical data (summarized in McNitt, 1963, fig. 14) suggest that an almost equal area extends out under the sea.

The brine has a salinity of about 30 percent, consisting dominantly of sodium, calcium, and chloride but with very high contents of potassium, iron, manganese, zinc, lead, copper, silver, and other rare elements. Economic interest is focused about equally on the energy and potassium contents of the brine. Other by-products of value, such as lithium, silver, and other metals, may also be recoverable.

The Casa Diablo area is in the large structural depression of Long Valley, which may be related to extensive volcanic activity during the past million years (McNitt, 1963; White, 1965). Porous and permeable volcanic tuffs and breccias are probably interstratified at depth with lava flows; in some respects this area is comparable to Wairakei, New Zealand. Ten wells have been drilled in less than 2 square miles, and most of these have produced satisfactorily.

PROBLEMS THAT THREATEN BROAD UTILIZATION

The presence of reservoirs sufficiently high in temperature and in supply of natural fluids must first be proved by exploration. Hot water areas are likely to be the most abundant but rapidly cooled water may deposit either $CaCO_3$ or SiO_2 in wells and treatment plant; other chemical substances, such as boron, arsenic, and salts may constitute effluent problems that require treatment or subsurface disposal. In addition, geothermal exploration is not adequately covered by existing state and federal laws; unsympathetic treatment can easily discourage the development of a promising new natural resource.

Appraisal of Regions

The appraisal of a region must be based on rates of temperature increase that are likely to occur with depth, and the probability of finding adequate reservoir rocks that will yield natural fluids to wells in required quantities. We have adequate temperature-depth data only from sedimentary basins that have been explored for oil and gas. Most of these are characterized by nearly "normal" rates of increase rather than the abnormally high rates demanded for geothermal energy. The Salton Trough (fig. 26) is one outstanding exception, and moderately high temperatures have also been reported locally in the Transverse Ranges and the Great Valley.

In other regions of the state, data on geothermal gradients and conducted heat flow are very inadequate. We can hypothesize that thermal springs are abundant where heat flow is high and permeable structures permit water to circulate deeply. Other regions may lack thermal springs because their average heat flow is too low. A combination of these factors probably explains the scarcity of thermal springs in the Sierra Nevada, the Klamath Mountains, and most of the California Coast Ranges.

The required heat sources are most likely to occur in regions of Pliocene and Quaternary volcanism. The clusters of thermal springs associated with Quaternary volcanic extrusions near Mono Lake, Mount Lassen, Modoc County, Lake County, southern Inyo County, and Salton Sea attest to the importance of volcanism in supplying abnormally high rates of heat flow.

The most favorable regions in California are the Salton Trough, the California segments of the Modoc Plateau and Great Basin; and local parts of the California Coast Ranges and the Southern Cascade Mountains.

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GOLD

(By W. B. Clark, California Division of Mines and Geology, Sacramento, Calif).

Of the various properties that give gold an outstanding place in the world of metals, the most important are resistance to corrosion, reflectivity, malleability, and high specific gravity. Man has used gold as a medium of exchange and in ornaments and the arts since prehistoric times. The principal use at present continues to be in monetary systems or in coinage. Federal controls closely regulate the ownership and distribution of gold, except for gold in the natural state. Although it is illegal to possess gold coins other than as curios in the United States, they are minted and circulate freely in a number of other countries. Considerable amounts are used in jewelry and the decorative arts, including watch cases, rings, gold leaf, gilding, gold plating and decorative finishes on ceramics and other materials. The growth of these uses has paralleled the growth in population and gross national product. Substantial amounts are used in dentistry and lesser amounts in the chemical industry and glass making. The development of new scientific devices and instrumentation has been reflected in increasing uses of gold.

To many persons, gold is California's best-known metal. It was the principal attraction to the early-day pioneers and stimulated the State's growth for many years.

In California, the principal primary deposits are mesothermal gold-quartz veins that are associated with the intrusion of granitic bodies and occur either in slates, schists, and greenstones that have been intruded by the granitic bodies, or in the granitic rocks themselves. The veins range from a fraction of an inch to tens of feet in thickness; many deposits consist of a series of parallel of branching quartz stringers separated by slabs of country rock.

In a typical deposit, the gold occurs as microscopic grains, plates, or threads in the quartz and is commonly associated with varying amounts of pyrite and small amounts of other sulfides; gold associated with tellurides has been found, the most notable occurrences being at Carson Hill. The extent of the ore shoots varies greatly. Many extend to depths of only a few hundred feet; in others, such as the veins at Grass Valley or in the Mother Lode, the deposits extend to inclined depths of 5,000 to 10,000 feet.

Massive or vein-like replacement deposits of pyrite that contain copper and zinc also contain some gold and silver. Also, the iron oxide-rich gossans that cap such deposits have yielded substantial amounts of gold. The most important deposits have been in the Shasta and Sierra Nevada Foothill copper-zinc belts and the Plumas County copper belt. Gold is a constituent of lead-zinc and lead-silver replacement deposits in the Great Basin. It is a minor constituent of contact metamorphic tungsten and copper ores in the Sierra Nevada and of a few mercury deposits in the Coast Ranges.

A number of important epithermal gold deposits are found in California, the most productive being the Bodie, Mojave, and Rand districts. These deposits consist of gold-bearing zones of alteration and silicification in igneous or metamorphic rocks. The ore commonly consists of silicified breccia containing fine free gold and disseminated sulfides. The zones of alteration often are extensive and usually have a bleached appearance. In a few deposits, the gold is associated with manganese.

Because of its high specific gravity and resistance to weathering, gold is easily concentrated in placer deposits; vast amounts have been recovered from California's placers. All of the streams that flow through the gold-bearing regions have been productive. The gold particles are flat or rounded and range from microscopic size "flour gold" to nuggets 100 or more ounces in weight. Many large nuggets have been found in California, especially in Alleghany, Columbia, Downieville, Magalia, and Sierra City districts. The gold particles are everywhere associated with black sands composed of magnetite and smaller amounts of ilmenite, chromite, zircon, garnet, pyrite, and in some places platinum.

The placer deposits in California range from early Tertiary to Recent in age. The Recent placers are in and adjacent to the present streams; the older gravels are on terraces adjacent to the present channels or high on the interstream ridges. The extensive older Tertiary channels in the northern and central Sierra Nevada have been preserved by a thick cover of volcanic rock. They are characterized by abundant quartz pebbles and cobbles and in places by coarse nuggets. There are dry desert placers in several areas in southeastern California. In these deposits, small rounded grains of gold are found in loose sand. Gold, usually in very fine grains, has been recovered from placers on some of the beaches along the coast.

Gold was first recovered in California some time between 1775 and 1780 on the lower Colorado River. These early operations were on a small scale and lasted only a few years. They extended west and north into the Cargo Muchacho and Picacho districts. Later in the 1820's, 1830's, and 1840's, placer gold was recovered near San Diego and in the San Gabriel Mountains. None of these early operations had much significance in the development of the State. On January 24, 1848, James W. Marshall made his historic discovery at Sutter's Mill at Colma on the American River. Soon afterward, the gold rush was in full sway as thousands of gold seekers poured into California. Gold also was discovered in the Trinity River by Pearson B. Reading in 1848. In a few short years, most of the State had been explored, and many areas had been permanently settled. California's gold rush had a profound influence on the entire western United States and many parts of the world.

The flush production of the first few years of the gold rush was from rich and virgin surface placers. In 1851, the State's output attained an all-time high of almost 4 million ounces valued at 81.2 million dollars. As the rich surface placers declined in the middle and late 1850's, river mining and then hydraulic mining became the chief gold sources.

As a result of hydraulic mining, which was first done in 1852 near Nevada City, Nevada County and at Yankee Jim's in Placer County, large quantities of evacuated material was allowed to flow into the rivers, and was alleged to cause flooding and silting of farmlands downstream. This eventually led to litigation between farmers and the hydraulic miners. In a famous court case in 1884 (Woodruff vs. North Bloomfield Gravel Mining Co. (16 Fed. Rep. 25)), Judge Lorenzo Sawyer issued an injunction prohibiting the dumping of debris into the Sacramento and San Joaquin Rivers and their tributaries. Injunctions against other mines followed. A few mines constructed tailings dams or reservoirs and continued to operate for a few years. For a short time, drift mining of buried gravel channels partly made up for the loss of placer gold production from hydraulic mines.

In 1876, rich gold-bearing deposits were discovered at Bodie in Mono County. The rush to that district continued until about 1888. In 1893, the discovery of gold in Goler Gulch in the El Paso Mountains in eastern Kern County led to the discovery and the resulting rush to the nearby Rand district. Other productive southern California districts of the 1890's and early 1900's were the Cargo Muchaco, Stedman, Picacho, and Mojave districts.

During these years, great improvements were made in mining and milling methods and equipment which enabled many more lode deposits, especially larger but low-grade ores, to be profitably mined. The first successful bucket-line dredge was started on the Feather River near Oroville in 1898. Gold dredging soon became a major industry that has continued for more than 65 years.

The general prosperity, that began during World War I and continued through the 1920's, with accompanying high costs, caused a significant decrease in gold production in California. In 1930, output started to rise because of the depression and resulting low operating costs. This rise was accelerated in 1934 when the price of gold was increased from $20.67 to $35 per fine ounce. Many mines were reopened, and there was much exploration which resulted in significant discoveries. Thousands of miners were employed in the quartz mines at Grass Valley, Nevada City, Alleghany, Jackson, Jamestown, Sutter Creek, and Mojave. There were many active bucket-line dredges, and dragline dredges became important gold sources. In 1940, gold production amounted to 1,455,000 fine ounces valued at nearly $51 million, the highest figures since the gold rush. Most of the major events are graphically recorded in figure 27.

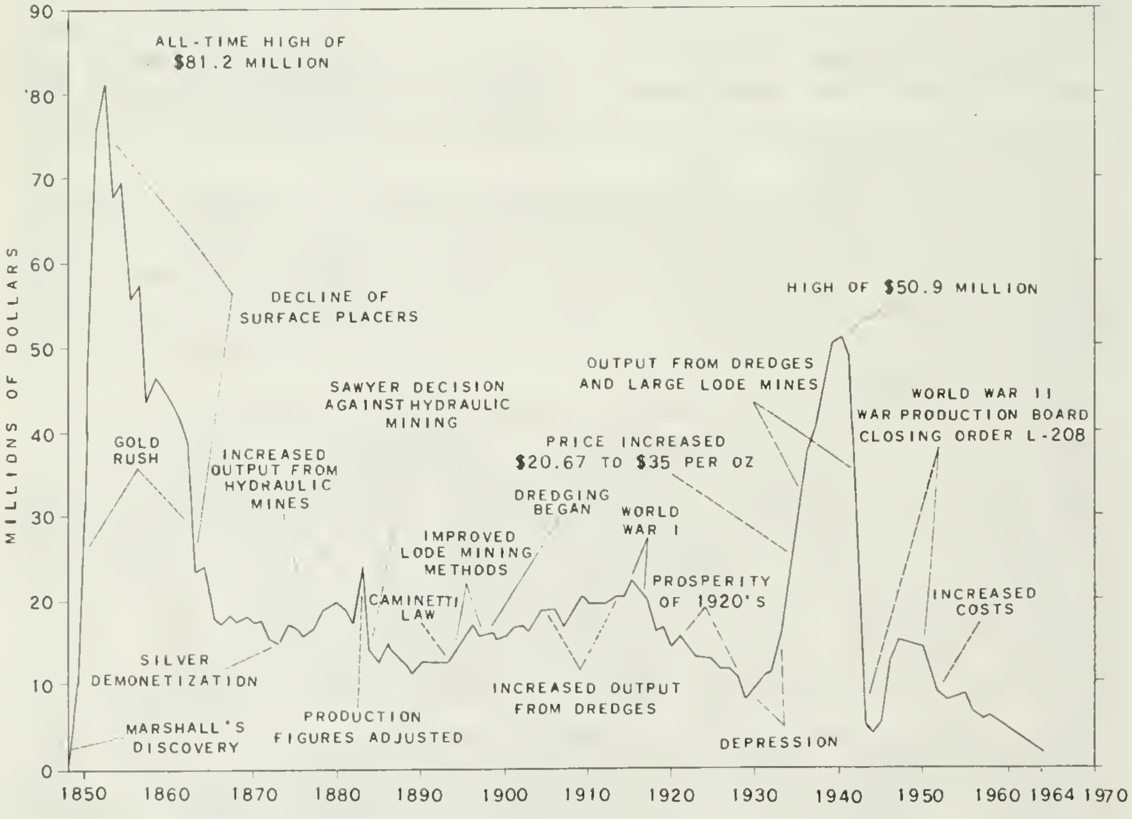

FIGURE 27. California's gold production.

World War II caused a precipitous drop in gold production. War Production Board Limitation Order L–208 was issued in 1942 and caused the gold mines to be shut down. Order L–208 was lifted in 1945. Some of the dredges resumed operations, and some of the major lode mines in Grass Valley, Alleghany, and Sutter Creek were reopened. Gold production increased slightly for 4 years. However, in 1950, production resumed its decline because of rising costs and depletion of dredging ground. This trend was accelerated by the Korean War. The last large mine on the Mother Lode shut down in 1953. The large mines at Grass Valley shut down in 1956, ending a major industry that had lasted 106 years. The last dredge in the Folsom district was shut down in 1962, ending more than 60 years of operations. The mines at Alleghany, the last active quartz-mining district, have recently curtailed operations or shut down, and the dredges at Hammonton, the last major dredging field have gradually curtailed operations.

Since 1848, California has yielded more than 106 million fine ounces of gold, valued at 2.42 billion dollars. These figures are far greater than those for any other State and represent about 35 percent of the total United States production. In 1964, California's gold production amounted to 71,028 fine ounces valued at $2,485,980 which placed it fifth among the States in output. Much of this production came from the three active bucket-line dredges in the Hammonton district of Yuba County. Some gold was produced from a few small lode mines in the Sierra Nevada and Klamath Mountains. In addition, gold was produced from small-scale placer-mining operations, including a few dragline dredges, prospectors, skin divers, and "snipers." Some gold was recovered as a byproduct in sand and gravel plants along the east margin of the Great Valley and from tungsten and lead-zinc mines in eastern and southeastern California.

Most of California's gold production has come from five geomorphic provinces: The Sierra Nevada, which has been by far the most productive, Klamath Mountains, Great Valley, Great Basin, and Mojave Desert. Lesser amounts have been recovered in the Transverse Ranges, Peninsular Ranges, and Modoc Plateau, and small amounts in the Coast Ranges. The distribution of gold-bearing areas is shown in figure 28.

The Sierra Nevada, the dominant mountain range in California, has been the source of the bulk of the State's gold output and contains the largest number of and most productive gold districts. Most of the primary deposits are associated with intrusions of the granitic rocks of the great Sierran batholith. The gold-bearing veins occur for the most part in the belt of metamorphic rocks that extends along the western slope of the northern half of the range, along the western foothills, and in granitic stocks that are branches of the main batholith.

In the northern part of the range lie such rich and famous districts as the Alleghany, Sierra City, Nevada City, and Grass Valley. The Mother Lode belt lies to the southeast extending from El Dorado to Mariposa County. It is a system of linked or en echelon gold-quartz veins and mineralized schist and greenstone that extends from Georgetown and Greenwood southeast to Mariposa, a distance of 120 miles.

The placer deposits of the western Sierra Nevada have yielded vast quantities of gold; some estimates have placed it to be more than 40

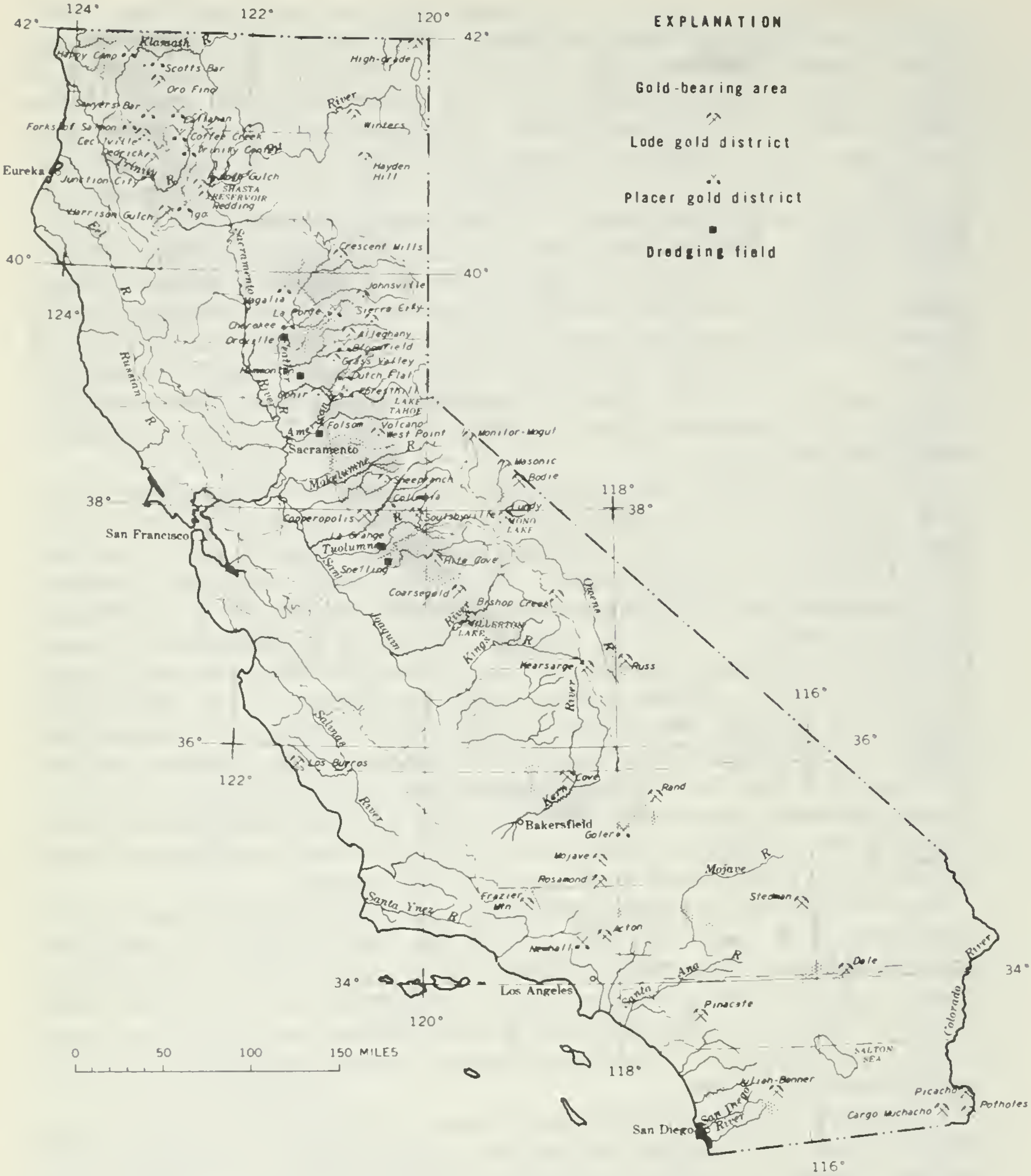

FIGURE 28. Gold-bearing areas in California.

percent of the State's total output. They are divisible into the older or Tertiary deposits which are on the interstream ridges, and Quaternary or younger deposits that are found in and adjacent to the present streams. The Tertiary deposits have been mined chiefly by hydraulicking and drift mining and the Quaternary deposits by dredging and various small-scale placer methods. The gold in the dredge fields along the east margin of the Valley was derived from the Sierra Nevada while that from the northern end of the Valley was derived from the Klamath Mountains.

The Klamath Mountains have been the second most productive area.

Here, the largest sources of gold have been the placer deposits of the Klamath-Trinity-Salmon River system and tributaries to the upper Sacramento River. Not only has gold been recovered from the present stream channels but also from adjacent older terrace and bench gravel deposits. Lode-gold deposits are found throughout the province, but the most productive have been the French Gulch, Liberty, and Harrison Gulch districts. The gold-quartz veins occur in slate and schist and often are associated with dioritic dikes. Large amounts of by-product gold have been recovered from the massive sulfide deposits of the East and West Shasta copper-zinc districts.

The Great Basin and Mojave Desert provinces of eastern and southeastern California have been significant sources of gold. The Bodie district has been the largest source of gold in the Great Basin, while the Rand, Mojave, Stedman, and Cargo Muchacho district contain the most productive mines in the Mojave Desert. Moderate amounts of gold have been mined in the Transverse Ranges, the principal sources having been the Acton and San Gabriel districts. Moderate amounts also have been recovered in the Cuyamaca, Julian, and Pinacate districts in the Peninsular Ranges and from the Hayden Hill district in the Modoc Plateau. Gold occurs in a number of places in the Coast Ranges including the Frazier Mountain district which sometimes is classified as being in the Transverse Ranges. Gold occurs in beaches along the ocean usually in very small amounts.

RESOURCE POTENTIAL

At the present time, the outlook for gold mining in California is poor. The few active commercial mining operations are gradually shutting down. There is very little possibility of a revival of gold mining under present economic conditions. A small rise in the price of gold would probably result in an increase in exploration and development in some of the more isolated "high-grade" or pocket mining districts. However, it seems doubtful if there would be much effect in the large mining districts, because of the great expense in reconditioning the mines, because many of the workable deposits have been largely depleted, and because in many districts land values have so greatly increased in recent years as to preclude their use in mining again. Another factor in the mountainous regions in California is the inundation or the plans to inundate many important mines and gold-bearing areas by reservoirs. A major change in economic conditions with a resulting large decrease in costs would undoubtedly stimulate gold mining in California as it did during the depression of the 1930's. A large rise in the price of gold would also stimulate the industry in California.

The largest undeveloped gold-bearing deposits in California are: (1) the deeply buried Tertiary channel gravels in the Sierra Nevada; (2) unmined terrace deposits in parts of the Klamath-Trinity River system; (3) low-grade gravel deposits adjacent to the dredging fields; (4) gravels too deep to be mined by existing equipment in the Great Valley; (5) deep but undeveloped veins in the major lode-gold districts; and (6) large bodies of mineralized schist and greenstone in certain districts. In addition, there are extensive zones of alteration in certain districts that are known to contain gold values, but which have not been systematically examined. Most of the above deposits are too low in grade to be mined commercially under the present economic conditions. The deeply buried channel gravels and the deep veins would have to be mined by expensive underground methods. The large bodies of mineralized schist and greenstone and the wide zones of alteration could possibly eventually be mined by open-pit and low unit-cost methods.

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GRAPHITE

(By G. B. Oakeshott, California Division of Mines and Geology, San Francisco, Calif.)

The mineral graphite is a crystalline form of pure carbon and is characterized by softness, perfect basal cleavage, and a greasy feel. A commercial distinction made between "amorphous" and "crystalline" graphite is based solely on relative grain size; the "amorphous" variety is the finer grained. The grades and specifications of graphite used in industry are complex and involved. Particles of crystalline flake graphite may be as large as 8-mesh; particles of artificial graphite in collodial dispersions may be only 5 millionths of an inch in diameter.

The most useful properties of graphite are its resistance to chemical action and the action of molten metals, its infusibility (graphite does not melt, but sublimes at about 6500°F), opacity, softness, and perfect cleavage.

A larger tonnage of graphite is used in the United States for foundry facings (41 percent of the amorphous graphite used in 1963) than for any other purpose. Consumption of natural graphite in the United States, by use, in approximate order of decreasing amounts, is in foundry facings, steel-making, lubricants, refractories, crucibles, filler for dry batteries, and "lead" pencils.

Presently (1965), natural crucible flake graphite is on the critical list and is eligible for government financial assistance up to 50 percent of exploration costs.

Much graphite has been formed by the metamorphism of carbonaceous sediments, including coal, with resultant crystallization of the carbon. However, some is associated with intrusive igneous rocks and with pegmatites; the mineral is also a constituent of meteorites. Graphite in California, all of the amorphous variety, occurs in schists and gneisses, most, if not all, of which are of sedimentary origin.

From 1865 to 1935, graphite was produced intermittently in California, but no production has been recorded since. A 50-ton concentration mill was constructed at the Kagel deposit, Los Angeles County, and produced small-flake graphite between 1918 and 1928. The total yield of California graphite is estimated to have been about 1,500 tons, valued at $137,000. The low quality of the graphite, low-grade ore, the small tonnage of graphite consumed, and ample world supply are the principal causes of the lack of production from California for the past 30 years.

World production of natural graphite in 1963 was 730,000 tons. The largest producing country was Korea (North and South); followed in order by Austria, U.S.S.R., China, and the Malagasy Republic. Statistics for the United States are concealed, so as not to reveal the production of any one company, as Southwestern Graphite Co. at Burnet, Texas, has long been the country's only producer (Drake, 1964). United States' consumption of graphite in 1963 was 47,000 tons, valued at $6,111,000 (Drake, 1964).

A third of the counties of California, chiefly in the Sierra Nevada, Klamath Mountains, Coast Ranges, and Transverse Ranges, contain graphite schists which have been prospected, but the small production has come almost entirely from Los Angeles, Tuolumne, Mendocino, and Sonoma Counties.

Several deposits in Los Angeles County were discussed by Beverly (1934). Deposits in the Placerita Formation (Paleozoic?), upper Kagel Canyon, and several in Pacoima Canyon and vicinity in the western San Gabriel Mountains of Los Angeles County were described by Oakeshott (1937; 1958). The crude graphite-bearing rock contains 7 to 15 percent graphite in flakes less than 0.25 mm in diameter.

Although graphite is widely distributed in pre-Cretaceous metamorphic rocks throughout California, owners of graphite deposits in the State have had difficulty in meeting competition provided by the higher quality imported material. No change in this situation is anticipated.

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GYPSUM AND ANHYDRITE

(By C. F. Withington, U.S. Geological Survey, Washington, D.C.)

The calcium sulfate minerals gypsum and anhydrite occur in beds formed by preciptation from saline waters, generally in partly isolated arms of the sea. Gypsum is hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$), generally white or light gray; impurities may color it dark gray, black, pink, green, or yellow. The most common form is massive rock gypsum, a compact aggregate of small crystals occurring in beds as much as 100 feet thick. Alabaster is a compact, very fine-grained variety of gypsum. Gypsite is an impure, earthy mixture of gypsum (rarely more than 70 percent), sand, silt, and clay formed near the surface in deposits that are seldom more than 15 feet thick and a few acres in extent. Gypsite is generally gray mottled with white, buff, or cream; iron may color it pink or red. Other gypsum varieties include satin spar and selenite.

Anhydrite, calcium sulfate ($CaSO_4$), is slightly heavier and harder than gypsum. It is gray, bluish gray, or white; impurities may color it red, pink, gray, or black. Anhydrite may occur as isolated crystals or lenses within a gypsum deposit, it generally replaces gypsum at depth.

Gypsum is the more useful of the two minerals; most gypsum is calcined to be used as plaster, principally in the manufacture of wallboard and other prefabricated gypsum products. Uncalcined or raw gypsum is used as a retarder for portland cement and as a soil conditioner. Gypsite is used extensively as a soil conditioner. Anhydrite is used primarily as a soil conditioner and to a lesser extent as a retarder for portland cement.

Since 1960 California has led the United States in the production of gypsum. From 1880, when the first gypsum was produced in the State at Point Sal (Santa Barbara County), through 1964, an estimated 27 million short tons of gypsum was produced. In 1964, production was 1,893,000 tons, of which about a million tons was gypsite. Nearly three-quarters of the gypsite was produced in Kern County for use as a soil conditioner for the potato and cotton crops in the San Joaquin Valley (Davis and others, 1963, p. 174). The annual production of gypsum and gypsite since 1945 is given in figure 29. Contrary to the national trend, the average price per ton of gypsum in California dropped between 1945 and 1964, due largely to the increased use of the less expensive gypsite. Resources of gypsite are sufficient to supply the State for many years; those of gypsum are not great and within a few years most of the gypsum used in the State will be imported. Imports of gypsum into California from Mexico and Nevada in 1963 amounted to more than 600,000 tons.

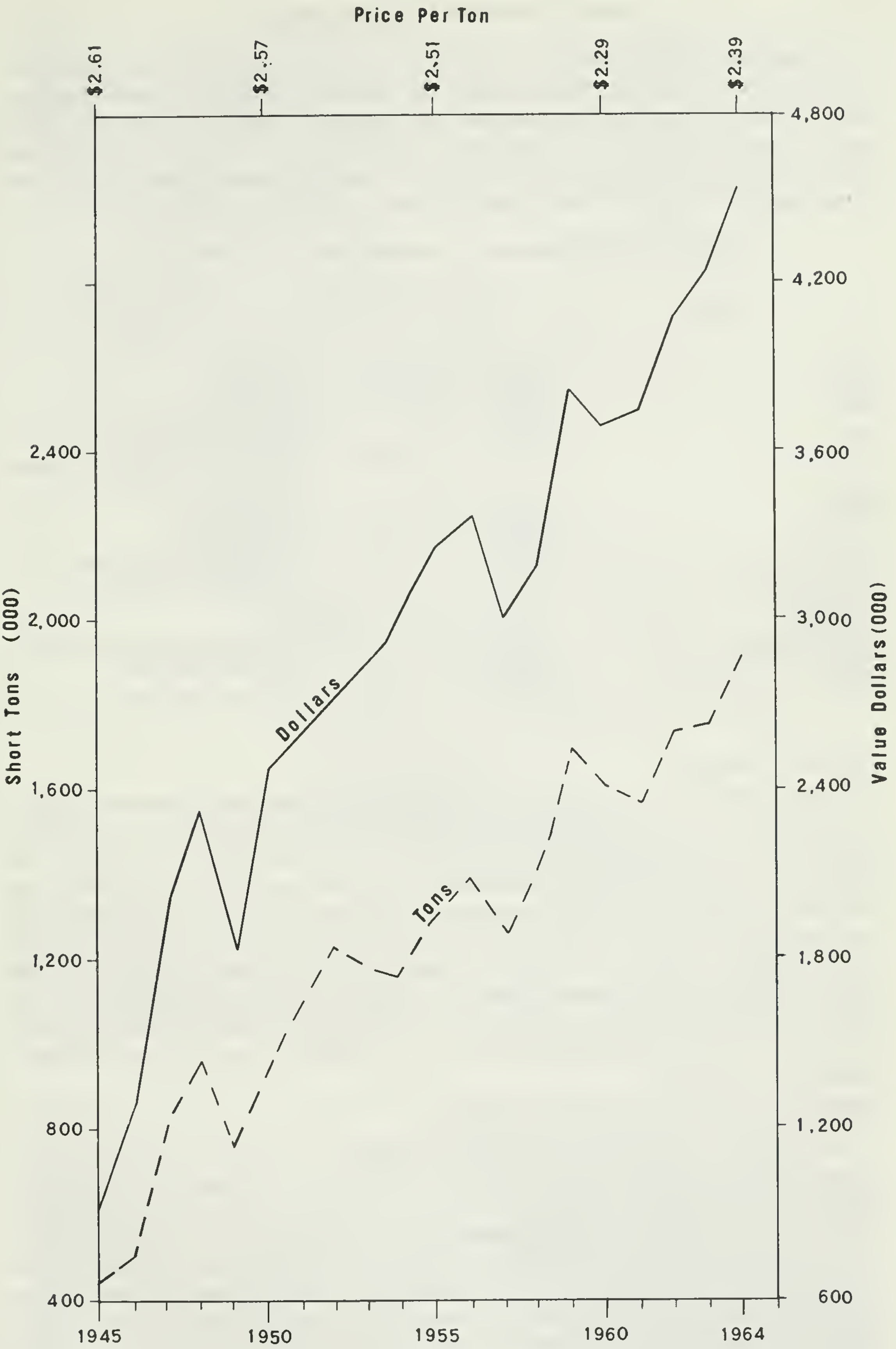

FIGURE 29. Production of gypsum in California, 1945–64.

OCCURRENCES IN CALIFORNIA

Gypsum and gypsite occur mainly in the southern part of the State. In addition to the deposits listed in table 21, gypsum was manufactured as a by-product of magnesium derived from sea water in Alameda County and as a by-product of phosphoric acid in Fresno and San Joaquin Counties. The gypsum and gypsite deposits are here described by county; their distribution is shown on figure 30.

TABLE 21.—*Distribution of calcium sulfate in California*

County	Type of deposit	Age
Fresno	Gypsite	Recent.
Imperial	Gypsum-anhydrite	Miocene.
Inyo	Gypsum	Pliocene (?).
Kern	do	Miocene (?).
	Gypsite	Recent or Pleistocene.
Kings	do	Recent.
Los Angeles	do	Recent and Oligocene or Miocene (?).
Merced	do	Recent.
Orange	Gypsum	Late Cretaceous.
Riverside	do	Permian (?).
	Gypsite	Recent.
San Benito	Gypsum	Pliocene and Pleistocene (?).
San Bernardino	do	Tertiary, Permian (?).
San Diego (described with Imperial County).	do	Miocene.
San Joaquin	Selenite veins	(?).
San Luis Obispo	Gypsite	Pliocene to Pleistocene, Recent.
Santa Barbara	Gypsum	Miocene to Pliocene.
Shasta	Gypsum-anhydrite	(?).
Ventura	Gypsum	Miocene and Pliocene (?).

Fresno County

Gypsite occurs in several small deposits in the northwestern corner of the county, including those in the Panoche Hills (No. 1) (see fig. 30), and in Tumey Gulch (No. 2) (Ver Planck, 1952, p. 49–51). In 1959, a plant was constructed near Mendota to process the gypsite from the Panoche Hills, which averages 40 percent or more gypsum; the overburden contains as much as 18 percent $CaSO_4 \cdot 2H_2O$ (Rock Products, 1959a, p. 58). The Little Panoche Valley deposit (No. 3) has yielded some gypsite guaranteed to average 70 percent gypsum, but no production has been reported since about 1953. Other gypsite deposits include: Monocline Ridge (No. 4), Oil Fields (No. 5), and those at Coalinga (No. 6).

Imperial and San Diego Counties

The gypsum deposits in Imperial County, the most extensive in the State, are in the western part of the county, extending westward into San Diego County.

Gypsum occurs on the northwest side of the Fish Creek Mountains and on the northeastern edge of the Vallecito Mountains, where it conformably overlies poorly consolidated gray sandstones and conglomerates of the Split Mountain Formation of which it is a part (Ver Planck, 1952, p. 30). Overlying the gypsum are the marine shales of the Imperial Formation.

The best exposures of gypsum are in the open pit of the United States Gypsum Co. at the north end of the Fish Creek Mountains (No. 7). Here it is white to light-gray, massive, fine- to medium-

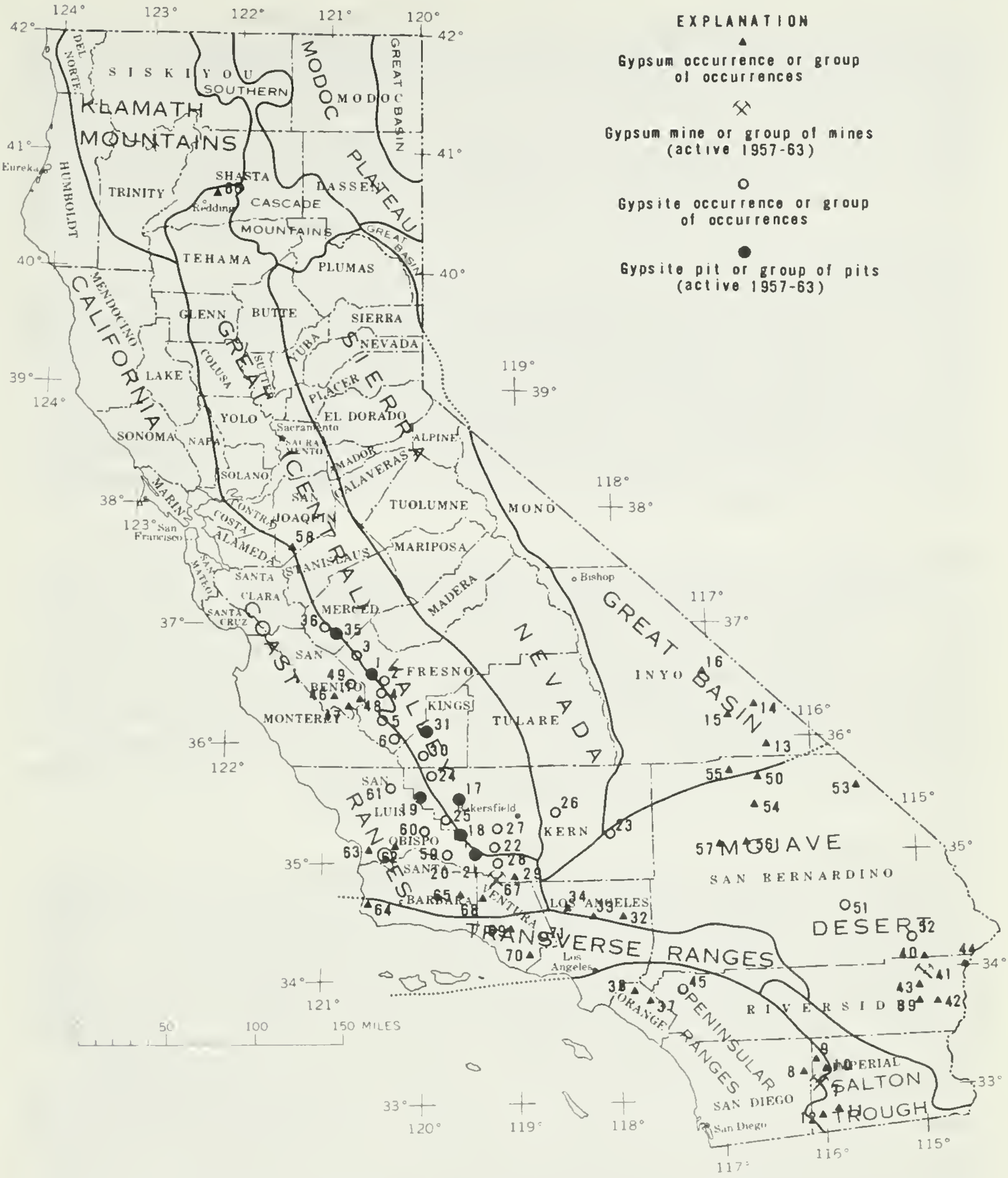

FIGURE 30. Gypsum and anhydrite in California (numbers refer to deposits named in text).

grained rock gypsum, in beds that range from about 5 to 100 feet in thickness; the thicker sections of gypsum appear to have been concentrated along the crests of minor folds where it has been squeezed from the flanks.

In the open pit, gypsum is found to a depth of 50 feet; below, it is mixed with lenses and thin stringers of anhydrite that gradually increase in thickness and quantity until the entire mass becomes anhydritic. The anhydrite is very fine to fine grained, bluish gray to white, becoming pink at the base, and includes traces of halite and other soluble sodium salts.

The original extent of the basin in which the gypsum was deposited is unknown, as the gypsum is now in isolated erosional remnants scattered over an area about 4 miles long and 2½ miles wide. The largest deposit, a mass about 2 miles long and half a mile wide, is being developed by the U.S. Gypsum Co. near the north end of the exposures. In the Vallecito Mountains northwest of the Fish Creek Mountains (No. 8), are other exposed deposits reported to be sufficient to supply a gypsum plant "* * * for 100 years" (Rock Products, 1959b, p. 50).

About 1 mile north of the open pit of the U.S. Gypsum Co. and separated from it by Fish Creek (No. 9) is an isolated outcrop of gypsum (Durrell, 1953, p. 5–7), thin bedded and dark at the base, grading upward to lighter and more massive rock.

A small gypsum deposit from which a limited amount of agricultural gypsum has been produced is on the extreme eastern side of the Fish Creek Mountains (No. 10). Other deposits include those in the Coyote Mountains (Nos. 11 and 12).

Inyo County

Southeast of Tecopa at China Ranch in the Death Valley region (No. 13), gypsum occurs in tilted lake beds of Pliocene(?) age (Ver Planck, 1952, p. 38–39). The gypsum beds range from 6 inches to 3 feet in thickness separated by thin laminations of shale. The gypsum is compact, white to light gray. Deposits at Black Mountain (No. 14), Copper Canyon (No. 15), and Furnace Creek (No. 16) are probably of early Pliocene age. They resemble the deposit at China Lake, where some mining was done in 1916 and 1917.

Kern County

Kern County is the largest producer of gypsite in the United States. In 1962 nearly three-quarters of all the gypsite produced in California, about 855,000 tons, came from this county (Davis and others, 1963, p. 202). The largest deposits are in the Lost Hills (No. 17), a low northwest-trending range about 25 miles west of Wasco. The gypsite occurs as flat-lying lenses, as much as 20 feet thick, of white, earthy, soft, and powdery material overlain by 3 to 10 feet of sandy soil.

The major producer in the Lost Hills is H. M. Holloway, Inc., of Wasco, California. In mining operations, drilling to determine the extent of the deposit is followed by removal of overburden by scraper, after which the gypsum is picked up by a mobile milling unit, which screens the material and piles it into windrows. The materials, as much as 3,000 tons daily, is sold by the truck load for soil conditioner in three grades, 60, 65, and 70 percent gypsum.

Gypsite also occurs in the vicinity of McKittrick in the western part of the county (No. 18), where it was formed in shallow basins by residual weathering of gypsiferous beds in the Monterey Shale and the Tulare Formation (Ver Planck, 1952, p. 53). It is white on the surface and gray at depth. Gypsite has been produced here intermittently since 1900. In 1955, the Superior Gypsum Co. of Bakersfield opened a deposit in the Bitterwater Creek area in the Temblor Range (No. 19) (Rock Products, 1955, p. 102). Gypsite is also produced near Maricopa (No. 20) and Taft (No. 21).

Other gypsite deposits are: at Kern Lake (No. 22), Koehn Lake (No. 23), McClure Valley (No. 24) (Hess, 1920, p. 64–65); Blackwells

Corner (No. 25) (Ver Planck, 1952, p. 123); Cottonwood Creek (No. 26), 16 miles east of Bakersfield (Hess, 1920, p. 70–71); Buena Vista Lake, (No. 27) (Hess, 1920, p. 73); and Pioneer (No. 28) (Hess, 1920, p. 70).

Gypsum occurs in Cuddy Canyon (No. 29) as thin lenses, interbedded with sandstone (Ver Planck, 1952, p. 39–40).

Kings County

Deposits of gypsite of playa lake origin are in the Avenal Gap and Kettleman Hills area, southeast of Avenal. Those at Avenal Gap (No. 30), average about 6 feet thick. The upper 2 feet consist of hard gray silt with streaks and blebs of finely divided gypsum, the lower 4 feet of fine-grained soft yellowish-white gypsite mixed with sand (Ver Planck, 1952, p. 56–57). The deposits in the Kettleman Hills (No. 31), similar to those at Avenal Gap, are being worked by the McPhaill Gypsum Co. of Visalia.

Los Angeles County

Gypsite occurs at Palmdale (No. 32), derived from the gypsiferous shales of the Escondido Formation. The deposits are exploited extensively from 1892 to about 1915 (Ver Planck, 1952, p. 57).

At Mint Canyon (No. 33), a gypsiferous zone as much as 15 feet thick occurs in the Vasquez Formation. The gypsum is gray to brown, in thin beds interbedded with coarse, angular, greenish sandstone.

Hess (1920, p. 75) reported the production of gypsite in 1904 and 1905 in Charley (Charles) Canyon (No. 34).

Merced County

Gypsite was being produced in 1952 from the western foothills of Merced County. The deposits are close to the surface and range from 6 inches to 6 feet in thickness (Davis and Carlson, 1952, p. 227–228). This material, guaranteed to contain 30 percent gypsum (California Bureau of Chemistry, 1954, p. 185), is produced by the Agricultural Minerals and Fertilizer Co. of Los Banos, in the Ortigalita Creek area (No. 35).

Another deposit occurs along the Los Banos Creek (No. 36) (Ver Planck, 1952, p. 125).

Orange County

White fine-grained gypsum occurs in Gypsum Canyon on the western slope of the Santa Ana Range (No. 37) (Hess, 1920, p. 77), in a bed 8 to 10 feet thick that contains dolomite inclusions. Apparently the gypsum-bearing rocks have been folded and gypsum thickened locally by plastic flowage. A similar deposit of unknown extent has been reported from Sycamore Canyon (No. 38) (Ver Planck, 1952, p. 125).

Riverside County

In Riverside County gypsum occurs in the Little Maria, Maria, Palen, and Riverside Mountains, and gypsite occurs in the foothills of the Santa Ana Mountains near Corona. Only in the Little Maria Mountains has there been extensive production.

The gypsum in the Little Maria Mountains is in an east-trending belt 2½ miles long to 1 and 2 miles wide that crosses the middle of the mountains. Gypsum is interbedded with shale, limestone, and gypsiferous schists of the Maria Formation of "post-Cambrian" age (Miller, 1944, p. 25), and can tentatively be correlated with the gypsum-bearing Kaibab Limestone of Permian age in southern Nevada and northwestern Arizona.

Most of the gypsum on the western side of the mountains is associated with buff limestone; minor amounts have been found with schists. The sequences of gypsum-bearing rock are as much as 150 feet thick and are poorly exposed; the surface is marked by a light-gray soil. The gypsum is interbedded with green schist, quartzite, and limestone, and generally is in masses too impure to exploit.

Coarse-grained white gypsum that averages about 93 percent pure is exposed in the southern part of the mountains (No. 39). This deposit was worked by open-pit methods by the Utah Construction Co. from 1947 to 1950. The gypsum is in beds that range from 3 to 60 feet in thickness and are associated with green schist. The beds strike N. 25° E. and have an average dip of 60° NW. Light-blue massive anhydrite was exposed in the workings.

The gypsum in the eastern end of the belt has been extensively exploited west of the town of Midland by the U.S. Gypsum Co. Two of the six beds of gypsum present are thick enough to be considered economic; the remaining beds are thin discontinuous lenses. Gypsum crops out on the north edge of the belt (No. 40), and on the south edge of the belt (No. 41).

The individual gypsum beds are faulted and folded into minor flexures; gypsum is thickest in the crests of the anticlines as the result of plastic flowage from the flanks during folding.

Dense anhydrite, white to light blue gray, is found at depths of 30 to 100 feet below the surface. Near the anhydrite gypsum is snow white and purer than at other places, suggesting that the waters which hydrated the anhydrite also introduced some impurities. Naturally-calcined anhydrite, formed by heat generated by movement along faults in gypsum, occurs as white powdery gouge 2 to 4 feet wide.

The U.S. Gypsum Co. has been mining gypsum from these deposits by open-pit and underground methods since 1925; at present only open-pit methods are used. The material is blasted, loaded by shovel into trucks for transport about 2½ miles to the mill at Midland, where it is crushed, ground in raymond mills, and calcined. The plant produces plaster, lath, and wallboard. The capacity of the open pit and mill is about 750 tons a day.

Gypsum occurs about 3½ miles east of Midland, on the west slope of the Maria Mountains (No. 42). The gypsum, in two beds separated by limestone in a bluff 300 to 500 feet high, is probably equivalent to that in the Little Maria Mountains (Tucker and Sampson, 1945, p. 170–172). Some development work has been done, but no gypsum has been produced. In 1957 this deposit was owned by the U.S. Gypsum Co.

Gypsum in three isolated masses in an east-trending belt about 3 miles long and from ½ to 1½ miles wide occurs at the north end of the Palen Mountains (No. 43). Massive beds of white, fine-grained gypsum are highly faulted and folded (Hoppin, 1954, p. 9).

Gypsum occurs on the east side of the Riverside Mountains in the northeast corner of the county, south of Vidal (No. 44) in the Colorado River Indian Reservation. Deposits include the Parkford and the Riverside gypsum deposits, both owned by the Indian Tribal Council. The age of the gypsum is unknown, but is probably equivalent to the Kaibab Limestone of Permian age. The gypsum in the Parkford deposit, is massive, white, and interbedded with limestone (Tucker and Sampson, 1945, p. 170). The individual beds, which crop out in four north-trending hogbacks, are as much as 50 feet thick, and dip 30° to 60° W. Some development work has been done, but no production reported. Gypsite in beds as much as 10 feet thick occurs below the outcrop.

The Riverside deposit is similar. The gypsum in beds alternating with limestone, has an aggregate thickness of 70 feet and is traceable along the outcrop for about 1,000 feet. Samples from this deposit are reported to average 98 percent gypsum (Tucker and Sampson, 1945, p. 170).

South of Corona, in the extreme western edge of the county, gypsite occurs in the foothills of the Santa Ana Mountains, in a belt 2½ miles long (No. 45) (Gray, 1961, p. 82–86). The gypsite is in Hagador, Gypsum (Main Street), and Eagle Canyons. The material assays only 15 to 38 percent gypsum.

San Benito County

Gypsum has been reported in Bitterwater Valley (No. 46), 10 miles northeast of King City. The gypsum is in the Paso Robles Formation in lenses 3 to 7 feet thick and as much as 900 feet wide. It is associated with beds of siltstone and light-gray sandstone (Ver Planck, 1952, p. 40). Some gypsum has been produced for agricultural use, but since 1949 the deposits have not been worked.

The Tully deposit (No. 47), on the eastern side of Bitterwater Valley consists of beds and masses of gray to white gypsum mixed with clay. A similar deposit from which some gypsite was produced around 1906 is found just west of Hernandez (No. 48) (California State Mining Bureau, 1906, p. 286–287).

A deposit of gypsite of unknown geologic setting was reported by Ver Planck (1952, p. 127) at Silver Creek (No. 49).

San Bernardino County

At the south end of Death Valley in the Avawatz Mountains gypsum is associated with salt and celestite in deformed Tertiary lacustrine beds. These beds are exposed in a northwest-trending belt about 10 miles long and 1 to 2 miles wide in the foothills on the north side of the mountains (No. 50). Ver Planck (1952, p. 45–46) has described the gypsum in five areas here.

Bristol Playa Lake covers an area of about 35 square miles (No. 51). Gypsum is present within the playa both as dunes and as irregular beds and isolated selenite crystals and plates as much as an inch long mostly along the northwest border of the lake (Hess, 1920, p. 81–82). This deposit was worked by open-pit methods from 1906 to 1924 (Ver Planck, 1952, p. 47) and the gypsum was shipped to a plaster mill at the rail head at Amboy.

Danby Playa Lake (No. 52), 14 miles long and 1 to 4 miles wide, has deposits similar to those of Bristol Lake. Selenite crystals associated with clay and silt make up as much as one-third of the lake sediments, and are concentrated along the northeast margins of the lake. Knobs of selenite crystals mixed with clay stand as much as 10 feet above the lake surface.

Gypsum occurs in the Clark Mountains in the northeast corner of the county near the Nevada State line (Ver Planck, 1952, p. 24–27) (No. 53). White, sugary gypsum, in rocks that can be correlated with the Kaibab Limestone of Permian age in Nevada, occurs in 4 or 5 beds or series of beds which crop out for about 2 miles along a dry wash. These beds range from a few feet to as much as 50 feet in thickness, strike N. 40° W., and dip about 50° SW.

The Red Canyon deposit (No. 54), is on the west-central part of the Shadow Mountains about 12 miles north of Baker (Wright and others, 1953). Gypsum is in layers a few inches thick in yellow siltstone of Tertiary age. The largest exposed body is a 6-foot sequence of thin beds of gypsum exposed for about 70 feet along strike. Some prospecting has been done.

The Owl Hole Spring deposit (No. 55) is similar to the Avawatz Mountain deposit (Ver Planck, 1952, p. 39). Thin beds of gypsum and gypsiferous shale occur in Pliocene(?) lake beds which strike east and dip north.

Deposits of unknown extent are reported from Field (No. 56) and the Calico Mountains (No. 57) (Ver Planck, 1952, p. 128). The latter was apparently worked briefly in 1916.

San Joaquin County

Selenite in veins near Vernalis (No. 58) has been reported by Ver Planck (1952, p. 129). These occurrences are of mineralogic interest only.

San Luis Obispo County

Gypsite occurs in the Carrizo Plain (No. 59) in rocks of the McKittrick Group of former usage (Jacalitos to Tulare interval) along the margins of playa lakes. The deposits are essentially elongate lenses, the largest about 1,500 feet long and as much as 4 feet thick, of limy tan, sandy or earthy gypsite associated with fine-grained gravels or gray silt. Deposits several miles east of Simmler (No. 60) are worked by the Superior Gypsum Co. of Bakersfield, which produces material guaranteed to contain at least 70 percent gypsum (California Bureau of Chemistry, 1954, p. 187).

Other deposits include: 1) tan limy gypsite at Shandon (No. 61) (Ver Planck, 1952, p. 58–59), in a lens about 500 yards long and 200 yards wide on the margin of a playa lake from which some mining has been reported, and 2) lenticular masses of gypsum along Alamo Creek (No. 62) and Arroyo Grande Creek (No. 63).

Santa Barbara County

Gypsum at Point Sal (No. 64) occurred as nodules and veins in shale of Miocene age. This deposit, mined from about 1880 to 1889, was the first important source of gypsum in the State (Ver Planck, 1962, p. 67).

Deposits in the Caliente Formation of Miocene to Pliocene age (Ver Planck, 1952, p. 41) crop out in a northeast-trending belt about 7 miles long on the northeastern edge of the county in Cuyama Valley (No. 65) and extend to Ventura County. The beds consist of interbedded dark-brown shale, sandstone, and thin lenticular gypsum as much as 10 feet thick. The gypsum is white and alabaster in texture and contains green shale laminae and lenses. In 1960, agricultural gypsite was produced from a small deposit one-half mile south of Ventucopa; the deposit is now exhausted.

Shasta County

Gypsum and anhydrite occur as large bunches or masses as gangue minerals in the deeper levels in the Bully Hill and Rising Star copper-zinc mines (No. 66), (Graton, 1910, p. 100, 103). Masses of gypsum are commonly banded by inclusions of thin parallel films of sericitic and chloritic material. Included in the calcium sulfate minerals are finely disseminated crystals of pyrite. Graton believed that the anhydrite was introduced by ore-bearing solutions and later altered to gypsum.

Ventura County

Gypsum has been produced in Quatal Canyon, from 10- to 30-foot-thick beds in the Santa Margarita Formation, which crops out at irregular intervals for a distance of 7 miles in a northwest-trending belt. On the northern edge of the belt (No. 67), on the north side of Quatal Canyon, the Monolith Portland Cement Co. has produced gypsum for cement retarder. Other deposits occur north and south of Quatal Canyon (Ver Planck, 1952, p. 35).

At the south end of the belt of gypsum-bearing rocks, in Burges Canyon, gypsum lenses as much as 10 feet thick are associated with green shale. Extremely fine grained alabaster, notably at French Point (No. 68), has been used locally for art objects.

Other gypsum deposits were reported from Ojai Valley (No. 69); on the east flank of South Mountain, 4 miles south of Santa Paula, (No. 70); and 4 miles south of Fillmore (No. 71) from which some production was reported (Hess, 1920, p. 85).

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IODINE

(By G. I. Smith, U.S. Geological Survey, Menlo Park, Calif.)

Iodine is produced in the United States from well brines. Plants operated by the Dow Chemical Co. in Michigan and California furnish the entire domestic output, and this satisfies a large part of United States requirements (Miller, 1964; Stipp, 1960).

Most iodine is first produced in crude form (at least 99 percent pure), but before use is either resublimed to a purer elemental form or converted to potassium iodide or other inorganic or organic compounds. Its uses are many. Iodine and its salts are used as antiseptics and for other medical purposes, as additives to food for both humans and animals, as components of photographic emulsions, and for sanitation, metal production, and other specialized chemical uses. The isotope iodine-131 is used as a tracer for industrial and research purposes. Consumption of iodine in the United States has increased steadily; in 1963 it was 8 percent higher than in 1962, and more than twice that of 1953. The current price of crude iodine in kegs is $1.18 per pound (Miller, 1964).

In the early 1800's, iodine was produced in Europe from seaweeds; these plants concentrate iodine from sea water, and, after treatment, some seaweed residues contain as much as 1.8 percent iodine. In the late 1860's, production of iodine as a by-product of the Chilean nitrate industry began, and that source dominated world supply for over a half a century. In 1928, production from brines began in Louisiana, and by 1932, production from California brines became the major domestic source. Similar sources were developed at about the same time in Russia, Germany, France, and England (Keiser, 1960; Ver Planck, 1957; Stipp, 1960; Miller, 1964).

Iodine production in California started in 1932 at a plant at Long Beach operated by the General Salt Co. Shortly thereafter, a plant operated by the Deepwater Chemical Co., Ltd., was started at Compton, and the Dow Chemical Co. started extraction operations at Seal Beach, Venice, and Inglewood. All use brines that accompany the oil pumped to the surface in oil wells. Several fields produce brines containing abnormal quantities of iodine, but only those at Dominguez, Playa del Rey, Inglewood, Seal Beach, and Long Beach contain recoverable amounts. These brines average 2½ to 3 percent total solids and contain an average of about 50 ppm iodine (Ver Planck, 1957). Only the Dow Chemical Co. plant at Seal Beach is still in operation, and production is currently being transferred from that plant to Michigan (Miller, 1964).

No other economic sources of iodine are known in California.

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IRON

(By Lyman Moore, U.S. Bureau of Mines, San Francisco, Calif.)

IMPORTANCE AND USE

Iron ore is the basic raw material for iron and steel, the foundation of industrialized civilization; in tonnage, over 90 percent of all metal consumed in the United States is iron or steel.

Iron in a relatively pure state, such as wrought iron, is a tough malleable inexpensive metal. *Steel* is a mixture (alloy) of iron and carbon. The term *alloy steel* is used to describe mixtures of steel and other elements such as tungsten, nickel, vanadium, and many others. By varying the carbon content, heat treatment, and forming methods, steels can be made having a wide range of physical properties. Properties range from those of low carbon steel with moderate yield strengths and the ductility required to allow cheap mass production by pressing and stamping, to spring steels having high yield strengths. Engineering, tool, razor, stainless, and other specialized steels possess extreme strength, hardness, toughness, resistance to corrosion and heat softening, and other desirable properties. The relatively low price of steel, along with its versatility, makes it the indispensible metal in our economy. The principal users in the United States, in decreasing order of importance are: 1) automotive, 19 percent of the total consumption; 2) construction, 17 percent; 3) containers, 8 percent; 4) oil and gas industry, 7 percent; 5) industrial machinery, 6 percent; 6) rail transport, 6 percent; 7) electrical machinery, 3 percent; 8) appliances, 3 percent; and 9) agricultural, 2 percent.

GEOLOGIC OCCURRENCE

Iron is an abundant metal, comprising about 5 percent of the earth's crust. Iron ore deposits are widely distributed throughout the world, and are estimated to contain over 70,000 million tons of iron ore. Under present economic conditions, only ore bodies located conveniently to steel markets and sources of coking coal or deposits either of unusual size and grade or particularly adapted to low-cost production can be utilized.

A variety of geologic processes have formed the iron concentrations which supply the world's industry. The most prominent, known as the *Lake Superior* type, occurs in northern Minnesota, Wisconsin, and Michigan, and in Labrador, Venezuela, Brazil, Russia, South Africa, India, Australia, and China. These deposits were formed in Precambrian time through the selective leaching of meteoric waters of thick sedimentary iron formation called taconites. Taconites consist of banded or irregularly intermingled chert and ferric oxide. Technologic advancements have made it profitable to utilize portions of the iron formation itself.

Sedimentary iron ores, although generally low grade, have been of great past importance, partly because of their frequent geographical proximity to coal measures. However, recent reductions in world iron ore prices, brought about by improved mining and processing methods and cheaper transportation, have reduced production from these deposits. The most important sedimentary iron ore districts have been Birmingham, Ala.; Lorraine, France; Luxembourg; and Yorkshire, England. The ores occur in well-defined sedimentary beds and have a wide regional extent. In some locations the beds are as thick as 40 feet, but they rarely exceed 12 feet. Hematite, limonite, or siderite may be the predominant iron mineral and the ores usually have an oolitic structure.

Kiruna-type deposits, mainly magnetite with considerable apatite, occur in northern Sweden. They commonly are tabular and were formed by processes of fractional crystallization and injection similar to those that result in the intrusion of igneous dikes.

Contact metamorphic deposits are common throughout the world and many examples are known in the western United States, including California. These deposits are formed at high temperatures in limestone or dolomite beds at their contact with intrusive rocks. Magnetite is the principal iron mineral and a gangue of garnet and other lime and magnesium silicates is characteristic. Contact deposits are not formed in chemically inert rocks and in these the mineralizing solutions proceed some distance from the source and deposition takes place as the solutions cool. These deposits are referred to as *hydrothermal* and are a type of deep-seated vein deposit. *Replacement* deposits are formed in limestone or other rocks.

History and Production

The first iron works in the United States was built near Jamestown, Va., in 1620 and the first steel was made in 1728 at Hartford, Conn. Modern United States steel manufacture began with the first pour of Bessemer steel in 1864, followed by the first open-hearth steel in 1868. The 1860 census reported United States production of 3.2 million long tons of iron ore, slightly less than 1 million short tons of pig iron, and only 11,838 short tons of steel. By 1900, United States production was 27.5 million long tons of iron ore, 13.8 million short tons of pig iron (34 percent of world output). In 1963, production was 73.6 million long tons of iron ore, 71.8 million short tons of pig iron (23 percent of world output), and 75.6 million short tons of finished steel (26 percent of world output). The United States has been the world's largest producer of iron and steel since 1897.

Only small quantities of iron ore were produced in California before World War II. Foundries and rolling mills have been active in the State since the pioneer period and the first open hearth was built in 1884. The steel furnaces were charged with scrap and imported pig iron; the rolling and finishing mills used imported ingots and coils as well as ingots cast locally. No blast furnaces were in operation. Production of pig iron in California was hampered by a lack of coking coal, which had to be shipped in from the Rocky Mountain or Appalachian fields; by the small size of the market, which prevented the use of more efficient large-sized furnaces; and by low shipping rates, as ballast for steel imports.

California's primary iron and steel production has grown rapidly since Kaiser Steel Corp. built a blast furnace in 1942 at Fontana. Although there is still only the one primary plant in the State, pig-iron capacity has been increased from about 400,000 short tons in 1942 to almost 2 million tons in 1960. This capacity is still only a little over 2 percent of United States capacity whereas California has 10 percent of the nation's population. Thus, continued growth of the industry within the State seems probable.

Present blast furnace capacity requires about 3.2 million long tons of iron ore containing 60 percent Fe. An export market for iron ore with Japanese steelmakers has developed since 1950 and contracts in force in 1964 provide for the shipment of 1 million long tons per year from mines within the State. Other California uses of iron ore are as lump in open-hearth steelmaking, as an ingredient in low-heat portland cement, as heavy aggregate for ballast and nuclear shielding, as a pigment, as a fluxing agent, and miscellaneous uses. These other uses require about 200,000 long tons of iron ore per year.

Iron ore production statistics for California have not been published since 1956. It is believed that in recent years blast furnaces have been operating at near capacity and that iron ore has been exported at somewhat above published contract levels. Thus, overall production is about 4.4 million long tons of 60 percent iron ore per year. This is about 3 percent of the United States total and places California sixth among the producing states.

Occurrences in California

The important iron occurrences in California are shown on figure 31 and basic information concerning each deposit is given in table 22.

Geographically, California's iron deposits are concentrated in the Mojave Desert province in western San Bernardino and Riverside Counties. About 99 percent of the State's production has come from this area. The area contains over 90 percent of the State's known resources. All of the Mojave deposits are of igneous origin and differ mainly in the kind of wall rock present and its consequent effect upon the type of deposit formed. Contact metamorphic deposits, the area's most prominent type, are formed at high temperatures in limestone or dolomite at their contact with intrusive rock. The Eagle Mountain and Lava Bed deposits are of this type. They are characterized by magnetite replacement and a gangue of contact silicates such as

TABLE 22.—*Iron ore districts, mines, deposits, and prospects in California*

Index No. (fig. 31)	District, mine, deposit, or prospect	County	Type of deposit	Production	Reference
1	Hirz Mountain	Shasta	Magnetite replacement of limestone along diorite contact.	Small	California Div. Mines Bull. 129.
2	Shasta and California	do	do	Medium	California Div. Mines Bull. 129.
3	Iron Mountain	do	Magnetite as lenses in rhyolite, 700 feet south of sulfide body.	Small	Shattuck and Ricker, 1948.
4	Bonner	Plumas	Magnetite veins and lenses in andesite	do	
5	Brown	do	Magnetite in small veins and as abundant float in andesite area.	do	
6	Rusty Ridge	Butte	Magnetite replacement in shaley limestone near granite.	do	
7	Martin	do	Magnetite in vein	None	
8	Lake Hawley and Spencer lakes	Sierra	Magnetite in irregular lenses	do	California Div. Mines Bull. 129.
9	Hotaling	Placer	Magnetite replacements in quartzite along diabase contact.	Small	Harder, 1909.
10	Ione	Amador	Residual capping of iron-rich sandstone	None	Carlson and Clark, 1954.
11	Wilson	Mono	Mineralized fracture zone in metavolcanic rocks	do	
12	Churchill	do	Magnetite veins in quartzite and replacement in gabbro dike.	do	
13	Minarets	Madera	Lenses of magnetite in dacite	do	California Div. Mines Bull. 129, Severy, 1946.
14	Red Top or Detroit Group	do	Magnetite replacement of limestone at granite contact	do	
15	Hart Group	do	Replacement lenses of magnetite and hematite in limestone.	do	Hubbard, 1950.
16	Morning Star	do	Lenses of magnetite and sulfides along quartzite-granodiorite contact.	None	Do.
17	Rising Sun	do	Magnetite and iron sulfides along quartzite–granodiorite contact.	do	Do.
18	Wedge Group	do	Magnetite and hematite replacement in limestone	do	Do.
19	Aptos Beach Sand	Santa Cruz	Beach sands	Small	Hubbard, 1943.
20	Prefumo (McKinney)	San Luis Obispo	Sedimentary limonite	None	Frank, 1935.
21	Le Cyr (Valley View)	Inyo	2 hematite veins in brecciated limestone	do	Norman and Stewart, 1951.
22	Coso	do	Hematite and magnetite veins in granite	Small	Do.
23	Millspaugh (Big 4)	do	Small irregular lenses of hematite and magnetite in granite.	do	Do.
24	Iron Cap (Hoot Owl)	do	Hematite and magnetite replacement in limestone along granite contact.	do	Do.
25	Iron Chief and Ferro	do	Hematite veins in granite	do	Do.
26	Mister Group	do	Low-grade zone of specular hematite in granite gneiss	do	Do.
27	Kingston District: Beck	San Bernardino	Magnetite and secondary hematite in limestone at amphibolite contact.	None	California Div. Mines Bull. 129, Wright, 1953.

28	Black Magic Iron	do	Hematite replacement in limestone near granite	Small	Wright, 1953.
	Silver Lake District:				
29	Iron Mountain	do	Magnetite and hematite replacement in limestone, now brecciated.	Medium	California Div. Mines Bull. 129, Wright, 1953.
30	Iron King	do	Contact metamorphic replacement of limestone breccia by hematite and magnetite.	None	Do.
31	Tiefort Mountains	do	Large hematite vein in gneissoid granite	do	Wright, 1953.
32	Mammoth Group	do	Unknown	do	Do.
	Cave Mountain District:				
33	Cave Mountain	do	Small bodies of magnetite in diorite	Small	Do.
34	Arrowhead Lode	do	Disseminated magnetite in vein in fine-grained diorite	None	
35	Meir Group	do	Hematite in 1- to 6-foot veins in metamorphic rock near granite contact.	do	
36	Cronese	do	Magnetite and hematite replacement along fault in biotite diorite.	Small	
37	Cave Canyon	do	Magnetite and hematite replacements in gneiss, quartzite, and limestone.	Medium	California Div. Mines Bull. 129. Wright, 1953.
38	Old Dad Mountain (Reat, Riet)	do	Magnetite and hematite replacement in limestone near monzonite contact.	None	Do.
39	Iron Hand	do	Lenses of magnetite and hematite in limestone near monzonite intrusive.	do	Wright, 1953.
40	Specular	do	Vein of specular hematite in dolomite	Small	Do.
	Providence District:				
41	Providence	do	Unknown	None	Do.
42	Cornfield Springs	do	Specular hematite replacement in limestone	do	Do.
43	Vulcan	do	Magnetite and hematite replacement in limestone	Large	California Div. Mines Bull. 129. California Div. Mines Bull. 176, Wright, 1953.
44	Burro	do	Magnetite and hematite replacement in limestone	None	
45	Altuda (Globerson)	do	Hematite veins and replacements along shear zones in metavolcanic rocks.	Small	Wright, 1953.
	Lava Bed District:				
46	Ord Mountain	do	Magnetite lenses in marble inclusions in quartz monzonite.	None	
47	Ball (Red Seal)	do	Small magnetite replacements in dolomite	do	Wright, 1953.
48	Cat	do	Unknown	do	
49	Man	do	do	do	
50	Ord	do	do	do	
51	Ebony	do	Magnetite veins in dolomite near granite contact	Small	California Div. Mines Bull. 129, Wright, 1953.
52	Bessemer	do	Magnetite veins and replacements in dolomite	do	Do.
53	New Bessemer (Alarm)	do	Tiny magnetite veins along granite-dolomite contact	None	California Div. Mines Bull. 129.
54	Morris Lode (Van Buren Group).	do	Irregular magnetite replacements in dolomite	Small	California Div. Mines Bull. 129, Wright, 1953.
55	Amboy	do	Small hematite lenses in limestone near granite contact	None	Wright, 1953.
56	Black Jack Iron	do	Magnetite replacements in dolomite near granite contact.	do	Do.

TABLE 22.—*Iron ore districts, mines, deposits, and prospects in California*—Continued

Index No. (fig. 31)	District, mine, deposit, or prospect	County	Type of deposit	Production	Reference
57	Iron Heat	San Bernardino	Magnetite in irregular replacements along dolomite-granite contacts.	Small	California Div. Mines Bull. 129, Wright, 1953.
58	Ship Mountain (Paul)	do	Brecciated hematite lenses in chloritic schist	do	Do.
	Dale District:				
59	Copper World	do	Magnetite and hematite veins in quartz diorite	do	Wright, 1953.
60	Iron Age	do	Parallel veins of magnetite and hematite in granite	Medium	Do.
61	Iron Age Extension	do	Magnetite and hematite in veins in andesite near monzonite contact.	Small	Do.
62	Unnamed	do	Hematite and magnetite veins in quartz diorite	None	
63	Doris	do	Kidneys of magnetite in large fault-fissure in quartz diorite.	do	
64	Titaniferous Magnetite	Los Angeles	Irregular bodies of titaniferous magnetite in anorthosite.	do	Wright, 1953.
65	East Wide Canyon	Riverside	Magnetite and ilmenite in lenses and layers in gneiss	do	Saul, Gray, and Evans (in press).
66	Sulfide Bismuth	do	Magnetite-rich sulfide body in gneiss	do	Do.
67	Storm-Jade Mountain	do	Unknown	Small	
68	Eagle Mountain	do	Magnetite and hematite replacement in limestone	Large	California Div. Mines Bull. 129, Saul, Gray, and Evans (in press)
69	Desert Eagle	do	do	do	Do.
70	Iron Cap (Iron King)	do	Magnetite in shear zone in contact silicates	None	Do.
71	Iron King (Iron Queen)	do	Magnetite lenses in fault zone	Medium	Do.
72	Little Maria	do	Magnetite replacement in limestone	None	Do.
73	Maria Mountains	do	Horizontal magnetite in dolomite capping hill	do	Do.
74	Lindy Loop No. 1	do	Hematite in veins along fault contact	do	Do.

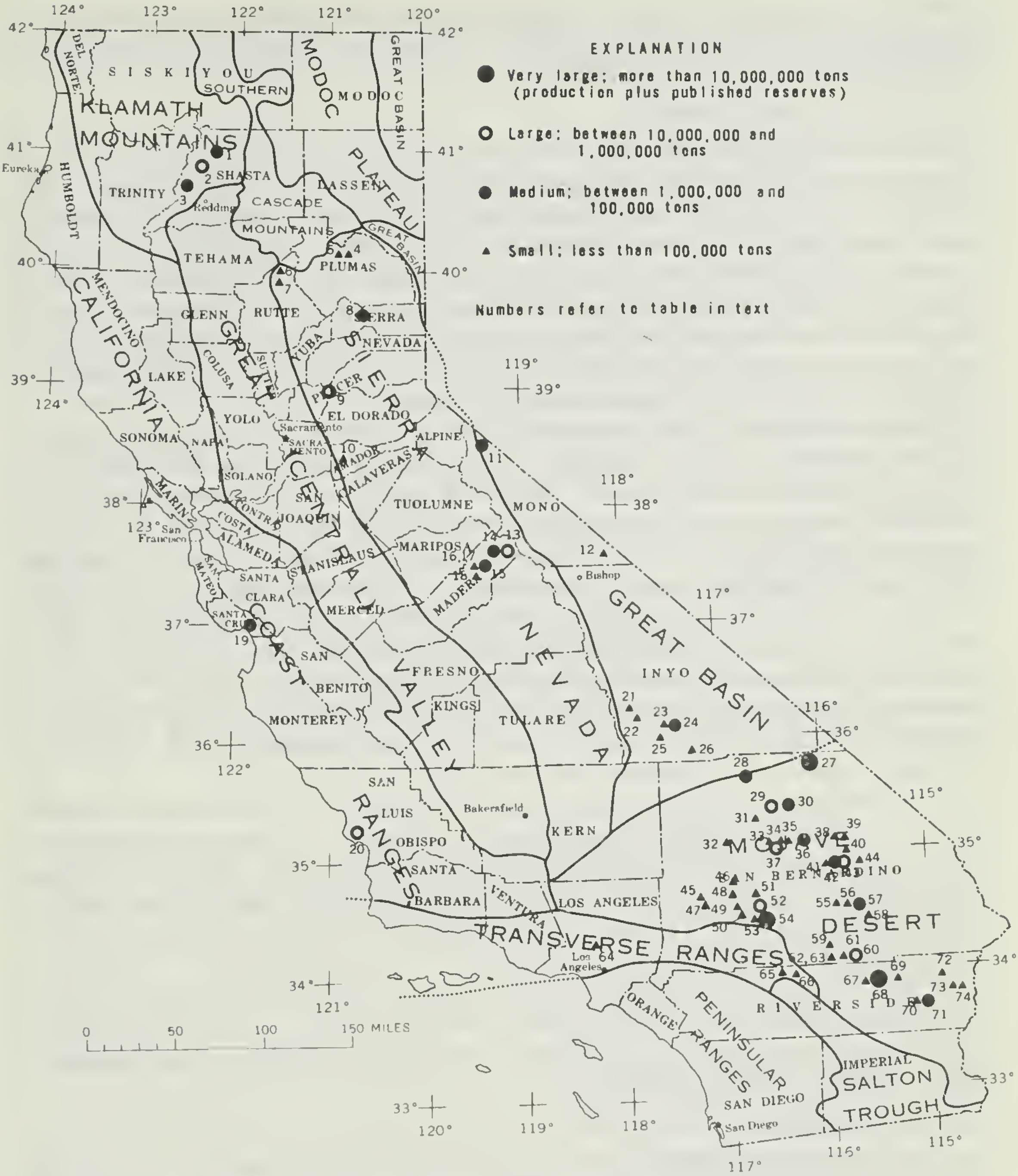

FIGURE 31. Iron ore in California (numbers refer to table 22).

garnet, epidote, and pyroxene. Other deposits, such as the Vulcan, show similar structural relationships but rock alteration processes were less intense. Some deposits are of the hydrothermal replacement and vein-filling type. An example is the Iron Age, where magnetite occurs as veins in granite some distance from any apparent source of ore-depositing solutions.

Other iron-ore deposits occur in the Sierra Nevada province, particularly in Western Madera County. The Minarets is the most important and is a hydrothermal replacement in dacite. Western Shasta County, in the Klamath Mountain province, contains contact metamorphic magnetite deposits. A small sedimentary limonite deposit occurs in San Luis Obispo County and some production has come from beach sands in Santa Cruz County. The State's most prominent iron-ore deposits are described below.

Eagle Mountain district

Most of California's iron-ore production has come from the Eagle Mountain district (No. 68, fig. 31) in Riverside County, 60 miles east of Indio. Deposits occur throughout a belt that extends 7 miles east-west and has a width of about 1 mile. Past production has been mostly from large ore bodies at the eastern end of the belt. Kaiser Steel Corp. is the only producer and owns most of the district's mineral rights. Most of the blast furnace feed for Kaiser's Fontana steel mill, plus the ore needed to satisfy a 1 million-ton-per-year export contract is obtained from the Eagle Mountain mine.

The mineralized area is underlain by a series of quartzites and dolomites which have been folded into a broad anticline that locally is closely folded and faulted. Large elongate bodies of quartz monzonite have intruded the sediments with the development of calcium magnesium silicates in the dolomite and with heavy iron mineralization, particularly in two dolomite beds. The ore deposits are roughly tabular in shape conforming to the distribution of the dolomite. Individual ore bodies extend for as much as 3,000 feet along the strike and have been developed to a depth of 1,000 feet on a dip of 45°. The ore width being mined consists of a footwall ore bed 40 to 140 feet in width and a hanging-wall ore bed 30 to 300 feet in width. The two beds are separated by 200 to 300 feet of barren quartzite.

The primary ore is magnetite but throughout a thick zone of oxidation it has been partially weathered to hematite. The ore ranges from 40 to 50 percent Fe and is beneficiated before use. Sulfur, the only contaminant, is low enough in the oxidized ore to permit use without further treatment. In the primary ore, sulfur content is reduced by sintering or pelletizing.

Kaiser Steel Corp. has estimated that 108,675,000 long tons of ore containing 45.2 percent Fe can be mined profitably at 1965 prices from the present open pit. No estimate has been published of resources in the remainder of the district.

Lava Bed district

The Lava Bed district, 30 miles northeast of Lucerne Valley, has produced over 50,000 long tons of direct shipping iron ore from the Bessemer, Morris Lode, and Ebony properties. Extensive exploration has been done on the Bessemer, Morris Lode, and Cat-Man-Ord properties.

Bessemer.—Production from this property (No. 52, fig. 31) totaled 28,000 tons from 1945 to 1951. The Bessemer deposit consists of replacements of magnetite in dolomite along an irregular contact with granite. The mineralized dolomite occurs as remnants, now engulfed in granite, or as points of dolomite surrounded on three sides by the intrusive. The largest ore body covers an area of about 50,000 square feet and has been mined by open pit. In the deposit medium-width veins of high-grade ore are interspersed with barren or selectively replaced beds of dolomite. Fourteen small ore bodies crop out in the area and additional bodies were found under nearby alluvium by magnetite prospecting and drilling (Wright, 1953, p. 86–100). The deposit was estimated to contain 1.8 million tons of 30 to 65 percent Fe ore of which 240,000 tons contained between 60 and 65 percent Fe (Calif. Div. Mines Bull. 129).

Morris Lode.—The Morris Lode (No. 54, fig. 31) produced 17,500 tons in 1949–1950 for use in cement manufacture and a few thousand tons of lump ore in 1957. The mineralized area is underlain by dolomitic limestone intruded by granitic rocks. Large skarn areas were formed in the dolomite along the granite contact. Two types of ore occurrences are present: (1) Small irregular bodies of high-grade ore are found along the dolomite-granite contact, often completely replacing small inclusions of dolomite, and (2) a large deposit of medium- and low-grade ore is found in a skarn zone adjacent to the contact. In 1944–1945, a magnetic anomaly 1,000 feet wide and 1,500 feet long was delineated. Subsequent drilling revealed an ore body with an area of about 10 acres. Eight drill holes intersected from 120 to 921 feet of iron ore with an average grade of 37.32 percent Fe. Two holes drilled in a zone of lower magnetic intensity surrounding this area intersected from 100 to 400 feet of material with more than 15 percent Fe (Wiebelt, 1947).

Magnetite is the predominant ore mineral but some primary hematite is found at depth and somewhat earthy secondary hematite and limonite occur near the surface. The ore has about 2 percent sulfur in the form of pyrite, but phosphorus and other impurities are low.

Baxter district

The Baxter district is about 16 miles west of Baker, and immediately north of the Mojave River. Although no production figures have been published the Cave Canyon mine has had moderate production, and small production has come from the Cronese and Cave Mountain properties. Shipments were made from 1934 to 1957. The iron ore was used almost entirely in the manufacture of low-heat portland cement.

Cave Canyon mine.—The area containing this deposit (No. 37, fig. 31) is underlain by Precambrian gneiss and quartzite, by a later Precambrian limestone, and by Tertiary sandstone and fanglomerate. Intrusive into the Precambrian rocks is a diorite porphyry to which the iron mineralization is related. The ore area is intensely brecciated by faulting and folding. The iron ore occurs as a replacement of the Precambrian rocks and the prevalence of remnants of unreplaced limestone in the ore zone indicates that this rock was most susceptible to mineralization. In places, quartzite also is mineralized and grades into ore. The iron was deposited as magnetite but has been oxidized to about one-half hematite. Some gypsum is present.

Reserves were estimated in 1944 as 4,105,000 long tons, of which only 1,350,000 long tons was recoverable at 1944 prices. Because of the intense brecciation, much dilution of the ore is inevitable during mining, and beneficiation would be required to make a high-grade product.

Providence district

The Providence district is on the west slope of the Providence Mountains in San Bernardino County about 9 miles southeast of Kelso.

All of the district's production has come from the Vulcan mine (No. 43, fig. 31), which provided the primary source of iron ore for the Fontana steel plant during World War II. It produced 2,643,000 long tons in the period from 1942 when the mine was opened to 1947 when demand was shifted to the Eagle Mountain mine. Subsequent production has consisted only of moderate quantities of lump ore and ore for use in low-heat portland cement manufacture.

The Vulcan area is underlain by marine sedimentary rocks ranging in age from Cambrian to Jurassic which were intruded by quartz monzonite in Jurassic time and which were later intruded and partly covered by Tertiary rhyolite. The iron-ore deposit occurs as a mushroom-shaped replacement in marbleized Cambrian limestone adjacent to quartz monzonite whose contact with the limestone and ore is a fault plane. At the surface the ore body was 700 feet long and 325 feet wide, but at depth the deposit decreased in horizontal cross section and became pipe shaped. The ore has been intersected to a depth of 900 feet in drill holes. Hard, dark magnetite is the primary ore mineral. A small amount of hematite, which decreases at depth, is present. Sulfur, occurring in pyrite, is prominent in the primary ore and is the only impurity of consequence. Weathering removed the sulfur from the upper 50 feet of the deposit.

The property was estimated in 1944 to contain 5,680,000 long tons of plus 50 percent Fe in the main ore body and additional ore in the south ore body. After consideration of ore mined subsequent to 1944 and after including the south ore body, reserves are estimated at 5,520,000 long tons.

Silver Lake district

The Silver Lake district is in San Bernardino County, about 13 miles northwest of Baker. All of the production has come from the Iron Mountain property which contains most of the district's resources. The adjoining Iron King is a small deposit similar in character to the Iron Mountain.

Iron Mountain mine.—Moderate quantities of ore were shipped by Kaiser Steel Corp. to its Fontana plant from this property (No. 29, fig. 31) during 1953 and from 1962 to 1964. The district was explored by the U.S. Geological Survey in 1943 and 1944, and in 1944, the U.S. Bureau of Mines drilled 12 holes on the property.

The ore-bearing formation is an extensive breccia over 200 feet thick consisting predominately of broken limestone but containing lenses composed of fragments of igneous and contact-metamorphic rocks and of iron ore. Individual lenses are chiefly of one type of rock. The breccia is underlain by sandstone and conglomerate and in the mine area is overlain only by alluvium. A few hundred feet south of the iron-ore deposits the sediments are in fault contact with andesite that has been intruded by quartz monzonite. However, no igneous rocks are known to intrude the sedimentary series containing the iron-ore breccia.

Iron occurs as lenses of both solid massive magnetite and of breccia ore. In addition to iron oxide, the latter ore contains fragments of contact-metamorphic rock and partly replaced limestone. The ore lenses are conformable to the limestone breccia and dip at angles of 20 to 35° with the long dimension of the oreshoots extending down the dip. Magnetite is the predominant iron ore mineral; a small amount of secondary hematite also is present. The ore is low in sulfur and phosphorus. Opinions differ as to the origin of the deposit; some geologists consider it a contact-metamorphic deposit that has been shattered by faulting; others consider it to be a product of coarse weathering of a now completely eroded iron-ore deposit; and it is not unreasonable to consider it a hydrothermal deposit derived from the quartz monzonite or from an unexposed igneous source.

Ore reserves as established by Bureau of Mines drilling in 1944 were 6,175,000 long tons of material containing 54 percent Fe.

Kingston district

The Kingston district (No. 27, fig. 31) is in northeastern San Bernardino County, 20 miles east of Tecopa. All of the ore, except for some small prospects, occurs in the Beck deposit in a single geologic horizon. The substantial size of the deposit was proven in 1924 when 14 holes were diamond drilled. However, only small quantities have been mined and shipped for test work, chiefly because of high transportation costs.

Magnetite occurs as the replacement of a 100-foot-thick white crystalline limestone bed in a Precambrian series of quartzite, dolomite, and limestone. A thick sill of amphibolite of uncertain age occurs immediately below the limestone. Along the limestone-amphibolite contact, iron ore replacements occur in the footwall of the limestone bed. In places the iron mineralization occurs across the full thickness of the limestone and extends into the igneous rock. The deposits dip steeply and are cut off at a depth of several hundred feet by a nearly horizontal post-ore thrust fault. The iron-ore deposits are thought to have been formed by hydrothermal processes from solutions emanating from a large body of quartz monzonite of Tertiary age that occurs south of the deposits.

Iron mineralization occurs for over 1 mile along the limestone-amphibolite contact and two main ore bodies are present. The western deposit is 1,100 feet long, has a maximum width of 140 feet, and has been intercepted by drilling at 600 feet below the outcrop. The eastern ore body is 1,100 feet long, 30 to 60 feet wide, and was intercepted by drilling 250 feet below the outcrop. A split and a smaller oreshoot 200 feet farther east are also considered part of the eastern ore body. Massive magnetite and hematite make up the bulk of the deposit, but the ore carries inclusions of quartz and calcite and patches of unreplaced limestone and dolomite as well as various silicates of iron, calcium, and magnesium. Pyrite is common and the sulfur content of the ore is about 0.40 percent; phosphorus is low.

No recent estimate of ore reserves is available. In U.S. Geological Survey Bulletin 871, published in 1936, reserves were estimated at 12 million long tons. The average grade of the ore is about 56 percent Fe.

Dale district

The Dale district is in San Bernardino County, 25 miles east of Twentynine Palms. Production to the end of 1963 was about 273,000 long tons of lump ore and concentrate. Except for several hundred tons, production has come from the Iron Age mine and almost all of the district's reserves are in the downward extension of the Iron Age deposit.

Iron Age mine.—The property (No. 60, fig. 31) was patented in 1902, but only about 11,000 tons was produced before 1956. A concentrating plant was installed in 1956.

The ore occurs in numerous steeply dipping, parallel replacement veins in porphyritic granite. The largest oreshoot is 15 to 100 feet wide and about 400 feet long. The other veins are much narrower. Persistence of the mineralization in depth has been established by drilling. The deposit is of the hydrothermal type. Dense magnetite, which has been oxidized to hematite near the surface, constitutes the bulk of the ore body. The ore is high grade, with very low sulfur, phosphorus, and other impurities.

Minarets deposit

The Minarets deposit (No. 13, fig. 31) is 69 miles northeast of Fresno in western Madera County, an alpine area inaccessible to motor vehicles. It has been known since the 1860's but its isolated location has discouraged exploration. The deposit was tested in 1944 and 1945 with surface sampling and two diamond drill holes.

The mineralized area is underlain by a slightly metamorphosed sequence of dacite and andesite flows which are the host for the iron deposition. Granite crops out nearby but it is clearly older than the mineralization, which is apparently derived from a deeply buried source. The main ore body is an elongated lens composed of somewhat irregular layers of magnetite, or magnetite and actinolite, which are completely enclosed within the volcanic series and seemingly have replaced it. The magnetite is distributed throughout the ore body as a series of sheets in which the proportions of magnetite and actinolite vary gradationally. The sheets or layers are roughly parallel to the trend of the ore body. The area of good-grade ore, in which the host rock is mainly replaced by magnetite and actinolite, is surrounded by an irregular zone in which the magnetite content grades from ore to waste. The iron values consist mainly of magnetite with a gangue of actinolite and minor feldspar and chlorite. Phosphorus ranges from 0.30 percent to 0.80 percent. The ore contains no other contaminants.

An ore body 1,500 feet long and 15 to 175 feet wide is exposed on the surface. It was cut at depths of 250 and 300 feet by two drill holes. In 1944 the deposit was estimated to contain 5 million tons of indicated and inferred ore with a grade of 60 percent Fe and 2 million tons of material containing 25 percent Fe. Bureau of Mines sampling and drilling indicated that the deposit was of lower grade but that the ore tonnage was larger (Severy, 1946).

Shasta and California deposit

The iron-bearing area (No. 2, fig. 31) is on the east side of Shasta Reservoir in Shasta County, about 12 air miles north of Redding. Iron ore has been produced intermittently since 1892 when it was used as a smelter flux. About 15,000 tons was mined from 1907 to 1918 for use in a nearby electric smelting plant and from 1942 to 1945 about 300,000 tons was sold for use as ship ballast. During 1944 the Bureau of Mines drilled and sampled the deposit and made beneficiation tests.

Iron-ore deposits occur in an irregular contact-metamorphic zone 2,000 feet long and 300 to 1,000 feet wide formed in the Permian McCloud Limestone along its contact with intrusive quartz diorite.

The contact zone contains large proportions of garnet and epidote along with small or localized occurrences of pyroxene, chlorite, and serpentine. Irregular masses and pods of magnetite are intercalated within the skarn and additional magnetite is disseminated throughout the skarn. Individual pods range in size from a few tons to 25,000 tons or more. Two areas, one about 250 feet in diameter, and the other 100 feet in diameter, contain concentrations of large magnetite masses and have an overall grade of about 40 percent Fe. Both of these areas have been proven to a depth of over 500 feet by drilling. These areas have been mined selectively. The ore contains magnetite with varying proportions of garnet, epidote, and other contact minerals, 0.17 percent sulfur, and minor phosphorus, and other impurities.

The Shasta and California iron-ore deposits were estimated in 1945 to contain 4,680,000 long tons of ore with an average grade of 37.82 percent Fe, above a depth of 500 feet.

Resource Potential

Known iron ore deposits in California were inventoried by the U.S. Bureau of Mines in 1964. These deposits were estimated to contain a total of 972 million long tons of ore with an average grade of 42 percent Fe. Approximately one-half of this ore was classed as proven or indicated and one-half was inferred on the basis of geomagnetic or other information. It was further estimated—after considering the stripping required or the mining difficulty expected, the anticipated beneficiation expense, and transportation costs—that the following quantities of 65 percent Fe pellets could be made from this material at the indicated price levels with delivery in Los Angeles or San Francisco:

Amount of 65 percent Fe pellets produceible (cumulative totals)

Price:	*Long tons*
$15.00	271, 000, 000
$20.00	430, 000, 000
$25.00	571, 000, 000

In preparing these estimates, the Bureau of Mines engineers assumed neighboring deposits could be combined and operated as a unit to secure lower operating costs and that processing losses could be limited to 10 percent.

The present posted price for California iron pellets delivered in Japanese steel centers is $16.25 per long ton of 64 percent grade. Contracts provide for delivery of 1.8 million tons per year from 1966 until 1974. This is equivalent to a price of $12.35 at Los Angeles or San Francisco and well under the $15.00 price used in the above estimate.

As exploitation of deposits progresses, it is likely that total resource figures will be expanded considerably.

Iron ore resists erosion and iron oxides have distinctive colors and are high in specific gravity, so surface accumulations are easily recognized. In addition, magnetite, a major iron mineral, is the easiest of all minerals to find by geophysical prospecting methods. For these reasons, it is probable that a greater proportion of the nation's iron occurrences have been discovered than is the case for other commodities. Nearly all of California's known surface deposits were described in reports dated prior to 1915. During the 1950's, private industry undertook extensive airborne geomagnetic prospecting throughout the

State's iron districts, spurred by the rapid growth of demand for steel on the Pacific Coast. This exploration, while it failed to find any new districts, resulted in the discovery of many additional ore bodies in previously known areas and indicated that large resources of iron ore were present in California.

Additional geomagnetic surveys will find new ore bodies, but the rate of future discoveries is certain to be much lower than in the past. Obviously, the most promising areas for exploration are in the Mojave Desert and Klamath Mountains regions where previously examined districts will be surveyed for deep-lying ore bodies and areas between districts will be prospected for completely buried deposits.

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KYANITE, ANDALUSITE, AND RELATED MINERALS

(By G. H. Espenshade, U.S. Geological Survey, Washington, D.C.)

Industrial Use

Kyanite and andalusite are aluminum silicate minerals that were once mined in California for the manufacture of refractory materials with high-alumina content. Related minerals of similar composition—sillimanite, dumortierite, and topaz—can be used for the same purposes and are also known to occur in California, but have not been mined here. These minerals are commonly known as the sillimanite group (also as the kyanite group), and are used to manufacture refractory materials that will withstand high temperatures and abrupt temperature changes such as occur in metallurgical and glass furnaces and certain types of kilns and boilers. When heated to high temperatures these minerals all convert to the compound mullite ($3\ Al_2O_3.2\ SiO_2$) and silica; refractories made from these materials are commonly known as mullite refractories. Mullite can also be made using other high-alumina materials, such as diaspore clay, bauxite, and alumina, provided the content of iron and other impurities is low; this type of mullite is known in the industry as synthetic mullite.

History and Production

The sillimanite group of minerals came into use for the manufacture of mullite-bearing materials in the 1920's and consumption of these materials has grown steadily ever since. United States demand was largely supplied for many years by lump kyanite imported from India, and later from Kenya. Kyanite, andalusite, dumortierite, and topaz have been produced domestically from mines in California, Georgia, Nevada, New Mexico, North Carolina, South Carolina, and Virginia (Klinefelter and Cooper, 1961; Espenshade, 1962). Production from the California mines (the White Mountain andalusite mine, Mono County, and the Ogilby kyanite mine, Imperial County) ceased about 1945. United States production from 1950 to 1962 consisted of kyanite concentrates from mines in South Carolina (Henry Knob deposit) and Virginia (Baker Mountain and Willis Mountain deposits). In 1962 production of kyanite concentrates was started from a mine at Graves Mountain, Georgia. Current United States production comes entirely from these four kyanite mines in Georgia, South Carolina, and Virginia.

Over the years the supply pattern has gradually changed from mainly foreign sources of material to predominantly domestic sources at the present time. Another very significant change in the industry has been the development of large-scale production of synthetic mullite. The United States is now no longer dependent upon imported kyanite. Kleinfelter and Cooper (1961, p. 30) state: "If imports were to be cut off completely, the United States could become self-sufficient within a few months by accelerating the production of synthetic mullite." Free world production of kyanite minterals in 1963 was about 170,000 short tons, which came mostly from the Republic of South Africa, India, the United States, and Australia, in order of production (Varley, 1965). The changing pattern of the domestic industry since World War II is indicated in table 23.

TABLE 23.—*United States production of kyanite and synthetic mullite, and imports and exports of kyanite* (*short tons*)

	1945	1951–55 yearly average	1963
Kyanite production (estimated) [1]	12,300	22,000	44,800
Synthetic mullite production [2]	(?)	17,000	29,588
Kyanite imports [2]	14,554	9,531	2,624
Kyanite exports [2]	307	1,203	5,050

[1] Varley (1965, p. 104).
[2] Klinefelter and Cooper (1961, p. 32–33) and U.S. Bureau of Mines Minerals Yearbooks.

Geologic Occurrence

Kyanite, andalusite, and sillimanite all have the same chemical composition (Al_2SiO_5, consisting of 62.9 percent alumina and 37.1 percent silica), but have different crystal structure. They typically occur in metamorphic rocks, but also in some quartz veins and pegmatites, and in some river and beach placers. Many deposits of these minerals are evidently metamorphosed aluminous sediments, but in some quartzose deposits hydrothermal processes seem to have been active. Although the Al_2SiO_5 minerals are very common in some metamorphic rocks, they are rarely abundant enough or sufficiently free of impurities (attached or included grains of other minerals) for the deposits to be of economic value. They are generally most abundant in quartzose metamorphic or altered rock, where they are associated mainly with quartz, and in some places with other aluminum silicates, and may constitute 20 to 40 percent of the rock; massive segregations of the Al_2SiO_5 minerals may occur locally. These quartzose deposits have been the most productive deposits in all parts of the world. The Al_2SiO_5 minerals are probably more widespread in micaceous schist, gneiss, and hornfels, but rarely make up more than about 15 percent of such rocks. Dumortierite (about 65 percent alumina and 30 percent silica, plus boron) and topaz (about 55 percent alumina and 33 percent silica, plus flourine) are not nearly so common as the Al_2SiO_5 minerals; they may occur in quartzose masses and quartz schist with other aluminous minerals, in quartz veins, and in pegmatites.

Occurrences in California

All of the kyanite group of minerals have been found in California, but in minable quantities at only two places: kyanite in a deposit near Ogilby, Imperial County, and andalusite at the White Mountain deposit, Mono County (fig. 32). Both deposits were mined during the same period, from the 1920's to about 1945, and yielded a total production of about 36,000 tons of aluminum silicate rock, according to Wright (1957).

At the Ogilby deposit, kyanite occurs with quartz in very large masses associated with quartzite and quartz-muscovite schist (Sampson and Tucker, 1931; Henshaw, 1942; and Wright, 1957). The quartz-kyanite rock occurs discontinuously over a distance of about a mile and has a maximum thickness of about 400 feet. Most of this rock contains more than 15 percent kyanite; the mined rock is said to have averaged 35 percent kyanite or better. Only a small part of the quartz-kyanite rock was mined; bodies of similar but unmined quartz-kyanite rocks are said to occur in the area (Wright, 1957). About 21,000 tons of ore was mined from several quarries; kyanite was separated from decrepitated quartz by screening to give two products, one with 50 percent kyanite and 50 percent silica, and the other with 70 percent kyanite and 30 percent silica (McLenegan, 1956). The Vitrefrax Corp. of Los Angeles operated the Ogilby mine until 1946; the Aluminum Silicates Co. of Los Angeles acquired the property in 1949 (McLenegan, 1956), and is said to have recently leased the property to Western Industrial Minerals Co. which may resume mining operations.

At the White Mountain deposit, Mono County, andalusite and diaspore occur in irregular veins and masses within a zone several

FIGURE 32. Principal kyanite and andalusite deposits in California.

miles long and less than a mile wide in quartzite and quartz-sericite schist associated with metaporphyry and quartz monzonite (Jeffery and Woodhouse, 1931; Lemmon, 1937; and Wright, 1957). The main mine working yielded about 20,000 tons of hand-cobbed ore that contained 53 percent or more andalusite. Because of very rugged terrain, this material had to be carried by mule back for 3½ miles to a truck depot. The mine was operated by Champion Sillimanite, Inc., and the ore shipped to the parent company, Champion Porcelain Co., Detroit, where it was mixed with clays, dumortierite from Nevada, or alumina for the manufacture of porcelain and spark-plug cores.

Minerals of the kyanite group occur in minor to moderate amounts at numerous other localities in California. All the localities known prior to 1958 are listed by Murdoch and Webb (1956; 1960), who note that andalusite is known to occur in 14 counties, kyanite and sillimanite in 7 counties each, topaz in 6 counties, and dumortierite in 4 counties. The Al_2SiO_5 minerals occur most abundantly in metamorphic rocks, particularly in roof pendants of hornfels and schist in the Sierra Nevada granitic batholith.

Resources

Probably the only deposits of the kyanite group of minerals known in California that can be considered as resources are the White Mountain andalusite deposit and the Ogilby kyanite deposit. Wright (1957) states that they have remained idle "largely because no ready market exists for the kyanite and because most of the known bodies of higher grade and easily recovered andalusite had been removed." McLenegan (1956) concluded that there is a potential market for these minerals in California and Nevada of about 10,000 tons annually, and that this demand could rise to 40,000 tons if adequate local sources were found. As Wright (1957) indicates, revival of the kyanite-andalusite mining industry in California will require the development of local markets, discovery of sufficient high-quality ores, and the ability to compete with synthetic mullite, as well as with kyanite produced from the southeastern states.

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LEAD

(By R. M. Stewart, California Division of Mines and Geology, San Francisco, Calif.)

Utilization

Lead probably was one of the first metals to be won from its ores by smelting. The properties of lead that make it most useful are its softness and workability, high specific gravity, extreme resistance to corrosion, and a combination of low-melting point and high-boiling point. Estimates of lead usage in the United States indicate that 10 percent is used primarily because of its specific gravity; 30 percent because of its softness, malleability and resistance to corrosion; 25 percent because of its alloying properties; and 33 percent because of the properties of its chemical compounds (Perry, 1945, p. 66–67). About three-fourths of the lead used is in a metallic form, alone or alloyed. Although lead has a very wide variety of uses, about 54 percent was absorbed during 1963 by the two principal uses, storage batteries, and gasoline antiknock additives. Pigments, chemicals, cable sheathing, and construction materials constitute other major uses of lead. Lead has the highest secondary recovery factor of the common metals; about 60 percent of the lead in use ultimately will be recovered as scrap.

Geology

The primary mineral galena (PbS) is the chief ore mineral of lead throughout the world, but the secondary minerals, anglesite ($PbSO_4$) and cerussite ($PbCO_3$) also are significant ore minerals in the oxidized zone of some deposits. Other significant, although less abundant, minerals in the oxidized zone of lead deposits are: those of the pyromorphite series ($Pb_5(PO_4AsO_4)_3Cl$); linarite, a basic sulfate of lead and copper; plumbojarosite ($PbFe_6(OH_{12}(SO_4)_4)$; and wulfenite ($PbMoO_4$). Silver and zinc minerals commonly are associated with lead minerals in California as well as throughout the world. (See sections on silver and zinc in this report.) Primary lead-zinc deposits in California typically occur as cavity fillings or replacement bodies, and most occur in Paleozoic carbonate rocks. Most lead-zinc deposits clearly are associated wtih intrusive igneous rocks.

In the oxidized zone, galena alters to anglesite which in turn alters to cerussite. Anglesite and cerussite are relatively insoluble, and lead ore is the most resistant of all base metal ores to further chemical alteration. Enrichment can take place in the oxidized zone, however, by leaching of sulfur, zinc, and iron and possibly other constituents from the ore. All of the lead deposits in California have been oxidized, but primary sulfide minerals are present, in minor to major proportions, in all of them.

History

The first lead mined in California probably was that produced from the southern part of the Panamint Range prior to 1859 by Mormons, and early developments were prompted by the silver content of the lead ores. The Cerro Gordo district, which ranks second after Darwin as a source of lead in California, was discovered prior to 1866, possibly as early at 1862. Production started in the Tecopa district at the Gunsight mine in 1865; and the first of the highly productive mines in the Darwin district was discovered in 1874. Although discoveries in other districts were being made during this same general period, or followed closely, none was to equal any of these three in importance.

The principal mines in the Darwin district yielded ore valued at about $3,000,000 prior to 1900; $4,000,000 between 1900 and 1945, when the Anaconda Copper Mining Co. purchased the principal mines; and $18,000,000 between 1945 and 1953 (Carlisle, and others,

p. 44). Following a mid-year drop in lead and zinc prices in 1957, Anaconda suspended operations at Darwin and at the Shoshone mines in the Tecopa district.

The Cerro Gordo district is credited with ore valued at $17,000,000; the Cerro Gordo mine has a total output valued at $15,000,000, and although it was worked intermittently until the late 1940's, has not been a significant source of lead since 1877.

Prior to 1947, all the mines in the Shoshone group had yielded about 250,000 tons of ore that had a gross value of about $5,000,000. More than half of this was produced by the Tecopa Consolidated Mining Co. during the period 1912–1928. As stated by Carlisle (1954, p. 46), operations by the Anaconda Co. since 1947 resulted in the production of more than 160,000 tons of ore that contained about 40,000,000 pounds of lead, 6,000,000 pounds of zinc, 870,000 ounces of silver, and 15,600 ounces of gold. The operations were suspended late in 1952, were resumed in 1956, but terminated during 1957.

Lead production in California has been affected most by the national and international situation and the resultant price structures, not only for lead but for the other base metals and for silver as well. Undoubtedly, the production of lead in the future will be similarly affected.

PRODUCTION

In terms of total production, the United States has, since 1893, been the world's chief source of lead, and, since 1900, has been the chief user of the world's lead. Since 1940, however, the United States has been forced to rely upon imports for a large part of the lead required by its expanding industrial complex. Since 1960, mines in the United States have produced less than 10 percent of the world's total and have supplied only about 23 percent of the total lead used domestically. Recently discovered deposits in Missouri are now being developed and may soon reverse this trend.

Deposits in California have yielded a total of about 495 million pounds of lead from 1877 through 1964. This output represents only about eight-tenths of one percent of the total mine production of lead in the United States for the same period. During the decade ending with 1964, the annual production of lead in California ranged from a low of 103 tons in 1961 to a high of 9,296 tons in 1956. The 1964 production of 1,546 tons was the highest since 1957, when production reached 3,458 tons. Mines in Inyo County have been the source of about 93 percent of the State's total.

OCCURRENCES IN CALIFORNIA

Most of the lead produced in California has been obtained from three districts in Inyo County shown on figure 33. These are: the Cerro Gordo district, about 13 miles east of Lone Pine and near the crest of the Inyo Range; the Darwin district, about 35 miles southeast of Lone Pine; and the Tecopa district, at the southern end of the Nopah Range in the southeastern corner of Inyo County.

The host rocks for the ore bodies in the Cerro Gordo district are limestone, marble, and quartzite beds of Devonian age. The Devonian and overlying Carboniferous rocks have been intruded by two small stocks of monzonite porphyry and by dikes of monzonite porphyry,

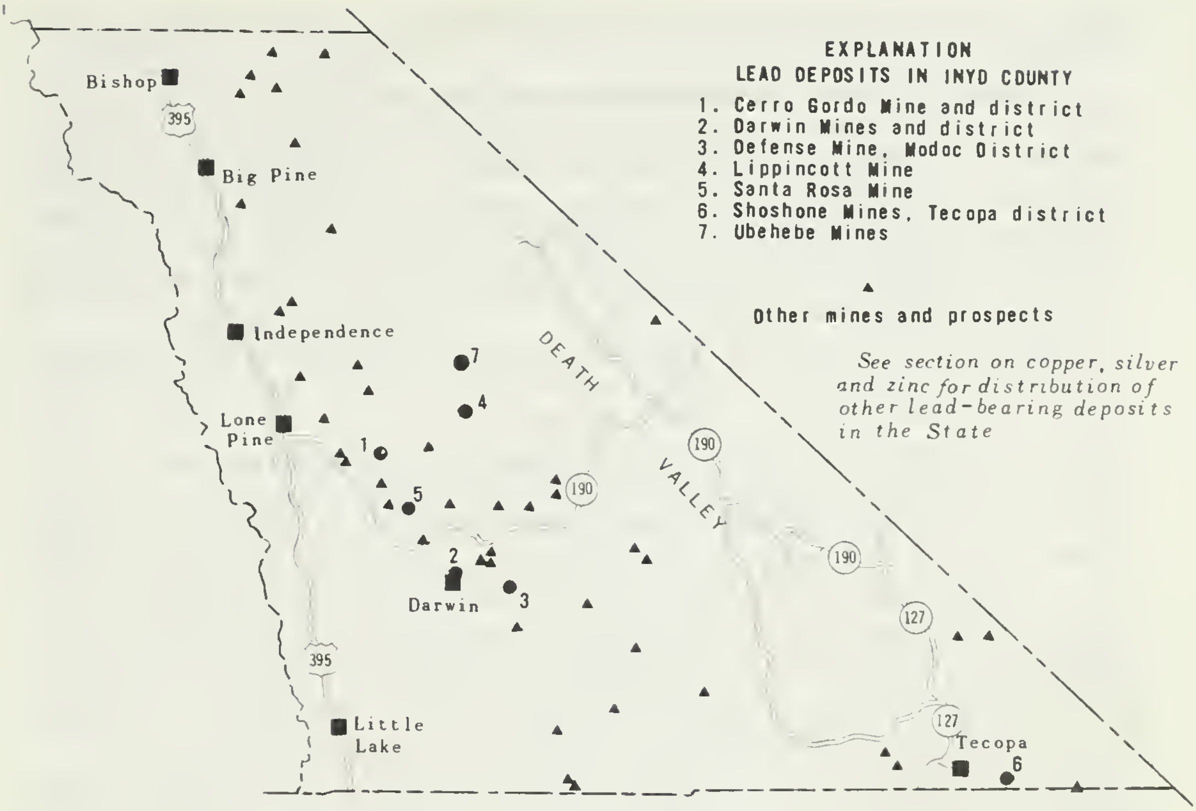

FIGURE 33. Lead deposits in Inyo County.

diabase, and quartz-diorite porphyry, in that order (Carlisle and others, 1954, p. 43). The ore bodies, all nearly vertical, south-plunging, chimney-like bodies, were distributed, according to Knopf (1918, p. 113), through a north- to northwest-trending zone 1,500 feet long and several hundred feet wide. The ore minerals are argentiferous galena, cerussite, anglesite, smithsonite, sphalerite, tetrahedrite, and pyrite. Much of the zinc in the lead-rich deposits was removed by meteoric water and formed secondary deposits.

The ore bodies of the Darwin district occur in Pennsylvania limestone which is folded about northeasterly to northwesterly axes. One of the major structural features influencing mineralization was a northwest-plunging anticline, the axis of which lies near the crest of the Darwin Hills. The limestone has been silicated in a wide zone peripheral to a quartz diorite stock that was intruded mainly along the core of this anticline and for an exposed distance of about 5 miles. Mineralization is contact metasomatic ranging to mesothermal (Hall and MacKevett, 1962, p. 69), related to the quartz diorite, and has been guided by igneous contacts, bedding planes, and cross fractures. "In order of importance, the orebodies are: (1) bedded replacements that commonly are more or less localized along anticlinal flexures and lie near but not in contact with the intrusive sills; (2) irregular replacements of the silicated limestone along fissures; and (3) fissure fillings" (Carlisle and others, 1954, p. 45).

The major primary sulfides are argentiferous galena and sphalerite. Minor to very minor proportions of pyrite, chalcopyrite, tetrahedrite, bornite, chalcocite, and covellite are present. Extensive but irregular oxidation has produced cerussite, anglesite, plumbojarosite, sooty argentite, and cerargyrite. Leaching of zinc, sulfur, and some iron has been important in the residual enrichment of the oxidized ore (Davis and Peterson, 1949, p. 138).

Nearly all the lead ore from the Tecopa district has been produced from several mines that were consolidated as the Anaconda Copper Co.'s Shoshone mines. The host rock for all the ore bodies is the Noonday Dolomite of late Precambrian age which lies unconformably upon Precambrian metamorphic and sedimentary rocks and is overlain by Lower Cambrian sedimentary rocks. The largest ore bodies appear to have formed at junctions of the northwest-trending Shoshone fault with cross fractures and faults (Carlisle, and others, 1954, p. 46). Most of the ore in each of the deposits is highly oxidized. Cerussite and anglesite are predominant, and are associated with iron oxides, smithsonite, calamine, linarite, and caledonite. Residual galena, pyrite, and sphalerite are present in minor proportions.

The Santa Rosa mine at the southern end of the Inyo Range, and several mines, notably the Defense, Minietta, and the Modoc, in the northern end of the Argus Range (the Modoc district) in Inyo County have been important sources of lead.

Most of the rest of the lead that has been mined in California has been a by-product of the copper-zinc and gold mines of the Klamath Mountains and Sierran foothill areas (see sections on copper, gold, and zinc). Other areas that have yielded relatively small quantities of lead ore include the Clark Mountain district in northeastern San Bernardino County, a small district on the west slope of the Santa Ana Mountains in Orange County, and the northern Panamint Range in Inyo County.

APPRAISAL

It is doubtful that the deposits that have yielded most of California's lead in this century are exhausted. The cessation of operations at the larger mines, such as Darwin, probably was due more to an unfavorable price structure for the metallic concentrates than to lack of ore of a grade that in prior operations had been economically successful. The districts that have been the source of major proportions of the California production undoubtedly will, again, be the sites of further exploration when the price structure for lead (perhaps with a boost from copper, silver, or zinc) becomes favorable. In the long view, this situation is inevitable.

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LIMESTONE, DOLOMITE, AND LIME PRODUCTS

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Importance of Calcareous Materials in California

California, the most highly populated state in the union and also among the fastest growing in population, is fortunate to have vast resources of carbonate rocks to supply its expanding industries. Her cement industry alone, largest in the United States and probably in the world, for an equivalent political unit, consumes about 13,000,000 tons of limestone and fossil seashells each year. In excess of 4,500,000 tons of carbonate rocks are consumed annually by a great number of other industries, led by: aggregates for the construction industry, magnesian and high-calcium lime manufacturing, limestone and dolomite for steel manufacturing, roofing granules for the construction industry, limestone for sugar refining and limestone for glass manufacturing, as shown in table 24. The value of carbonate rocks to the State's economy is immense, as it occurs widely distributed and is available at a relatively low cost compared to other raw materials.

TABLE 24.—*California consumption of limestone and dolomite during 1964* [1]

	Tons
1. Cement (from limestone, siliceous limestone, oyster shells)	12,750,000
2. Aggregates—including concrete aggregate, road base, etc. (from limestone, magnesian limestone, dolomite)	2,000,000
3. Magnesian lime (from dolomite, magnesian limestone)	500,000
4. Steel flux (from limestone)	450,000
5. Roofing granules (from limestone and dolomite)	450,000
6. Sugar refining (from high-calcium limestone)	285,000
7. White fillers (from high-calcium limestone; includes whiting, paper fillers, asphalt tile, linoleum, etc.)	210,000
8. Glass (from high-calcium limestone)	200,000
9. High-calcium lime (from high-calcium limestone)	200,000
10. Agriculture (from limestone and oyster shells; includes fertilizer fillers, mineral foods, soil amendments)	135,000
11. Poultry grit (from limestone, oyster shells)	105,000
12. Riprap (limestone, magnesian limestone)	100,000
13. Dimension stone (limestone, magnesian limestone, dolomite)	70,000
14. Terrazzo chips	40,000
15. Asphalt filler (limestone, magnesian limestone)	12,000
16. Miscellaneous (chemicals, concrete pipe, stucco, oil well drilling, etc.)	150,000
Total	17,607,000

[1] Tonnages are estimated and include commercial and noncommercial items as well as imports. Data adapted in part from the U.S. Bureau of Mines, U.S. Census Bureau, and sources in industry.

Limestone is one of the few raw materials that are absolutely basic in modern industry and necessary to our present civilization. In addition to its major use in the manufacture of portland cement, it is the source of lime, for which there are over 7,000 uses. Most of these uses depend on the caustic properties of calcium oxide or calcium-magnesium oxide produced by calcination of limestone or dolomitic limestone. In some of these uses, it serves to combine with and remove unwanted materials from a desired product as in the manufacturing of steel, and the refining of sugar and petroleum. Many of its uses are almost as old as recorded history, and because it is economical it has been widely employed.

Origin, Accumulation, and Characteristics of Limestone and Dolomite

Limestone occurs in nature in many degrees of purity. Calcium is the principal metallic alkaline element which gives limestone the characteristics which make it a fundamental raw material. Magnesium is another metallic alkaline element present in all dolomites and in some limestones. For some industrial uses, magnesium is an important desirable constituent; for others, it is a harmful impurity. Aluminous, siliceous- and iron-bearing impurities may be critically deleterious in some chemical processes and beneficial in others—as in the manufacture of portland cement. Sulfur and phosphorus may be present only in trace amounts if the limestone or dolomite is to be used in steel manufacturing. For glass manufacturing, the iron content must be extremely low. Limestone, fossil seashells, magnesian limestone, and dolomite are at present the only carbonate raw materials that are economically feasible to mine in California at the present time.

Calcite ($CaCO_3$) is the predominating mineral in limestone. Dolomite ($CaCO_3.MgCO_3$) is the principal mineral in rock dolomite. Aragonite (also $CaCO_3$) is the chief mineral secreted by organisms and found in seashells, but it is metastable and in time changes to calcite. In common industrial usage, a carbonate rock containing 95 percent or more of $CaCO_3$ is termed high-calcium limestone; one containing between 5 and 10 percent MgO is called magnesian or dolomitic limestone; one containing between 10 and 15 percent is limy dolomite; and one between 15 and 21.6 percent MgO is called dolomite. The terms "high calcium" and "chemical grade" are used more or less synonymously. In California, however, open-market availability of high-grade limestones is such that any producer who expects to compete in selling limestone or dolomite on the open market has to produce a rock having more than 97 percent $CaCO_3$, if he expects to sell it as "high-calcium" or "chemical-grade" limestone, or it must contain 20 percent or more MgO to compete as dolomite.

Many aquatic plants and animals, secrete calcium carbonate or a mixture of calcium and magnesium carbonates for protective and supporting parts. As many of these organisms are colonial or at least gregarious in habit, their remains may accumulate and be preserved in large concentrations. Micro-organisms also may contribute indirectly to the chemical precipitation of carbonate minerals by up-setting the equilibrium of the aqueous system, by catalytic activity, and so on. Changes in temperature and composition of ocean and lake waters also may result in direct chemical precipitation of carbonate minerals. Organisms appear to play the predominating role in limestone formation, mechanical concentration of carbonate detritus plays an important secondary role in limestone formation, and chemical precipitation appears to play a lesser role. A few large deposits of limestone have accumulated by direct chemical precipitation from vents of warm mineral springs. Dolomite apparently forms chiefly by replacement of pre-existing limestone masses, predominantly by diagenetic replacement on the sea floor, but also by mobilization of magnesian agueous solutions during the granitic emplacement phase of fold-mountain building.

A great majority of California limestone and dolomite deposits occur in metamorphosed or partly metamorphosed marine sedimentary rock sequences. Most commonly, they are interbedded with noncarbonate sedimentary rocks and make up only a small part of the stratigraphic section in which they occur. In a few remotely situated parts of the State, i.e., southern Inyo and northern San Bernardino Counties, carbonate rocks do form the bulk of some sedimentary sections and reach thicknesses of more than 10,000 feet. In contrast to many other limestone and dolomite-producing states, California deposits tend to occur in steeply dipping, structurally complex, lenticular bodies of small areal extent rather than in flat-lying or gently dipping formations of large areal extent. Consequently, prospecting for limestone in California is more complex than in most other states.

Probably the most common deleterious ingredient found in limestone and dolomite is silica (SiO_2) in the form of chalcedony or chert. It occurs disseminated or in the form of streaks, nodules, or beds. Quartz and feldspar sand grains as well as rock detritus are abundant in parts of some California limestone and dolomite formations. These impurities may be disseminated through limestone matrix or concentrated as partings and beds. Clay in the form of illite or kaolinite is a common minor constituent of limestones and dolomites. In some formations it is present in large amounts, so that the limestone grades into shaly limestone or into marl in some parts of a formation. Such rocks may be valuable sources of material for portland cement manufacture, but, for most other purposes, clay is a harmful ingredient in both limestone and dolomite.

Another widely distributed impurity in California carbonate rocks is organic matter in the form of hydrocarbons or gas, hydrogen sulfide being the commonest gas. In strongly metamorphosed carbonate rocks, where recrystallization has been widespread, solid organic matter generally has been converted to graphite, and the evolved gas has been trapped in pores, minute fractures, and along cleavages in the rock. In crystalline limestone valued for its light color, graphite is harmful because it smears badly during grinding and discolors the ground product. A large amount of organic matter can be deleterious in chemical processes where it commonly causes scumming of a solution.

Other constituents that may be troublesome in carbonate rocks are pyrite, chlorite, glauconite, and collophane, but with the possible exception of pyrite, none of these is common in California deposits.

Invasion of a limestone by granitic intrusive rocks may result in introduction, by replacement, of pyrite and other metallic sulfide minerals.

History of Utilization of Carbonate Rocks in California

The use of lime-bearing materials in California dates back to the building of the Spanish missions, where witewash and lime mortars were widely used in small quantities. Abalone shells, pismo clams, and other shells obtained on the beaches were probably the first materials burned into lime. Later, accumulations of fossil shells were found and finally it was discovered that the crystalline limestones, so widely distributed throughout California, could be used. Not until the gold rush days of the early 1850's did lime become important to the construction industry in California, but from then on hundreds of lime kilns sprang up all over California. This rising demand was directly related to the hazardous fires which repeatedly swept through towns made of frame buildings. Field stone or brick buildings laid up in mud or in lime mortar became the standard type of construction throughout the gold country, and many of these remain in use today. A great deal of lime was imported from Europe to supply demand during the early part of the gold rush period.

Both marble and limestone were used as structural materials in buildings as early as 1850. The marble-cutting business, once substantial in California, has almost disappeared, because high labor costs make California marble noncompetitive with marbles from Italy, Georgia, and elsewhere. Limestone has been used as railroad ballast, road metal, and the like from gold rush days, and as concrete aggregate since the turn of the century.

The lime manufacturing business probably had its heyday between 1880 and 1900—in relation to its importance to the then current economy, if not in actual tonnage produced. Vast banks of lime kilns were constructed in the Santa Cruz Mountains, Santa Lucia Range, Sierran foothills, Tehachapi Mountains, and the southwestern Mojave Desert. Many of the lime companies were as important for their day as the portland cement companies now are—in relation to the rest of the economy.

Although portland cement was invented in England as early as 1824, it was not used to any great extent in California until the late 1850's and 1860's. The first cement used here was imported from Europe. Even then its use did not greatly supplant lime mortars nor did concrete become serious competition to masonry construction until about the turn of the century. This was partly due to primitive methods of making and handling cement which resulted in non-uniformity of the product. Also, it was difficult to keep dampness from deteriorating the stored cement.

Cement manufacturing in California dates from 1860, when a hydraulic cement (a type manufactured at considerably lower temperatures than portland cement) was placed on the San Francisco market. Apparently, limestone from beds in the Martinez Formation (Paleocene) and from Pleistocene fossil seashells were blended with clay as the raw materials for this venture. The first cement approaching a true portland cement was made at Santa Cruz in a brick kiln about 1877 from crystalline limestone and clay. Another early plant that produced portland-type cement was built on the Jamul Ranch in southern San Diego County in 1891. The California Portland Cement Co. built a plant at Slover Mountain near Colton in 1895 that, although enlarged and rebuilt several times, has been in continuous operation through the present day.

Since the early 1900's, cement plants have been the largest consumers of limestone in California, but numerous other industrial users of limestone have been equally important to the economy of California, even though the quantity of material they consume is smaller. The many chemical industries which consume limestone, for its lime content, for the carbon dioxide that can be evolved, or both, seem to have developed principally since 1900. Many had their beginnings through the impetus of World War I. Limestone was quarried for steel flux and copper refining flux as early as the 1880's, possibly as early as 1860. The use of limestone in sugar refining dates back at least to 1870 when E. H. Dyer built the first successful refinery at Alvarado, Alameda County. The glass industry, another major consumer of California limestone, was initiated by the Illinois Pacific Coast Glass Co. at San Francisco about 1897 and by the San Francisco Glass Works (1890–1898).

Dolomite probably was first used in California as marble building stone, particularly around Sonora and Columbia in the gold country. Dolomite marble dimension stone was produced commercially in Inyo County about 1888 and may have been produced in the Sonora-Columbia area of Tuolumne County in the 1870's and 1880's. Production of dolomite in California was intermittent and not large up to 1942. Except for durable material used as crushed stone, the commonest use for dolomite up to 1942 was as a basic flux in the manufacture of steel. In 1942, the Henry J. Kaiser interests initiated the use of calcined dolomite and seawater in the manufacture of magnesia for use in the production of magnesium metal, and in 1945 began to produce magnesia refractories. Within a decade, the other California producers of magnesia altered their processes to use dolomite. These firms are by far the greatest consumers of dolomite in California. Prior to the advent of the use of dolomite in manufacture of magnesia, it had been made by interaction of lime with sea water. Interaction of calcined dolomite with sea water gives a substantially larger yield of magnesia.

Occurrence of Limestone and Dolomite in California

Most of the limestone and dolomite deposits in California occur in strongly deformed and metamorphosed marine sedimentary rocks. Most commonly they are of Paleozoic age although there are some of Precambrian, Mesozoic, and Cenozoic ages. Unmetamorphosed Tertiary algal limestones of good grade are found in the Eocene Sierra Blanca Formation of Santa Barbara County, and the Paleocene Martinez Formation of the Santa Monica Mountains. Oligocene (?) and Miocene shell limestone of the Vaqueros Formation is extensively quarried in San Luis Obispo County. Quaternary seashell deposits have been exploited at San Francisco, Newport, and San Diego Bays. Recent marl of caliche type has been quarried in a small way in Fresno and San Diego Counties. Chalk, an earthy foraminiferal limestone, is unknown in California.

The principal areas where carbonate rocks are abundant and reasonably near to markets and to transportation facilities are: (1) the Klamath Mountains of Shasta and Siskiyou Counties, particularly the southeast part adjacent to Redding; (2) the foothill belt of the Sierra Nevada from Placer to Tulare County; (3) the Santa Cruz, Gabilan, and Santa Lucia Mountains of the central Coastal Ranges; (4) the Tehachapi Mountains and adjacent southernmost Sierra Nevada; (5) the Argus and Panamint Ranges of Inyo County; (6) the Victorville-Oro Grande-Adelanto vicinity of the southwestern Mojave Desert; (7) the northern San Bernardino Mountains adjacent to Lucerne Valley; (8) the Mescal, New York, and Providence Mountains of eastern San Bernardino County; (9) the northern part of the San Jacinto Mountains including the Palm Springs-Lake Hemet and Beaumont-San Jacinto areas; (10) the Big and Little Maria Mountains of eastern Riverside County; and (11) the Coyote Mountains of Imperial County, largest potential source for the San Diego marketing area.

Four formations have yielded industrial limestone in Shasta and Siskiyou Counties: the Hosselkus Limestone (Triassic), the Kennett Formation (Devonian); the McCloud Limestone (Permian); and the Gazelle Formation (Silurian). The Hosselkus Limestone extends south into the northern Sierra Nevada, but the others are confined largely to the Klamath Mountains. The Kennett and Hosselkus formations yield limestone that is predominantly blue-gray to black; the McCloud yields predominantly dove-gray rock. The Hosselkus Limestone has been metamorphosed very little and is fine grained; rock from the other three formations commonly is recrystallized and ranges from fine grained to medium grained. None of these formations has yielded white rock of high-calcium grade. Limestone, probably of Paleozoic age and of medium to course grain and blue-gray to white hues, exist in the relatively inaccessible interior of the Klamath Mountains, notably in the subrange known as the Marble Mountains. Among the four formations, the McCloud Limestone probably contains the largest resources, but in the most accessible parts both magnesia and silica tend to be widely and sporadically distributed. The Hosselkus Limestone contains more uniform rock. Limestone has been quarried from the McCloud Limestone, near Redding, from the Kennett Formation on Backbone Creek (a tributary to the McCloud River), from the Hosselkus Limestone near Ingot, and from the Gazelle Formation near Gazelle.

Several deposits of Hosselkus Limestone of potential economic importance are in and adjacent to the Genessee Valley of Plumas County, near the Western Pacific Railroad. They have not yet received much attention because of the availability of more accessible materials. The same is true of several deposits on the Feather and Yuba Rivers of the northern Sierra Nevada.

In the west-central Sierra Nevada, most industrial limestone and dolomite deposits are in discontinuous series of simple lenticular masses in other metamorphic rocks or as pendants in granitic rock. Less commonly, they occur in masses having complicated outlines because of severe folding. A few of the limestone deposits have yielded fossils ranging, at various localities, from Mississippian to Permian, but fossil evidence is very sparsely distributed. A few small bodies

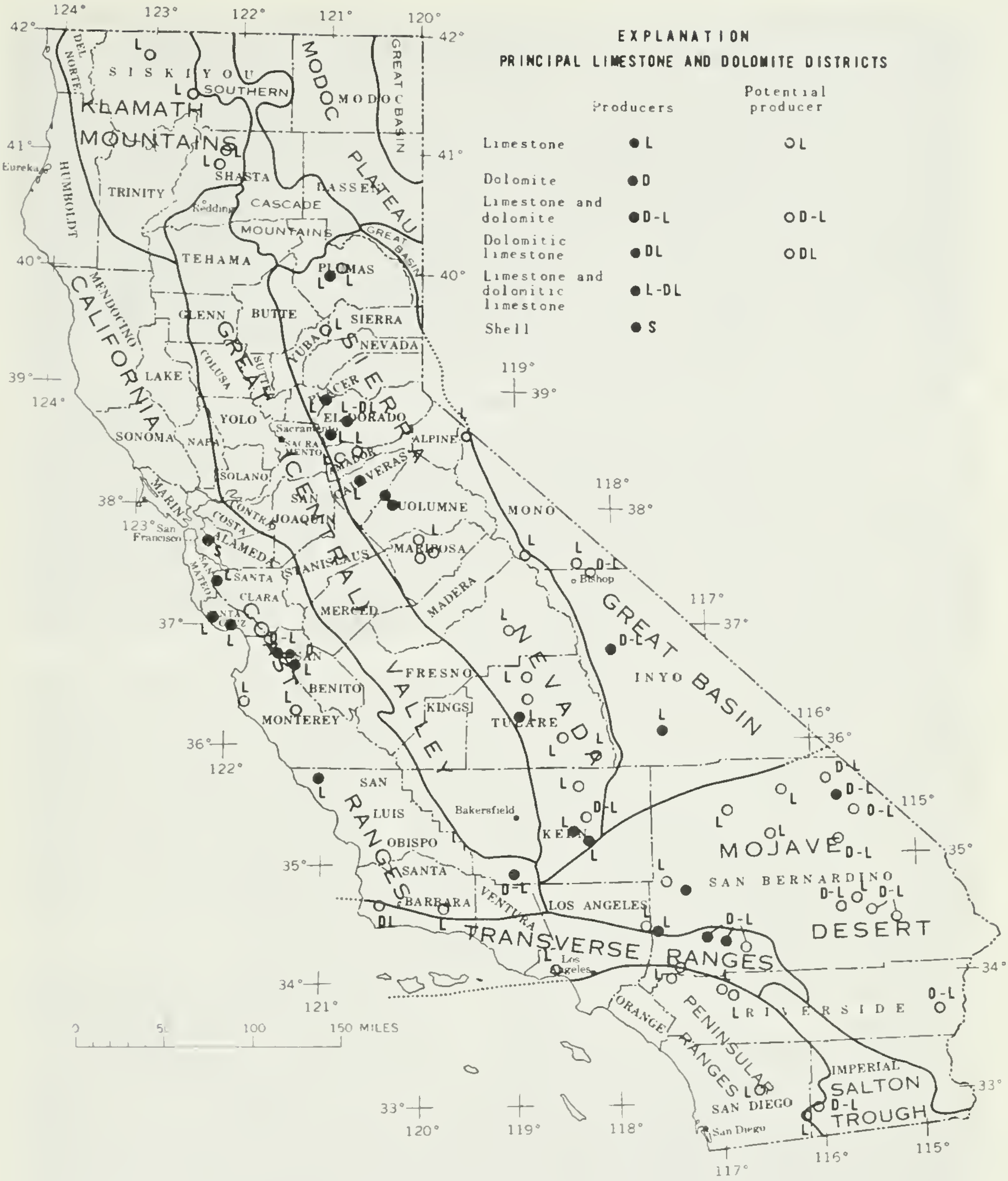

FIGURE 34. Principal limestone and dolomite districts in California.

occur in Jurassic rocks. The principal districts in the west-central belt that are producing commercial limestone or dolomite are the Cool-Cave Valley and Diamond Springs-Shingle Springs areas of El Dorado County; the Volcano district of Amador County; the San Andreas district of Calaveras County; and the Standard-Sonora-Columbia district of Tuolumne and Calaveras Counties.

The crystalline limestones of the west-central Sierran foothill belt are associated with slate, metachert, phyllite, mica schist and greenstone of the upper Paleozoic Calaveras Formation. The largest masses occur east of the Mother Lode belt, but these are medium to coarse grained and commonly are mixtures of limestone and dolomite so that careful sampling and selective mining is often necessary. Rock colors most commonly are blue-gray or white or variations of these. Dolomite generally is white to off-white. A succession of relatively small lenses (most not over a quarter of a mile long by 300 feet or less thick) containing predominantly fine-grained, dense dove-gray to blue-gray limestone is found in a narrow belt in the foothill area west of the Mother Lode, from Placer County south to western Calaveras County. On the whole, these lenses have been less intensely metamorphosed than deposits east of the Mother Lode, and limestone from them holds its lump form much better during calcination. However, only a few are large enough and of sufficiently high purity to be either active or potential sources of industrial limestone.

Many of the central Sierran limestone masses are too magnesian to be useful for purposes other than magnesian lime, although there are a few nearly pure calcitic and dolomitic masses from which commercial rock may be obtained without selective mining. The Standard-Sonora-Columbia district contains the largest, continuously exposed masses of carbonate rock in the Sierra Nevada, rocks of this kind underlying many square miles. However, replacement masses and smaller patches of dolomite of very irregular shape make selection of quarry sites difficult in this district.

In the southern Sierra Nevada, faulting along both east and west margins of the range has resulted in greater elevation of the granitic core and greater removal of the metasedimentary cover by erosion. Consequently, there are notably fewer limestone deposits there than in other parts of the province, and these are more remotely situated from transportation systems and markets. Deposits in Tulare County along the Kaweah and Tule River drainages (Three Rivers and Porterville districts) are being developed in a small way as well as those clustered south of Lake Isabella in Kern County.

Very few reasonably accessible limestone deposits exist in the northern Coast Ranges, and the market is limited because of the small population. In the central Coast Ranges, large roof-pendants of crystalline limestone and dolomite are found in the Santa Cruz, Gabilan and Santa Lucia Mountains and in the Sierra de Salinas. Carbonate rocks of these complexes, of probable Paleozoic age, commonly are coarse grained, and white and blue-gray colors predominate. Both high-grade limestones and high-grade dolomite occur in deposits large enough for major exploitation (masses aggregating tens to hundreds of millions of tons); deposits of the northern Gabilan Range and southern Santa Cruz Range supply much of the current demand in the San Francisco Bay area. Nearly all of the dolomite currently used in northern California is quarried from deposits in the northern Gabilan Range. Dense, fine-grained limestones found in the Franciscan Formation of Jurassic and Cretaceous age also supply notable tonnages to San Francisco Bay industries, particularly to the cement plant at Permanente, Santa Clara County. Quaternary oyster shells dredged from San Francisco Bay supply one cement plant at Redwood City, San Mateo County.

The immense resources of coarse-grained, white crystalline limestone of the Pico Blanco district constitute virtually the only undeveloped major deposits of high-grade limestone close to tidewater anywhere on the California, Oregon, and Washington coasts. They are close to State Highway 1, 25 miles southeast of Monterey and only 3 airline miles from the Pacific Ocean. Lack of close railroad facilities and access roads has hindered their development thus far. Tertiary unmetamorphosed limestones of considerable present economic importance, and even greater future significance as the population increases, are sparsely distributed in the southern Coast Ranges of San Luis Obispo, Santa Barbara and Ventura Counties. Beds of shell limestone in the Oligocene(?) and lower Miocene Vaqueros Formation are quarried at Lime Mountain west of San Miguel for use in sugar refineries of Salinas Valley. Deposits of algal limestone in the Eocene Sierra Blanca Formation can supply good quality, dense limestone to industries in Santa Barbara and Ventura Counties should the demand rise.

Extensive deposits of carbonate rocks in the Tehachapi Mountains between Mojave and Frazier Mountain support two cement plants, one at Mojave and one at Monolith. Other industries to be based on these deposits are in the planning stages. The carbonate rocks occur as pendants more or less encased in granitic rocks, either alone or interbedded with mica schist and quartzite in sequences referred to either the Bean Canyon Formation or the Kernville Series. These rock groups are probably of late Paleozoic and/or early Mesozoic age, although fossils have not been found in them. The rocks are commonly coarse grained and colors range from white to blue-gray. Masses of dense, fine-grained rock are unknown in this area. Limestone, dolomite, and magnesian limestones are all present within the district. Some very pure, very white, very coarse-grained limestones exist west of Cantil at the headwaters of the Back Canyon drainage. Potentially exploitable deposits of both limestone and dolomite occur in Neenach quadrangle east of Lebec, and large deposits of cement-grade rock are distributed through the district. Granitic intrusions are common within many of the limestone bodies, and silica and silicate minerals introduced by contact metamorphism are also a common problem in the district.

The chemical plants located at Searles Lake, Inyo County, together with the rail facilities that serve them, create a favorable economic environment that allows the extensive limestone deposits (Carboniferous?) of the Argus Range to be exploited. Carbonate rock deposits across Panamint Valley in the Panamint Range may ultimately be brought into production. Both high-grade dolomite and limestone are found there. Light-gray colors prevail, and both limestones and dolomites are medium to fine grained.

Extensive deposits of fine-grained white dolomite are being mined underground near Keeler in the Owens Valley of Inyo County for use as terrazzo chips and white aggregate for the Los Angeles marketing complex. Immense reserves of dolomite exist there, and limestone deposits can be developed farther to the east. The dolomite is in the Ely Springs and Hidden Valley Dolomites of Ordovician to Devonian age, whereas the best limestone is in the Lost Burro Formation of Middle and Late Devonian age.

In the Victorville-Oro Grande district of southwestern San Bernardino County, limestone, dolomite, and dolomitic limestone are all found in commercial quantities.

These may occur singly or together in a given deposit and in places are interbedded with other metasediments such as mica schist, quartzite, and hornfels. The carbonate rocks are in the Carboniferous (?) Oro Grande Formation and also in the conglomerate member of the Permian Fairview Valley Formation. A majority of the carbonate masses of the district consist of strongly metamorphosed, coarsely crystalline rock, but there are a few bodies of weakly metamorphosed, dense, fine-grained rock of notable size at Sparkhule Hill and Black Mountain. Limestone ranges from pure white to nearly black, but white and gray or variegated combinations of the two colors are commonest. The Victorville-Oro Grande district ranks among the largest limestone producers in the State, but only a little dolomite and dolomitic limestone has been marketed thus far from the district because of small demand. Granitic intrusions and introduction of silicate minerals along granitic contacts are the principal problems in exploitation.

There are immense resources of limestone and magnesian limestone in the northern part of the San Bernardino Mountains of San Bernardino County in the Furnace Limestone. This is at least partly equivalent in age and lithology to the Oro Grande Formation of the nearby Victorville-Ore Grande district. In general, these rocks are strongly metamorphosed and coarsely crystalline, but there are some patches of finer-grained, dense, more weakly metamorphosed rock. White and blue-gray hues prevail, and select white rock is in demand for white filler and roofing granules. White rock has been quarried intermittently in the Cushenbury district for many years, and there is a cement plant near the mouth of Cushenbury Canyon.

Extensive deposits of white, coarsely crystalline limestone and cream-colored dolomite occur in the Little and Big Maria Mountains of eastern Riverside County near the railhead at Midland, particularly a few miles northwest of Midland. The relatively long distince from the Los Angeles marketing area and unfavorable freight rates have limited production thus far, but it is likely that they will be activated in the near future. The limestone and dolomite occur in strongly deformed, intensely metamorphosed crystalline complexes of Paleozoic or Precambrian age. Many of the limestone deposits are of very high purity. The dolomites have too high an iron content for some uses, but otherwise some deposits are of good grade.

In the Riverside-Colton district pendants of limestone of Paleozoic or Triassic age have supplied cement plants and numerous users of industrial limestone since 1895. Enormous tonnages of limestone have been quarried at Slover Mountain near Colton and at Crestmore near Riverside. The cement plant at Colton has been in continuous operation since 1895. Plants at Crestmore and Colton have just been rebuilt, indicating that reserves are far from depleted. White, and blue-gray colors prevail and the rock is coarsely crystalline. Both cement-grade and high-purity limestones are present. Properties in the district are owned almost exclusively by the two operating cement companies. Several large, undeveloped deposits occur in the San Jacinto and Santa Rosa Mountains of Riverside County within the area enclosed by a line connecting Beaumont, San Jacinto, Hemet, and Palm Springs, particularly northeast of Lake Hemet. Limited water supply and competing land use plans have hindered development of these favorably located deposits.

A series of pendants and structural blocks containing crystalline limestone deposits are along the San Andreas fault zone in the vicinity of Wrightwood in the northeastern San Gabriel Mountains. As these deposits are near the Los Angeles marketing complex, several have intermittently produced industrial limestone. Few if any of them are sufficiently large to support a cement operation. The limestone ranges from white to blue-gray and is generally coarse grained.

The rapid growth of the San Diego metropolitan area has greatly increased the market potential for limestone, cement, and lime products. Large deposits found in the Coyote Mountains of western Imperial County or rock imported from Baja California below Todos Santos Bay ultimately will have to supply this increased demand, although smaller deposits exist in the Dos Cabezas, Jacumba, and Verruga vicinities of eastern San Diego County. There are no large deposits in either San Diego or adjacent Orange Counties. In the Coyote Mountains, very large resources of blue-gray to white, medium- to coarse-crystalline limestone and some dolomite occur in a crystalline complex of late Paleozoic or early Mesozoic age. Overlapping this crystalline core are discontinuous masses of shell-bearing limestone up to 50 feet thick of Miocene age. These are of two sorts, one a compact, pinkish-cream-colored limestone (by far the most abundant), and a friable, dark-colored shell limestone or coquina which occurs in lenticular beds less than 20 feet thick. Both types are low in magnesia and could serve as supplemental sources of cement-grade limestone if the much larger crystalline limestone deposits are brought into production. Some of the latter are a little high in magnesium for cement, but large bodies suitable for cement are present, notably in the vicinity of Carrizo Mountain.

The Mescal, New York, and Providence Mountains are adjacent mountain ranges in eastern San Bernardino County reasonably close to the Union Pacific Railroad that contain very large resources of limestone and dolomite. These have been exploited in only a small way, because water supply, living conditions, distance from markets and rail-freight rates have been unfavorable. They are likely to be more extensively developed in the near future. The carbonate rocks range from white through dove-gray to dark blue-gray. Both fine-grained, dense rocks and medium- to coarse-crystalline varieties are found in the district. Limestones of industrial grade occur in the Triassic Moenkopi Formation, the Yellowpine and Bullion Members of the Mississippian Monte Cristo Limestone, the Crystal Pass Member of the Devonian Sultan Limestone, and even in some parts of the Cambrian to Devonian (?) Goodsprings Dolomite. Potentially usable dolomite occurs in Goodsprings Dolomite, the Ordovician Ely Springs Dolomite, the Ironside Dolomite Member of the Devonian Sultan Limestone and in the Cambrian Bonanza King Dolomite.

Limestone and Dolomite Resource Potential

California's resources of limestone, dolomite, and cement materials are very large in most grades of rock for most use categories and are more than adequate for the foreseeable future. The carbonate rock commodities are low-priced, and, as transportation costs form a significant part of total cost to the user, adjacency to markets is of prime importance. The areas of coastal or tidewater industries, for example, are very poorly supplied, and demand there may ultimately be satisfied by imports because water-freight rates are cheap. The search for higher valued deposits of very high purity, or deposits of very white or attractively colored rock continue—particularly for deposits well located with respect to potential consumers. At the present time, most producing deposits lie within 150 miles of marketing centers and a majority are within 75 miles of such centers. As the better-grade deposits close to market are depleted, it will be necessary to go farther from market or else to go more intensively into beneficiation of low-grade deposits situated close to markets. Competition and conflicting uses for land also tend to drive quarry and mine based industries farther and farther from markets.

Because of remoteness, lack of water, or poor living conditions at some southern California deposits, some classes of carbonate rock for southern California markets are supplied from Nevada. Improved transportation and freight handling or adjustment in current rail-freight rates could change this situation. The burgeoning population, with its resultant expanding manufacturing and construction industries, offer business opportunities unmatched elsewhere.

Carbonate Rock Districts of Particular Major Future Importance

The San Diego marketing area ultimately will have to be supplied from the Coyote and Fish Creek Mountains of Imperial County, as this is the closest district containing major resources. Smaller deposits such as those at Dos Cabezas, Jacumba, and Montezuma Valley may be developed for local needs. Deposits south of Punta Banda, Baja California, could provide imports into the San Diego area.

The notable resources of white crystalline limestone in the Little and Big Maria Mountains of eastern Riverside County may soon be developed, particularly if favorable rail-freight rates are established. Deposits in the San Jacinto and Santa Rosa Mountains of Riverside County are large and of fairly good quality.

Deposits in the Mescal, Ivanpah, New York, and Providence Mountains, all of which are reasonably close to a railroad, are of near-future interest. Also, those in the Tehachapi Mountains and southernmost Sierra Nevada between Mojave and Frazier Mountain are of future interest.

With the opening up of the interior of Santa Barbara and Ventura Counties, the extensive high-grade limestone deposits in the Eocene Sierra Blanca Formation ultimately will be utilized. Lack of good access roads has limited their development thus far, and the population and market situation is just reaching a favorable stage to attract new industries.

Development of deep-water port facilities and an industrial complex around Moss Landing on Monterey Bay probably will result in development of the immense, high-grade, white crystalline limestone deposits at Pico Blanco, Monterey County. These are the only large deposits of high-grade limestone close to tidewater on the Pacific Coast of California, Oregon, and Washington.

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LITHIUM

(By G. I. Smith and W. P. Irwin, U.S. Geological Survey, Menlo Park, Calif.)

Most of the lithium obtained in California comes from saline brine in Searles Lake, one of the chief sources of the world's lithium, although known mainly for its other extractable components (see chapter on Sodium carbonate). Much larger production of lithium concentrate has come from pegmatite deposits in North Carolina; smaller quantities of pegmatite material come from the Black Hills in South Dakota. Other states from which lithium has been obtained are Arizona, New Mexico, Colorado, Wyoming, Massachusetts, New Hampshire, and Maine.

Lithium has many uses. Major quantities are used in lithium greases, ceramics and glass, welding and brazing, and air conditioning. Large quantities have also been purchased by the Atomic Energy Commission whose interests probably include both the neutron absorption capacity of the lithium-6 isotope, and the high-energy potential of the nuclear reaction between lithium-6 and deuterium. Smaller quantities of lithium are used in production of batteries, pharmaceuticals, alloys, and as a catalyst. Future uses may include lithium as a heat-exchange medium in thermonuclear reactors, as a catalyst for new processes, and in new alloys. The lithium-6 isotope forms about 7.5 percent of the lithium in natural deposits, and, if it becomes widely used for shielding and as a reactant in nuclear power plants, large quantities of the more abundant lithium-7 isotope might be left over for other uses (Schreck, 1960; Kesler, 1960; Eilertsen, 1964).

Minable lithium deposits are known on every continent. Of those being mined today, all except the deposit in California are pegmatites. Published data suggest that in 1963 the largest production outside the United States was in Rhodesia, but large quantities also came from other African nations, Australia, and Canada. Unreported amounts were produced in South America, and production from one or more Communist nations is likely (Eilertsen, 1964).

In 1954 the United States produced about 38,000 tons of lithium minerals and compounds containing almost 2,500 tons of lithium oxide. This was valued at $3,126,000 (Schreck, 1961). At about the same time, the American Potash & Chemical Corp. at Searles Lake was estimated to have an annual production capacity of lithium carbonate equivalent to 200 to 300 tons of lithium oxide, or about 10 percent of national production (Ver Planck, 1957). Production figures for the years after 1954 have not been published.

The production of lithium from the concentrated brines of Searles Lake started in 1938. The complex process used yields dilithium sodium phosphate along with six other products, then converts it to lithium carbonate for shipment. The brines, which average about 0.015 percent lithium oxide, are pumped from the upper of two saline layers that were deposited during late Quaternary time (see section on Sodium carbonate). Lithium minerals, however, have not been found. Although the total production of lithium from this deposit will actually be determined largely by the reserves and future prices of its co-products, the lithium in it constitutes a sizable percentage of the United States indicated reserves (Norton and Schlegel, 1955; Kesler, 1960).

Prior to the recovery of lithium from the brines of Searles Lake, California production of lithium-bearing minerals was from pegmatites of the Pala district in northern San Diego County. The total reported production of lithium minerals mined from these pegmatites is 23,480 short tons, valued at 432,800, for the period 1900–1928. Nearly all of this production was from the Stewart mine. The principal lithium-bearing mineral of the Pala district is the lithium-rich mica lepidolite, followed in order of importance by spodumene and amblygonite. The lithium deposits of the Pala district are chiefly zoned pegmatites; the spodumene generally occurs in the core and intermediate zones, and the minable concentrations of lepidolite mostly occur as a replacement of the primary pegmatite minerals along the lower parts of the spodumene-rich zones (Jahns and Wright, 1951).

Additional sources of lithium in California appear to be few. Abnormal concentrations occur in clays in the Mojave Desert. One, near Hector, contains a little over 1 percent lithium oxide (Foshag and Woodford, 1936; Ames, Sand, and Goldich, 1958); another, northeast of Amboy, contains 0.50 percent (Foshag and Woodford, 1936); still another, near Boron, is reported to contain 0.5 to 1.0 percent (Kesler, 1960). These percentages are close to those required for profitable operations from pegmatites (Norton and Schlegel, 1955), but the deposits are not currently considered economic sources of lithium. Brines from geothermal wells in the Salton Sea area contain about 0.065 percent lithium oxide (White, 1965), but whether such components as lithium can be extracted will not be determined until several complex engineering problems have been solved.

In two other western States, however, steps are being taken to extract lithium from brines in amounts which may have major impact on all facets of the industry. A dry lake at Silver Peak, Nevada, is being developed by the Foote Mineral Co. as a source of lithium; the subsurface brines are reported to be 6 to 7 times richer in lithium than other known source brines (Eng. Mining Jour., 1965; Wall Street Jour., 1965). An option on brines from Great Salt Lake, Utah, has been taken by Lithium Corp. of America for future extraction of lithium chloride plus other products (Eilertsen, 1964).

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MAGNESIUM COMPOUNDS

(By A. R. Smith, California Division of Mines and Geology, San Francisco, Calif.)

Three plants in California produce magnesium compounds from sea water and sea water bittern by treatment with calcined dolomite (Ver Planck, 1957). Plants at Newark, Alameda County, and Moss Landing, Monterey County produce magnesia refractories and specialty magnesias. Magnesium compounds of high purity for pharmaceutical and other chemical uses are manufactured in South San Francisco. A fourth operation in Chula Vista, San Diego County produces magnesium chloride from bittern without the use of dolomite.

The most important commercial magnesium compounds produced in California are: the hydroxide, oxide, chloride, carbonate, trisilicate, and sulfate. The production of magnesium oxide from sea water is essentially one of reacting calcined dolomitic lime (combination of calcium and magnesium oxides) with sea water to form magnesium hydroxide; the magnesia comes from both the calcined dolomite and sea water in about equal amounts. This magnesium hydroxide is then fired in rotary kilns to form magnesia that ranges from 65 to 98 percent MgO.

In California, magnesium hydroxide also is the raw material for manufacturing basic magnesium carbonate which elsewhere is made from dolomite. Magnesium chloride is obtained at the Chula Vista plant, San Diego County by evaporating, with heat, bittern from an adjoining salt plant—discarding the precipitate and concentrating the liquor. To produce the trisilicate, sulflate, and other magnesium compounds, caustic calcined magnesia is used in chemical combination with the necessary acid radical. These are, for the most part, specially processed to meet rigorous physical and chemical standards. Location of the plants is shown on figure 35, and products are listed in table 25.

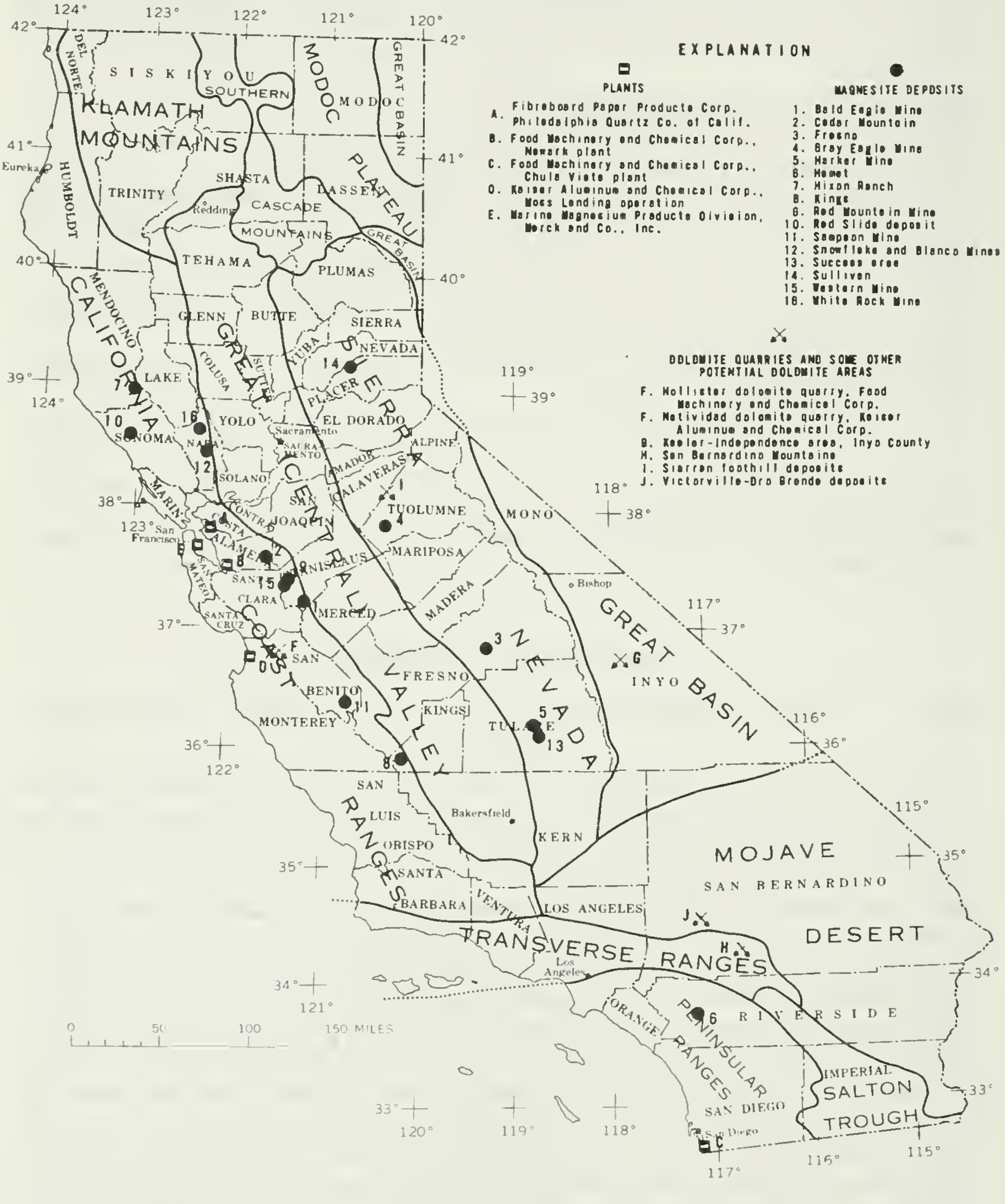

FIGURE 35. Map showing locations of plants producing magnesium compounds in California, some areas with commercial grade dolomite, and selected magnesite deposits.

TABLE 25.—*Plants producing synthetic*[1] *magnesia, other magnesium compounds, and calcined dolomite in California, 1964*

[Source: Modified after Comstock, H. B., 1963, table 49, p. 107.]

Letter on fig. 35	Company	Location of mine or plant	Products	Raw materials
A	Fiberboard Paper Products Corp.	Emeryville, Alameda County	Precipitated magnesium carbonate	Magnesium hydroxide slurry
B	Food Machinery and Chemical Corp.	Newark, Alameda County	Caustic-calcined and refractory magnesia; magnesium chloride crystals; magnesium hydroxide; bromine compounds and gypsum.	Sea water bittern, calcined dolomite.
C	Food Machinery and Chemical Corp.	Chula Vista, San Diego County	Magnesium chloride	Sea water bittern.
D	Kaiser Aluminum & Chemical Corp. (Refractories Div.).	Moss Landing, Monterey County	Caustic-calcined and refractory magnesia; magnesium hydroxide; magnesium oxide, extra-light, light and heavy.	Sea water, calcined dolomite
E	Marine Magnesium Products Div., Merck & Co., Inc.	South San Francisco, San Mateo County.	High-purity compounds: magnesium oxides, extra-light, light, and heavy; magnesium hydroxide; precipitated magnesium carbonate; magnesium trisilicate.	Sea water, sea water bittern, calcined dolomite.
A	Philadelphia Quartz Co.	Berkeley, Alameda County	Epsom salt	Brucite, calcined magnesia.
F	Food Machinery and Chemical Corp.	Hollister dolomite quarry, San Benito County.	Crushed calcined dolomitic rock, dolomite granules.	Dolomite.
F	Kaiser Aluminum & Chemical Corp.	Natividad dolomite quarry, Monterey County.	Crushed, calcined dolomitic rock, dolomite granules.	Do.

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[1] *Synthetic* refers to magnesia produced from sources other than the insoluble minerals magnesite or brucite.

The chemical and physical properties of the two general classes of magnesium oxides are largely defined by the temperature of calcination:

a. *Dead-burned magnesia* (refractory grade) is produced by burning magnesite or magnesium hydroxide above 1,450° C. The resulting magnesium oxide granules are chemically inert (with less than 2 percent carbon dioxide) and contain various proportions of iron oxide, silica, alumina, and lime, either as impurities in the raw material or as additives. "Periclase", of which most refractory brick is presently made, is a dense crystalline magnesia containing over 90 percent MgO, with chromite and silica as the principal additives. It is made by firing this mixture to extreme temperatures, 1,760° C or greater, depending on the type of bond desired for the brick. Natural magnesia is the mineral periclase.

b. *Caustic-calcined magnesia* is produced by calcining magnesium hydroxide at temperatures of at least 1,200° C or to such degree that it contains less than 10 percent ignition loss (carbon dioxide and water), and slakes in water or air. It may contain 90 to 98 percent MgO: iron oxide, silica, alumina, and lime are undesirable impurities.

Refractory magnesia is consumed mainly by the steel industry to line open-hearth steel furnaces, either directly as grains or in refractory bricks and mortars. Other major uses of magnesia refractories are in copper and lead smelters, in rotary kiln applications of the portland cement industry, and the magnesia calcining plants themselves. The use of dead-burned magnesia is increasing at a rate greater than the growth in use of metals, since magnesia refractories have increasingly supplanted other refractories in the metal-making industry. In 1930, the total apparent consumption of dead-burned magnesia by all industries was equivalent to about 4.16 pounds per ton of steel. By 1945, the figure had increased to 6.5 and in 1963 was about 14 pounds per ton of steel produced in the United States.

The largest single market for caustic-calcined magnesia is in magnesium oxychloride and oxysulfate cements, which are used mainly for fireproof, resilient flooring. The cement is prepared by mixing a solution of magnesium chloride or sulfate with ground, caustic-calcined magnesia. Other major uses for caustic-calcined magnesia are in the paper pulp, rayon, fertilizer, insulation, and chemical industries. The other specially prepared magnesium compounds made in California are used to manufacture a variety of products. The rubber industry uses magnesium oxide in various synthetics (hypalon, neoprene, butyl); magnesium oxide, carbonate, hydroxide, and trisilicate are primary ingredients in antacid preparations.

Magnesium metal is used as a structural metal, an alloying constituent for other metals, and as a reducing agent to produce titanium, zirconium, hafnium, uranium, and beryllium. Since 1956, the metallurgical uses for primary magnesium have exceeded the structural uses, and in 1964 amounted to about 62 percent of the total use figure. Magnesium as an aluminum alloy accounts for two-thirds of this metallurgical classification. Since 1945, primary magnesium has not been produced in California. Magnesium production is shown on table 26.

TABLE 26.—*Salient statistics on magnesite, magnesia, and dead-burned dolomite*

[In thousand short tons]

	1917-30 average	1931-40 average	1941-50 average	1951-55 average	1956	1957	1958	1959	1960	1961	1962	1963
California production of refractory and caustic-calcined magnesia				87	122	139	140	167	164	171	142	152
U.S. production [1] of refractory magnesia	25	65	278	385	431	468	415	518	506	599	576	713
U.S. production [1] of caustic-calcined magnesia	11	8	63	40	36	61	45	54	66	80	87	135
U.S. production of crude magnesite	157	153	431	501	687	678	493	594	499	604	492	528
World production of crude magnesite [2]	700	1,400	2,200	4,420	5,400	5,650	6,100	6,600	7,100	8,300	8,600	9,050
U.S. production [1] of dead-burned dolomite	317	453	1,308	1,968	2,424	2,251	1,659	1,988	1,949	1,983	1,857	1,949

[1] The term "production" refers to that amount sold or used by producers.

[2] These figures vary somewhat in different tabulations by the U.S. Bureau of Mines but are generally in the same range.

Source: Data through 1960, U.S. Bureau of Mines Inf. Circ. 8201, table 24, p. 82; 1961-63 data from U.S. Bureau of Mines Minerals Yearbook.

Magnesium, the eighth most abundant element in the earth's crust, averages 2.09 percent in igneous rocks and about 4.77 percent in limestones. Magnesium is the second most abundant metal after sodium in sea water, which contains the equivalent of 0.21 percent MgO as a chloride or sulfate. The most important magnesium-bearing minerals are dolomite (Ca,Mg) (CO_3), magnesite $(MgCO_3)$ and brucite $(Mg(OH)_2$. With the exception of a few hundred tons of imported brucite (used in the manufacture of epsom salt), sea water and dolomite are the only raw materials presently used in California's magnesia industry. Magnesite is mined at Chewelah, Washington, and Gabbs, Nevada (also the source of some brucite); elsewhere, olivine $(MgFe)_2SiO_4$, forsterite (Mg_2SiO_4), and serpentine $(H_4Mg_3Si_2O_9)$ have minor uses as refractories, and as a source of magnesium compounds.

Prior to World War I, magnesite was not regularly produced in the United States; the needs for industry were met by imports, largely from Austria and Hungary. The first recorded production in California, and possibly in the United States, was from Cedar Mountain, Alameda County in 1886. However, the amount mined was small, and annual magnesite production in the United States (centered entirely in California) did not reach 10,000 tons until 1910. The first commercial production of magnesium compounds from sea water was obtained in 1928 at South San Francisco. The present operation is still on the original site and, since 1951, has been the Marine Magnesium Products Division of Merck & Co.

The volume of magnesite mined in California between 1910 and 1945 followed the fortunes of two world wars, until it finally succumbed to dolomite and sea water as a source. Annual production of magnesite, used mainly for refractory purposes, rose to more than 200 thousand tons by 1917, most of which came from California. Production dropped to a low in 1938, and rose slightly in 1941 to only 50 thousand tons in California during the start-up period of the magnesia plant built by Westvaco Chlorine Products Corp. at Newark. The mining of magnesite, henceforth, declined steadily in California, with the increasingly efficient manufacture of magnesia from dolomite and sea water, until the Western mine stopped regular production in 1945.

Calcined dolomite was initially used by Marine Products, followed by Kaiser in 1942, and was substituted for oyster shells as the precipitating agent in 1947 at the Newark operation. Since then, the use of dolomite has increased concurrently with that of magnesia. In 1964, the manufacture of magnesia used about 500,000 tons of California dolomite.

Dolomite, which now accounts for approximately one-half of the magnesia produced in California is generally restricted in occurrence. The dolomite used at Newark and Moss Landing is mined from separate quarries in the Gabilan Range between Salinas and Hollister. These deposits consist of large roof pendants of crystalline dolomite (with some limestone) in Paleozoic(?) complexes. (Refer to the section on "Limestone, dolomite, and lime products" for description of dolomite resources in California.)

Magnesite has three major types of occurrence: (1) as large crystalline bodies in dolomite, (2) within shear zones and veins, and as replacement-like bodies in serpentine, and (3) as sedimentary deposits associated with playa lake beds. The larger magnesite deposits of the world, including those of Chewelah, Washington, and Gabbs, Nevada, and those in Austria and Manchuria, are of the dolomite replacement type. The magnesite of these deposits is crystalline, as constrasted with the cryptocrystalline or "amorphous" variety, characteristic of deposits associated with serpentine and with lake sediments.

Most of the magnesite deposits in California are associated with serpentine and occur in the California Coast Ranges and in the western foothills of the Sierra Nevada. Many of the deposits and mines have been discussed briefly by Bradley (1925, p. 41–140), and others by Hess (1908), and Gale (1914). The Red Mountain magnesite district, on the border of Santa Clara and Stanislaus Counties, is a typical replacement deposit which has been studed in detail by Bodenlos (1950).

Certain terrestrial brines are important sources of magnesium chemicals. The best known are the magnesium-calcium chloride brines of Michigan, Ohio and West Virginia. In California, the brine of Bristol Lake, San Bernardino County belongs to this class; but magnesium compounds are not recovered from it.

The manufacturing process is fundamentally alike in the large operations of Food Machinery and Chemical Corp., Kaiser, and Marine Magnesium. Sea water is treated with a regulated amount of slaked dolomite or lime to precipitate the soluble bicarbonates as calcium carbonate. At the Food Machinery and Chemical Corp. plant, which uses concentrated salt water bittern, the sulfate must first be removed by combining the bittern with calcium chloride. Then, the calcium carbonate is removed by thickening and the "purified" sea water is combined with either dry or slaked calcined dolomite. The resulting magnesium hydroxide is washed with fresh water to remove calcium chloride and thickened in a counter-current system to concentrate the slurry of magnesium hydroxide. The thickened magnesium hydroxide is filtered and fed into kilns for conversion to caustic-calcined or dead-burned magnesia.

Synthetic magnesia (produced from sources other than brucite, magnesite, or magnesium silicate ores) supplies an increasing portion of the total domestic supply of both dead-burned and caustic-calcined magnesia. In 1947, synthetic magnesia accounted for about 30 percent of the usage; by 1956, it increased to 50 percent; and in 1963 the figure was 74 percent. Production from well brines, dolomite, and/or raw sea water, and sea water bittern in 1963 accounted for about 48 percent of the caustic-calcined magnesia sold or used, and for about 79 percent of the refractory magnesia sold or used by producers in the United States. Because the economically useful supply of natural magnesite and brucite is exhaustible, the long-term trend will continue to favor production of synthetic magnesia.

California's 1963 production of synthetic magnesia produced entirely from dolomite and sea water, accounted for about 18 percent of the total United States production of refractory and caustic-calcined magnesia from all sources (see fig. 36).

California's production increased from 1950 to 1961 but has fallen off slightly since then (see table 26). This growth is mainly attribu-

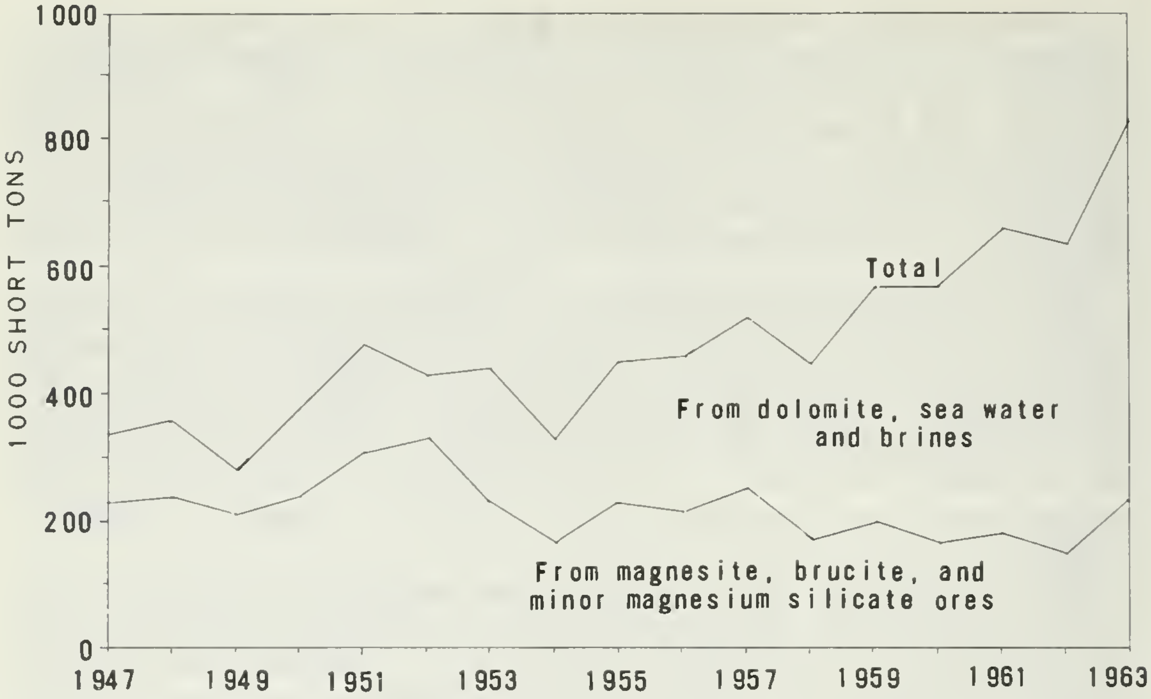

FIGURE 36. Domestic production of magnesia from ores and brines in the United States, 1947–63 (U.S. Bureau of Mines Minerals Yearbook, 1956 and 1963 editions).

table to the increasing volume of refractory magnesia, with the ratio of caustic-calcined to refractory magnesia (produced in California) ranging from a low of 0.04 in 1950 through 0.26 (1955); 0.15 (1960); to 0.29 in 1963. Future production will probably reflect the general increasing demand for basic refractories and the use of various magnesium compounds with our expanding population.

The resources of dolomite in southern California are great, especially along the north part of the San Bernardino Mountains and in the Victorville area. In northern California, however, the known commercial dolomite deposits are presently in use except for the much less accessible Sierran foothill dolomite. The enormous amount of dolomite rock in the eastern Mojave Desert is, at present, quite remote.

A source of magnesia could result from combining the dolomite resources of San Bernardino County with sea water. Presently, Kaiser's Steel plant at Fontana and various portland cement plants are the prime users of magnesia in southern California. Should the market for magnesium compounds improve considerably with additional heavy industry, this potential may some day be realized.

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MANGANESE

(By F. F. Davis, California Division of Mines and Geology, San Francisco, Calif., and D. F. Hewett, U.S. Geological Survey, Menlo Park, Calif.)

Manganese plays an extremely important role in the metallurgical technology of the modern steel age. It is used for pig iron and in a series of ferrous alloys used in steel-making. The principal alloys are ferromanganese, spiegeleisen, silico-manganese, and silicospiegel. Manganese from these alloys serves to remove free oxygen and sulfur in the melt, increases the strength and hardness of steel, and imparts a mobility which permits the steel to be rolled and forged more easily. Elemental manganese metal, 99.9 percent pure, is now produced electrolytically from an acid solution of oxide ores. The high purity of this product makes it especially useful for making stainless steel, alloy steels, and manganese alloys of the non-ferrous metals copper, zinc, aluminum, magnesium, nickel, tin, and lead. The chemical industry is an important but relatively small consumer of manganese ore for such products as dry cell batteries, paints, varnishes, ceramics, chemicals, and miscellaneous items. About 96 percent of manganese used in the United States is consumed in the metal industries, 2½ percent is used in dry cell batteries and the rest is used in a variety of chemical industries.

Although the United States is the principal consumer of manganese ores, consuming some 1,840,000 tons in 1963, its deposits of high-grade metallurgical ores, containing over 40 percent manganese, are extremely small, and domestic production rarely has exceeded 10 percent of consumption. In 1963, domestic production was only 10,622 short tons and general imports were 2,093,473 short tons.

Although magmatic solutions are the primary source of manganese, usually the primary manganese minerals are not concentrated sufficiently to form ore (Jenkins and others, 1943). Most of the large ore deposits throughout the world, however, are associated with sedimentary rocks; in others, minerals are principally oxides of secondary origin. Some of the hydrothermal and sedimentary deposits have been altered to manganese silicates. Because the silicates do not constitute ore, only the oxidized portions of the metamorphic deposits are mined.

The Indians found and utilized manganese deposits in eastern and southeastern California as a source of face paint in prehistoric times. Gold seekers were probably the first white men to note manganese minerals in California, since a deposit near Sonora in the heart of the gold country was reported in 1857. The first production came from San Francisco Bay area where 200 short tons of manganese-bearing rock was mined from Red Rock Island in 1866.

The Ladd mine in San Joaquin County was discovered in 1867 and produced ore regularly on a small scale until 1903. Production from California mines was negligible until World War I. Between 1915 and 1921 inclusive, about 75,000 short tons of ore were produced. During this period more than 300 new manganese prospects were opened, and about one-third of them produced ore, much of it below peace-time specifications (Jenkins, 1943). Mining activity centered in the Coast Ranges, where the principal producing mines were the Ladd, Buckeye, and Thomas. Two mines, the Braito and the Mount Hough, at the north end of the Sierra Nevada, and mines in the Arlington and Paymaster districts in the desert of southeastern California also contributed substantially to the total production.

Mine production again became sporadic between 1922 and 1940, but increased in 1941, as submarine warfare reduced foreign supply. In 1943, a dry concentrating plant was built near Patterson to process ore from the Buckeye mine for use in dry cell batteries. Several new deposits, such as the Blue Jay and the Trout Creek, were discovered in Trinity County and were the sources of high-grade, direct shipping ore. The Kaiser Steel Plant, erected at Fontana in 1943, provided an additional outlet for southeastern California, so that production increased from the manganese deposits in San Bernardino County and the Arlington and Langdon districts of Riverside County. The price of manganese ore declined after World War II, and only a token production of ore was reported from 1946 to 1951.

During the Korean War period battery-grade ore was produced and milled at the Ladd mine from 1951 until the end of 1954 and in 1952 the U.S. Government established strategic mineral stockpiles in Arizona and New Mexico to encourage the production of low-grade (15 to 40 percent Mn) domestic manganese ore. Important contributors to this program were the Pioneer (Whedon) mine, Imperial County;

Blackjack mine, Riverside County; and the Big Reef and Logan mines, San Bernardino County. Concentrators were established at Poe's siding to serve the mines in central San Bernardino County; at Inca and Tasco siding to treat low-grade ores from the Arlington district, Riverside County; and at Ripley to treat ore from Imperial County. This program ended in 1959, and all California manganese mines closed.

Except in wartime, there is little inducement for the capital investment necessary to develop the large, low-grade deposits known in the United States. During 1954 when the government was accumulating a stockpile of this strategic mineral material, shipments of manganese ore from all domestic mines reached 206,128 short tons.

California manganese mines yielded an all-time peak production of 37,747 short tons valued at $1,543,949 in 1954. This output included ores ranging from 15 to 50 percent manganese. A token production of ore (battery grade) was made in 1962 and none in 1963. Total production from Califronia deposits between 1866 and 1964 was 320,205 short tons valued at $12,784,533.

Occurrences in California

The California deposits as shown in figure 37, lie chiefly in four geologic provinces within which they are concentrated in several rock or formation units:

1. Most of the unmetamorphosed deposits of sedimentary origin lie in the Coast Ranges in a belt that extends from Humboldt to Santa Barbara Counties. The deposits occur in chert of the Franciscan Formation (Jurassic and Cretaceous) which is widely exposed. The explored ore bodies are lenses of carbonate which range in width from 3 to 8 feet and extend several hundred feet along the outcrop.

The rocks of the Franciscan Formation commonly are folded and faulted so that the ore zones now dip steeply. The primary minerals are manganese carbonate and manganiferous opal, which weather to high-grade "black oxide" ore. Oxidation extends to depths of as much as 200 feet below the surface. It is believed that the silica and manganese were discharged by submarine springs or volcanos into ocean basins of restricted circulation, where they formed chert and managanese sediments (Jenkins, and others, 1943). Principal mines are the Ladd, Buckeye, Foster Mountain, Thomas Mountain, and Blue Jay.

2. Metamorphosed sedimentary manganese deposits are widespread throughout the Sierra Nevada and are chiefly in rocks of the Calaveras Formation (Upper Paleozoic) and Amador Group (Jurassic). The depth of oxidation is generally very shallow, and most of the deposits are currently of little economic importance. Representative mines are the Braito and Mount Hough in Plumas County.

3. In the Klamath Mountains of northern California, the manganese host rocks are both metamorphic and metasedimentary, ranging from Paleozoic to Jurassic in age. The depth of oxidation in these bedded deposits is shallow, and little ore has been produced.

4. At numerous localities in the Mojave Desert region of southeastern California, hypogene veins of manganese oxides with calcite

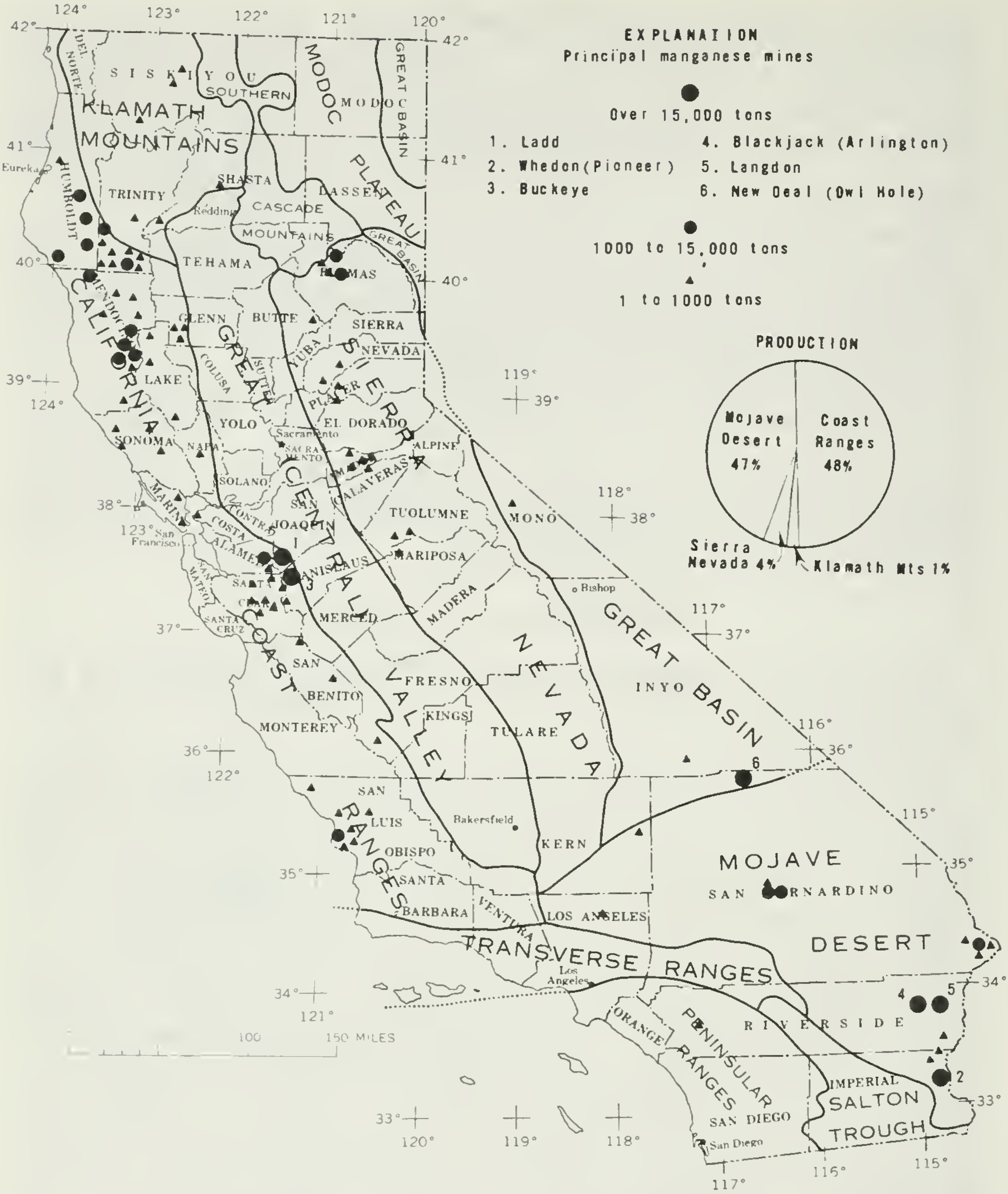

FIGURE 37. Principal manganese mines in California.

and barite have formed in fissures that cut fanglomerate and volcanic rocks of Tertiary age, and older quartz porphyry. Most of the deposits consist of brecciated rocks cemented, impregnated, and partly replaced by manganese oxide, principally a hard oxide similar to psilomelane. The average manganese content of the deposits mined is from 15 to 30 percent. The hard oxide can be hand-sorted in some places to give a product containing 40 to 45 percent of manganese (Jenkins, 1943). Principal mines are the Whedon (Pioneer), Blackjack, New Deal, Langdon, Logan and Big Reef.

Recent work shows that manganese oxides also occur (a) in travertine aprons near hot springs, either uniformly distributed through the calcium carbonate or as layers of manganese oxide alternating with layers of calcium carbonate; and (b) as layers in stratified sedimentary rocks. The best evidence for a genetic relationship between hypogene veins and stratified deposits is based on the presence in the stratified deposits of minor metals such as tungsten, and on the areal distribution of the deposits (Hewett and others, 1963).

The total manganese ore produced in California from 1866 to 1964 inclusive, is about equal to 16 percent of the current (1965) annual consumption in the United States. Most of the ore produced from 1869 to 1954 came from sedimentary deposits in the Coast Ranges. During the decade 1954–1964, practically all the ore produced has come from the hypogene vein deposits of southeastern California.

Even though much is known about the number and distribution of the manganese deposits in California, there is little information about the ore reserves. No bodies of high-grade shipping ore or bodies of moderate grade concentrating ore which can be mined and sold at competitive prices are known. Some deposits in the Coast Ranges and in the desert provinces could no doubt produce small quantities of ore at premium prices, but the size of these deposits is undetermined. Additional prospecting during periods of high prices probably will disclose a number of new small deposits in these provinces.

Because many California deposits contain siliceous manganese minerals, some long-range potential for these refractory materials may exist if a satisfactory process can be developed for the recovery of the manganese. No data are available on the size and extent of the siliceous deposits.

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MERCURY

(By F. F. Davis, California Division of Mines and Geology, San Francisco, Calif., and E. H. Bailey, U.S. Geological Survey, Menlo Park, Calif.)

Mercury, the silver-colored liquid metal commonly known as quicksilver, possesses physical and chemical properties which make it extremely valuable for many industrial uses, in most of which no suitable substitutes are known. California is, and has been, the source of most of the mercury produced in the United States. Some of the properties of mercury and the industrial uses that result from these properties are listed below, and the proportion of the total domestic consumption used in each category during the past 5 years is shown in parentheses:

1. High electrical conductivity: switches, relay tubes, rectifiers, oscillators, batteries, lamps, signs, and other electrical devices (22 percent).
2. High specific gravity and uniform rate of expansion: industrial and control instruments such as weightometers, pressure gauges, analytical apparatus, flow meters, pendulums, pumps, gyrocompasses, clutches, barometers, thermometers, and heat-control devices (16 percent).
3. Amalgamation with other metals and fluidity: mercury electrolytic cells used in the production of chlorine and caustic soda (11 percent).
4. Poisonous character of its compounds: seed disinfectants, turf fungicides, and plant germicides (5 percent); mold and mildew inhibitors and anti-fouling paints (8 percent); mercury salts and pharmaceuticals (5 percent).
5. Combinations of physical and chemical properties: hundreds of other uses, such as dental inlays and castings, power production, munitions industry, in the plup and paper industry, in the recovery of gold, in general laboratories, and in atomic energy applications (33 percent).

Since satisfactory substitutes are generally unavailable, mercury has been considered an essential commodity both for civilian and military purposes, and it is generally included in lists of strategic materials during times of national emergency.

Annual world production in the 1955–1964 period averaged about 235,000 flasks, and the United States economy required each year about 60,000 flasks, or about one-fourth of the world supply. Although the United States has in the last hundred years produced nearly as much mercury as it has used, the domestic production in the recent 10-year period has been only 48 percent of consumption and in 1964 amounted to only 21 percent. For the past 50 years the gap between supply and demand in the United States has been bridged by imports from Spain, Italy, Mexico, and Yugoslavia, where mercury can be recovered somewhat more cheaply than at most domestic mines. As Spain and Italy have dominated world supplies in the past, they have been able to control the price of mercury simply by oversupplying or withholding stocks from the market, often to the detriment of domestic producers. In wartime, however, foreign sources are less accessible, and domestic mercury mines have been temporarily stimulated by price increases; concurrently foreign stocks accumulate, and, with the cessation of hostilities, the large quantity of mercury that becomes available has resulted in greatly depressed prices. This has lead to wider price fluctuations for mercury than for most other commodities and has given the mercury mining industry the reputation of being one of high risk.

Beginning in early 1964, a new and more healthy trend in the mercury mining industry was initiated when the price began to rise as a result of normal peace-time demand exceeding the world's production. The upward trend in price began from a level of about $225 a flask and continued into mid-1965, when it exceeded $700 a flask. This drastic increase generated a renewed interest in mercury mining and started a scramble to lease properties and put them into production. However, no immediate great increase in production can be expected, because most of the California mines were inoperative prior to the price increase and must not only be rehabilitated but must also find new ore to exploit.

Cinnabar, HgS, the bright-red stable form of mercury sulfide, is the principal mercury ore mineral. Metacinnabar, HgS, the black sulfide of mercury, and silvery metallic mercury are found in the ore of some mines, but only in a few are they important ore minerals. Other very rare mercury minerals occasionally found in California are calomel, $HgCl$; eglestonite, $HgCl_2O_4$; and montroydite, HgO. Mercury ores contain few other metallic minerals. Pyrite or marcasite is generally present in small amounts, and stibnite, though commonly absent, is abundant in a few deposits. The principal gangue minerals are quartz, opal, chalcedony, calcite, dolomite, and magnesite. Liquid or solid hydrocarbons are present in minor amounts in many deposits. None of these minerals normally is abundant enough in California mines to require special treatment in ore extraction, but pyrite or stibnite, if very abundant, can introduce difficulties.

Mercury deposits are found chiefly in regions of extensive Tertiary or Quaternary volcanic and tectonic activity. The deposits are classed as epithermal, being formed by the deposition of ore minerals from aqueous solutions at relatively low temperatures and at shallow depths. Their close association with hot springs is shown by the presence of cinnabar at Coso Hot Springs in Inyo County, The Geysers in Sonoma County, the Sulphur Bank mine in Lake County, and at Amadee Springs in Lassen County, in all of which cinnabar is either being deposited or was very recently deposited. However, in most districts the mercury was deposited during an earlier period, the hot springs have ceased flowing, and any surficial spring deposits that were once present have been removed by erosion leaving the mercury-bearing roots of the spring systems.

Mercury ore bodies commonly are small, irregular, and more erratically distributed than are the ore bodies of other minerals. Cinnabar, perhaps with some metacinnabar or native mercury, fills fractures and voids or has replaced the host rock. Many ore bodies have been formed by the concentration of primary minerals in openings in porous or broken rocks, especially where they are overlain by relatively impervious rocks. Others that are equally as large and rich are the result of replacement of silica-carbonate rock, which is a hard brittle rock formed by the hydrothermal alteration of serpentine to a mixture of quartz or opal and a carbonate that is generally magnesite.

More than 50 percent of the larger mercury deposits in California occur in this silica-carbonate rock, with the cinnabar in some deposits replacing the rock and in others just filling fractures. The silica-carbonate rock is associated with so many deposits it is commonly called "quicksilver rock," but it is much more widespread than the ore and is not very useful as a guide in prospecting. Other mercury deposits in California occur in highly deformed sedimentary rocks of the Franciscan Formation, of Jurassic and Cretaceous age, with which the serpentine and silica-carbonate rock are associated. Still others occur in the less deformed sedimentary rocks of the Knoxville, Paskenta, Chico, and Panoche Formations of similar age. Tertiary sedimentary and volcanic rocks locally contain major deposits in California, as do also Quaternary volcanic rocks. Even a few small Recent placer deposits have been successfully exploited.

The history of the discovery and development of these deposits is as long and fully as colorful as the saga of California gold mining. In prehistoric time, cinnabar was used as a source of paint for war and tribal ceremonials by the California Indians, and they are known to have mined it at the site of the New Almaden mine, as well as elsewhere in the State, long before civilization reached California. The New Almaden deposit was rediscovered by white men in 1824, began producing in 1846, reached its peak in 1865 when nearly 50,000 flasks were recovered, and has been in production, though at a declining rate, almost ever since then. It is the oldest metal mine in California, and the first mercury deposit discovered in North America. In 1853 the deposit of the New Idria mine in San Benito County was discovered. It, too, has been mined almost continuously since its discovery, and, in 1965, was the most productive mercury deposit in the United States.

As the demand for mercury for amalgamation increased following the gold rush of the 1850's, exploration for mercury expanded northward in the Coast Ranges, and soon important new discoveries were made at Knoxville, Oat Hill, and Aetna Springs in Napa County; at Sulphur Bank and near Wilbur Springs in Lake County; and in the Mayacmas district of Lake and Sonoma Counties. During the 1860's, hydraulic mining for gold on a grand scale, and the discovery of the Comstock lode in Nevada, led to still greater demand for mercury, and exploration southward from New Almaden led to the discovery of new mercury deposits in Santa Barbara and San Luis Obispo Counties. Many of the mines reached their peak of production in the mid-1870's, which were also peak years for the State as a whole. The Sawyer decision of 1884 adversely affected the hydraulic mines and curtailed the need for mercury. As a result, mercury production declined almost continuously for the next 37 years and many mines closed. All the major deposits were discovered by 1895, although a rich short-lived open-pit mine was developed in the Emerald Lake district of San Mateo County in 1955, and a rich new ore body was found at the Buena Vista mine in San Luis Obispo County in 1957.

Since 1914, mercury production has been encouraged by five separate stimuli: the strategic demands of World War I, the industrial expansion of the late 1920's, the demands of World War II, the Korean War and Governmental aids of the late 1950's, and the industrial demands of 1964–1965. During each of these periods, the increased price led to renewed activity that resulted in an increase in production, but this came largely from deposits that had been known for many years. If history is repeated, we may expect many of the California mines now regarded as "worked out" to be successfully reactivated.

The worldwide unit of trade in mercury is the flask—a cast iron or steel cylinder about 5 inches in diameter and 12 inches long containing 76 pounds of liquid mercury. Total world production amounts to about 20 million flasks, and United States production is a little less than 3½ million flasks. Deposits in California have yielded about 85 percent of the domestic production, or about 2⅘ million flasks valued at about $200 million. This value is exceeded among metallic mineral producers in California only by the value of the output of gold and copper mines.

Occurrences in California

The highly productive mercury deposits of California lie in a belt extending through the California Coast Ranges from central Lake County southward to Santa Barbara County. It contains the Nation's eight most productive mines, dominated by the great New Almaden mine with a production record of over one million flasks, and the New Indria mine, which has yielded more than half a million flasks. Also included are about a hundred other productive mercury mines, many prospects, and the major mercury reserves of the United States. These are clustered in 21 districts, shown on figure 38, most of which contain one, or at most two, prominent deposits and numerous smaller ones, though an exception is provided by the Mayacmas district, in Napa, Sonoma, and Lake Counties, which contains several major deposits.

One of the State's principal mercury mines, the Altoona in northeastern Trinity County, is in the Klamath Mountains province. Another less productive mine, the Walibu, is in the Tehachapi district at the southern end of the Sierra Nevada province. Relatively small amounts of mercury also have been obtained from outside the Coast Ranges province in the Patrick Creek and Beaver Creek districts in the Klamath Mountains, the Coso district in the Great Basin province of southwestern Inyo County, and the Tustin district of Orange County in the Peninsular Ranges province.

The New Almaden mine, a few miles south of San Jose in Santa Clara County, is the most productive mercury mine in North America and provides a good example of ores in silica-carbonate rock. The mine area is underlain mostly by graywacke, shale, and greenstone (altered mafic lavas) of the Franciscan Formation, and serpentine. The dominant structure is a northwest-trending anticline whose southwest limb has been highly sheared. Two major sills of serpentine appear to have been intruded up the north limb, to have converged near the crest, and to have continued down the southern flank. The serpentine was hydrothermally altered, particularly along its margins, to silica-carbonate rock. Cinnabar, the principal ore mineral, was introduced along a series of narrow northeast-trending fractures and replaced the silica-carbonate rock bordering them to form unusually rich ore bodies. The most productive ore bodies were formed along the margins of the two altered serpentine sills, and the largest was 200 feet wide, 15 feet thick, and extended 1,500 feet on the dip. Cobbed ore mined during the first 15 years of recorded production averaged more than 20 percent mercury, and the ore produced during the entire productive history of the mine averaged only a little less than four percent. The workings at the New Almaden mine reach a point 2,450 feet below the surface, making it the deepest mercury mine in the world, but almost half of the ore was removed above the 800-foot level.

The New Idria mine, in San Benito County, ranks second in production among mercury operations of North America and in 1965

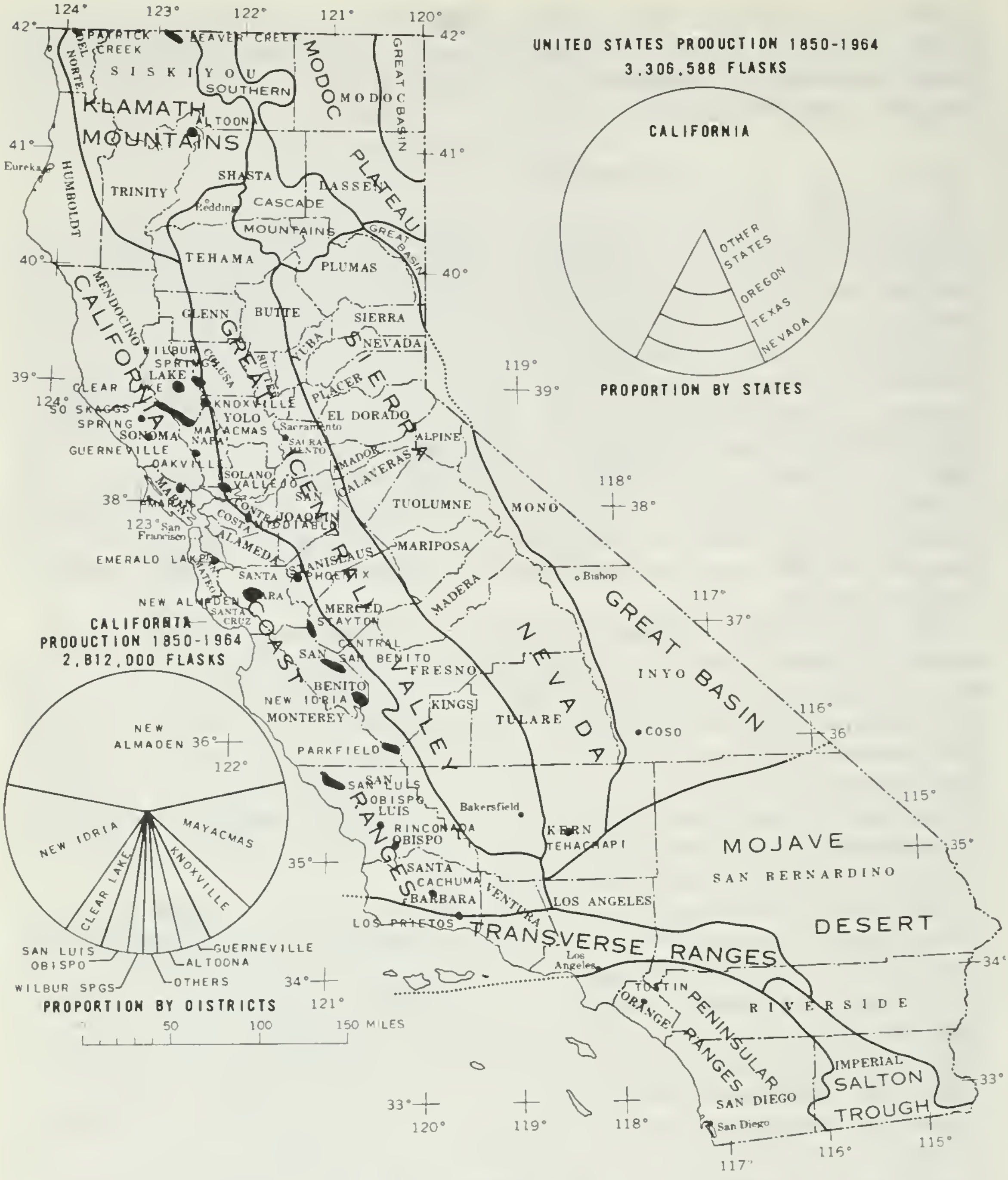

FIGURE 38. Mercury districts in California.

was the leading producer. It provides an example of a major producer having ore bodies in rocks other than silica-carbonate or Franciscan sedimentary rock, though both are present in the area. The major structure in the New Idria district consists of a pluglike mass of serpentine and Franciscan graywacke pushed up through shale and sandstone of the Panoche Formation (Upper Cretaceous) and Tertiary sedimentary rocks. The margins of the plug are steep faults which dip away from the central core, except in the New Idria mine area, where the contact dips inward to form the New Idria thrust fault. Beneath the New Idria thrust fault, the upper shales of the Panoche are crumpled and overturned; in some places highly broken Franciscan sandstone and, in other places, serpentine lie above the fault.

The ore bodies occur chiefly in altered and indurated Panoche rocks beneath the thrust fault, and irregularities in the plane of the fault have closely controlled zones of deposition. Cinnabar fills open spaces, forming veins and stockworks, and rich ore formed where the fracturing was most intensive. Some ore also occurs in the altered Franciscan rocks and in silica-carbonate rock. Known ore extends in places through a vertical range of more than 1,400 feet and a horizontal span of about ten miles. One ore body was 300 feet long, 25 to 150 feet thick, and extended through a depth of 800 feet. This ore shoot occupied a steep inverted trough at the intersection of the New Idria thrust fault with a tear fault.

The other mines of the Coast Ranges are too numerous to be discussed individually here, but reports on essentially all of them have been published (see references at the end of this article). Although formed under similar geologic conditions, the deposits show marked differences in the character, size, grade, and distribution of the ore bodies largely because of the diversity of rocks in which they formed.

The relatively few mercury mines in California that are outside of the Coast Ranges province are even less similar. The only large one is the Altoona mine in the Klamath Mountains, which has yielded about 35,000 flasks. The mine is in porphyritic diorite and serpentine, both of which are intensely altered and replaced by quartz and carbonate. Three major faults traverse the area, and cinnabar and some native mercury form irregular ore bodies in and near the fault gouge. Ore shoots average 5 feet in width, extend along the strike 100 to 300 feet, and down the dip for as much as 300 feet. The average grade has been about 1 percent mercury.

The Walibu (Cuddeback) mine, 10 miles northwest of Tehachapi in Kern County, exploits the southernmost of several small mercury occurrences in the Sierra Nevada province. Here, mercury ore occurs in a rhyolite dike which has intruded the granitic rocks of the Sierra Nevada batholith. Cinnabar encrusts fracture walls, fills small breccia veins, and is disseminated as minute crystals through the more altered rhyolite.

Farther east, in the Great Basin Province, small amounts of mercury have been obtained from Recent hot-spring deposits in the Coso district of southwestern Inyo County. These mercury deposits consist of small irregular cinnabar veins in silicified and kaolinized tuff and granite. Near Tustin, Orange County, cinnabar and native mercury are associated with small veins of barite in country rock of Tertiary sandstone.

One may expect that California will continue to provide most of the mercury recovered in the United States. Although known and indicated reserves are only sufficient to sustain production for a few years, the history of the industry indicates that with the price of mercury high enough to stimulate exploration, as it was in mid-1965, new ore bodies will be sought and discovered. Although most of these will be satellitic to known deposits, new exploration techniques involving geochemical sampling, or the use of the recently developed mercury detectors may be able to locate wholly new areas with sufficient mercury concentration to be minable at the high prices likely to prevail in the years to come.

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MICA

(Muscovite, biotite, and vermiculite)

(By F. G. Lesure, U.S. Geological Survey, Washington, D.C.)

Moderate amounts of muscovite and small amounts of biotite and vermiculite have been mined in California since 1902. Most of the muscovite has come from six deposits (nos. 7, 11, 12, 15, 19, and 24, table 27), the biotite from one (no. 6, table 27), and the vermiculite from one (no. 22, table 27). The total production of muscovite, 1902–1951, is valued at more than $198,574.

The principal mica minerals are muscovite (white mica), biotite (black mica), and phlogopite (amber mica). All have a perfect basal cleavage and form crystals that can be split into thin sheets having various degrees of transparency, toughness, flexibility, and elasticity. The micas are common minerals, but only muscovite is mined extensively in the United States. Vermiculite is a micaceous mineral derived mainly from the chemical alteration of biotite and chlorite.

Two types of mica are sold: (1) sheet mica which must be relatively flat, free from most defects, and be large enough so that it can be cut in pieces 1 square inch or larger; and (2) scrap mica which is all mica that does not meet sheet mica specifications; it is generally ground to a powder. Small sheets of untrimmed mica of poorer quality that can be punched or trimmed into disks 1 inch or larger in diameter are classified as punch mica and are included in the general term sheet mica. Sheet muscovite is an important insulating material in the electronic and electrical industries. Built-up mica made from very thin sheets, and reconstituted mica made from scrap can be substituted for larger sheet mica for some uses. The principal uses of scrap mica are in the roofing, wall paper, rubber, paint, and other industries.

Vermiculite has little value in its natural form but when expanded by heat it forms a low density product with excellent thermal and acoustic insulation properties. It is used as a light-weight aggregate in concrete and plaster, as an extender or filler in paper, plastics, and paint, as a packing material, and as a soil conditioner.

Sheet-quality muscovite is obtained from large crystals scattered throughout unzoned pegmatites or concentrated in certain units of zoned pegmatites. The value of sheet mica depends on the color, size, structure, and quality of the natural crystals. Details of the preparation and classification of mica and trade practices of the industry are too elaborate to discuss here. The best published reference is by C. M. Rajgarhia (1951), whose knowledge of the subject was based on a lifetime of experience in the sheet mica business in India, which supplies most of the world's mica. Excellent references written in the United States are by Skow (1962), Montague (1960), Jahns and Lancaster (1950), and Wierum and others (1938).

The discontinuous nature of most mica concentrations, the great range of quality of material, the expense of mining, and the large amount of hand labor needed for preparation generally limit sheet mica mining to periods of very high prices. Since the end of the Government purchasing program in June 1962, little sheet mica has been mined in the United States. Most of the sheet muscovite used in the United States comes from India and Brazil and the sheet and scrap phlogopite comes from Canada and the Malagasy Republic. Most of the recent domestic production of sheet mica has come from North Carolina, New Hampshire, and South Dakota. Only a few hundred pounds of poorer quality sheet mica have been produced in California, mostly from the Mount Alamo deposit, Ventura County. No deposits of high-quality sheet mica are known to occur in the State. Large quantities of fabricated sheet mica for electronic equipment are shipped into California from eastern manufacturers.

Many pegmatite deposits contain only scrap mica, and a large amount of scrap is produced during the mining, trimming, and fabricating of sheet mica. Scrap mica is also recovered from muscovite and biotite schists and as a byproduct from the mining of feldspar and clay. Such scrap mica is generally referred to as flake mica. Most of the mica mined in the United States is scrap mica and all the resources and most of the production of mica in California has been scrap quality. Scrap mica mined outside the State was ground by the Sunshine Mica Co. in Los Angeles County in 1963 (Davis, 1964, p. 204). A new mill in Mariposa County will process mica schist using a modification of a method for mica recovery developed by the U.S. Bureau of Mines (Browning and Bennett, 1965).

California has several plants that expand vermiculite ores shipped into the State. California Zonolite Co. operates plants in Sacramento and Los Angeles Counties using ore from Montana, and La Habra Products, Inc. operates a plant in Orange County using South African ore (Davis, 1964, p. 185). No vermiculite has been mined in the State in recent years.

The selling price of mica can range from only a few cents per pound for punch or scrap to many dollars a pound for large sheets of the best quality. In 1958 the price schedule under the U.S. Government purchase program for sheet mica of superior quality (termed "good, stained or better") ranged from $17.70 per pound for the smallest sizes to $70 per pound for the large sizes. Prices in 1958 for India mica of similar quality ranged from $2.50 to $37 per pound (Montague, 1960, table 8). In 1965 prices for sheet mica as quoted in the Engineering and Mining Journal Metals and Markets ranged from $0.07 a pound for sheets 1½ inches across to $8.00 a pound for sheets 8 inches or more across. Scrap mica is valued at the mine at $20 to $30 per short ton. Most of the buyers of mica are in the eastern United States. Prices for vermiculite ore, short ton, f.o.b. Montana, are listed by Engineering and Mining Journal Metals and Markets as $9.50 to $18.00, and South African ore, crude, c.i.f. Atlantic ports, $27.85 to $38.50.

OCCURRENCES IN CALIFORNIA

Mica-bearing rocks are widespread in California. Mica schist is found in parts of the Klamath Mountains, the Sierra Nevada, and the mountain ranges and deserts of the southern part of the State. In general, the mica schists that are mined are parts of extensive areas of metamorphic rock and are available in large tonnages. Pegmatites containing muscovite are also widespread but are neither large nor abundant. Sheet muscovite is rare or sparse in the pegmatites of the Sierra Nevada, Great Basin, Mojave Desert, and Transverse Ranges, and none is known in the pegmatites of the Peninsular Ranges (Jahns, 1954, p. 48). Scrap muscovite is common in the pegmatites of the Great Basin and rare to sparse in the pegmatites of the Sierra Nevada, Mojave Desert, Transverse Ranges, and Peninsular Ranges (Jahns, 1954, p. 48). The known mica deposits are listed in table 27 and the locations shown in figure 39. The most important deposit is the Micatalc mine of Imperial County which has produced, since 1929, several tens of thousands of tons of flake mica from mica schist (Wright, 1957, p. 359).

TABLE 27.—*Mica and vermiculite occurrences in California*

Index No. on fig. 39	Name	Reference
1	Unnamed occurrence	Oesterling and Spurck, 1964b, p. 184.
2	do	Tischler, 1964, p. 70.
3	Pacific	Wright, 1957, p. 359.
4	Brushy Canyon	Bowen and Gray, 1957, p. 212–213.
5	Ruth Hill	Logan and others, 1951, p. 511.
6	Pacific Grove	Wright, 1957, p. 359.
7	Death Valley Mica	Norman and Stewart, 1951, p. 103.
7a	Silver Lady Prospect	(L. A. Wright, written communication, 1965).
8	Lucky Betty	Tucker and Sampson, 1931, p. 377–379.
9	Unnamed prospect	Oesterling and Spurck, 1964a, p. 179.
10	do	Do.
11	Hodge	Bowen, 1954, p. 151–152.
12	Dewillibie	Bowen, 1954, p. 152–153.
12	Marshall and Davis	Bowen, 1954, p. 153–154.
12	Marter-White	Bowen, 1954, p. 154–158.
13	Snow White	Bowen, 1954, p. 158.
14	Unnamed occurrence	Oesterling and Spurck, 1962a, p. 179.
15	Unnamed prospect	Do.
16	Nora-Evalyn	Gay and Hoffman, 1954, p. 676.
17	Apex, Dorothy Ann, and Mica 1	Do.
18	Independent American Mining Co	Do.
19	Mount Alamo	Sterrett, 1923, p. 48.
20	Unnamed occurrence	Oesterling and Spurck, 1964a, p. 179.
21	Carlsbad	Weber, 1963, p. 79.
22	Circle Group	Weber, 1963, p. 280–282.
23	Mica Gem	Weber, 1963, p. 193.
24	Micatalc	Henshaw, 1942, p. 195.

FIGURE 39. Mica in California (numbers refer to table 27).

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MINOR METALS

(By M. C. Stinson, California Division of Mines and Geology, San Francisco, Calif.)

“Minor metals” is a term that is loosely applied to a group of metals each of which is uncommon and used in much smaller amounts than the common base metals. Of the 8 minor metals described herein, 6 are recovered from residues collected in the smelting and refining of sulfide ores. Gallium, germanium, indium, and thallium are recovered from zinc residues; selenium is recovered from copper residues; and rhenium is recovered from molybdenum residues. Cesium and rubidium are recovered from pegmatite minerals.

Each of these metals probably has been obtained from ores mined in California, but no data are available on their distribution or recovery by the custom smelters. Flue dusts and other residues from American Smelting and Refining Company's smelters at Selby, California, as well as from other western smelters, are treated at the Globe Smelter in Denver where some of the minor metals are recovered and refined.

Cesium and Rubidium

Cesium and rubidium are similar in occurrence, properties, and uses. Both are soft, silver-white metals, liquid at near room temperature, and react with oxygen and water. Because of their sensitivity to light, cesium and rubidium have been employed in photography, television, photomultiplier tubes, and scintillation counters. Recently, interest has been shown toward the use of cesium in ionic propulsion and thermionic power conversion.

Pollucite (hydrous cesium aluminum silicate), which occurs only as a rare constituent of pegmatites, is the principal source of cesium and rubidium; it contains as much as 36 percent cesium oxide and about three percent rubidium oxide. Cesium and rubidium also are found in the pegmatite minerals lepidolite (lithia mica), beryl (beryllium aluminum silicate) and rhodizite (complex borate of beryllium, aluminum, and alkalies), as well as in carnallite (hydrous potassium magnesium chloride) which normally occurs in some saline deposits. Pollucite has been reported in the pegmatites of San Diego County, but these occurrences have not been of commercial importance.

Cesium and rubidium were discovered by spectroscopic means about 1860 by Bunsen and Kirchkoff.

Production data on cesium and rubidium and their compounds are not available for publication.

Gallium

The uses of gallium are limited mainly because of its scarcity, high cost of extraction and purification, and its corrosive nature. The wide temperature range through which gallium remains a liquid makes it of use in high-temperature thermometers and in special use alloys. Gallium arsenide is being studied for application in high-frequency transistors, in tunnel diodes, and especially in the field of lasers.

Gallium is as plentiful as lead in the earth's crust, but is much more widely dispersed. Gallium is a gray metal which is liquid at or near room temperatures. Because of its chemical similarity to aluminum, gallium is concentrated in clay-rich soils and clay minerals, particularly in those derived from bauxite. It is also concentrated by some plants, and, therefore, exists in certain coal deposits. Gallium was discovered by Lech and Bojsbaudian by spectroscopic means in 1875.

Gallium is obtained commercially by the treatment of residues from aluminum and zinc smelting and refining. The gallium content of zinc ores from California is not known to the writer, nor has the gallium content of California coals and clays been investigated. In recent years, the demand for gallium has been very small, and production has not been reported.

Germanium

Germanium, a metalloid, is of value principally because it is a semi-conductor. This property has led to its use in the electronic industry, first as diode crystal rectifiers, and later in germanium triodes or transistors.

Germanium occurs as a minor constituent in the sulfides of zinc, copper, and silver, and in trace amounts in coal deposits. Virtually all of the germanium produced in the United States is recovered during the treatment of zinc ores from the Tri-State district. The germanium is extracted from dust collected in electrostatic precipitators at the zinc smelter.

Germanium was first identified and named by C. Winkler about 1886. The use and production of germanium increased rapidly with the invention of the transistor. The estimated United States production of germanium in 1964 is 20,000 pounds. The United States production of germanium has dropped steadily in the past few years, because increased manufacturing efficiency and smaller devices have resulted in lower demand for the material. Germanium has not been recovered from California zinc ores.

INDIUM

Indium is a soft gray metal resembling tin. It is softer than lead, is extremely plastic, and is stable in air. Deformation can be repeated almost indefinitely without causing the metal to become work hardened. Indium has a viscosity that changes very slightly over a wide temperature range. The metal has important lubricating properties and alloys readily with other metals.

Because of its mechanical and chemical properties, indium has a wide variety of uses and a great potential for new uses. One of the principal uses of indium is in sleeve-type bearings to promote resistance to corrosion and wear. It is also used in electronic devices in a variety of ways.

Indium is not an essential constituent of any of the known minerals but is widely dispersed in the earth's crust. It is found in proportions of as much as one percent in iron-rich sphalerite, in tin ores, and in tungsten ores. It also occurs in pegmatites and has been reported in alunite, manganotantalite, phlogopite, pyrrhotite, rhodonite, samarskite, and siderite.

Indium was discovered by F. Reich and T. Richter by spectroscopic means in 1863.

Most of the domestic production of indium is obtained from the chemical treatment of flue dust and other residues from lead and zinc smelters. The American Smelting and Refining Co. at Perth Amboy, New Jersey, is the only domestic producer of indium.

RHENIUM

Rhenium is a dense silver white metal with a high-melting point (3,440° C). Rhenium has limited use in industry, principally because of its scarcity and high cost. The principal use of rhenium is in high-temperature alloys of tungsten and molybdenum. These rhenium alloys have exceptionally good high-temperature strength properties and sufficient ductility to be work-formed at room temperature. Other uses are in electronic devices, electrical contacts, thermocouples, and catalysts.

Although no minerals are known to contain rhenium as an essential element, it is widely dispersed in the earth's crust. It is concentrated in molybdenite in proportions of as much as 0.30 percent and in a number of rare-earth minerals in proportions up to 0.001 percent. Rhenium is commercially extracted from flue dust residue collected in the roasting of byproduct molybdenite concentrates from copper ore mined in Arizona.

Rhenium was first discovered in 1925 by W. Noddack and I. Tache by chemically treating columbite.

Production data for rhenium are not available. There is no published data on the rhenium content of California molybdenite.

Selenium

Selenium is a gray crystalline solid with a semimetallic luster. It is a semi-metal found with, and related to sulfur and tellurium. Selenium has a wide variety of uses which would be more numerous if sufficient supplies were available. Probably the most important use of selenium is in the electronic industry where, owing to its semiconductivity, it is of great value as a rectifying medium. Other uses are in the manufacturing of glass, rubber, steel, and industrial chemicals. Selenium was first used in the glass and ceramic industry as a decolorizer. The consumption of selenium has increased rapidly since the invention of semiconductor devices.

Selenium is found in native sulfur and occurs in the forms of selenides of lead, mercury, silver, copper, and zinc. Selenium is present in many base metal ores in small proportions.

In 1817, J. J. Berzelius obtained a red to brown precipitate from a sulfuric acid plant. From this precipitate he obtained a new element which he called selenium.

The United States produced about 900 thousand pounds of selenium in 1964. This amount is about one-third of the world production of selenium.

Some selenium was recovered until 1961, by Anaconda Co. from the processing of sulfur mined at the Leviathan sulfur mine in Alpine County. No other data are available on selenium recovered from California ores.

Thallium

Thallium is a soft bluish-white metal that alloys readily with most other metals but not with copper, aluminum, manganese, nickel, zinc, or selenium. The principal use for thallium is in insect and rodent poisons. Thallium has a significant use in electronics, low-melting alloys, and in glass.

Thallium occurs in minute quantities in the sulfides of the common metals. Three thallium minerals are known: crookesite (copper thallium silver selenide), lorandite (thallium arsenic sulfide), and hutchinsonite (complex thallium-bearing arsenide); but they have not been found in commercial quantities.

Thallium was discovered in 1861 by W. Cookes by spectroscopic means.

Commercial thallium is produced in the United States from flue dusts and other residues that are recovered as byproducts of the roasting of lead and zinc ores. There are no production figures available.

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MOLYBDENUM

(By R. U. King, U.S. Geological Survey, Denver, Colo.)

Molybdenum is a vitally important metal in our modern ferrous metals industry. About 85 percent of the molybdenum produced domestically is used as an alloying element in the manufacture of high-temperature alloy steels, stainless steel, castings, and special steel products. When alloyed with iron and steel it improves the properties of hardness, toughness, and resistance to corrosion. Molybdenum also is used in the manufacture of chemicals, pigments, catalysts, lubricants, and agricultural products. New uses currently being developed in the nuclear power field and in the missile and aerospace industries promise a continued increase in demand for this versatile metal.

Molybdenum is widely but sparsely distributed in the rocks of the earth's crust. It is found in trace amounts in most igneous and sedimentary rocks, in ocean water, in soils, and in plant and animal tissues. The average content of the earth's crust has been estimated to be about 0.00025 percent (2.5 parts per million). It is not found in its pure or native state but only in combination with other nonmetallic elements such as sulfur and oxygen, and metallic elements such as iron, calcium, tungsten, and lead. About a dozen minerals are known to contain molybdenum as an essential element, but of these, only two: molybdenite (molybdenum disulfide, MoS_2) and wulfenite (lead molybdate, $PbMoO_4$) have been the source of most of the molybdenum produced to date. Other molybdenum minerals which are of more than passing interest, either for their molybdenum content or their geologic significance, as the demand for this metal continues to rise include ferrimolybdite (yellow hydrous ferric molybdate); powellite (calcium molybdate), which commonly occurs with tungsten, jordisite (black, powdery molybdenum sulfide), and ilsemannite (blue, water soluble molybdenum oxysulfate). Several rarer minerals of doubtful significance contain molybdenum combined with one or more of the following elements: bismuth, copper, magnesium, vanadium, cobalt, and uranium.

Deposits or concentrations of molybdenum minerals of economic significance are found chiefly in igneous rocks of granitic composition and in rocks of sedimentary origin closely related to granitic rocks, but also are known to occur in sandstone and lignite. In some deposits molybdenite is sparsely distributed through rather large masses of fractured and altered rock; these are known as disseminated deposits. Molybdenite may be the sole or chief economic mineral, such as at Climax, Colorado, and Questa, New Mexico, or it may be a minor metal associated with copper sulfides as in the large "porphyry" copper deposits of the southwest. Most of the world's production of molybdenum comes from the disseminated type of deposit. Probably the most common type of molybdenum deposits are quartz veins, in which molybdenite is associated with minerals containing copper, tungsten, bismuth, lead, and zinc. Pegmatite bodies are a common host for unusually coarse crystals of molybdenite. Much of the early production of molybdenite came from vein and pegmatite deposits.

Deposits of molybdenite often associated with scheelite, powellite, bismuthinite, or copper sulfides occur in zones of silicated limestone, or in tactite bodies near contacts with intrusive granitic rocks; they are known as contact metamorphic deposits and are the source of molybdenum in California.

In the United States today, the grade of the ore in large deposits (at least several million tons) mined primarily for the molybdenum content, ranges from 0.2 to 0.5 percent MoS_2, but molybdenum also may be profitably extracted as a byproduct or coproduct from certain copper, tungsten, and uranium ore bodies in which the molybdenum content is not greater than a few hundredths of one percent. Vein deposits, pegmatites, and many contact metamorphic deposits because of their limited size have meager economic potential except in those deposits where molybdenite content is at least several percent.

Molybdenum is marketed either in the form of molybdenite concentrates (at $1.55 per pound of contained molybdenum, 95 percent MoS_2) or as roasted concentrate (molybdenum trioxide). Concentrates, however, are not readily marketable in small or individual lots, a limiting factor to the economic potential of small deposits.

Although the element molybdenum was identified in the latter part of the 18th century, its use for many years was restricted largely to chemicals and dyes. It was not until the early part of the present century that its potential value was recognized and wide applications for its use were developed. Intensive search for domestic sources of the metal followed, resulting in the discovery of vein deposits of wulfenite and molybdenite in Arizona, and New Mexico, and of the large disseminated molybdenum and copper-molybdenum porphyry deposits of the southwestern states.

Commercial production of molybdenum began in the United States just before the turn of the century, and was small and intermittent until 1914. Since 1914, domestic production of molybdenum has increased each year with few exceptions, exceeding 500 short tons for the first time in 1925, and growing to a current annual rate of over 33,000 short tons. The United States ranks first in world production of this valuable metal, accounting for about 70 percent of the total. About one-third of our domestic production is exported to some 30 nations around the world.

Mining of molybdenum in California is reported as early as the year 1894, from a disseminated molybdenite deposit near Ramona, San Diego County. Small quantities of molybdenum concentrates were produced from several properties between 1914 and 1918, and a small production is reported from a vein deposit between 1932 and 1935. From about 1937 through 1953 more than 6 million pounds of molybdenum were produced from contact metamorphic tungsten deposits at the Pine Creek mine, Inyo County (Bateman, 1956, p. 23). Over the years California has ranked from 4th to 6th in U.S. production of molybdenum due solely to the consistent yield from the Pine Creek mine.

Occurrences in California

California's molybdenum deposits are widespread, being reported from more than 80 localities in 24 counties. Of these, ten have yielded significant quantities of molybdenum, and one, the Pine Creek mine, is being successfully exploited today. Forty-four deposits or groups of deposits are briefly described in table 28, and their locations are shown on figure 40.

TABLE 28.—*Molybdenum deposits in California*

Index No. on fig. 40	Deposits	Location	Manner of occurrence	Remarks	Reference
1	Yellow Butte	Near Weed, Siskiyou County	Molybdenite with copper sulfides, gold and silver, in quartz veins.		
2	Boulder Creek mine (Coggins, Brown property).	South of Boulder Creek, Shasta County.	Molybdenite disseminated in aplite dike cutting peridotite.	Three carloads of 3 percent MoS_2 reported shipped about 1917.	Averill, 1939, p. 168–169; Kirkemo, Anderson, and Creasey, 1965, p. 41–43.
3	Lowden Ranch	Between Weaverville and Douglas City, Trinity County.	Molybdenite and some ferrimolybdite in veins.	Small production reported in 1917.	
4	Mohawk, Murdock claim, Jumbo.	Near Chilcoot, on southwest slope of Adams Peak, Plumas County.	Molybdenite in veins	Small production in 1916 and 1917.	
5	Allen, German, Canadian group, Southern Pacific adit.	English Mountain, Nevada, County.	Molybdenite with pyrite in quartz veins in granodiorite.		
6	Excelsior mine	Meadow Lake district, Nevada County.	Coarsely crystalline molybdenite in veins.		
7	Red Mountain deposits	Signal Peak district, Nevada County.	Coarse molybdenite in quartz veins		
8	Fern Leaf, Cleveland	Near Camptonville, Yuba County.	Molybdenite with pyrite and chalcopyrite in quartz veins in slate.		
9	Mayflower mine, Wisconsin and Illinois claims.	Near Nevada City, Nevada County.	Coarse molybdenite in quartz veins		
10	Elder mine, Willet, Golden Stag.	West of Clipper Gap, Placer County.	Molybdenite with copper sulfides in granodiorite.		
11	Cosumnes (Consumnes) copper mine.	Middle Fork Cosumnes River, near Fairplay, El Dorado County.	Molybdenite with copper sulfides in skarn zone along contact of granodiorite and marble.		Robertson, and Tatlock, 1965, p. 35–36.
12	Alpine mine	South of Lake Tahoe, Alpine County.	Molybdenite, powellite and scheelite in tactite.		
13	Moore Creek, (Bay Horse, White Horse), Garnet Hill mine.	North Fork Mokelumne River, Calaveras County.	Molybdenite with scheelite, powellite and chalcopyrite in tactite along contact of granodiorite and metamorphic rocks.	Production of a few hundred pounds of molybdenum.	Stager, 1965, p. 33–35.
14	Polaris, Dean's mine	West Walker district, Mono County.	Molybdenite in quartz veins and in pegmatite.		Pabst, 1954, p. 109–117.
15	Blue Speck mine, Cannon's claim, Amigo and MacLean.	Near Bridgeport and Masonic, Mono County.	Molybdenite in quartz veins in granodiorite.	Molybdenite ore mined and shipped in 1917, and about 6 tons of concentrates produced from 1932 to 1935.	Kirkemo, Anderson, and Creasey, 1965, p. 38.
16	Tower Peak prospect	3 miles west of Tower Peak, Tuolumne County.	Molybdenite in quartz veins along contact of marble and schist.		Turner, 1898, p. 427.

17	September claims	Near Tioga Pass, Mono County.	Molybdenite scheelite, powellite, and ferrimolybdite, in tactite in granite.		Stager, 1965, p. 40–41.
18	Laurel Creek prospect	South of Casa Diablo Hot Springs, Mono County.	Molybdenite, scheelite, and powellite in tactite and marble.		Kirkemo, Anderson, and Creasey, 1965, p. 38–39.
19	Pine Creek area (includes Pine Creek mine and numerous tungsten deposits).	Bishop tungsten district, Inyo County.	Scheelite and molybdenite with powellite and chalcopyrite in tactite.	More than 6 million pounds of molybdenum produced as coproduct with tungsten from Pine Creek mine through 1953. Adequate reserves for continued production of molybdenum for many years.	Bateman, 1956.
20	Atkins prospect	Near Mt. Emerson, Inyo County.	Molybdenite and pyrite in aplite dike cutting quartz monzonite.		Horton, 1916, p. 62. Kirkemo, Anderson, and Creasey, 1965, p. 37.
21	Buchanan prospect, Kenawyer, King's River Canyon copper mine.	South Fork King's River, Fresno County.	Molybdenite with chalcopyrite in veins in granite.		Horton, 1916, p. 62.
22	Kaweah molybdenite property.	Near Three Rivers, Tulare County.	Molybdenite, wolframite, scheelite and pyrite disseminated in granodiorite.	Small production reported for 1917 and 1921.	Krauskopf, 1953, p. 81.
23	War Baby	Hogback Creek, Inyo County	Molybdenite with pyrite and pyrrhotite in silicified zone in aplite.		Kirkemo, Anderson, and Creasey, 1965, p. 37–38.
24	Wingrove prospect	Near California Hot Springs Tulare County.	Sparse flaky molybdenite in quartz vein.		Horton, 1916, p. 62–63.
25	White River prospect	South of California Hot Springs, Tulare County.	Molybdenite with copper sulfides in quartz veins and disseminated in aplite dike.		
26	Kergon (Buckeye group)	Kern River Canyon, Kern County.	Jordisite and ilsemannite with sooty pitchblende in shear zone in granodiorite.		McKevitt, 1960, p. 197–205 Walker and others, 1956, p. 30.
27	Fidgie group	On Erskine Creek south of Isabella, Kern County.	Molybdenite with scheelite and powellite in tactite.		
28	Golden group	Near Caliente, Kern County	Finely divided molybdenite disseminated in granite.		Horton, 1916, p. 63.
29	Lucky Boy	Seven miles east of Kearsarge, Inyo County.	Molybdenite in quartz vein along contact of granite and limestone.	Small production reported in 1916.	
30	Coso molybdenite mine (DeSoto)	Southeast of Olancha, Inyo County.	Molybdenite disseminated in granite		Tucker, and Sampson, 1939, p. 459.
31	Fletcher prospect (Corona quarry).	Four miles northeast of Corona, Riverside County.	Molybdenite in pegmatite and granite		Hess, 1908, p. 238.
32	Imperial Mining and Reduction Company.	Near Lavic, San Bernardino County.	Wulfenite in veins cutting quartz porphyry.	Small amount of molybdenum produced in 1918.	
33	War Eagle mine	Nine miles south of Bagdad, San Bernardino County.	Wulfenite with vanadium minerals in oxidized lead-zinc veins.		
34	Vancouver Pinnacles Molybdenum Company.	Eight miles east of Soledad, Monterey County.	Molybdenite in quartz veins in granite.		
35	MacDonald group	Snowy Mining district, on Alder Creek, Ventura County.	Small kidney-like deposits of molybdenite with copper ores in granite.		

TABLE 28.—*Molybdenum deposits in California*—Continued

Index No. on fig. 40	Deposits	Location	Manner of occurrence	Remarks	Reference
36	Lowman claims	Tujunga Canyon, Los Angeles County.	Coarse flakes of molybdenite in quartz veins in granite.		
37	Winter Creek group	Five miles north of Sierra Madre, Los Angeles County.	Quartz veins cutting granite contain molybdenite, pyrite, and copper sulfides.		Sampson, 1937, p. 176–177.
38	Cole, Neal, Williams Camp	Near Azusa, Los Angeles County.	Small amounts of molybdenite in veins in schist and granite.		
39	Dewey mine (Ready Relief claim).	At Grapevine, San Diego County.	High grade molybdenite in 4-foot wide vein.		
40	Bour mine, Purdy and Judson Ranches, and Santa Maria prospect.	Near Ramona, San Diego County.	Molybdenite and pyrite disseminated in aplite dikes and granite.	Molybdenum produced in 1894, 1908, 1914, and 1917.	Calkins, 1917, p. 73–76; Weber 1963, p. 194–195; Tucker, and Reed, 1939, p. 30–31.
41	Woolsey deposit (Fernbrook mine.	Eight miles southwest of Ramona, San Diego County.	Molybdenite disseminated in aplite granite.		Tucker, and Reed, 1939, p. 31.
42	Harvey Ranch, Echo mine	West of Alpine, San Diego County.	Finely crystalline molybdenite in 130-foot wide zone in aplite dike.		
43	Campo, Dillbeck, Lippner, and Hammond.	Near Campo, San Diego County.	Molybdenite disseminated in aplite dikes.	Small shipment of concentrates made in mid-1940's.	Weber, 1963, p. 195–198.
44	Meyers Ranch, Scheckler deposit.	South of Dulzura, San Diego County.	Molybdenite in quartz veins		Weber, 1963, p. 196.

FIGURE 40. Molybdenum in California (numbers refer to table 28).

Most of the known molybdenum deposits of California are in the Sierra Nevada province. They include the very productive deposits of the Pine Creek mine (no. 19, figure 40), which contain the largest molybdenum reserves in the State. According to Bateman (1956) the ore bodies are in a pendant of metamorphic rocks enclosed in granite and quartz monzonite of the Sierra Nevada batholith. Both molybdenum and tungsten occur in distinct shoots along the contact of a belt of marble on the west side of the pendant and quartz monzonite. The molybdenum ore shoots are subordinate to the tungsten shoots and are mostly confined to the upper parts of the deposit. Ore minerals are scheelite and molybdenite with substantial amounts of copper. Some of the molybdenum shoots contained an average of about 1 percent MoS_2. Although data are not available on which to calculate reserves, they can be fairly estimated to be large and adequate for continued production of molybdenum as a co-product with tungsten for many years. A number of other contact metamorphic deposits are known in which molybdenite is associated with scheelite, powellite, and copper sulfides, in skarn, tactite, or marble, but they are too small and their molybdenum content is too low to be of economic significance.

Vein deposits of molybdenum also occur over the length of the Sierra Nevada province, but only two, the Mohawk (No. 4) and the Blue Speck (No. 15) have yielded any molybdenum of consequence. In these deposits, molybdenite occurs alone or with pyrite and chalcopyrite in quartz veins.

Molybdenite is weakly disseminated in granodiorite at the Kaweah molybdenum property (No. 22) and at the Golden group (No. 28) in the southern part of the Sierra Nevada province. Although ore-grade material has been reported in these deposits, the average molybdenum content is too low for economic exploitation under present conditions.

The southern Cascades and Klamath Mountains provinces contain only a few molybdenum deposits. Small shipments of sorted ore have been made from high-grade ore zones at the Boulder Creek mine (No. 2). The molybdenite is disseminated in an aplite dike, and is reported to average about 1 percent.

Molybdenite occurs in a few vein deposits and in a disseminated deposit in the granitic rocks in the western part of the Great Basin province, and wulfenite is present in the upper parts of lead-zinc veins in porphyritic and metamorphic rocks in the Mojave Desert province. A little molybdenum has been produced from the quartz-molybdenite vein deposits at the Lucky Boy Prospect (No. 29) and from the wulfenite-bearing deposits at the Imperial Property (No. 32).

Molybdenum deposits in the Coast Ranges and Transverse Ranges provinces consist of quartz veins in granitic rocks that contain small amounts of molybdenite. They have not been productive of molybdenum.

Small amounts of molybdenum have been produced from two disseminated deposits in the western part of the Peninsular Ranges province in the very southern part of the State. The deposits are in a belt of aplitic rocks that trends northwestward from the Mexican border and include the Campo (No. 43) and Bour (No. 40) mines. The molybdenum content of these deposits is too low to be economically mined under present conditions.

Potential sources of molybdenum in California are most likely to be found in disseminated deposits in aplitic rocks in the Peninsular Ranges and in the southern part of the Sierra Nevada, but the possibility of finding high-grade bodies in some of the contact metamorphic deposits in the central and northern parts of the Sierra Nevada should not be overlooked.

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NATURAL GAS LIQUIDS

(By C. D. Edgerton, Jr., U.S. Bureau of Mines, Pittsburgh, Pa.)

Natural gas liquids are those hydrocarbon mixtures contained in natural gas in a subsurface reservoir, and which are recoverable as liquids by condensation, adsorption, absorption, compression, or refrigeration. They include natural gasoline, condensate, or distillate (cycle products) and liquefied petroleum gases, commonly called LP-gases or more simply LPG.

The types of natural gas liquids differ from each other in chemical composition and physical properties. Natural gasoline and condensate contain principally N-pentane and heavier hydrocarbons of the paraffin series. The boiling point of N-pentane under normal atmospheric pressure is 96.9° F. LP-gases include propane, N-butane, and iso-butane, with boiling points of minus 43.7° F, plus 31.1° F, and plus 10.9° F, respectively. Thus, LP-gases, which are nearly always in the gaseous state, vaporize in any ambient air temperature greater than 31.1° F.

Natural gas liquids are found in association with natural gas although not all natural gas contains enough liquids to permit their economical extraction. Therefore, the geographic distribution of natural gas liquids is less than that of natural gas. Natural gas in association with crude petroleum in a subsurface reservoir, and containing economic quantities of natural gas liquids, is termed oilwell gas, wet gas, or casinghead gas. Natural gas from reservoirs in which there is little or no accumulation of crude petroleum, and which thus contains no appreciable quantities of natural gas liquids, is called dry gas.

In California, natural gas liquids production comes entirely from eight contiguous counties situated in the southern part of the San Joaquin Valley, the southern coastal area, and the Los Angeles basin (fig. 41). The five largest counties, by rank, of natural gas liquids production, are Kern, Los Angeles, Ventura, Santa Barbara, and Orange. Fresno, Kings, and San Luis Obispo Counties produce relatively small quantities of natural gas liquids.

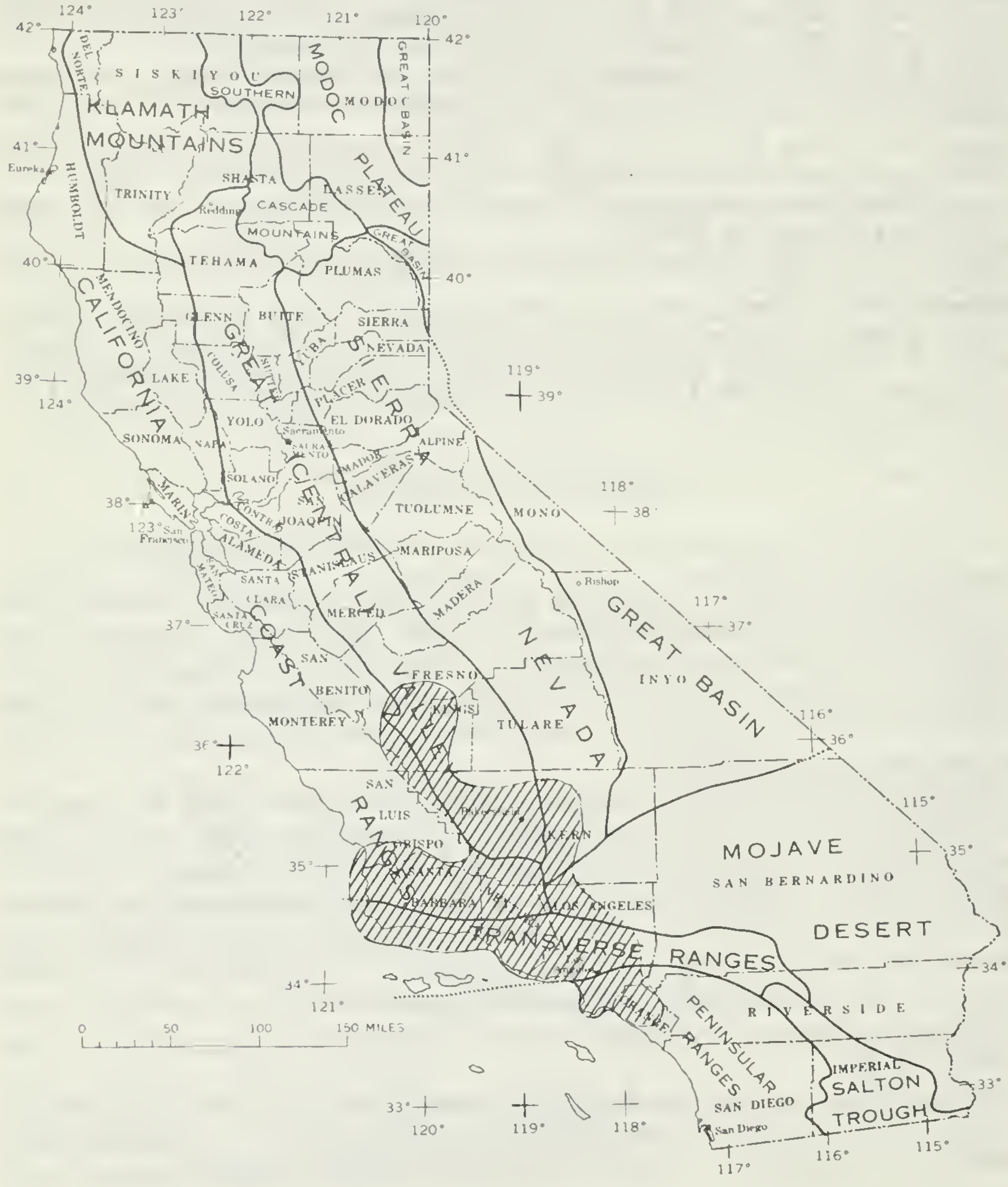

FIGURE 41. Area producing natural gas liquids (lined pattern).

TABLE 29.—*Production of natural gas liquids in California, 1911–64*

[Thousand gallons per year]

1911	210	1929	840, 336	1947	1, 064, 112
1912	1, 050	1930	829, 710	1948	1, 115, 058
1913	3, 486	1931	680, 358	1949	1, 140, 468
1914	7, 770	1932	551, 376	1950	1, 189, 776
1915	12, 852	1933	499, 968	1951	1, 240, 386
1916	17, 178	1934	507. 612	1952	1, 266, 048
1917	28, 812	1935	544, 404	1953	1, 307, 922
1918	32, 256	1936	611, 898	1954	1, 319, 346
1919	40, 404	1937	641, 508	1955	1, 290, 551
1920	48, 216	1938	690, 396	1956	1, 287, 134
1921	58, 212	1939	640, 542	1957	1, 234, 121
1922	67, 116	1940	635, 124	1958	1, 196, 037
1923	173, 334	1941	659, 778	1959	1, 230, 589
1924	232, 554	1942	633, 318	1960	1, 203, 035
1925	303, 198	1943	693, 336	1961	1, 187, 645
1926	389, 382	1944	771, 288	1962	1, 124, 282
1927	498, 036	1945	891, 744	1963	1, 108, 806
1928	584, 094	1946	910, 518	1964	1, 072, 987

Source: U.S. Bureau of Mines.

Table 29 gives the total annual production of natural gas liquids in California from 1911 through 1964; figure 42 presents these data graphically.

The peak year for natural gas liquids production was 1954, when more than 1.3 billion gallons was produced. From 1955–1964 production trended downward and in 1964 was 1.06 billion gallons, about 81 percent of the 1954 figure.

FIGURE 42. Production of natural gas liquids in California, 1911–64.

TABLE 30.—*Production of natural gas liquids in California, by counties, 1954–64*

[Thousands of gallons]

County	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964
Fresno	123, 237	122, 555	125, 981	114, 849	47, 381	55, 679	53, 702	55, 190	(1)	(1)	(1)
Kern	369, 947	373, 020	380, 468	281, 464	323, 518	359, 069	371, 204	364, 397	340, 022	324, 023	301, 581
Kings	(1)	(1)	22, 892	24, 738	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Los Angeles	313, 791	339, 869	330, 261	287, 013	316, 498	307, 142	283, 540	274, 882	269, 225	260, 474	250, 145
Orange	185, 067	134, 593	129, 984	116, 087	117, 619	114, 774	120, 014	117, 730	104, 705	106, 256	104, 895
San Luis Obispo	(1)	(1)	15, 308	5, 015	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Santa Barbara	60, 055	61, 968	61, 184	72, 814	76, 916	73, 320	79, 955	96, 089	96, 874	120, 441	131, 470
Ventura	187, 900	220, 168	220, 736	332, 141	234, 765	244, 166	223, 220	218, 142	209, 007	200, 335	185, 186
Undistributed	79, 349	38, 368	320	----------	79, 790	76, 439	71, 400	61, 215	104, 449	97, 295	(1)
Total	1, 319, 346	1, 290, 551	1, 287, 134	1, 234, 121	1, 196, 037	1, 230, 589	1, 203, 035	1, 187, 645	1, 124, 282	1, 108, 806	1, 072, 987

[1] Included in "Undistributed" to prevent disclosure of individual company data.

Source: U.S. Bureau of Mines.

Table 30 gives the total yearly production of natural gas liquids in California, by counties, from 1954 through 1964. Data for the five major producing counties are shown on figure 43. Since 1954, only Santa Barbara County has shown steady growth in natural gas liquids production largely from development of offshore oilfields.

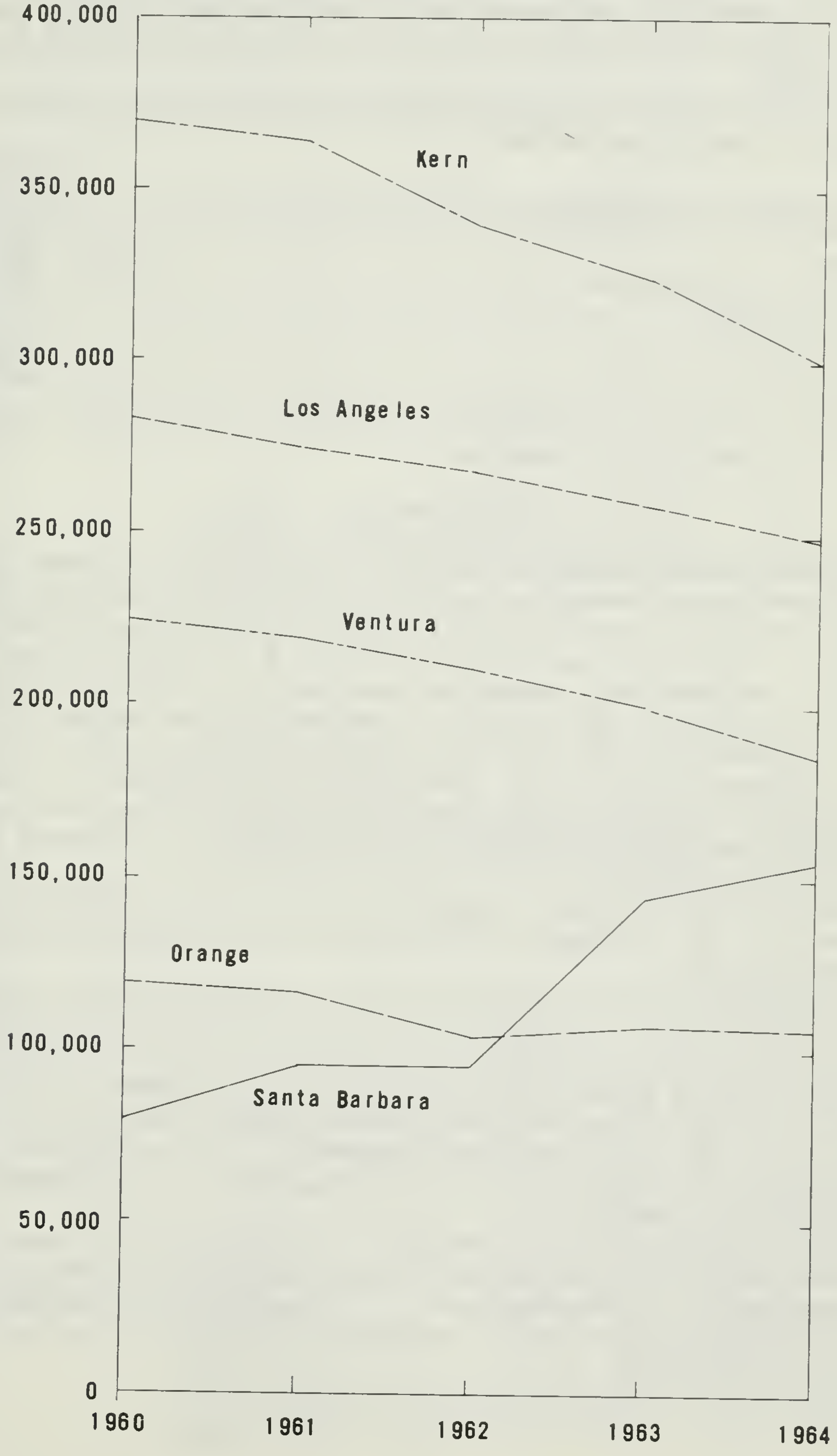

FIGURE 43. Production of natural gas liquids in California, by counties, 1960–64.

As of January 1, 1964, there were 66 natural gasoline and cycle plants in California with a total capacity of 4,688,000 gallons of natural gas liquids per day. The average operating plant capacity was 71,000 gallons per day. By comparison, there were 623 plants in the United States with a total capacity of 66 million gallons per day and an average operating plant capacity of 106,000 gallons per day.

In California, 20 companies operate natural gas liquids plants. (This figure does not include the U.S. Naval Reserve mothball plant at Elk Hills.)

Companies with natural gas liquids production capacities greater than 250,000 gallons per day are:

	Gallons per day
Standard Oil Co. of California	677, 000
Shell Oil Co	622, 000
Palomaco	590, 000
Union Oil Co. of California	449, 000
Richfield Oil Corp	434, 000
Tidewater Oil Co	347, 000
Socony Mobil Oil Co., Inc	307, 000
Texaco, Inc	251, 000

Table 31 gives the companies that operate natural gas liquids plants, and plant capacities and locations.

PRODUCTION

Natural gas liquids are extracted from natural gas at plants that are almost always located in the fields which produce the gas. The liquids are shipped from the field to refineries or dealers, by pipeline or truck, and the processed gas, devoid of most of its liquids content, is either reinjected into subsurface reservoirs to maintain reservoir pressure, or for secondary recovery operations, utilized for fuel in the field, or transported by pipeline to markets. In some areas of the United States, 60 percent or more oilwell gas is vented to the atmosphere. In California, less than 1 percent of oilwell gas is vented. Thus, the conservation of this natural resource in California approaches the maximum.

There are four basic plant designs for the extraction of liquids from natural gas: (1) absorption, (2) adsorption, (3) compression, and (4) refrigeration.

The absorption process is by far the most commonly utilized in both California and the United States. Plants representing about 90 percent of the total gas processing capacity make use of the absorption method, either by itself or in combination with refrigeration or compression methods. The absorption process utilizes a solvent oil which flows in an absorbing tower countercurrent to the wet natural gas stream coming from the field. In so doing, the solvent oil strips the natural gas of its liquids.

The rich solvent oil then goes into a distillation unit where the natural gas liquids are vaporized, leaving the solvent oil lean again for recycling to the absorbing tower. The gases then are condensed and usually refined further in a rectifying system before leaving the plant for the refinery.

TABLE 31.—*Operating natural gasoline and cycle plants as of Jan. 1, 1964*

Company	Location		Daily capacity (thousands of gallons)				
	Field	Nearest town	Natural gasoline	Propane	Butane	Bu-Pro mixtures	Iso-Butane
Belridge Oil Co	North Belridge	McKittrick	58	35			7
Brea Canon Oil Co	Brea-Olinda	Brea	15				
Coline Gasoline Corp	Rincon-Padre	Ventura	15	20	10		
Humble Oil & Refining Co	Huntington Beach	Huntington Beach	19	2			
Inglewood Gasoline Co	Potrero	Inglewood	7			2	
Lomita Gasoline Co. (Plants 2, 7, and Signal Hill)	Signal Hill and Long Beach	Long Beach	135	25			
Marathon Oil Co. (Cycling)	South Coles Levee	Taft	42	45	30		15
Palomaco (Cycling)	Paloma	Bakersfield	315	165	110		
Reserve Oil & Gas Co	Tejon, North	do	8				
Richfield Oil Corp	North Coles Levee	Tupman	120	95			
Do	Rincon Island No. 24	Ventura	5				
Do	Russell Ranch	Cuyama	20	23		14	
Do	South Cuyama	do	39	80	38		15
Shell Oil Co	Brea-Olinda	Brea	60				
Do	Long Beach	Signal Hill	42				
Do	Monlino	Gaviota	65				
Do	Ten Section	Bakersfield	35	45	20		15
Do	Ventura	Ventura	210	130			
Signal Oil & Gas Co	Elwood	Goleta	5	2		1	
Do	Huntington Beach	Huntington Beach	150	40			
Do	Inglewood	Inglewood	25	12			
Do	Midway-Sunset	Maricopa	10				
Socony Mobil Oil Co., Inc	Helm	Burrel	20	18	22		
Do	Santa Fe Springs	Santa Fe Springs	62				
Do	Wilmington	Wilmington	185				
Standard Oil Co. of California	Carpenteria	Carpenteria	15				
Do	Gaviota	Gaviota	60				
Do	Greeley	Bakersfield	25	29		17	
Do	Inglewood	Inglewood	37				
Standard Oil Co. of California (Plants 3P, 11), 33J, and 2 Western Huffman Plants).	Kettleman Hills	Avenal	93	75	44		19
Standard Oil Co. of California	Lost Hills	Bakersfield	14				
Standard Oil Co. of California (Plants 1C, 7D, 29G)	Midway-Sunset	Taft	83	24			
Standard Oil Co. of California	Mountain View	Bakersfield	20				
Do	Murphy Coyote	La Habra	43	17			
Standard Oil Co. of California (Colonia Vapor Plant)	Oxnard	Oxnard	7				
Standard Oil Co. of California (Oxnard Booster)	Plaines	do	5				
Standard Oil Co. of California	Seal Beach	Seal Beach	41				
Do	Torrance	Torrance	9				

TABLE 31.—*Operating natural gasoline and cycle plants as of Jan. 1, 1964*—Continued

Company	Location		Daily capacity (thousands of gallons)				
	Field	Nearest town	Natural gasoline	Propane	Butane	Bu-Pro mixtures	Iso-Butane
Sunray DX Oil Co	Newhall-Potrero	Newhall	35	75	15		
Superior Oil Co	Rio Bravo	Shafter	21	28	15		7
Texaco, Inc	Castaic	Castaic	16	12		16	
Do	Gaviota	Gaviota	10				
Do	Santa Fe Springs	Santa Fe Springs	35	4			
Do	Shiells Canyon	Santa Paula	33	18		17	
Do	Signal Hill	Long Beach	75	15			
Tidewater Oil Co	Cymric	McKittrick	30	15		30	
Do	Midway	Taft	20	6			
Tidewater Oil Co (Plants 2, 4, and 6)	Ventura	Ventura	120	65	35		26
Union Oil Co. of California	Coalinga Nose	Coalinga	30			47	
Do	Del Valle	Newhall	35			50	
Do	Dominguez	Compton	46			25	
Do	Santa Fe Springs-Bell	Santa Fe Springs	50				
Do	Santa Maria Valley	Santa Maria	45			55	
Do	Stearns	Brea	48			28	
U.S. Naval Reserve, Unit Operator[1] (Standard Oil Co. of California, Operator).	Elk Hills	Elk Hills	5				
West Coast Refining Co	Richfield	Placentia	50				
(66 plants)			2,823	1,120	339	302	104

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[1] Does not include U.S. Naval Reserve mothball plant at Elk Hills.

Source: U.S. Bureau of Mines.

The adsorption process utilizes a solid adsorbing agent instead of a solvent oil in a minimum of two towers. In one tower the wet natural gas is introduced, where the entrained liquids are adsorbed (taken up on the surface) by the adsorbing agent. When the latter has accumulated all the liquids it can hold, the wet natural gas stream is diverted to the other tower. The natural gas liquids on the surface of the adsorption agent in the first tower are then driven off by the application of heat, and are condensed and recovered. The adsorption agent is thus regenerated for the next cycle. By using a minimum of two towers, a continuous operation is effected. Adsorption plants account for about 10 percent of United States and less than 2 percent of California processing capacity.

A compression plant separates the natural gas liquids by compressing the incoming wet gas and then allowing it to expand. In so doing, the entrained liquids are cooled below their dew points, and thus separate out and are recovered. Often several cycles of compression followed by expansion are necessary to effect the practical ultimate in liquids separation.

A refrigeration plant, like a compression plant, operates on the principle of cooling the natural gas liquids below their dew points so they will condense and separate from the natural gas. However, in this plant design, the liquids are cooled by circulating refrigerants rather than expansion following compression.

A number of plants employ a combination of two or more of the above processes such as absorption-refrigeration, refrigeration-compression, and absorption-compression. Natural gas liquids extraction plants are individually designed using such parameters as total liquids content of the natural gas to be processed, composition of the liquids component, reservoir pressure, and local economics.

By far the largest number of plants in California, as in the United States, utilize the absorption design, followed by combination refrigeration, compression, and adsorption designs.

Utilization

Most of the natural gas liquids produced in California, and especially the natural gasolines, are shipped to petroleum refineries (commonly by pipeline, but occasionally by tank truck) where they usually are catalytically reformed and blended to produce high-octane gasolines. LP-gases are sold, either by companies specializing in their sale and distribution, or by refineries, for residential, commercial, and industral fuel, as fuel for internal combustion engines, or as petrochemical plant feedstocks where they are used in the manufacture of a multiplicity of chemicals including synthetic rubber. Some LP-gases are used in the secondary recovery of crude petroleum by injecting them as a "slug" prior to injecting water or natural gas. Small quantities of natural gas liquids are used as solvents and in portable heating and lighting equipment such as camp stoves and lanterns, blow torches, and weed-burning units.

Consumption of natural gas liquids in California during 1963 for various purposes is given below:

Use:	*Thousand gallons*
Residential and commercial fuel	233,962
Chemical plant feedstock	[1] 116,902
Petroleum refinery fuel	[1] 49,476
Exports	36,582
Industrial fuel	36,090
Internal combustion engine fuel	33,799
Synthetic rubber manufacture	[1] 24,066
Secondary recovery of petroleum	[1] 9,072
Utility gas	26,494
Miscellaneous	3,245
Total	569,688

[1] Estimated.

Source: U.S. Bureau of Mines.

VALUE AND PRICES

The relative value of natural gas liquids compared with the total value of all mineral commodities produced in California has shown an overall decline since 1954. In 1954, natural gas liquids accounted for nearly 8 percent of the total mineral revenue, but by 1964 this figure had dropped to less than 5 percent. The total value of natural gas liquids also declined during this period from $111.6 million to $70 million.

These declines reflected not only the decreasing output of natural gas liquids, but also an overall erosion of prices throughout the 10-year period. The average price of natural gasoline and cycle products dropped from 9.7 cents per gallon in 1954 to 7.5 cents per gallon in 1964; that of LP-gases went from 5.6 cents to 4.5 cents per gallon.

The values of California mineral production and natural gas liquids, from 1954 through 1964, are shown in table 32.

TABLE 32.—*Comparative values of California's total mineral production and natural gas liquids, 1954–64*

Year	Total value of all mineral production	Total value of all natural gas liquids	Percent of total mineral value represented by natural gas liquids
	Thousand dollars	*Thousand dollars*	
1954	1,430,000	111,555	7.8
1955	1,458,000	108,382	7.4
1956	1,555,000	105,947	6.8
1957	1,651,000	101,776	6.2
1958	1,501,000	87,163	5.8
1959	1,424,000	89,283	6.3
1960	1,402,000	83,978	6.0
1961	1,421,000	79,450	5.6
1962	1,467,000	73,754	5.0
1963	1,525,000	71,517	4.7
1964	1,561,000	69,981	4.5

The price per gallon and total value of natural gas liquids, by type, from 1954 to 1964, are shown in table 33.

TABLE 33.—*Price per gallon and total value of natural gas liquids, by type, 1954–64*

Year	Natural gasoline and cycle products		LP-gases	
	Price per gallon (cents)	Total value (thousand dollars)	Price per gallon (cents)	Total value (thousand dollars)
1954	9. 7	89, 293	5. 6	22, 262
1955	9. 6	89, 003	5. 4	19, 379
1956	9. 6	84, 615	5. 2	21, 332
1957	9. 6	81, 355	5. 2	20, 421
1958	8. 0	68, 485	5. 4	18, 678
1959	8. 2	68, 023	5. 4	21, 260
1960	7. 9	62, 496	5. 3	21, 482
1961	7. 6	57, 645	5. 1	21, 805
1962	7. 6	54, 460	4. 7	19, 294
1963	7. 6	54, 188	4. 4	17, 329
1964	7. 5	54, 088	4. 5	15, 893

RESERVES

Table 34 gives reserves for California and the rest of United States as estimated by the American Gas Association Committee on Natural Gas Reserves.

TABLE 34.—*Estimated proved recoverable reserves of natural gas liquids in California and in the United States, Dec. 31, 1964* [1]

[Thousands of 42-gallon barrels]

Locale	Nonassociated with oil	Associated with oil	Dissolved in oil	Total
California, including offshore	9, 745	80, 513	182, 706	272. 964
United States, excluding California	4, 782, 088	984, 535	1. 707, 045	7, 473, 668
Total	4, 791, 833	1, 065, 048	1, 889, 751	7, 746, 632

[1] Includes condensate, natural gasoline, and liquefied petroleum gas.

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NICKEL

(By P. E. Hotz, U.S. Geological Survey, Menlo Park, Calif.)

Nickel, a hard, silvery white metal, has, besides its use in coinage, a multitude of industrial uses as an alloy with other metals. The principal consumption is in the production of ferrous alloys, but it also is combined with other metals, especially copper and chromium. To a lesser extent, uncombined metallic nickel is used for electroplating, in certain kinds of storage batteries, and in powder form it has many applications in the chemical and electronic industries. With each year, continuing research finds new uses for nickel, primarily as an alloy.

The United States production of nickel in 1963 was about 4 percent of the free world production of 271,000 tons, while the consumption by this country was 125,000 tons or slightly more than 46 percent of the free world output. Most of the United States imports of nickel are from Canadian sulfide deposits; some, smelted from Canadian ores, comes from Norway; and a small amount derived from New Caledonia nickel silicate ores is imported from France. The output from Cuban laterite deposits, formerly developed and mined by United States companies, now goes to the U.S.S.R. and Czechoslovakia in the form of concentrates(Ware, 1964). The entire domestic mine output of nickel is from a lateritic deposit at Nickel Mountain, near Riddle, Oregon, owned by the Hanna Mining Co. There is no recorded production from California.

The useful deposits of nickel ores are of two main types: (1) sulfide deposits, and (2) laterites. Both types have representatives in California.

In the sulfide deposits pentlandite $(Fe,Ni)_9S_8$, and pyrrhotite, an iron sulfide which is commonly nickeliferous due to inclusions of pentlandite, are the principal nickel-bearing minerals. Minor quantities of other nickel minerals, including violarite, Ni_2FeS_4, and siegenite $(Co,Ni)_3S_4$, and millerite, NiS, may also be present. The sulfide deposits are associated with mafic intrusive igneous rocks such as gabbro and peridotite, and occur in large disseminated bodies and small to moderate-size massive sulfide bodies. The mineralization is closely related to deep-seated magmatic processes which were responsible for the emplacement of the igneous intrusions into the surrounding county rocks.

Lateritic deposits can be subdivided into two closely related types: (1) nickel silicate laterites of low iron content, and (2) ferruginous nickeliferous laterites. In nickel silicate ores the nickel-bearing minerals are green hydrous nickel-magnesium silicates with rather widely variable nickel content, which are commonly referred to under the general name garnierite. The ferruginous nickeliferous laterites are surficial blankets of reddish-brown soil of variable, complex mineralogy in which there is no specific, discernible nickel mineral. The nickel, invariably accompanied by smaller amounts of cobalt, is intimately combined in an unidentified way with hydrated iron compounds, clays, and serpentine minerals in the soil. The nickel silicate and ferruginous nickeliferous laterites are everywhere underlain by bodies of ultramafic rock, commonly peridotite or serpentinite, from which the nickeliferous deposits have been formed by extensive weathering. Hence this type of deposit is referred to as secondary. Most peridotite and its altered equivalent, serpentinite, contains between 0.1 and 0.3 percent nickel and about .01 percent cobalt, which occur as minor chemical constituents in one or more of the magnesium-iron silicate minerals of the parent rock. Under the influence of natural weathering processes, the rock-forming minerals are decomposed and the more soluble compounds, principally magnesia and silica, are carried away by downward percolating rainwater, while the less mobile constituents, including hydrous iron oxide, nickel, and cobalt are concentrated in a residual blanket. Under some circumstances some nickel is dissolved, removed, and redeposited with silica to form a boxwork of microcrystalline quartz and garnierite below the soil zone, above a substratum of partially weathered peridotite or serpentinite (Hotz, 1964).

SULFIDE DEPOSITS

A sulfide deposit occurs in the Julian-Cuyamaca area of San Diego County near the town of Julian, in the eastern part of the Peninsular Ranges province (fig. 44). The Friday mine (Creasey, 1946), which was probably discovered in the 1880's, has been intermittently explored and developed by underground workings and diamond drilling.

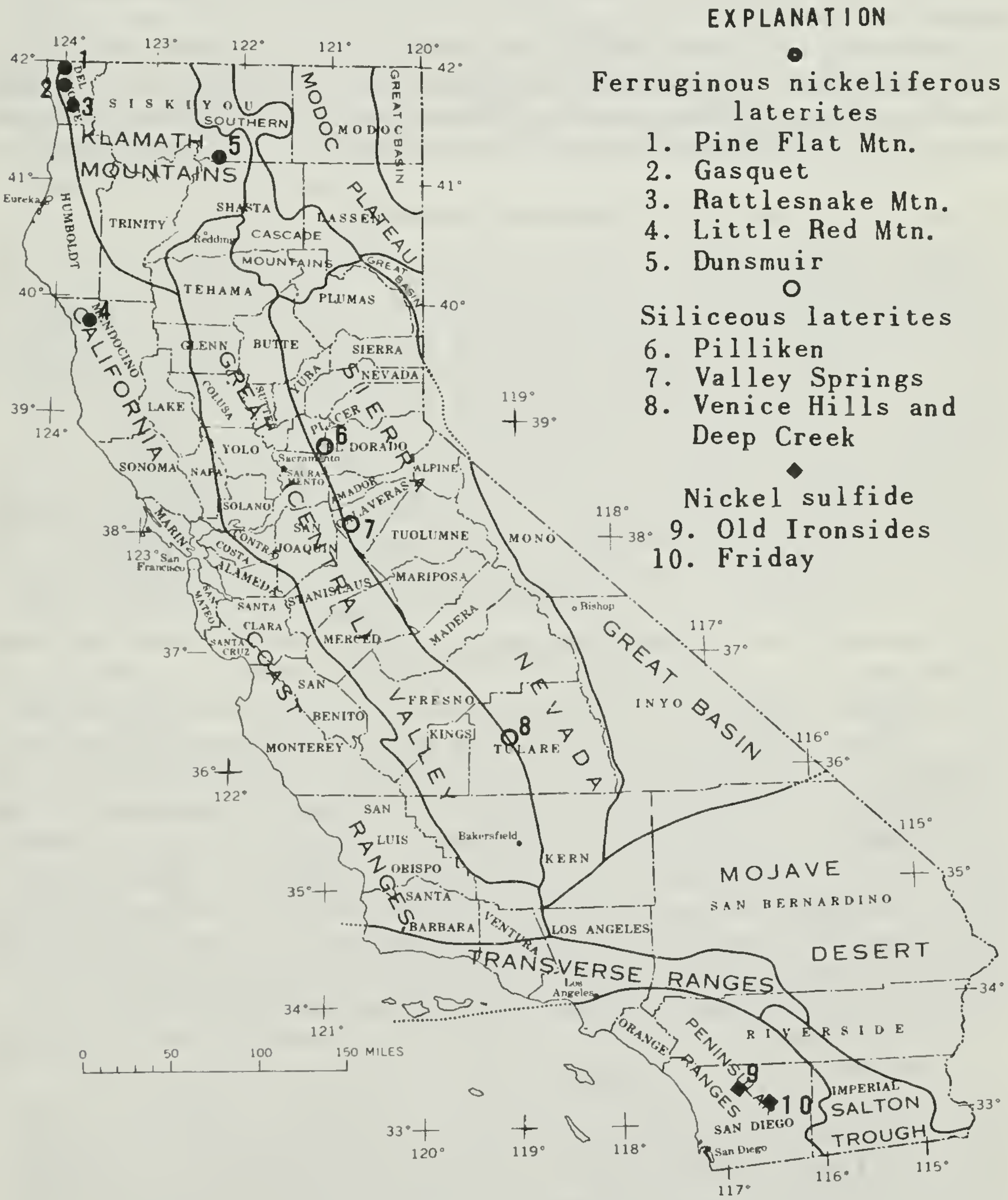

FIGURE 44. Nickel in California.

There is no recorded production; however, the size of the underground workings indicates that several hundred tons of ore have been mined. The deposit is a partly oxidized sulfide replacement of gabbro adjacent to a schist inclusion. Creasey (1946, p. 27) estimated the indicated reserves to be approximately 5,000 tons averaging approximately 2.5 to 3 percent nickel, from 0.5 to 1.0 percent copper, and as much as 0.15 percent cobalt. Subsequent exploration under a DMEA contract confirmed these estimates and showed that approximately three-fourths of the deposit is predominantly oxidized ore. Several other occurrences of gossan (masses of oxidized sulfides) containing from 0.01 to 1.45 percent nickel (Creasey, 1946, p. 27–28) are known in the Julian-Cuyamaca area, which suggest the presence of other nickel sulfide bodies, but limited exploration has not revealed any important deposits. Creasey (1946, p. 19–22) reports as much as 3 percent pyrrhotite in the gabbro body, suggesting that the rock may contain small amounts of nickel, but no analyses of the rock for nickel have been reported.

Exploration under a DMEA contract of a small nickel- and copper-bearing gossan at the Old Ironsides mine, approximately 9 miles north-northeast of Ramona, San Diego County (Peninsular province) revealed a small shallow deposit averaging about 0.35 percent nickel.

Lateritic Deposits

The principal lateritic nickel deposits in California occur in the northwestern part of the State, chiefly in Del Norte County and in southern Siskiyou County (Klamath Mountains province); deposits are also known in northern Mendocino County (California Coast Ranges). Some eroded remnants of deposits in the western Sierra Nevada province have been reported by Rice (1957, p. 396).

The deposits in northwestern California are accumulations of lateritic soil resting on peridotite. They occupy nearly flat-lying to gently sloping areas on broad ridge crests, in saddles, and on benches on the sides of ridges in a thoroughly dissected and deeply eroded rugged mountainous terrain. The individual deposits are scattered, discontinuous areas that range from less than 100 acres to about 300 acres. Thickness of the blankets vary widely and are only approximately known, but range from as little as 10 to 15 feet to as much as 80 to 90 feet. Characteristically, the deposits in northwestern California are blankets of reddish-brown soil at the surface grading downward 1 to 3 feet below the surface to ocherous soil, which passes more or less gradationally downward into bedrock. Except for an occasional veinlet or film of garnierite coating joint surfaces, no nickel minerals have been recognized. In places isolated, residual blocks or boulders of leached, barren silica boxworks are scattered on the surface of the lateritic blankets, and chips of microcrystalline quartz occur in the soil and occasionally as veinlets near the base of the soil zone.

Several deposits are known in Del Norte County where lateritic soil has accumulated on a large pluton of peridotite and serpentine. The best known deposits, which have been explored by drilling by private companies and the U.S. Bureau of Mines (Benson, 1963), are at Pine Flat and Diamond Flat on Pine Flat Mountain about 20 miles northeast of Crescent City, near the California-Oregon boundary. Several others, some of which have been tested by private companies, are known near Gasquet, a town on Smith River approximately 18 miles east of Crescent City. Some small patches of lateritic soil are also known along a long, narrow north-south ridge of ultramafic rock south of Gasquet, known as Rattlesnake Mountain. A few other isolated deposits only a few acres in extent are also known in this general region.

One deposit is known in northern Mendocino County at Little Red Mountain, approximately 2.5 miles east of Leggett. The deposit occurs on the southern part of an isolated ultramafic body in the northern Coast Range province, and has been explored by a private company.

In southern Siskiyou County a small lateritic deposit occupies the nose of a ridge in the Sacramento River Canyon north of the mouth of Little Castle Creek, approximately 2 miles south of Dunsmuir. No active exploration of this deposit has been undertaken.

Reconnaissance sampling and data from Bureau of Mines exploration (Benson, 1963) show that the thicknesses of the lateritic blankets vary widely and are only approximately known, but they are estimated to be less than 50 feet thick and probably, on the average, seldom more than 25 to 330 feet. The average nickel content ranges from 0.5 to 0.8 percent nickel, 0.01 to 0.1 percent cobalt, and the iron content is less than 20 percent.

Several lateritic remnants on serpentinite are known in the western Sierra Nevada province (Rice, 1957, p. 396). They consist mostly of cappings of dense silica boxwork grading into jasperlike silicified serpentinite. Some garnierite fills cavaties in the boxwork and occurs as veinlets in the serpentinite. The cappings are more than 100 feet thick in places but the rocks are leached and the average nickel content is less than 0.5 percent. Siliceous laterite remnants are exposed at the Pilliken chromite mine in El Dorado County; a few miles east of Valley Springs in Calaveras County; and in the Venice Hills and Deer Creek areas of Tulare County. The only known exploration of the western Sierra lateritic deposits through 1956 (Rice, 1957, p. 396) was in a small area in the eastern part of the Venice Hills.

RESOURCE POTENTIAL

The resources of nickel are only imperfectly known. Reserves of nickel-bearing sulfide ores are very meager, probably amounting to less than a few thousand tons. There may be on the order of 25 million tons of nickeliferous laterites in northwestern California which average 0.8 percent nickel or less, distributed among several widely scattered deposits. It seems unlikely that these resources will be commercially exploited in the foreseeable future, because of their low grade and dispersal among several relatively small deposits. Unlike the Nickel Mountain deposit in Oregon they do not have bodies of high-grade nickel silicate with which to increase the average nickel content of the ore.

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NIOBIUM AND TANTALUM

(By R. L. Parker, U.S. Geological Survey, Washington, D.C.)

The rare metals, niobium and tantalum, have become increasingly important in modern technology and are required in certain electronic, nuclear, chemical, and high-temperature metallurgical applications. Both metals are used for vacuum tube elements, super conductors, corrosive-resistant vessels, and laboratory ware, and as constituents in high-temperature alloys and austenitic stainless steel. Niobium is specially used for cladding nuclear fuels, whereas tantalum is used for capacitors, rectifiers, and surgical implants and as a catalyst in the manufacture of butadiene rubber (Miller, 1959; Barton, 1962).

Although the United States is the world's largest consumer of niobium and tantalum, it is a small producer and relies on foreign sources for its ore supply. Critical shortages of these metals resulted in government allocation controls during World War II and the Korean War, and a strategic stockpile of niobium-tantalum raw materials is now maintained by the Government. During the last 10 years imports of niobium-tantalum concentrates have ranged from an alltime high of 11,520,262 pounds in 1955 to a low of 3,591,530 pounds in 1958. In 1963, 6,853,971 pounds of niobium-tantalum concentrates were imported. Domestic production reached a peak of 428,347 pounds of concentrates in 1958, most of which came from Idaho placers. This production, however, amounted to only about one-tenth of that year's domestic consumption. No domestic production has been recorded since 1959 (U.S. Bur. Mines Minerals Yearbooks, 1955–1963).

Niobium and tantalum commonly occur together in the same minerals. These minerals also commonly contain subordinate amounts of titanium, iron, manganese, rare earths, uranium, thorium, and other metals. Important ore minerals are columbite-tantalite, $(Fe, Mn)(Nb, Ta)_2O_6$; pyrochlore, $NaCaNb_2O_6F$; microlite, $(Na, Ca)_2Ta_2O_6(O,OH,F)$; euxenite, $(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$; fergusonite $(Y,Ca,U,Th)(Nb,Ta)O_4$; and samarskite, $(Fe,Y,U)_2(Nb,Ti,Ta)_2O_7$.

Niobium-tantalum minerals are found in granitic rocks and pegmatites, in alkalic rock complexes and associated carbonatites, and in placers derived from these rocks. Some granite massifs contain disseminated columbite-tantalite, euxenite, or other niobium-tantalum-bearing minerals as primary rock constituents, and in some places weathering and fluvial processes have concentrated these minerals into commercial deposits. Granite pegmatites are well known for their concentrations of rare minerals, including minerals of niobium and tantalum, but the erratic distribution and limited tonnage of these minerals in pegmatites commonly exclude pegmatites as an important source of supply. Even so, pegmatites are the principal source of the world's tantalum.

Large low-grade deposits of niobium occur in alkalic rock complexes and related carbonatites in many parts of the world. Some multi-million ton deposits are known in central Africa, southeastern Canada, Norway, and Brazil, and at least five alkalic complexes with carbonatites have been found in the United States. Niobium is contained in the mineral pyrochlore, which commonly is disseminated in the carbonatite. Many such deposits are under extensive development and are expected to be the principal source of niobium in future years.

Commercial deposits of niobium and tantalum have not been found in California, although an undisclosed—but presumably very small—amount of tantalum was produced from San Diego County in 1920 (Weber, 1963, p. 41, 68). Niobium-tantalum minerals have been reported from widely scattered pegmatites in the State (see fig. 45), but many of the reported occurrences are poorly documented. So far as known, all of the niobium-tantalum minerals reported are present only as minor accessory constituents in the pegmatites and are not regarded as potential sources of niobium and tantalum.

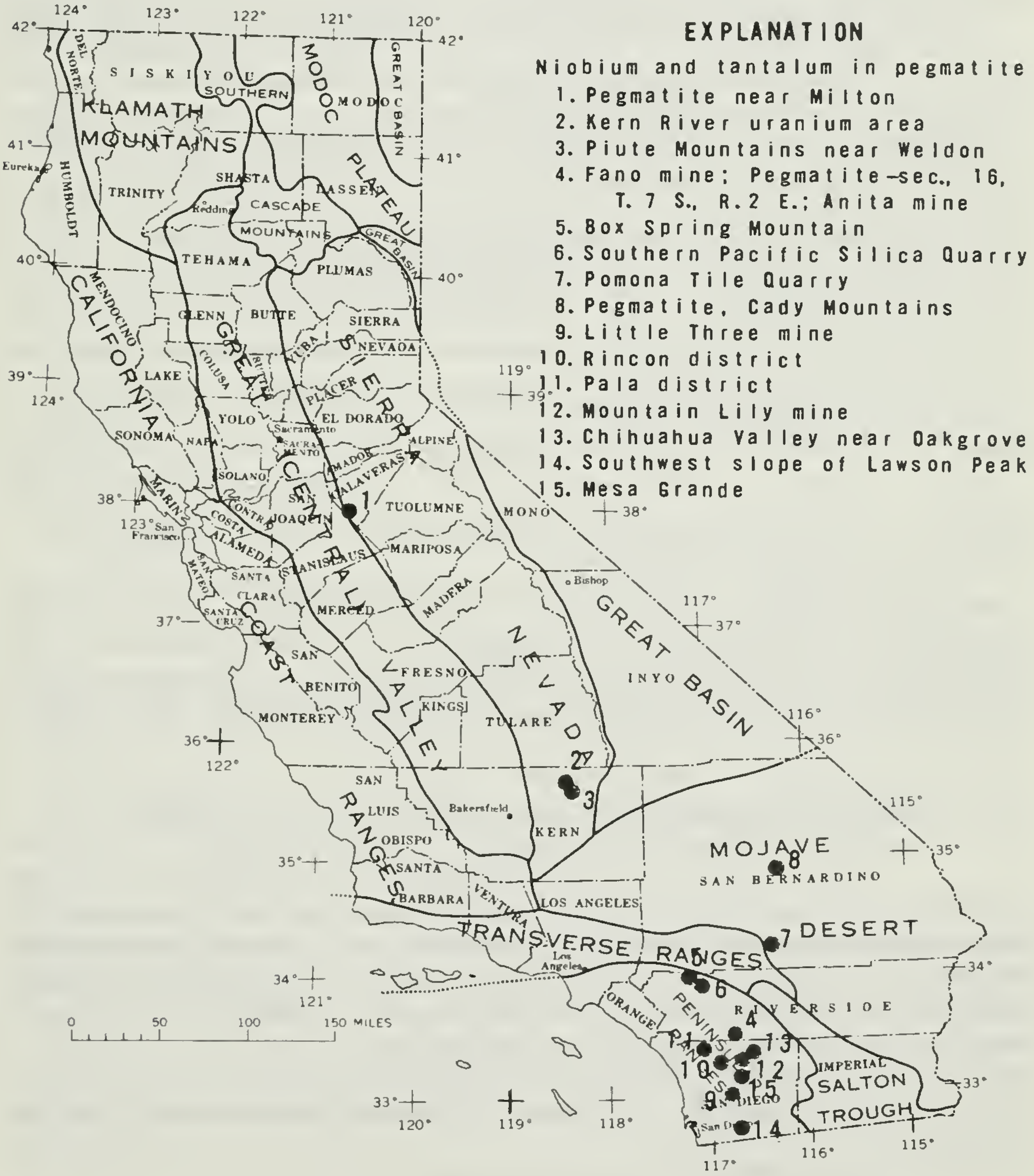

FIGURE 45. Niobium and tantalum in pegmatites in California.

A carbonatite body associated with alkalic rocks at Mountain Pass, San Bernardino County contains one of the world's largest deposits of rare-earth minerals, although only traces of niobium have been found in the deposit (see p. 351, Rare-earth chapter, this volume). The occurrence of carbonatite and alkalic rocks in this region, however, opens the possibility of finding similar and perhaps niobium-bearing rocks through future geologic study.

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OFFSHORE RESOURCES (EXCLUSIVE OF PETROLEUM)

(By J. W. Padan,[1] Ocean Resources, Inc., La Jolla, Calif.)

One has only to read the popular press to gain an idea that mammoth rich accumulations of sea-floor minerals exist to enrich anyone with imagination enough to tool up for exploitation. In reality, the much-heralded day of large scale mining of marine minerals must be preceded by years of detailed geologic exploration.

What are the facts? First, sea-floor minerals do exist. Second, in a few areas of the world, including California, they are being mined.

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Third, most of the mineral occurrences have crept into print on the basis of a solitary sample. Many of the "vast sea floor mineral deposits" have been delineated on the basis of only 3 or 4 samples. Although they may fire our imaginations, to a statistician, these data are almost meaningless.

This era of promotional literature has served a purpose—considerable interest has been provoked in industrial, academic, and governmental circles. All eyes are on the next offshore move.

What is the situation with respect to California's offshore minerals? The immediate industrial interest here, as elsewhere, is focused upon the near-shore area. Sand and gravel is being mined from several onshore beach deposits. As coastal metropolitan areas expand and encroach on much-needed deposits of inshore sand and gravel, offshore sources are certain to be sought both for construction purposes and for the restoration of storm-eroded beaches. Sea shells are dredged from San Francisco Bay as a source of lime for the manufacture of cement. Sand and silt are dredged for fill material in several coastal areas. Salt, bromine, and magnesium are recovered from sea water in many areas of the world, including California. As the saline water conversion program gains momentum, additional elements and compounds no doubt will be economically recovered as byproducts. Heavy minerals, or black sands, will become exploration targets, especially offshore from the mouths of rivers that have coursed through mineralized zones. Monterey, Drake's, and Half Moon Bays all have aroused some industrial interest for this reason. Ancient drainage patterns may offer further clues to offshore targets of heavy minerals. The heavy minerals of present economic interest are tin, gold, and iron ore (these three all are being mined offshore somewhere in the world), titanium ores, platinum, gem stones (diamonds are being mined off the African Coast; specimens of jade have been recovered by skin-divers off California), and tungsten ores.

Of all the minerals on the continental shelf, the one that perhaps will be exploited first is phosphorite, an essential fertilizer material. The concentrations of phosphorite appear to be widespread; samples have been recovered from more than 250 locations, from Baja California to San Francisco. An attempt to mine one deposit was abandoned, reportedly because of the presence of unexploded naval projectiles on the sea-floor at the site. Considering the economic potential of this material, if it truly exists in the great tonnages that are indicated, the sampling to date has been rather modest. Samples of barite nodules and glauconite have been recovered from the shelf, but their presence in economic concentrations has not been proved, and their exploitation appears to be far in the future.

California's continental shelf is narrow. In fact, some of the occurrences of the above-mentioned minerals actually are on the continental slope. However, the opportunity to "widen" her shelf was presented to California last year when the Fourth Convention of the 1958 Geneva Conference on The Law of The Sea became international law. The shelf now is defined as, ". . . the seabed and subsoil of the submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200 meters or, beyond that limit, to where depth of the superjacent waters admits of the exploitation of the natural resources of the said areas . . .". Thus, mining of the deep water nodules containing manganese, nickel, cobalt, and copper will legally extend the continental shelves of many coastal nations. The nodules have been sampled fairly well and appear to be present in quantity, but the deposit selected for initial exploitation will certainly have to be sampled in considerably more detail. Once the extent and market value are determined with reasonable confidence, then there will be reason to solve the mining technology problems that may remain. Deep ocean red clays someday may become a source of alumina, and calcareous and siliceous oozes may find use as construction materials.

Assessing the marine minerals in perspective, we can see that an expanded marine mineral industry in California depends upon an evaluation of "what is down there." Only an exploration program can supply the answers. The California-based federal program originally was conceived to fill this gap. However, Congress has reoriented the program and the next move appears to be up to industry.

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PEAT

(By C. W. Jennings, California Division of Mines and Geology, San Francisco, Calif.)

Utilization

The principal use of peat in the United States is as a soil conditioner. Peat contains a large percentage of fibrous and porous organic matter (humus) which improves the physical structure of the soil and promotes plant development when used in large enough quantities. Peat mixed with heavy clay soils makes them more granular, less plastic, and consequently more permeable to water, air, roots, and micro-organisms. In sandy soils, peat helps bind the soil particles, retards excessive percolation, and makes the soils more retentive of moisture and nutrients. Contrary to popular belief, peat is not a fertilizer, and the nitrogen that it contains is not readily given up as a plant food like the "soluble nitrogen" of artificial fertilizer. However, peat does contain soluble humic acid and is desirable for preparing soil for plants that prefer an acid condition, such as rhododendrons, azaleas, camellias, and gardenias. Peat commonly is mixed with sand and loam soil in the preparation of potting mixtures or media for the germination of seeds.

The second largest market of peat in this country is as an ingredient or filler in mixed fertilizers in which it acts as a carrier for the primary nutrients—nitrogen, phosphoric oxide, and potash—not as an agent for supplying plant food. Well-decomposed peat dried and ground is ordinarily used for this purpose.

Because of its moisture-absorbing qualities, fibrous peat sometimes is used as a litter material for bedding livestock, and its deodorizing capacity makes it useful in stable and poultry yards. Nurserymen, gardeners, and others use peat as a packing material for plants, fruit, vegetables, eggs, fish bait, and fragile materials, and as a medium for growing mushrooms and earthworms. Other uses of peat include filtering agents, dye stuffs, tanning substances, and as absorbent in surgical dressings, but the quantities so used are small.

In several European countries, peat is used as a fuel, but is is not so used in the United States because of ample supplies of superior fuels with much higher calorific values.

Geologic Occurrence

Peat is an accumulation of partly decomposed and disintegrated vegetal matter, representing the first stage in the transition of plants to coal. It forms in undrained depressions, plains, or river deltas that contain environments favorable to luxuriant growth of peat-forming plants. The plants range from woody shrubs and trees of swamps, to mosses, sedges, reeds, and grasses of marshes. Poor drainage is essential in the formation of peat, because standing water largely excludes oxygen and prevents complete decay, thus enabling the carbonaceous matter to be preserved.

The type of vegetation that accumulates determines the type of peat that is formed. The most valuable commercial peat is formed from aquatic mosses. Other commercial grades of peat include reed or sedge peat, and peat humus, which is a soil high in organic matter. Most of the peat deposits in California are classified as reed-sedge peat or peat humus. A high-grade peat moss, however, is recovered from a single bog in Modoc County in northern California.

Production

World production of peat in 1963 was estimated at 170 million short tons of which 60 percent was used for agricultural purposes and 40 percent for industrial fuel. The U.S.S.R. is the leading producer with 95 percent of the world output. The United States production is relatively small and represents less than 1 percent of the world total.

The demand for agricultural peat in the United States has steadily increased in recent years, and, in 1963, the production reached nearly 600,000 tons—more than double the production of 10 years ago. In addition, 261,000 tons of peat were imported, principally from Canada. Whereas the domestic production of peat has been increasing from year to year, the quantity of imported peat has remained relatively constant. The principal peat producing states in the United States are Michigan, Indiana, Pennsylvania, California, and Washington; together these states account for three-fourths of the nation's output.

In 1963, California ranked fourth among the states in the amount of peat produced and second in the value of sales. The average value per ton of peat in California was $11.29. The demand for peat in this

State has risen phenomenally in the past 10 years. The value of peat sold in 1963 was $450,000—more than 6 times the value produced in 1953. All of the peat produced in this State, as far as is known, was used for soil improvement.

California Occurrences and Reserves

Four widely scattered peat deposits are being worked in California as shown on figure 46. These range from a peat moss operation near Likely, Modoc County, in the northeastern part of the State, to a reed-sedge type peat bog in a sag pond along the San Andreas fault near Banning, in southern California. The largest peat reserves are situ-

Figure 46. Peat in California.

ated in the Sacramento-San Joaquin Delta area, where peat and peaty muck deposits cover an estimated 400 square miles. Two operators are dredging reed-sedge peat from Frank's Tract in this area. A small tonnage of peat humus is being extracted from a deposit near Huntington Beach, in Orange County.

Peat has been mined from San Diego, Santa Cruz, and San Bernardino Counties, and U.S. Soil Survey maps show peat and peaty muck occurring in Round Valley, Inyo County; near the mouth of Salinas River, Monterey County; along San Antonio River and south of the mouth of Santa Maria River, Santa Barbara County; and in various sites in Siskiyou and Humboldt Counties (U.S. Department of Agriculture, 1919–1944).

Reserves of peat in California have been estimated by the U.S. Geological Survey (U.S. Geol. Survey Circ. 293, 1953, p. 38) to be 72 million short tons (air-dried basis). The peat reserves of the United States have been estimated at approximately 14 billion short tons.

OUTLOOK

The outlook for the California peat industry is favorable and production is expected to increase. As the population of the State grows and more homes are built, more peat will be in demand by homeowners, landscape gardeners, and nurseries. Peat deposits in California have not been thoroughly studied for economic development; however, the location of many small deposits are shown on U.S. Department of Agriculture soil maps. Possibly a number of these deposits could be worked.

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PETROLEUM AND NATURAL GAS

(By M. B. Smith and F. J. Schambeck, U.S. Geological Survey, Los Angeles, Calif.)

INTRODUCTION

Oil is used primarily to produce energy for power or heat, and for lubrication. More than 2,300 separate products are made by the petroleum industry, some of the principal products being gasoline; lubricants; residual and distillate fuel oils; jet fuel; raw materials for the petrochemical, rubber, and fertilizer industries; and asphalt.

Most of the crude oil produced in California is of napthenic base (often called asphaltic base). The crude oil is transported from the oil fields by pipe lines, ocean tankers, or tank trucks to the 34 refineries in the State, most of which are near Los Angeles and San Francisco. These refineries have a capacity of about 1,350,000 barrels per day.

Natural gas is used primarily for space heating and for fuel, but some is used as a chemical raw material. Most gas in California occurs in two ways: (1) as "wet gas" in oil sands or closely associated with oil in an overlying gas cap, or (2) as "dry gas" in separate zones in oil fields or in gas fields not associated with oil. Wet gas commonly contains valuable constituents which are removed at processing plants to obtain natural-gas liquids before the residue gas is used. Dry gas usually does not contain enough of these constituents to make the processing economically profitable, so after removing impurities and blending with other gas to increase the heating value if necessary, it is distributed by pipe line and used. Slightly more than one-third of the gas produced along with oil in California is reinjected under pressure into the oil reservoirs for the purpose of restoring or maintaining the reservoir pressure and thereby increasing the recovery of oil. Most of this gas will be produced again at some later date. At present, less than 1 percent of the gas accompanying oil production is wasted by being allowed to escape into the air, and even this wastage generally occurs during testing operations.

The production of oil and gas in California is extremely important to the economy of the State as it provides a local source of supply for a large part of the energy requirements of the large and rapidly growing industry and population. The production, refining, and distribution of petroleum utilizes a capital investment of $6.9 billion in facilities and equipment and furnishes employment to some 106,000 persons. Oil producers pay an estimated $140 million annually as royalties to owners of interests in the production, and some $30 million annually for rentals on some 5.5 million acres of nonproductive land held under oil and gas leases. Taxes paid to state and local governments (exclusive of those paid by gas utilities) are estimated at $620 million for 1964. There are 69 plants in the growing petrochemical industry employing 45,000 persons with a $325 million payroll. Oil accounts for 79 percent of all tonnage through California harbors.

The 1964 output of California's 42,000 producing oil wells and 900 producing gas wells in some 350 fields (figs. 47, 48, 55, 56) was 299 million 42-gallon barrels of oil and 675 billion cubic fee (net) of gas with a value at the wells of about $940 million. This amounted to 60 percent of the value of the entire mineral production in California for the year. The production was obtained from depths as shallow as 200 feet to as deep as 13,000 feet. The productive area totals about 425,000 acres, or less than ½ of 1 percent of the area of the State. The only substantial shut-in production is about 100,000 barrels per day from one zone in the Elk Hills field in Naval Petroleum Reserve No. 1. However, the daily yield from many large flowing wells is controlled and is less than their potential.

The production of crude oil declined nearly continuously from the peak of 1 million barrels per day in 1953 to 813,000 barrels per day in 1962. Since that year production has increased to 860,000 barrels daily

Figure 47. California oilfields.

by mid-1965, and may increase to 1,000,000 barrels per day in the next few years. It has been estimated that the need for crude oil in California will increase about 3.8 percent annually through the year 2000.

The gravity of California crude oil ranges from 6° to 60° API, but 347,800 barrels per day, or 42 percent of the State's production in January 1965, was heavy crude below 20° API gravity. The price received by the producer at the well depends largely on the gravity. It ranges from $1.07 to $3.42 per barrel at present and averages about $2.47.

Along with the oil, the State's wells produce about 2.9 million barrels of water per day which must be disposed of according to the require-

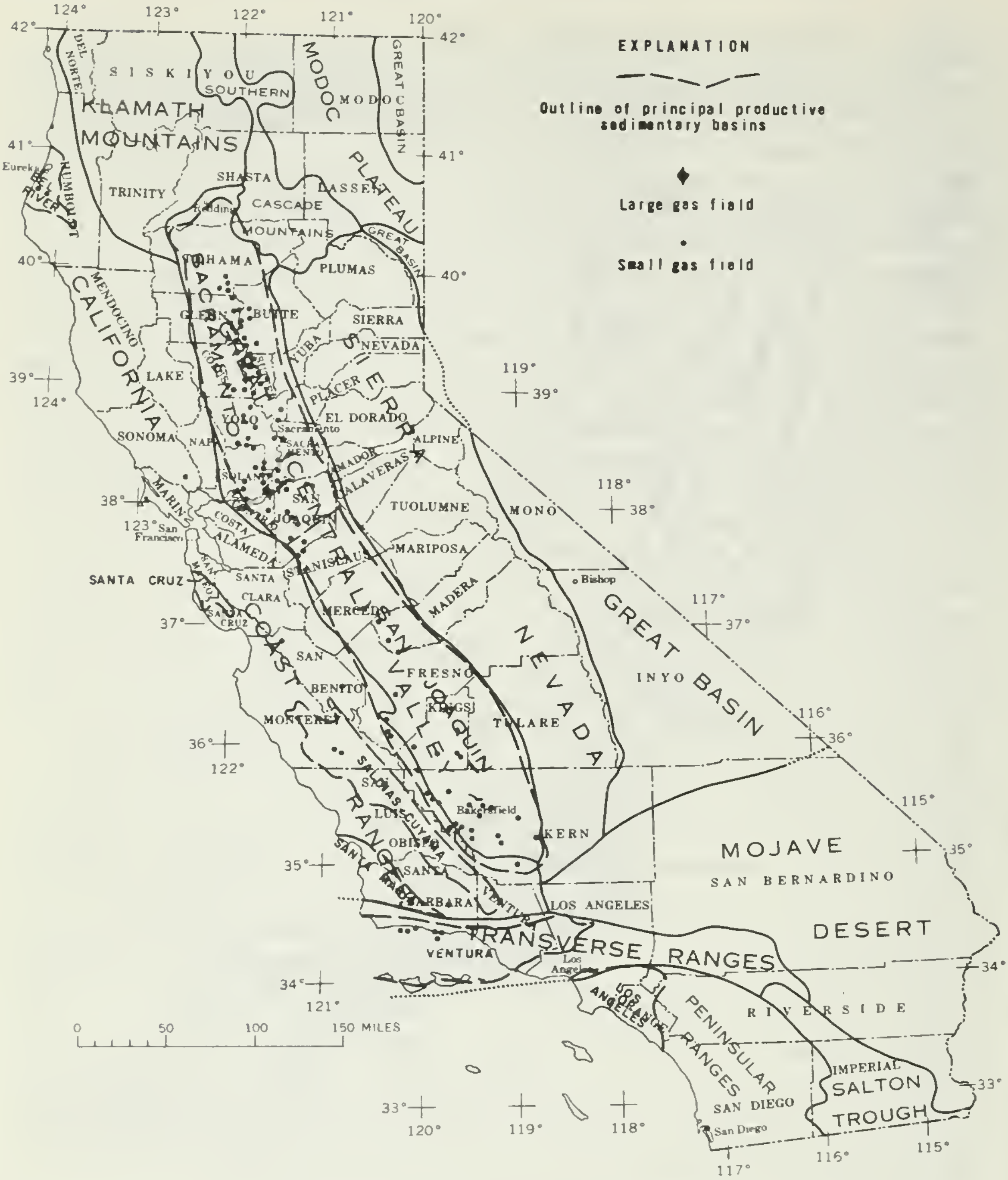

FIGURE 48. California gasfields and principal productive sedimentary basins.

ments of the State Water Pollution Control Board. Both the production and disposal of water increase the cost of producing oil.

Forty-six pools or fields in the State are today partially or fully unitized, the first unit having been formed at the Kettleman North Dome field in 1931. Nineteen pools or fields, although not unitized, are operated essentially as units.

The State Oil and Gas Supervisor, Division of Oil and Gas, is charged with the responsibility of carrying out the provision of State laws for the conservation of oil and gas. Among other things, these laws provide for supervision of operations so as to prevent, as far as possible, damage to underground oil and gas deposits from infiltrating water, and the loss of oil and gas; these laws also prohibit the unreasonable waste of gas. The Division also supplies oil and gas field maps, publishes detailed descriptions of most fields in the State, and provides statistics on production.

The Conservation Committee of California Oil Producers recommends schedules for production from 75 pools, based on determinations by engineering studies of what is considered the Maximum Efficient Rate (MER) of production. The Committee also provides production statistics.

The California Division of Mines and Geology, the U.S. Geological Survey, and the American Association of Petroleum Geologists have published many maps and articles concerning the geology and occurrence of oil in the State. The last also provides exploration statistics. On Federal lands the Conservation Division of the U.S. Geological Survey supervises drilling and producing operations and determines and collects the royalty.

Information used in this chapter concerning the petroleum industry, the geology, and the occurrence of oil in the State has appeared in published reports too numerous to list; it is gratefully acknowledged. A selected list of references is included with this report.

UNITED STATES RANK AS WORLD PRODUCER OF OIL

The demand for petroleum products in the United States in 1964 was 11.3 million barrels daily. This demand was met largely by domestic production of 7,664,000 barrels of crude oil and gas condensate, by the production of 1,147,000 barrels of natural gasoline and other liquid petroleum products, and by imports of 2,260,000 barrels of crude oil and products. Only 202,000 barrels per day of products and crude oil was exported.

For many years until the mid-1940's, the United States produced approximately two-thirds of the oil in the world. In recent years, however, imports of crude oil and refined products into the United States have increased while exports have decreased, so that imports have exceeded exports since about 1948. In 1964, the United States produced about 33 percent of the free world's production, and about 27 percent of the entire world's production which has been estimated at 28.1 million barrels daily.

CALIFORNIA'S RANK IN UNITED STATES PRODUCTION

California was the major oil producing state from 1903–1914 and 1923–1926. It was second to Texas until 1958 when Louisiana exceeded California, mainly because of the development of large production in southern Louisiana, including offshore. California now ranks third in both current crude oil production and reserves (table 35).

GEOLOGIC OCCURRENCE

Commercial quantities of oil and gas occur under pressure in the interconnected pores of reservoir rocks in pools or fields. All oil underground contains some dissolved gas, so when oil is mentioned the contained gas is included also. The interconnected pores between the grains of sand or conglomerate comprise the space which holds most of the oil in California as in many other oil regions. It is estimated that 98 percent of the oil in the State occurs in rocks of those types. In addition, weathering, solution, chemical changes, and fracturing also create porosity, and some oil is produced in California from

TABLE 35.—*Oil and gas production and reserve data for 6 leading producing States*

[Compiled from Oil and Gas Journal, Jan. 25, 1965, v. 63, no. 4, p. 147–153]

Rank	Daily production of crude oil and lease condensate in 1964		Wells producing oil in 1964		Total production of crude oil and lease condensate, 1859–1964		Daily marketed production of natural gas in 1964	
	State	Thousand barrels	State	Number	State	Thousand barrels	State	Million cubic feet
1	Texas	2,710	Texas	200,088	Texas	27,668,697	Texas	17,595
2	Louisiana	1,529	Oklahoma	83,068	CALIFORNIA	13,223,496	Louisiana	11,980
3	CALIFORNIA	816	Pennsylvania	54,080	Oklahoma	9,022,978	Oklahoma	3,586
4	Oklahoma	556	Kansas	46,146	Louisiana	7,498,089	New Mexico	2,519
5	Wyoming	394	CALIFORNIA	41,752	Kansas	3,751,445	Kansas	2,174
6	New Mexico	308	Illinois	30,249	Illinois	2,525,048	CALIFORNIA	1,940
	Others	1,346	Others	145,641	Others	12,610,000	Others	3,305
	Total, United States	7,659		601,024		76,299,753		43,099

Rank	Estimated proved recoverable reserves of crude oil as of Jan. 1, 1965		Estimated proved reserves of natural gas as of Jan 1, 1965		Estimated proved reserves of natural gas liquids as of Jan. 1, 1965		Estimated total liquid reserves as of Jan. 1, 1965	
	State	Thousand barrels	State	Billion cubic feet	State	Thousand barrels	State	Million barrels
1	Texas	14,212,000	Texas	126,219	Texas	4,394,828	Texas	18,606.8
2	Louisiana	7,147,500	Louisiana	76,871	Louisiana	1,977,884	Louisiana	9,125.4
3	CALIFORNIA	4,147,999	Oklahoma	19,931	New Mexico	620,580	CALIFORNIA	4,418.8
4	Oklahoma	1,961,000	Kansas	17,474	Oklahoma	312,071	Oklahoma	2,273.0
5	Wyoming	1,402,000	New Mexico	15,834	CALIFORNIA	270,807	New Mexico	1,698.6
6	New Mexico	1,078,000	CALIFORNIA	9,015	Kansas	154,700	Wyoming	1,498.8
	Others	5,172,316	Others	25,245	Others	456,249	Others	5,686.5
	Total, United States	35,120,815		290,589		8,187,119		43,307.9

fractured cherts, fractured shales, fractured sandstones, and from weathered and fractured basement rocks beneath the sedimentary rocks.

The pore spaces in most sedimentary rocks more than a short distance beneath the surface were filled with water at some time in their history, so in oil reservoirs they generally contain what is called interstitial water as well as oil.

For commercial production to be obtained, the reservoir rock must also be permeable as well as porous. Permeability is the measure of the ease with which fluids move through the interconnected pore spaces.

The original pressure in most California reservoirs is roughly equivalent to that which would be exerted by a vertical column of water extending nearly to the surface, but it exceeds that pressure in some fields.

When the drill penetrates the reservoir rock and any drilling fluid in the hole is partially or completely removed, the reservoir energy causes the oil to move into the hole. The gas expands, the fluid moves toward the surface, and oil may flow from the well (a "gusher" if the flow is large and uncontrolled). If the fluid does not reach the surface, it is removed by pumping or by other mechanical means. The gas-free oil in stock tanks at the surface occupies less volume than it did underground because the compressed gas dissolved in the oil in the reservoir escapes from the oil as the pressure is reduced from that in the reservoir to that in the tank.

How the oil and gas were formed, how they move (oil and gas are migratory fluids), and how they accumulate at the places where they are now found—the origin, migration, and accumulation—is still the subject of much scientific speculation, although a great deal is now known about characteristics of the traps in which they have accumulated, as a result of studies of thousands of oil fields. It is now widely accepted that commercial petroleum is derived from the organic remains of plants and animals that were deposited in a low-oxygen, reducing environments in marine sediments, principally fine-grained muds, but also in sediments deposited in brackish to fresh water (Hedberg, 1964). The chief sources of oil and gas in California are believed to be the thick organic shales (consolidated muds) so widespread in marine sedimentary rocks primarily of Tertiary age, but also of Cretaceous age (Hoots, 1943).

It is believed that oil, along with water, escapes from the muds as they are compacted, and moves into coarser sediments through which it moves laterally into the traps in which it now occurs. Vertical migration, possibly along faults, may account for the present location of some of the oil at shallow depths in some California fields (Hoots, 1943).

Regardless of the processes involved, oil usually moves toward higher elevations because these are areas of lower pressure, and because oil is lighter than water. It accumulates in traps which may be classified as structural, stratigraphic, and combination (strati-structural). A trap involves a porous reservoir rock, an overlying impermeable cap rock, and a barrier in the reservoir which prevents further updip or lateral movement of the fluids. In traps that contain free gas, oil, and water, the fluids are arranged in approximately horizontal layers—gas being the lightest, at the top, then oil, and then water. The water almost always moves slowly into areas in which the pressure has been reduced by removal of the oil, and this movement may assist in recovering more of the oil in the reservoir.

Levorsen (1954) defines a structural trap as one whose upper boundary has been made concave, as viewed from below, usually by folding or faulting or both, of the reservoir rock; a stratigraphic trap as one in which the chief trap-making element is some variation in the stratigraphy or lithology of the reservoir rock; and a combination trap as one in which both causes are in approximately equal proportions. Most stratigraphic traps in California involve some element of structure. Commonly, multiple productive sands separated by impermeable shales are present in structural traps in California, an obvious favorable circumstance for additional accumulations.

Environments favorable for a source of oil are not necessarily favorable for the development of reservoirs, so oil occurrence depends in part on a favorable relationship of the two. Normally, either without the other does not result in a commercial oil occurrence (Weeks, 1958).

Hedberg (1964) stated that California is in one of the two principal belts of oil occurrence in the world. In the United States, the north-south belt also includes the major oil field areas of the Rocky Mountains, the Mid-Continent, and the Gulf Coast regions.

California is also in a mobile belt bordering the Pacific. Traps in which oil and gas may accumulate are commonly smaller but more numerous in such regions than in more geologically stable regions.

The petroliferous provinces of the world, including California, are in sedimentary basins—geologically depressed areas in which great thicknesses of sedimentary rocks that were deposited in the interior of the basin thin toward the edges.

In California, most of the oil is obtained from marine sands and conglomerates of Miocene and Pliocene ages (fig. 49). Lesser amounts come from sands and conglomerates of Eocene, Oligocene, and Pleistocene ages and from fractured rocks of Miocene age; still smaller amounts come from sands of Late Cretaceous and Paleocene ages, and from fractured and weathered basement rocks of pre-Tertiary age. Gas is produced along with the oil from rocks of the previously mentioned ages, but most of the dry gas is obtained from rocks of Late Cretaceous, Paleocene, Eocene, and Pliocene ages. The surface evidence of many geologic structures, both anticlines and faults, has resulted from the mid-Pleistocene deformation. Many fields are located on prominent hills or ridges which approximate the location and shape of the anticlinal structure of these hills or ridges because the anticlinal hills rose more rapidly than streams could erode and level them.

Economic Factors Affecting Exploration

The principal economic factors affecting exploration (including the drilling of exploratory wells) for oil and gas are, of course, the price (fig. 50), market demand, and accessibility to markets for the raw material at the time and in the foreseeable future in a free economy—in other words how much of the production, if found, can be sold and at what price.

EPOCH	LOS ANGELES	VENTURA	SAN JOAQUIN	SANTA MARIA	SALINAS-CUYAMA	SANTA CRUZ	SACRAMENTO	EEL RIVER
Pleistocene		•	●					
Pliocene	●	●	●	●	•	•	☼	☼
Miocene	●	●	●	●	●	•		
Oligocene		●	●	•?			☼	
Eocene		•	●			•	☀	
Paleocene		•	•				• ☀	
Late Cretaceous		•	•				• ☀	
pre-Tertiary basement rocks age uncertain	•		•		•			

EXPLANATION

● Oil production, large

☀ Gas production, large

• Oil production, small to moderate

☼ Gas production, small to moderate

FIGURE 49. California oil and gas production in principal sedimentary basins, according to geologic age of rocks.

Commonly, exploration has decreased in times of economic stress, lower prices, or an over-supply of oil, notably during the years of the great depression in the early thirties when exploration virtually ceased. Even in the thirties, however, the application of new exploratory tools such as the reflection seismograph was instrumental in causing farsighted organizations to search for prospects and to acquire rights to lands.

Following the development of large flowing production in the twenties, principally from the Long Beach and Santa Fe Springs fields in 1929, voluntary curtailment of production was generally accepted and has continued to some extent to the present, except for regulation of production by the Federal government from 1933 to 1935.

Prior to World War II, and occasionally since then, production of crude oil in California was greater than the demand, and large quantities of crude and products were sold on the world's markets, often at depressed prices. Since World War II, however, the local demand for both oil and gas has increased greatly as a result of industrial and population growth, and in recent years production in California has been insufficient to meet the local demand. Large and increasing amounts of gas have been brought into the State since 1947 through gas transmission lines from Texas, New Mexico, and Canada, and since 1951 large and constantly increasing amounts of crude oil and petroleum products have been imported from other states and foreign sources (fig. 51). Among the consequences of this change in supply and demand are a relative stabilization in the price for crude oil but an increase in the price for gas. This latter increase has provided an incentive for expanded exploration for gas in the Sacramento sedimentary basin.

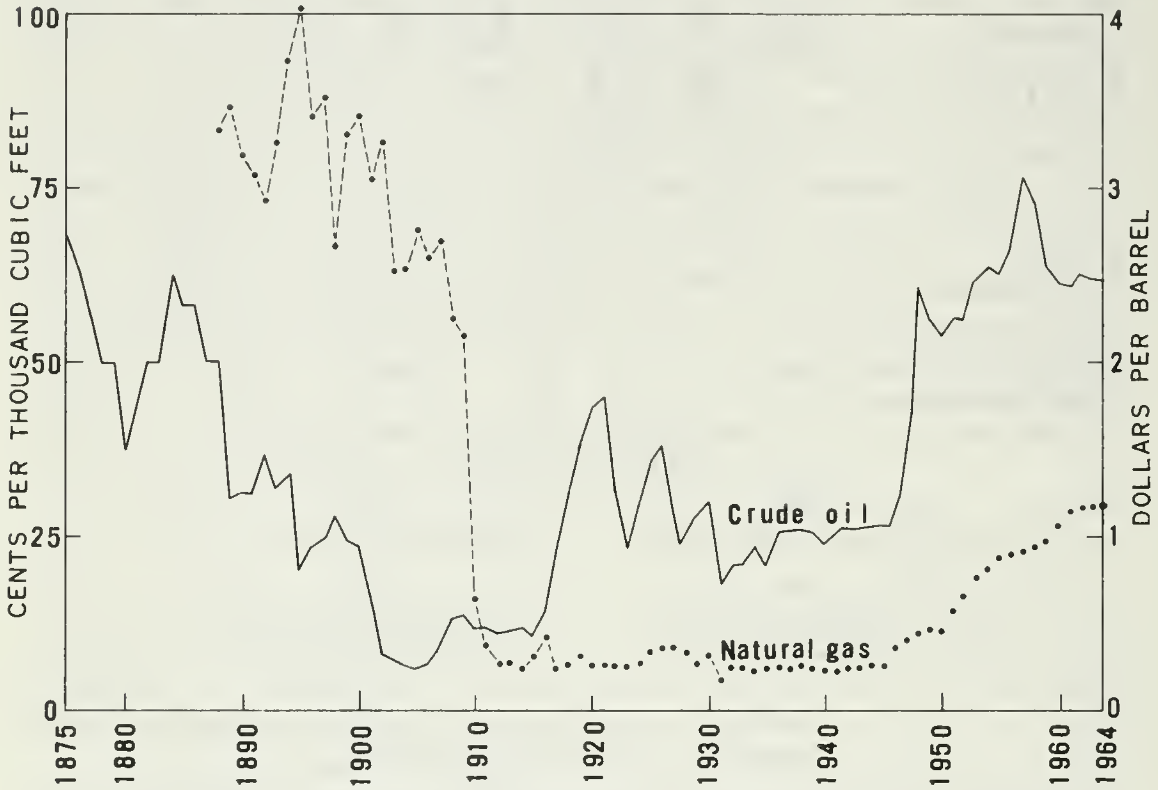

FIGURE 50. Average price of California crude oil and natural gas.

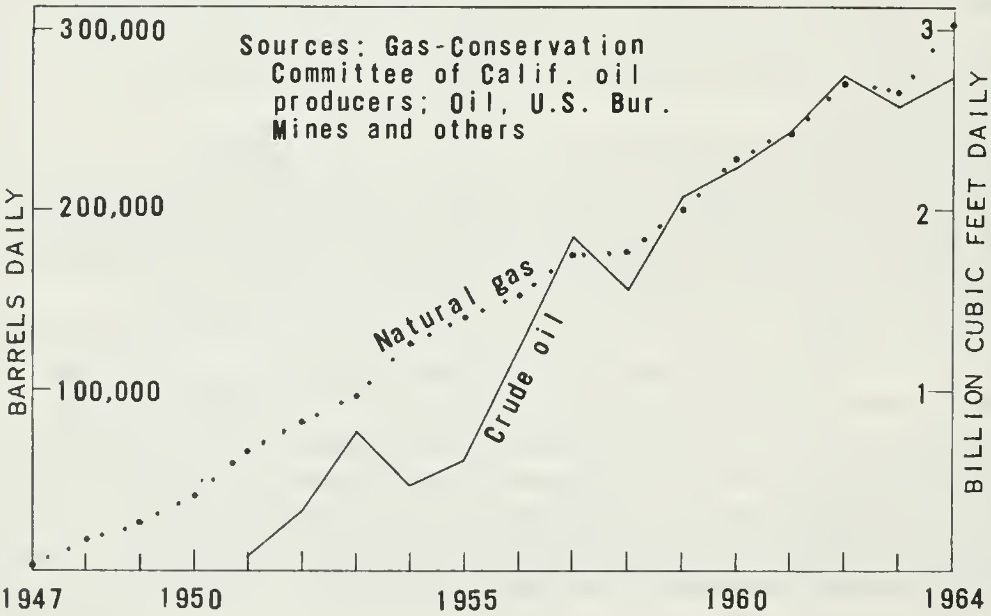

FIGURE 51. Imports of crude oil and natural gas into California.

Perhaps the most remarkable feature of the California oil-producing industry is the small size of the productive area that has produced, and still contains, so much oil (Hoots, 1943). About 13.25 billion barrels of oil has been produced prior to 1965 from approximately 330,000 acres of productive land, or ⅓ of 1 percent (1/333) of the area of the State. The average recovery of 40,000 barrels per acre to date, and the estimate that this will increase to more than 53,000 by production from the presently known fields, is extremely high in comparison to other large areas in the United States. Several fields in the Los Angeles and Ventura basins have produced more than 100,000 barrels per acre, and the Long Beach field has yielded about 500,000 barrels per acre. The yield of the average well in California during its productive life is expected to be 260,000 barrels, 3.5 times the average of wells in the rest of the United States. These large recoveries provide an incentive for exploration, and large rewards often result from a discovery.

Political considerations and Federal, State, and local laws and ordinances, also affect exploration. Restrictive provisions such as prohibitions against drilling within cities, or uncertain titles to offshore lands, at least delay exploration. Notable examples of the first were restrictions against drilling in Los Angeles and in Long Beach. After the restriction against drilling in Los Angeles was removed in 1950 exploration was intensified and several large fields have been discovered. The restriction against drilling at Long Beach, because of the fear of subsidence, was partially the cause of the delay in developing the huge East Wilmington field. An example of the second type is the more than 10-year delay in the leasing of a large part of the favorably regarded submerged lands offshore from southern California, because the Supreme Court did not decide the ownership of the mineral rights in these lands, whether State or Federal, until early 1956. Even though it was possible to explore these submerged lands by geophysical methods and, with certain restrictions, to drill wells for geologic information, it had not been possible to complete the exploration by testing wells to determine their productive capacity.

Urbanization and the consequent increase in land values has locally retarded exploration and was a factor in the abandonment of the largest parts of some fields, notably the Los Angeles and Salt Lake fields in the Los Angeles basin. Exploration by ordinary seismic methods in urban areas is made almost impossible by ordinances and fear of large claims for alleged damages. Exploratory wells must often be directionally drilled from drill sites which may be costly and sometimes difficult to obtain.

Prior to about 1910, most wells in California were drilled with cable tools, equipment not well adapted for drilling to depths greater than in the old shallow fields in the relatively unconsolidated rocks in the oil regions in the State. The introduction of rotary tools soon permitted deeper exploratory wells, and discoveries were made at greater depths.

The drilling of exploratory wells has been greatly aided since the 1920's by many improvements in the quality of equipment and in the technique of drilling. The principal improvements in technique are the ability to obtain cores of the rocks, to control the quality of the drilling fluid, and to evaluate the fluid-yielding capacity of the rocks without installing casing in the hole. Evaluation may be made by numerous devices which are lowered by cables, or by testers which permit the obtaining of samples of the fluids in the rocks and the approximate determination of the volume of production that may be expected. The ability to survey holes, which was pioneered by Alexander Anderson at Long Beach, and the ability to drill directionally to predetermined locations are of great assistance. Directional drilling has aided exploration because wells can be drilled beneath built-up areas, beneath closed areas, beneath mountainous land in which access roads would be very costly, and from land to favorable locations beneath the ocean. Hydraulic fracturing has been used to create permeability in the reservoir rocks, and in at least one local area has resulted in a discovery.

History of Discovery and Development

That California is a petroliferous region was indicated as early as 1542 when Cabrillo landed near Carpinteria in Santa Barbara County and found oil which had drifted from seeps beneath the ocean onto the beaches. In 1769, the Portola expedition found Indians using tar from the Rancho La Brea tar pits near Los Angeles. Portola used this tar as fuel for camp fires. Heizer (1943) mentions that explorers in 1775 reported that Indians used tarry material (chapapote) from springs near San Luis Obispo for caulking boats, and the Yokut Indians used oil from seepages in the San Joaquin Valley.

In the 1800's, many seepages of oil and of gas, and other near-surface indications such as gas in water wells or railroad tunnels, were found in the provinces on land which are now productive. Oil odors, oil slicks, and floating tar are evident on the water off the coast, and seeps off Redondo Beach and west of San Miguel Island are shown on maps by the U.S. Coast and Geodetic Survey. Many other evidences of these oil seeps have been observed on the water off southern California, tar and globules of oil have been observed in samples of the shelf sediments, and tar mounds on the ocean floor near Santa Barbara beneath 90 feet of water have been photographed by Vernon and Slater (1963).

Seepages are important because they indicate the presence of a source rock. Nearby all of the early fields within the oil provinces in the world have been found by drilling near seepages, but after the early stages most fields have been found following geological and geophysical studies. However, even in recent years many fields have been found by random drilling.

Discovery by prospecting near seepages, 1865–1907

Many of the early wells in search of oil in California were drilled near seepages in the central and northern parts of the State. The first oil produced in California amounted to a few barrels from shallow wells on the Mattole River in Humboldt County. It was shipped to San Francisco in 1865. Several small producing wells were drilled near Ojai in the Ventura basin, including one said to be capable of producing 15 to 20 barrels per day in 1866, but there was no market for the oil. The first truly commercial well in the

State (Pico 4) was completed by the California Star Oil Works Co. near Newhall in 1876. It produced 30 barrels per day from a depth of 300 feet, and later made 150 barrels per day after it was deepened to 600 feet. The first California pipeline was laid in 1879 to carry this oil to the first California refinery near Newhall.

Several fields were discovered in the latter 1800's, some of the present major oil companies were organized, and the first tankship was put into use. The first large well was completed in 1892 by the Union Oil Co. near Santa Paula, and the Los Angeles field was discovered in 1892 by E. L. Doheny. The Los Angeles field was the site of the first town-lot drilling in the State, and it soon became the State's largest producer. Thirty-two fields and some 2.5 billion barrels of oil were found in California during this period (Hoots, 1954).

Some spectacular gushers—spectacular because they flowed out of control—were drilled. The famous Lakeview No. 1 gusher in the Midway-Sunset field flowed out control for 1½ years in 1910–1911 from a depth of 2,225 feet. It produced as much as 68,000 barrels per day, and made a total of about 8.25 million barrels before sand entered the hole and choked off the flow. This is said to be the largest well in the United States. Large flows came from other wells, such as 12,000 barrels per day from a well in the Orcutt field near Santa Maria, and 10,000 to 20,000 barrels per day from early wells in the Midway-Sunset field. A well drilled in Midway-Sunset by the Lakeview Oil Co. is said to have flowed as much as 50,000 barrels per day. Other spectacular wells were those that blew out and caught fire. Many wells capable of large production have been completed in more recent years, but they are brought in under control and are produced at only a fraction of their potential.

Discovery primarily by the use of geology, 1908–35

Beginning about 1900, geologic mapping of rocks at the surface began to be used in a small way in the search for oil, but it was not until 1908 that this method resulted in the discovery of several fields (Hoots, 1954). Early studies of the geology by personnel of the California State Mining Bureau (now California Division of Mines and Geology), the U.S. Geological Survey, the universities, and by members of the oil industry greatly increased the knowledge of the geologic conditions favorable for accumulation, and thus aided exploration (fig. 52).

The use of surface geologic mapping, and the interpretation of surface topography, in order to find anticlinal folds and fault traps, was accompanied by a gradual increase in geological interpretation of information obtained during drilling—known as subsurface geology. These came to be accepted as exploration tools by the oil industry. Random wildcat drilling continued to supplement the search for oil, but it was usually conducted along production-trend lines, on some supposed favorable topographic expression, or because of a showing in a nearby well. Fifty-three fields and about 7.6 billion barrels of oil were found in California during this period 1908–1935 (Hoots, 1954). Improved drilling techniques were partially responsible for some of these discoveries, as wells could now be drilled to depths greater than early wells on the same structure—for example, in the Kettleman North Dome field. Many of the large fields in the productive basins

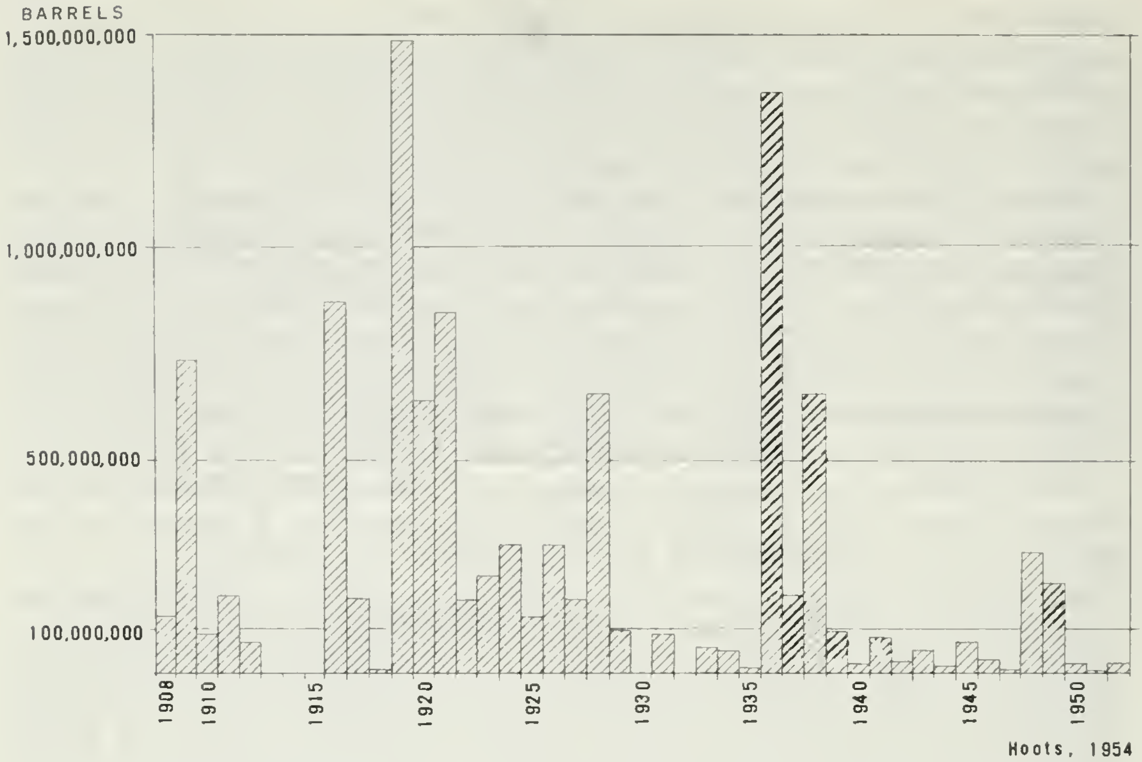

FIGURE 52. Oil discovery record for California by individual years.

were discovered during this period, including the large Long Beach, Santa Fe Springs, Huntington Beach, and Wilmington fields. The latter was discovered by a small edge well in 1932; at the time it was assumed to be only an extension of the Torrance field.

Discovery by the use of geology and reflection seismometry, 1936 to present

Since about 1936, exploration prior to drilling has been carried on mainly by the use of geology (surface and subsurface) and by the use of geophysical methods, principally the reflection seismograph. Geophysical methods which measure certain physical properties of rocks that are related to potential traps in reservoir rocks were first used in California in 1924. The methods used in the early stages did not result in the discoveries of new oil and gas fields, although they did contribute to the knowledge of the general geological structure of the oil-productive basins.

The reflection seismograph, however, has proved to be successful in finding traps favorable for the accumulation of oil and gas in California. It also supplies data that is useful for subsurface geologic studies. No method has been found except the drill that can locate commercial amounts of oil directly. A small gas field (Paloma) was discovered in 1934 in the San Joaquin basin a result of reflection seismograph surveys, and this was followed in 1936 by the significant discovery of the Ten Section oil field in the central part of the San Joaquin basin, also as a result of seismic maping. The latter discovery not only demonstrated that anticlinal folds concealed beneath the thick alluvial fill of the San Joaquin basin could be found by the reflection seismograph, but also that thick Miocene sands provide adequate reservoir rocks beneath the valley floor. The prolific main part of the Wilmington field was discovered in 1936 as a result of reflection seismograph surveys.

The importance of stratigraphic traps had been emphasized by the discovery of the huge East Texas field in 1930, and the applicability of this new phase of geologic exploration to California was apparent. The search for traps of this kind resulted in the discovery of the Santa Maria Valley field in the Santa Maria basin in 1934, in the finding of the prolific East Coalinga Eocene field in the San Joaquin basin in 1938, and later in the discovery of other fields in stratigraphic traps.

The first major discoveries in a previously nonproductive sedimentary basin since the days of prospecting near seepages were made in 1947–1949 when the San Ardo, Russell Ranch, and South Cuyama fields were found in the Salinas-Cuyama basin. Stratigraphic thinking played a large part in the discovery of these fields. Three small fields—Oil Creek, La Honda, and South La Honda—were discovered in the period 1953–1959 in the Santa Cruz (La Honda) basin, largely as the result of surface and subsurface geologic studies. Beginning in the late 1800's, several small doubtfully commercial wells had been drilled in this basin, but the discoveries in the 1950's first established commercial production.

About 3.2 billion barrels of oil was found in California in the period 1936–1952 (Hoots, 1954). The estimated amount of oil discovered annually from 1908 to 1952 and the methods of exploration which accounted for these discoveries is shown in figure 52 after Hoots (1954). This figure emphasizes the fact that the annual discovery rate has fluctuated widely, to a large extent due to the application of new methods or concepts of exploration. It is somewhat misleading, as all the oil in any one field is allocated to the year of first discovery of the field. This figure does, however, bring out the poor discovery record during the depression from 1929 to 1935 and the World War II period from 1940 to 1947. In recent years, the geological and geophysical methods employed in exploration have become so intermingled that it is futile to attempt to separate the methods that have led to many discoveries. However, most exploratory wells in California's highly explored onshore regions have been located by subsurface geological studies, assisted by some geophysical information where wells are sparse.

According to Hoots (1954), about 13.3 billion barrels of oil had been found in the State to the end of 1952. If this estimate is used, it appears that about 4.1 billion barrels was found during the period 1953–1964, as production to the end of 1964 plus proved reserves at that time totaled 17.4 billion barrels.

Figure 53 shows the total number of exploratory wells drilled annually in the State for oil and gas in the period 1942–1964. It also shows the percentage of these wells that were successful in finding oil or gas, and the percentage of success in terms of footage.

Development drilling—the drilling of proved locations within known fields—has been sporadic since the early days of the oil industry in California. This sporadic drilling is due mainly to: (1) the development of new fields following discovery, (2) the price and demand for the crude of the quality that can be expected, (3) lease requirements, and (4) the operator's desire to maintain or increase his production. An average of about 2,000 development wells were drilled annually during the 4-year period 1961–1964.

As in other oil-producing regions, a large part of the production comes from the "giant" fields—those fields which are expected to produce more than 100 million barrels. There are 40 of these fields in California (table 36). These fields produce nearly three-fourths of California's oil and contain more than 80 percent of the estimated proved reserves.

TABLE 36.—*Grant*[1] *oilfields in California*

[Reserves from Oil and Gas Journal, v. 63, no. 4, Jan. 25, 1965, p. 155; others from Conservation Committee of California Oil Producers]

Basin and field	Daily-average production in 1964	Number of wells producing in 1964	Production in 1964 (thousand barrels)	Accumulative production to Jan. 1, 1965 (thousand barrels)	Estimated remaining crude oil reserves as of Jan. 1, 1965 (thousand barrels)
Los Angeles sedimentary basin:					
Wilmington	96,337	2,583	35,259	1,013,488	586,422
Huntington Beach	43,977	1,712	16,095	730,628	150,284
Inglewood	19,669	601	7,199	247,966	53,552
Brea-Olinda	14,797	710	5,415	299,510	49,637
Long Beach	12,507	1,000	4,577	843,301	36,602
Coyote West	8,373	305	3,064	207,245	22,590
Domingquez	7,954	254	2,911	236,953	27,957
Seal Beach	6,953	254	2,545	171,659	28,190
Santa Fe Springs	5,529	470	2,023	587,995	26,929
Richfield	5,470	424	2,002	145,178	14,838
Torrance	5,001	636	1,830	164,714	25,232
Coyote East	4,223	269	1,545	87,693	12,386
Montebello	3,202	285	1,171	176,036	9,050
Ventura sedimentary basin:					
Ventura	31,533	1,125	11,540	693,997	120,956
South Mountain	10,568	472	3,867	106,705	48,180
Rincon	8,828	353	3,231	87,885	28,082
Elwood	630	27	231	101,723	8,098
San Joaquin sedimentary basin:					
Midway-Sunset	50,675	4,376	18,546	947,890	164,566
Coalinga East Extension	27,724	80	10,147	408,523	111,016
Kern River	26,813	3,592	9,813	393,479	56,091
Coalinga	23,256	2,342	8,512	549,952	63,309
Buena Vista	22,791	1,300	8,341	524,291	90,785
Belridge South	20,099	2,584	7,356	109,401	27,412
Cymric	9,499	689	3,476	91,417	25,152
Coles Levee North	8,848	178	3,238	124,270	35,715
Elk Hills	8,205	220	3,003	271,471	1,031,108
Lost Hills	7,511	1,025	2,749	94,027	10,546
Greeley	7,432	43	2,720	94,344	20,570
Kettleman North Dome	6,765	268	2,476	440,395	34,624
Kern Front	6,227	774	2,279	105,937	16,082
Edison	6,176	552	2,260	96,634	23,317
Mount Poso	6,136	597	2,245	149,464	26,932
Fruitvale	5,702	418	2,087	88,449	86,362
Rio Bravo	4,612	65	1,687	105,100	29,992
McKittrick	4,553	350	1,666	112,566	13,260
Santa Maria sedimentary basin:					
Cat Canyon West	7,356	274	2,692	108,167	31,764
Orcutt	4,394	208	1,608	127,118	7,918
Santa Maria Valley	4,312	276	1,578	138,982	21,008
Salinas-Cuyama sedimentary basin:					
San Ardo	27,379	874	10,020	144,989	97,205
Cuyama South	19,513	203	7,141	175,628	108,332
Total, 40 fields	601,529	32,768	220,145	11,305,170	3,382,051

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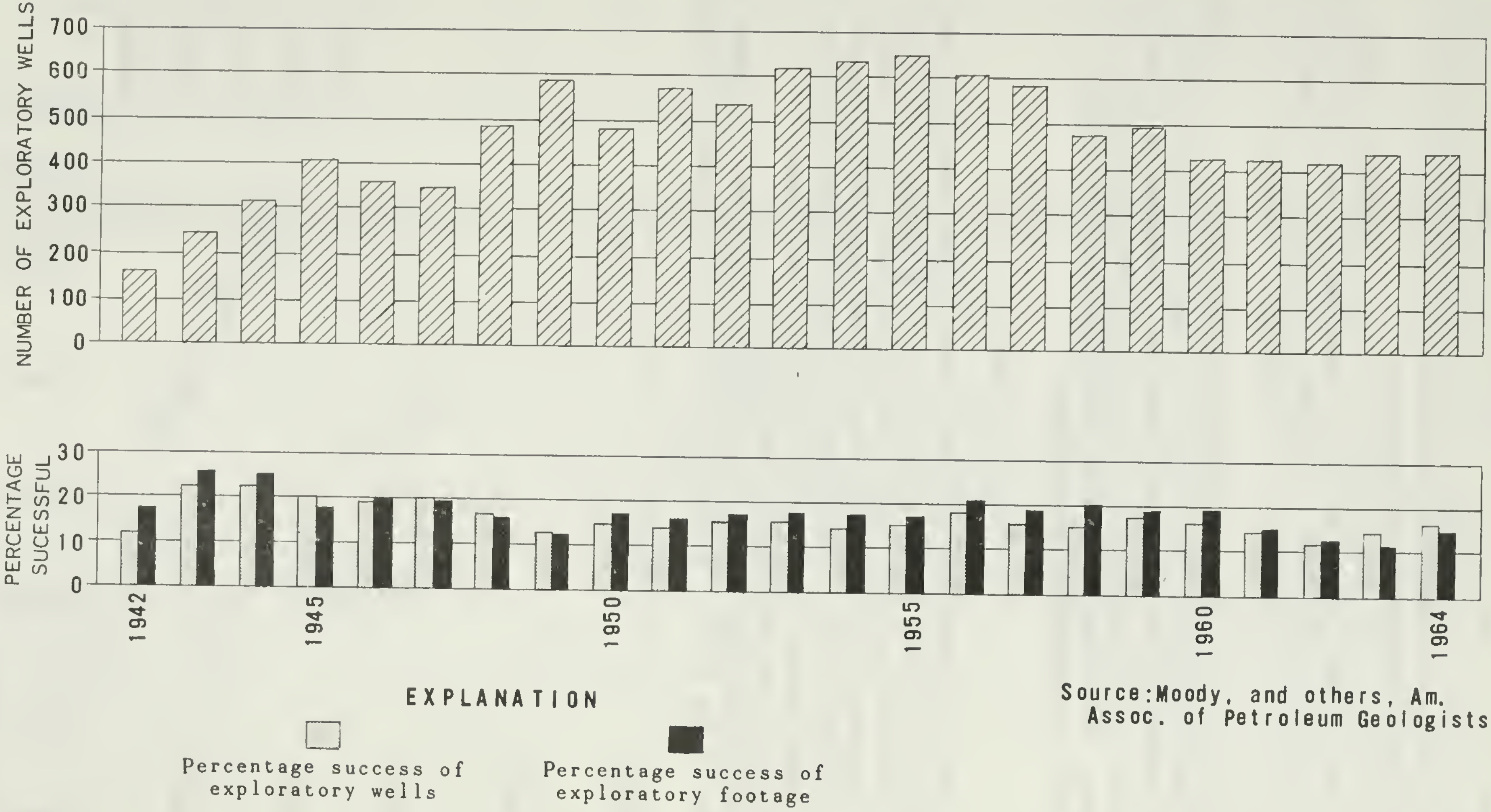
[1] One hundred million barrels or more of recoverable oil.



Source: Moody, and others, Am. Assoc. of Petroleum Geologists

FIGURE 53. Exploratory wells for oil and gas in California.

In 1964, 42,000 producing oil wells in the State yielded 817,395 barrels per day, or an average of 20 barrels per well daily (fig. 54). However, production increased toward the end of the year and reached 830 thousand barrels per day in December.

In recent years, most large flowing wells are allowed to produce at only a part of their potential daily production in order to conserve reservoir energy, to increase the efficiency of production, and to increase the amount of oil that can ultimately be recovered from the reservoir.

Unitization or some form of cooperative agreement is very desirable for efficient production, for conservation, and for maximum ultimate recovery, especially in California with its diversified land interests. Unitization or such agreements are necessary for secondary recovery operations. More than 65 units or agreements are now in effect in the State, and several more are being formed.

NATURAL GAS

Gas, like oil, is believed to originate from organic material deposited principally in marine sediments, but why only gas is found in some large regions such as large parts of the Sacramento Valley is unknown. It seems probable that only gas was originally generated in such regions (Hedberg, 1964). It has been suggested that gas rather than oil may originate due to differences in the organic source material or in the depositional or post-depositional environment.

Gas produced with water from shallow wells was furnished to Stockton in the 1850's. Later, in the early 1900's, many California

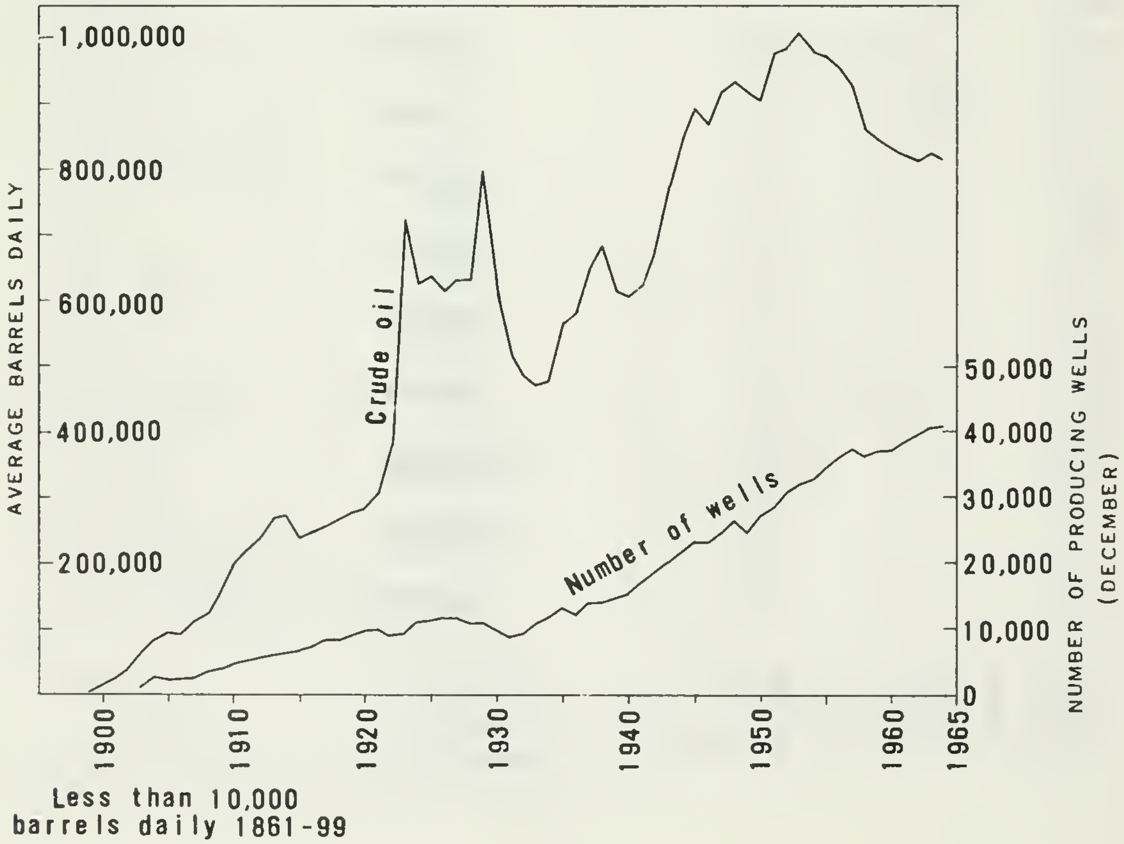


FIGURE 54. California crude oil production.

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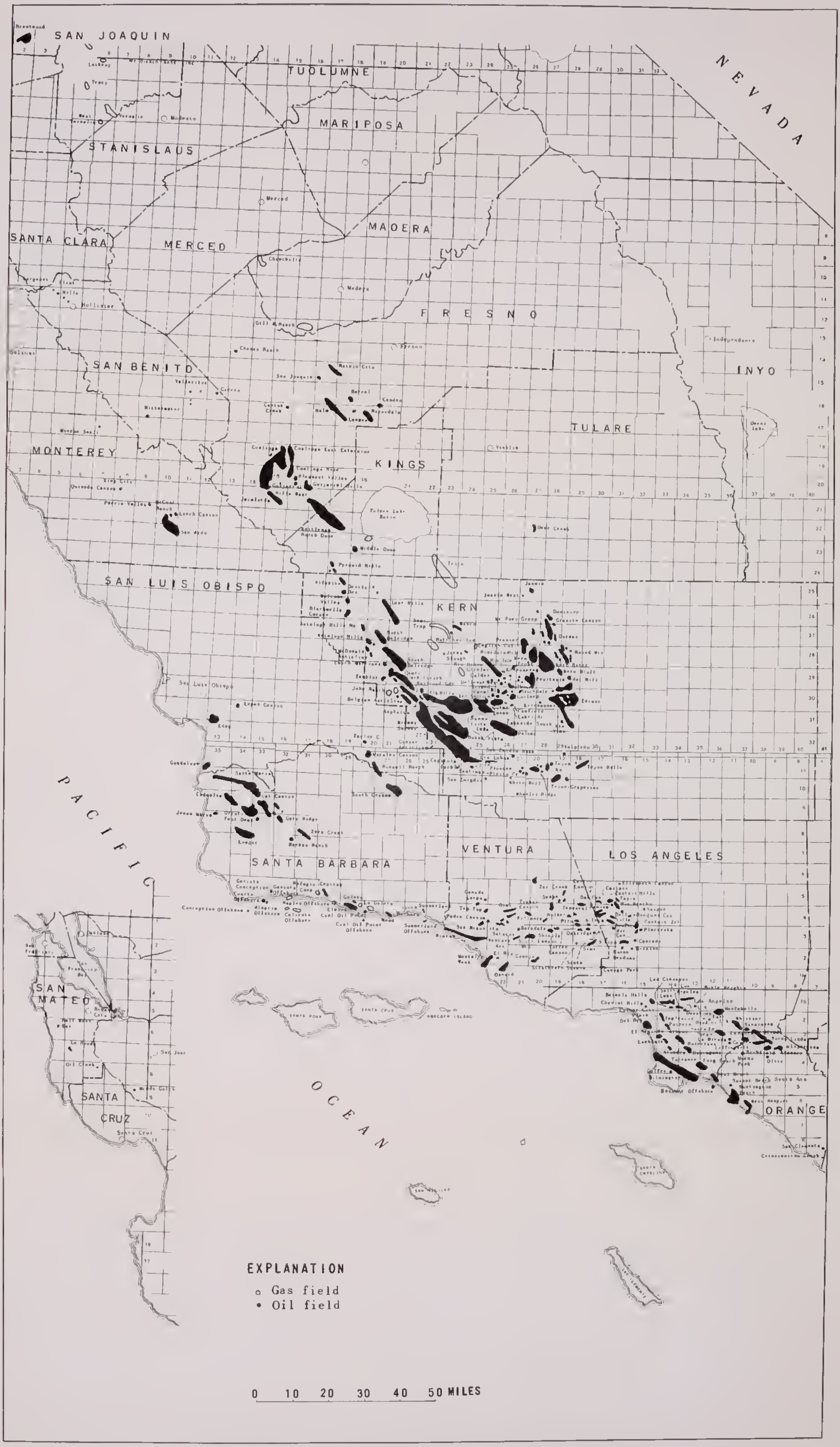

Figure 55. Southern and central California oil and gas fields.

cities were supplied from gas zones in oil fields. Considerable gas has been produced from these dry gas zones in oil fields since 1909 when a gas zone was discovered in the Buena Vista field (fig. 55) in the San Joaquin basin. A prolific gas zone was discovered in the nearby Elk Hills field in 1919 and it is said that one well in that field produced more gas than any other single well in the country prior to 1940.

The first dry gas field of importance was discovered at Buttonwillow (fig. 55) in the San Joaquin basin in 1927, but this discovery was soon overshadowed by the completion of wells producing large amounts of wet gas from the gas cap at the Kettleman North Dome field. In 1933, the first high-pressure gas well in the Sacramento basin (fig. 48) was completed adjoining Sutter (Marysville) Buttes. A few additional rather small dry gas fields were found prior to 1936, but the first two large dry gas fields, McDonald Island and Rio Vista (fig. 56), were discovered in the Sacramento basin in that year. The latter has produced 2.25 trillion cubic feet of gas, more than one-half of the State's dry gas production. It is by far California's largest gas field.

Many dry gas fields have been found in the Sacramento basin (figs. 48, 56) since 1936. Exploration there increased in the late thirties, was interrupted by World War II, and has been aggressively pursued since then, encouraged by the increasing price for gas (fig. 50), which is now about $0.30 per thousand cubic feet at the well. Four dry gas fields (fig. 55) have been found offshore in the Ventura basin in recent years. Another new offshore oil field in that basin yields dry gas from one sand.

Large amounts of wet gas accompanying the production of oil were wasted in the early 1900's, especially from the town-lot fields of Huntington Beach, Long Beach, and Santa Fe Springs (fig. 55) in the Los Angeles basin. Also, large amounts of wet gas were wasted from the Ventura and Kettleman North Dome fields. Wells in those fields flowed at large rates, and the amount of gas produced along with the oil was far in excess of available outlets. At that time the price of gas was low, and the present State laws which prohibit the unreasonable waste of gas were not passed until 1929. Beginning in the 1930's, the amount wasted decreased to 5 to 10 percent. The wastage now is less than 1 percent of the wet gas and practically none of the dry gas.

Since 1947, when gas was first imported into California, the demand has exceeded the amount produced in the State. Increasing amounts have been brought in from Texas and New Mexico, and later from Canada (fig. 51), so that now 64 percent of the gas consumed here comes from outside the State.

Gas production and the number of gas wells have increased rapidly in recent years (fig. 57), and 896 billion cubic feet was produced in California in 1964. About two-thirds was wet gas accompanying oil. However, more than one-third of the gas from oil wells was returned to the sands to increase the recovery of oil, so that the net withdrawal of wet gas in 1964 was 384 billion cubic feet. Per barrel of oil, wet gas production was 2,020 cubic feet gross and 1,280 cubic feet net. Dry gas production in 1964 was 291 billion cubic feet from 898 producing wells. The average heating value of this dry gas is approximately 1,000 Btu per cubic foot.

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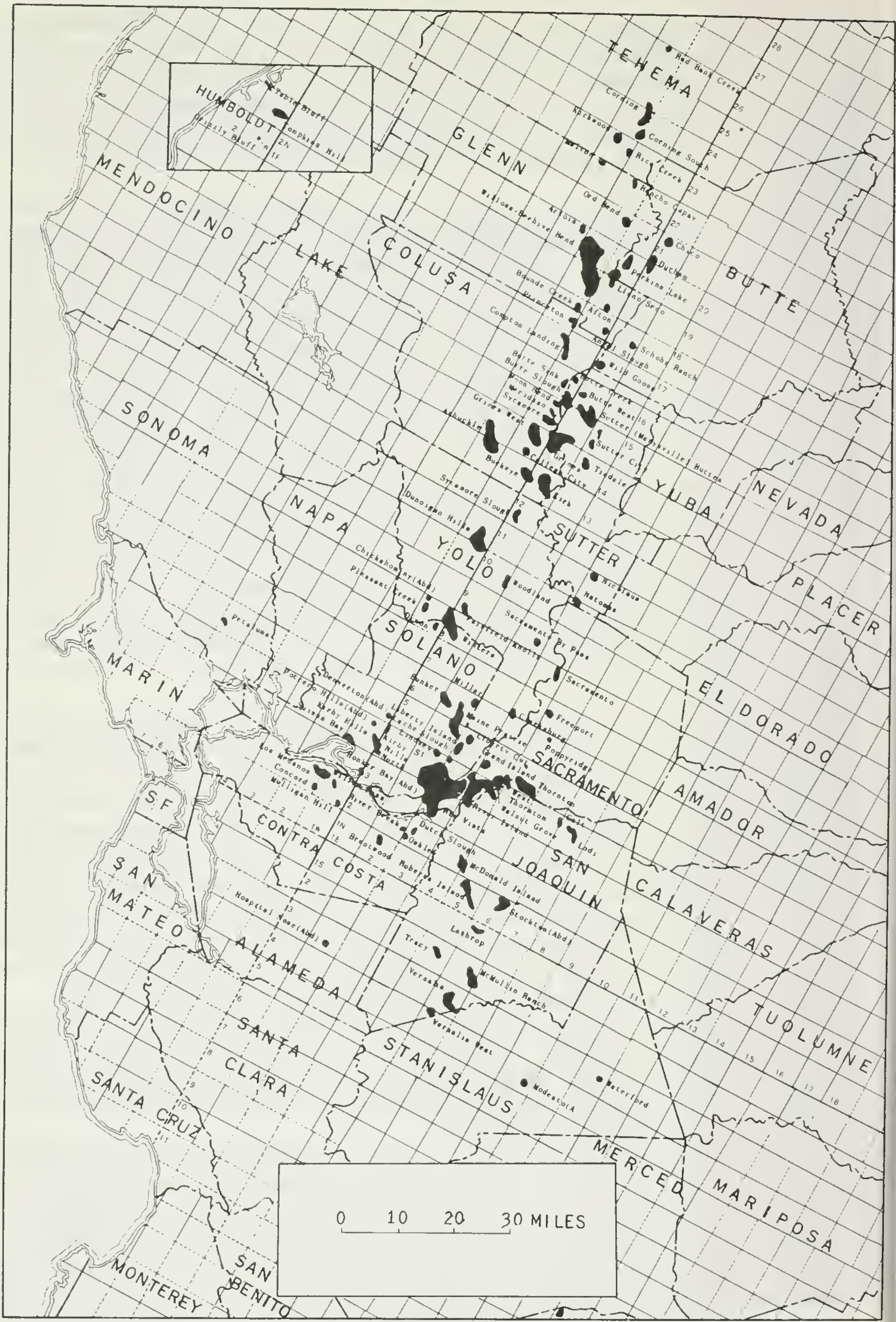

FIGURE 56. Northern California dry gas fields.

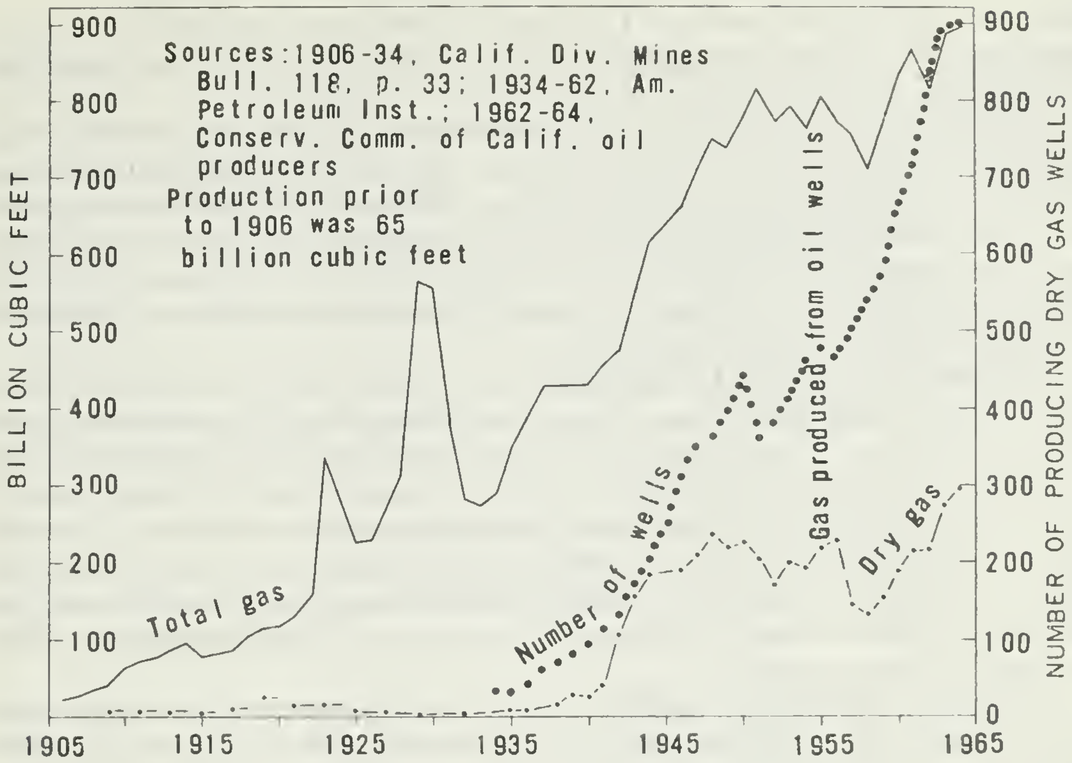

FIGURE 57. California gas production.

The oil fields in the San Joaquin and Los Angeles basins are the largest producers of wet gas, with lesser amounts from the Ventura, Salinas-Cuyama, and Santa Maria basins. About 80 percent of the dry gas produced in 1964 came from fields in northern California (fig. 56), and nearly all these fields are in the Sacramento basin. Lesser amounts were produced in the offshore part of the Ventura basin (13 percent), the San Joaquin basin (6 percent), the Eel basin (1 percent), and a few other minor areas.

OIL AND GAS PROVINCES IN CALIFORNIA

There are eight principal productive sedimentary basins (figs. 47, 48) in the State which derive their names from the valleys or districts in which they occur. The major oil-producing basins and their percentage of California's 1964 production are the San Joaquin (41), Los Angeles (34), Ventura (15), Salinas-Cuyama (6.3), and Santa Maria (3.4). The major dry-gas producing basin is the Sacramento which yields about 80 percent of the State's production. The Sacramento, Santa Cruz, and a few other small basins yield less than 1 percent of the State's oil, and the Eel River basin yields less than 1 percent of the dry gas. These eight basins, the outlines of which are slightly modified from those shown by Vlissides and Quirin (1964), have an area of about 31,000 square miles, about 19 percent of the area of the State.

Los Angeles sedimentary basin

The Los Angeles sedimentary basin (figs. 47, 48) extends along the coast about 70 miles and inland as much as 40 miles. It has an area of about 1,450 square miles. This basin is the principal part of a more extensive structural depression which extends westward an uncertain distance beneath the ocean.

The most distinctive geologic characteristics of the basin is the large concealed structural relief and the structural and stratigraphic complexity (Yerkes and others, 1965). Three principal west-northwestward-trending structural blocks are separated by the steep Newport-Inglewood and Whittier fault zones. The former probably separates genetically distinct groups of basement rocks on which the sedimentary rocks were deposited.

Deformation, chiefly that beginning in Miocene time and culminating in mid-Pleistocene time, formed anticlines and faults in the sedimentary rocks. These generally trend northwestward except in the northern part of the area where the structural trend is more nearly west. Deformation has continued to modern times as shown by earthquakes, warping of Recent rocks, and subsidence in some areas and uplift in others. A nearly unique combination of geologic factors and timing of events seems to account for the prolific oil production from the basin (Barbat, 1958).

At least 31,000 feet of sedimentary rocks are present above the basement floor in the deepest part of the central synclinal trough, about 10 miles southeast of the center of Los Angeles (McCulloh, 1960). Edwards (1951) estimated that the volume of sedimentary rocks in the basin is about 2,250 cubic miles, and Barbat (1958) estimated that the volume of basinal sedimentary rocks within the drainage area of the oil fields is some 1,600 cubic miles. Even if the former volume is used because it seems to be more comparable to estimates of the volume in other basins, the recovery per cubic mile of sedimentary rocks already slightly exceeds the phenomenal amount of 2.33 million barrels.

Most of the known fields are structural accumulations on anticlines or in fault traps, although some production of minor importance is obtained from stratigraphic traps. The more important fields occur along seven general productive trends which follow structural trends. The most publicly noticed fields are those that lie on anticlinal structures along the Newport-Inglewood fault zone—Huntington Beach, Seal Beach, Long Beach, Domiquez, Inglewood, and Cheviot Hills.

Most of the oil has been obtained from sands and conglomerates. More than one-half has come from the Repetto (?) Formation of early Pliocene age, and slightly less than one-half from rocks of late Miocene age (fig. 49). Relatively minor amounts are obtained from rocks of late Pliocene, middle Miocene, and pre-middle Miocene ages.

Surface evidence—seepages, geology, and topography—supplemented by subsurface studies led to the discovery of most of the fields in the basin prior to 1936. In that year, the prolific production in the Wilmington field was discovered as a result of seismic work. Since 1953, advanced geological exploration techniques, core-hole drilling, and sparse seismic work have resulted in the discovery of seven new fields and several new pools in known fields.

The Los Angeles sedimentary basin has been intensively explored. If the deep central part of the basin, where very few deep wells have been drilled is excluded, the density of exploratory wells is over 11 per square mile.

Some 56 fields (fig. 55) in the basin have produced 5.33 billion barrels of oil to January 1, 1965 from 47,500 acres, or a recovery of about 112,000 barrels per acre. Long Beach, an outstanding field, has produced 843 million barrels from only 1,695 acres, or a recovery of 500,000 barrels per acre. Several developments in recent years have greatly increased the production and reserves in the basin:

1. The removal of restrictions which prohibited drilling within the cities of Los Angeles and Long Beach has resulted in intensified exploration and in the discovery of several new fields and new pools in known fields in Los Angeles, and in the leasing of the huge East Wilmington field at Long Beach. New fields and new pools in Los Angeles were producing more than 20,000 barrels of oil and 70 million cubic feet of gas daily in early 1965, and it is estimated that some 100 to 150 million barrels of oil has been found since 1953. Also, it is estimated that production from the largely offshore East Wilmington field will be from 150 to 200 thousand barrels daily by 1968, and that the field will eventually yield 1.2 to 1.5 billion barrels.

2. Water is being injected into the oil reservoirs in several fields, especially in the Wilmington field where about 565,000 barrels of water is injected daily. The injection in the Wilmington field has nearly stopped subsidence of the land surface which had reached a maximum of about 27 feet, and is believed to have increased the daily oil production approximately 53,000 barrels. The field now produces about 95,000 barrels per day, and it has been estimated that it would have declined to 42,000 barrels per day without water injection. The estimate of recoverable oil from the field has been increased about 400 million barrels, of which some 218 million barrels is expected to come from the tidelands area of the field.

Striking features of the production in this basin are: (a) prolific production from the relatively small sedimentary basin, and the small areal extent of some of the prolific fields; (b) the thick oil zones—a zone includes several sands separated by thin beds of shale; (c) the fact that the vertical thickness (oil columns) of the oil zones often greatly exceeds the "closure" of the anticline—Long Beach, for example, has 2,200 feet of oil sand in six oil zones with a total thickness of 5,200 feet, although the estimated "closure" is only 1,600 feet; (d) subsidence of the surface along the ocean front in the Wilmington field; (e) subsurface damage to several hundred wells at Wilmington as the result of earth movements notably from 1947–1951. The movement in 1951 occurred at the time of an earthquake with an intensity of V on the Modified Mercalli Intensity scale; (f) oil wells in citrus and avocado groves and in business and high-class residential districts, often requiring development by directional drilling from soundproofed derricks, and production from landscaped "islands"; (g) the close spacing of wells in areas of town-lot drilling; (h) the rows of pumping units a few feet apart along the ocean front, notably at Huntington Beach. Wells drilled from these surface locations were directionally drilled to properly spaced locations beneath the ocean; (i) the drilling and production platforms and islands a few miles offshore and the large refineries close to the oil fields and the ocean.

Ventura sedimentary basin

The Ventura sedimentary basin (figs. 47, 48) is an elongated eastward-trending basin at least 130 miles long and 20 to 40 miles wide with an area of about 3,600 square miles. About 1,500 square miles of the eastern part of the basin, including the Soledad subbasin at the east end and a strip along the northwestern part of the basin, is on land; the rest of the western part is submerged beneath as much as 2,000 feet of water.

Structurally, the basin is a regional syncline on which numerous eastward-trending folds have been superimposed, and which is broken by numerous large thrusts and reverse faults. Some faults dip southward, others northward. The central part of the basin has been subjected to north-south compression with the result that most of the structural features trend westward in contrast to the northwestward structural trend in most of the other oil regions of the State. Many of the principal valleys reflect their synclinal structure, and many of the hills or mountains reflects their anticlinal structure.

Sedimentary rocks about 58,000 feet thick were deposited in the basin and rest on a granitic and schist basement. Included in the sedimentary rocks are 13,000 to 15,000 feet of marine Pliocene rocks in the vicinity of Ventura, perhaps the greatest thickness of these rocks in the world. Rand (1951) estimated that some 17,000 cubic miles of sedimentary and volcanic rocks are present in the basin. If it be assumed that about 40 percent of this volume is on the land part of the basin from which production to January 1, 1965 has been about 1.4 billion barrels, then about 206,000 barrels have been produced per cubic mile of sedimentary rocks in that part of the basin.

Production is obtained from rocks of several different ages (fig. 49), but most of the oil comes from Pliocene and Miocene marine sands and from nonmarine sands of Oligocene age. Lesser amounts are produced from Cretaceous, Paleocene, Eocene, and Pleistocene sands, and from fractured rocks of Miocene age.

Most of the 78 fields in the basin (fig. 55) are structural accumulations on faulted anticlines, but accumulations in fault or stratigraphic traps are common. In recent years, prospecting along thrusts and reverse faults has resulted in the discovery of several concealed anticlinal and fault accumulations beneath these faults.

The outstanding field in the basin is the Ventura field, which has produced 694 million barrels to January 1, 1965. It is 7 miles long and about 1 mile wide, and is on the structurally highest part of the 16-mile-long, severely faulted, Ventura anticline. The recovery from the 3,470 productive acres has been about 200,000 barrels per acre. Gas from shallow wells in the field was supplied to Ventura as early as 1903.

Striking features of the production in this basin are: (a) thick Pliocene reservoirs in the Ventura field where there is a maximum of about 7,500 feet of oil-bearing Pliocene strata, excluding repetition by faulting; (b) the location of several fields in the rugged mountainous regions overlooking the Santa Clara River valley; (c) accumulation of oil in the colorful nonmarine red beds of the Sespe Formation of late Eocene to early Miocene age; (d) higher-than-normal pressures in the Ventura field, especially in the deeper zones where pressures at a depth of 9,200 feet were 8,300 pounds per square inch, or about double that due to a column of water extending to the surface; and (e) the development of moderate production in one field in the basin by the unusual methods, for California, of drilling with air and artificial fracturing of the reservoir rocks in order to increase the permeability.

San Joaquin sedimentary basin

Two large productive sedimentary basins—the San Joaquin and the Sacramento—occur in the Great Valley (figs. 47, 48) and include the valleys of those names and parts of the adjoining foothills. The Stockton arch separates these two basins about 60 miles east of San Francisco, and structurally unites the Diablo uplift on the west with the Sierra Nevada block on the east. On this broad arch, Cretaceous rocks are only about 3,500 feet beneath the surface.

The San Joaquin sedimentary basin (figs. 47, 48) trends northwestward for 250 miles with a width of 50 to 60 miles. It has an area of about 11,350 square miles. The maximum thickness of the sedimentary rocks in the basin exceeds 30,000 feet, and the volume of those rocks has been estimated at about 31,000 cubic miles (Kilkenny, 1951). As the 105 fields (fig. 55) in the basin have produced 5.5 billion barrels to January 1, 1965, the production has been about 180,000 barrels per cubic mile of sedimentary rocks, but that amount would be much larger, perhaps doubled, if only the volume of the rocks in the oil-productive southern part of the basin were used.

Structurally, the basin is an asymmetric syncline, the axis of which lies near the west side of the San Joaquin Valley. According to Repenning (1960), the structural basin was formed by the westward tilting of the Sierra block against the eastern flank of the Coast Ranges. The basin floor slopes gently westward to its deepest part. East of the syncline, tension faults and gentle folds predominate; west of the syncline closer to the San Andreas fault, the strata are more steeply tilted and are broken by faults many of which are reverse faults resulting from compression.

The Bakersfield arch trends southwestward across the valley near the city of that name, and separates the San Joaquin basin into subbasins. North of the arch the structural trend is northwestward; to the south the trend is more nearly westward. Near the southern border of the basin, southward-dipping faults along which the upper block has moved northward and asymmetric folds such as Wheeler Ridge, in which the north flank dips more steeply than the south flank, suggest stresses from the south.

Prominent anticlines in the Diablo and Temblor Ranges west of the San Joaquin Valley trend southeastward into the valley, and many are marked by prominent topographic features such as Kettleman Hills and Elk Hills on which large oil fields have been developed.

The oil fields are concentrated in the southern part of the basin which contains a large thickness of organic shales of Tertiary age. These shales contain abundant remains of very small (microscopic) plants and animals. Several gas fields, and gas sands in oil fields, occur in the southern part of the basin, but only gas fields have been found between Fresno and Stockton.

Oil has accumulated in many varieties of traps, but much is in stratigraphic traps associated with some element of structure. However, there are many structural accumulations on anticlines, and fault traps are more important than in other California basins, especially along the east side of the valley.

Commercial accumulations occur in both marine and nonmarine rocks and are widely distributed through 10 to 15 thousand feet of strata ranging in age from Cretaceous to Pleistocene (fig. 49). Some production on the east side of the valley is obtained from pre-Cretaceous schist where it is overlain by oil-bearing sediments. About 90 percent of the production has come from rocks of Miocene and later age (Simonson, 1958) including a large amount from nonmarine rocks.

The Miocene, Pliocene, and Pleistocene rocks thin from south to north and become largely nonmarine in the north and east parts of the basin. The greatest thickness of sedimentary rocks is near the southern end where they are more than 6 miles thick. Cretaceous rocks, on the other hand, thin southward from the Stockton arch and are absent in the southern end of the valley.

Striking features of the production in this basin are: (a) the great concentration of oil fields in the southern part of the valley; (b) the low API gravity of much of the oil near the margins of the basin; (c) the long-continued drilling of new wells in old fields; (d) the continual discoveries of new fields and extensions of old fields in the highly explored Bakersfield-Taft-Coalinga area in the southern part of the valley; (e) the large number of steam-injection secondary recovery operations; and (f) the presence of Naval Petroleum Reserves No. 1 (Elk Hills) and No. 2 (Buena Vista Hills). The former is maintained as a billion-barrel reserve by the Navy, and only a relatively small amount of oil is produced for protection of the reservoirs; the latter is not maintained as a reserve, but is actively produced.

Sacramento sedimentary basin

The Sacramento sedimentary basin (figs. 47, 48) extends north-northwestward from the Stockton arch for 200 miles and is about 50 miles wide, except at the southern end where it widens to 70 miles. It also may be divided into sub-basins. Rocks ranging in age from Late Jurassic to Pleistocene are present in this basin, but the Miocene and Pliocene rocks which yield prolific production in the southern part of the Great Valley are thin and nonmarine, and yield only minor amounts of gas.

Sedimentary rocks cover an area of 11,350 square miles (Hobson, 1951), but in this report the area of the basin is considered to be 9,200 square miles. The sedimentary rocks probably have a maximum thickness beneath the valley of more than 35,000 feet, and the volume of Lower Cretaceous to Pliocene sedimentary rocks was estimated to be 44,000 cubic miles by Hobson (1951). The fields (fig. 56) in the basin have produced about 3.5 trillion cubic feet of gas to January 1, 1965, or some 80 million cubic feet of gas per cubic mile of sedimentary rocks.

Nearly all the production from the basin has been dry gas, although some condensate is produced from a few fields. Recently, moderate oil production has been found in sands of Paleocene and Late Cretaceous ages in one field and a small amount of oil has been produced from a sand of Late Createaceous age in another field. Gas is obtained mostly from sands of Eocene, Paleocene, and Late Cretaceous ages, but some comes from younger Tertiary rocks (fig. 49).

Structurally, the basin is an asymmetric syncline the axis of which is near the west side of the valley. The basement floor slopes gently westward from the Sierra Nevada into the deepest parts of the basin. Steeply dipping Jurassic and Cretaceous sedimentary rocks along the west border are separated from older basement rocks farther west by faulting.

Sutter (Marysville) Buttes, a unique feature in the sedimentary basins of California, rises 2,000 feet above the lowlands in the central part of the valley, and is an eroded volcanic plug. Magma rising to the surface arched and tilted the adjoining Createaceous and Eocene rocks. The first commercial gas discovery in the basin was made in 1933 close to the igneous plug, and there are now many gas fields north, south, and west of the Buttes. A second unique feature in the basin is the presence in the subsurface of sediment-filled channels or gorges of pre-existing streams. Gas is found in stratigraphic traps in these gorges.

Striking features of the production in the Sacramento basin are: (a) gas, rather than oil, production, perhaps because the source material, or the environment in which the rocks were deposited, differed from those in the oil-productive basins; (b) the large amount of gas produced from Cretaceous sands in contrast to the small amount of oil from rocks of that age in other California basins; (c) the much greater distance between wells than in the oil-productive areas because gas travels farther and more freely through the reservoir sands; (d) the accumulations near the igneous plug of Sutter Buttes; and (e) the abnormally high reservoir pressures in many Cretaceous sands.

Although many seeps of high API gravity oil on the west side of the Sacramento Valley have long been known and some wells drilled near these seeps yielded a few barrels of oil, it was not until 1960 that a possible commercial amount of crude oil was found in one gas well. Early in 1963, the second and most important discovery of oil in the basin was made unexpectedly during the development of the Brentwood field where only gas had been found previously. Oil production from these two fields to January 1, 1965, has been 1.6 million barrels, nearly all from the Brentwood field.

Santa Maria sedimentary basin

The Santa Maria sedimentary basin (figs. 47, 48) which includes several sub-basins extends about 40 miles along the coast, as much as 25 miles inland, and an uncertain distance offshore. The area of the onshore part is slightly less than 1,000 square miles. The maximum thickness of Tertiary and Pleistocene rocks in the basin is believed to be about 16,000 feet, and the onshore part of the basin possibly contains some 1,100 cubic miles of unaltered sedimentary rocks above the Jurassic basement (Hobson and Lupton, 1951).

Production of oil from the basin to January 1, 1965, has been approximately 500 million barrels, or a recovery of about 450,000 barrels per cubic mile of sedimentary rocks.

The major structural features have a general west-northwestward trend, and the last period of deformation was so geologically recent that the topography generally reflects the structure of the rocks—the major valleys are synclinal, and the hills are anticlinal. The Santa Maria Valley is an asymetric syncline, the axis of which is close to, or beneath, the anticlinal folds of the Casmalia and Solomon Hills which border the valley on the south.

Production is obtained from the hard, brittle fractured cherts and shales in the Miocene Monterey Shale, from fractured sandstones of Miocene age, from fractured sandstones of the Jurassic Knoxville Formation, and from several sands of Miocene and Pliocene ages. Also, a few barrels of oil are produced from a sand that may be of Oligocene age. In contrast to the production from sands and conglomerates in other regions in California, Regan and Hughes (1949) estimated that 77 percent of the production from the basin prior to 1947 had come from fractured rocks, nearly all of Miocene age, and that only 23 percent had come from sands. The percentage from sands has probably increased since that time.

Most of the 16 fields (fig. 55) in the basin are structural accumulations on anticlines, but some are stratigraphic accumulations, for instance, the Santa Maria Valley field. This field, which was discovered in 1934, was the first major stratigraphic trap accumulation discovered in California after the search for that type of trap began in the State. Oil accumulated in the Monterey Shale, which overlaps the basement rocks and is truncated updip by younger rocks. The latter, in turn, rest on the basement farther north. "Closure" of 3,000 feet at the top of the Miocene sequence distinguishes this field from any other in California.

Striking features of the production in this basin are: (a) the generally low API gravity of the oil; (b) the location of several fields on high hills overlooking the Santa Maria Valley; (c) the loss of drilling fluid while penetrating the fractured reservoir rocks often being an indication of high permeability and, usually, of large initial production; and (d) the first large California gusher in the Orcutt field in 1904 flowed 12,000 barrels per day for several months, and produced some 3 million barrels of oil during its flowing life.

Salinas-Cuyama sedimentary basin

The Salinas-Cuyama sedimentary basin (figs. 47, 48) is an elongated northwestward-trending basin between the much-publicized San Andreas fault zone on the northeast and the Nacimiento fault zone on the southwest. This basin is approximately 160 miles long and as much as 28 miles wide, and includes the Cuyama and Salinas Valleys and some of the intervening mountainous areas. The area of the basin is about 3,100 square miles, and it contains approximately 3,500 cubic miles of Miocene and younger rocks (Schwade and others, 1958). The Tertiary rocks, or older sedimentary rocks which underlie those rocks in places, rest on a granitic basement in a large region called Salinia (by Reed (1933). The maximum thickness of sedimentary rocks in the basin probably exceeds 15,000 feet, but the depth to the granitic basement is much shallower in large parts of the basin. The 14 fields in the basin have produced approximately 380 million barrels of oil to January 1, 1965, or about 110,000 barrels per cubic mile of sedimentary rocks of Miocene or younger age.

The three large fields (fig. 55)—San Ardo, South Cuyama, and Russell Ranch—in the basin greatly overshadow the several minor fields. The first field is on a broad, flat anticline overlying a basement high; the latter two fields are accumulations on faulted anticlines. Nearly all of the oil is in sand reservoirs.

Striking features are: (a) the many dry holes that were drilled prior to the discoveries in the late 1940's; (b) the more than 350 exploratory tests drilled since the three major discoveries, finding only a few relatively small fields; (c) the many closed structures that are barren probably because they were formed in late geologic time after migration of the oil; (d) the very large accumulation of low API gravity oil in the San Ardo field—the only major field in the Salinas Valley part of the basin; and (e) the tilted water table underlying the oil in the San Ardo field.

Santa Cruz and Eel River sedimentary basins

The Santa Cruz sedimentary basin (figs. 47, 48), which is along the coast about 25 miles south of San Francisco, has an onshore area of about 260 square miles. Small oil production is obtained at present from two fields in the basin from rocks of Eocene and Miocene ages (fig. 49). An old field which is not now producing yielded a few thousand barrels of oil from Pliocene rocks.

The Eel River sedimentary basin (figs. 47, 48), which borders the coast in the northwestern part of California, has an onshore area of about 575 square miles. Two dry gas fields which yield gas from Pliocene rocks (fig. 49) have been found in the basin. Eleven producing wells in the Tompkins Hill field produced an average of about 5 million cubic feet of gas daily in 1964. Only a small amount of gas has been produced from the Table Bluff field. No production has been reported from a possible third gas field, Grizzly Bluff.

Offshore

Seaward from the coastline of California a submerged region of more than 27,000 square miles is known as the continental shelf. The continental shelf is usually defined as that part of the ocean lying between the low-water line and the sharp change in inclination of the sea bottom that marks the beginning of the continental slope (the shelf edge). Geologically, this abrupt change in inclination, rather than the present shoreline, marks the true edge of the continents (Trumbull, 1958). For convenience, the 100-fathom (600-foot) line is useful for an approximation of the shelf edge in most regions. On plate 1 of this report the 500-foot contour line may be used as an approximation.

North of Point Conception, the continental shelf off California is comparatively narrow, generally less than 10 miles and sometimes less than 1 mile wide. West of San Francisco, however, it widens to about 30 miles.

South of Point Conception, the region between the mainland and the continental slope is broad and extends as much as 160 miles seaward. It is complex, with islands, flat-topped banks some of which are only slightly submerged, and about 14 closed basins (closed depressions deeper than the surrounding area). Because of this complexity this region has been called the continental borderland by Shepard and Emery (1941) to distinguish it from typical continental shelves in most other areas of the world. Its area is more than 19,000 square miles, and it is covered by water with an average depth of about 3,500 feet and a maximum depth in one locality of nearly 7,000 feet.

The 1958 United Nations Conference on the Law of the Sea provides that the sovereign rights of a nation to the subsoil off its coasts extend to where the sea is 656 feet deep and, beyond that limit, as much farther as it can exploit the resources of the undersea area.

Early in 1965, the Supreme Court of the United States decided that the boundary of the State of California would be measured by a line 3 geographic (3.45 statute) miles from the low-tide line of the mainland shore, and by lines a like distance around each island. As a consequence, the State of California or its grantees owns the mineral resources on slightly more than 5,000 square statute miles within the 3-mile limit, as measured on 1961–62 maps. This area will likely be modified by the Supreme Court's decision which included Monterey Bay in the State. The United States owns, or can exploit, the mineral resources on the more than 22,000 square statute miles more than 3 miles from the mainland or the islands.

Public information concerning the geologic conditions offshore is very limited, especially north of Point Conception. Inferences may be made from geologic maps of the mainland and the islands. Perhaps the most important inference concerning oil and gas is that five of the onshore productive sedimentary basins (figs. 47, 48) doubtless extend offshore. There are sparse published records on the ages of the rocks from which oil production is now obtained offshore, and on the depths of some of the exploratory wells. In addition, published reports by Emery (1960), and by Bromery, Emery, and Balsley (1960) contain considerable geological and geophysical information on the continental borderland south of Point Conception, the best known area off the California coast. The following brief descriptions is taken from these reports.

Structurally, the borderland consists of many blocks of roughly equal size. Emery suggests that these blocks are crossed by seven long primary faults most of which trend northwestward, and that many shorter features which may be faults or folds trend more westward between the primary faults. The anticlinal structure of some of the islands and of the sea bottom in places is known or inferred. The anticlinal structures on which several of the productive onshore oil fields are located extend beneath the ocean, and production is also obtained offshore on these features. Most of the fields off the coast from near Santa Barbara to Point Conception are on a westward trend of faulted anticlines.

The area of the closed basins and other deep flat areas in the borderland is about 9,000 square miles. Most of the basins are oriented parallel to the structural trend of the Peninsular Ranges on land, but the most northerly one which is believed to be the submerged extension of the Ventura basin is oriented parallel to the Transverse Ranges. These basins are closely related in form and probable origin to the land basins. Both are probably controlled by the regional structure.

The most widely distributed rocks on the sea floor in the borderland are of Miocene age, but the ocean bottom in the basins is largely covered with Pliocene and younger sedimentary rocks and unconsolidated sediments. It can be inferred that Miocene, and possibly older sedimentary rocks, are also present at depth in some or all of the basins. The present nearshore fields in the borderland produce oil from rocks of Pliocene, Miocene, and Oligocene ages. Early Tertiary and Cretaceous rocks crop out on some of the islands.

The thickness of sedimentary rocks in the borderland is believed to be about 4,500 feet in one basin, and about 10,000 feet in another. Thicker sedimentary rocks are doubtless present in parts of the borderland as the deepest offshore well, about three-fourths of a mile from the coast southeast of Santa Barbara, was drilled to a depth of approximately 16,000 feet.

North of Point Conception, thick sedimentary rocks are obviously present at places on the continental shelf but there is very little public information about the geology of this region. Outside of the 3-mile line at least one exploratory well was drilled to a depth of approximately 10,400 feet, and several other wells have been drilled to depths of 7,000 to 8,000 feet. It can probably be assumed that sedimentary rocks were penetrated for most of these depths. The presence of thick sedimentary rocks west of the granitic Farallon Islands off San Francisco has been inferred by Thompson and Talwani (1964).

Very large amounts of money have been spent by the oil industry in exploring for and developing oil and gas off the coast. Baldwin (1965) estimated that approximately $310 million was spent from 1949 to early 1965 off the Pacific Coast for exploration, for acquiring leases, and for platforms prior to the drilling of development wells. Probably about $270 million of this has been spent off California including $172 million for State leases, $12.8 million for Federal leases, $25 million for seismic geophysical lines, $35 million for the drilling and coring of some 2,650 holes, and $25 million for platforms and islands. The industry has also spent very large amounts of money for drilling development wells that produce oil from beneath the ocean, and for other costs incident to producing operations.

History of discovery and development offshore

The old Summerland field in the Ventura basin was the first field in California in which oil was produced from beneath the ocean. The field was discovered onshore prior to 1894, and in 1896 the first shallow wells beneath the water were drilled from wharfs, some of which extended a quarter of a mile from shore. A 1902 map shows 187 productive offshore wells, and others may have been drilled later. The wharfs and wells have been destroyed by storms or torn down. About one-third million barrels of oil were produced offshore.

Since 1929, many oil and gas leases for submerged lands within the 3-mile limit have been issued by the State or its grantees. From 1927–1956, eight oil fields (fig. 55) in the Los Angeles and Ventura basins were extended beneath the ocean by directional drilling from land.

The first discovery of a new field beneath the ocean, which at the time did not seem to be connected with an onshore field, was made in 1948 at the Belmont offshore field in the Los Angeles sedimentary basin (fig. 55). Further development of the field did not start until 1954, when a man-made island was constructed 8,300 feet from shore.

Six additional producing oil fields and four producing dry gas fields have been discovered offshore in recent years.

Leases on 516 square miles of Federal submerged land outside of the 3-mile limit north of Point Conception were issued in 1963. Several exploratory wells, some of which were in about 600 feet of water, have been drilled on these lands recently, but no discoveries were reported to August 1965. No leases have been issued on Federal submerged lands south of Point Conception, but exploratory wells as deep as 8,000 feet were drilled on these lands prior to 1965.

Cumulative production to January 1, 1965, from about 2,000 offshore wells was 778.1 million barrels of oil, 79 billion cubic feet of dry gas, and more than 57 billion cubic feet of wet gas. Statistics for wet gas are incomplete. The value of this oil, using the current average price of $2.47 per barrel, was about $1.75 billion.

The eight oil fields that are extensions of onshore fields have produced 95 percent of the offshore oil, mostly from the submerged parts of the Wilmington and Huntington Beach fields (fig. 55) in the Los Angeles sedimentary basin. The seven oil fields that have been discovered offshore are more recent fields. They have produced 38 million barrels, or only 5 percent of the total.

In 1964, the offshore fields produced 40.5 millions barrels (fig. 58) at an average daily rate of 110,700 barrels, or slightly more than one-eighth of California's production. Offshore oil and gas production has increased rapidly in recent years (figs. 58, 59). Three of the offshore fields are small, and each yielded less than 100 barrels per day in 1964. The production of dry gas in 1964, all of it in the submerged part of the Ventura sedimentary basin, was 35.6 billion cubic feet (fig. 59), or about 100 million cubic feet daily.

On January 1, 1965, oil and gas were being produced in 14 offshore oil fields and 4 offshore dry gas fields. One of the 14 oil fields now yields only a small amount of oil, but produces a moderate amount of dry gas. A small amount of oil was obtained prior to 1959 from the offshore part of one additional field. All these fields are in the submerged extensions of the Los Angeles and Ventura sedimentary basins. All are on submerged lands leased from the State or its grantees.

Resources

The oil and gas resources of California may be divided into proved reserves and potential resources.

Proved reserves

Proved reserves are defined by the American Petroleum Institute as "the amount of oil in *known* petroleum deposits recoverable under existing economic and operating conditions," or as sometimes stated by others, the recoverable reserves whose location and extent have been proved and measured by drilling.

Generally, the published estimates of reserves as so defined are probably on the conservative side. Among the reasons for this are:

1. Revisions and additions to reserves are commonly made for new fields as they are developed, and it is seldom that the amount of recoverable oil in a new field can be quantitatively estimated with rea-

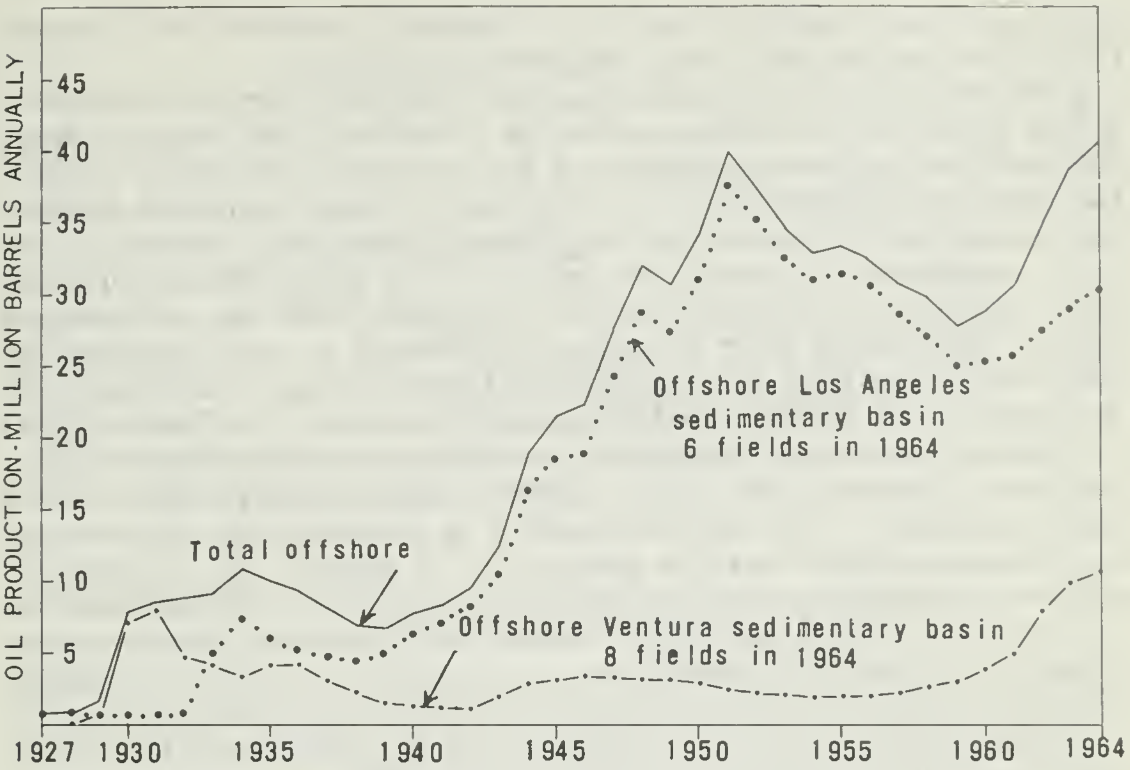

FIGURE 58. California offshore oil production.

FIGURE 59. Offshore oil and dry gas production in Ventura sedimentary basin, California.

sonable accuracy early in the life of the field. Several new fields in California are now in the early stages of development.

2. Secondary recovery methods, some of which verge on well-stimulation methods, are being applied in more than 300 pools in some 100 fields in the State. Because of the recency of the use of some of the thermal methods which are reported to have increased production about 30,000 barrels per day, it is impossible to estimate how much additional oil may be recovered. It is quite certain, however, that additions of this kind are not included with the statistics on proved reserves in most instances. Although it was estimated in 1962 that about 29 percent of the oil found in the United States to that time would be recovered by primary methods, it is believed that the primary recovery in California will on the average be somewhat less than 25 percent. In many California fields which produce viscous heavy (under 20° API gravity) oil, it is believed that the recovery by primary methods may be only about 10 percent. It is quite certain that secondary recovery methods will considerably increase the recovery from California fields. Statements have been made by representatives of the oil industry that the use of secondary recovery methods will increase California reserves by more than 1 billion barrels.

3. New techniques of well logging, testing, and completion sometimes result in increased reserves in existing fields.

4. The large East Wilmington field, partly onshore but mostly offshore, is estimated to contain at least 1.2 billion barrels of recoverable oil. The field is known and has been approximately outlined, but development was not begun until the middle of 1965. Published reserves include 500 million barrels for this field.

The proved reserves of crude oil in the United States as of January 1, 1965, have been variously estimated at 35.1 billion barrels by the Oil and Gas Journal and at 31 billion barrels by the American Petroleum Institute. The proved reserves of crude oil in California are estimated at 4.1 billion barrels (fig. 60, table 35), about 14 times the 1964 production, or 13.3 percent of the United States reserves according to the American Petroleum Institute.

The estimated proved reserves of crude oil in California declined from a high of 3.9 billion barels on January 1, 1954, to 3.6 billion barrels on January 1, 1964. This declining trend was reversed in 1964 when reserves increased 526 million barrels to 4.1 billion barrels, the largest ever estimated, due largely to the assignment of 500 million barrels to the East Wilmington field.

Several features of these reserves of crude oil are of importance.

1. Although the proved reserves of California are 14 times the annual production, a much longer period than 14 years will be required to bring the oil to the surface. Several fields more than 50 years old are still producing large amounts of oil.

2. Nearly all the proved reserves are in five sedimentary basins in the southwestern part of the State, mainly in the San Joaquin basin (2.2 billion barrels) and the Los Angeles basin (1.25 billion barrels).

3. More than 80 percent of the proved reserves in California are in the "giant" fields—those which are expected to yield more than 100 million barrels of oil. There are 40 of these fields in California at present, the last one having been discovered in 1949. However, recent

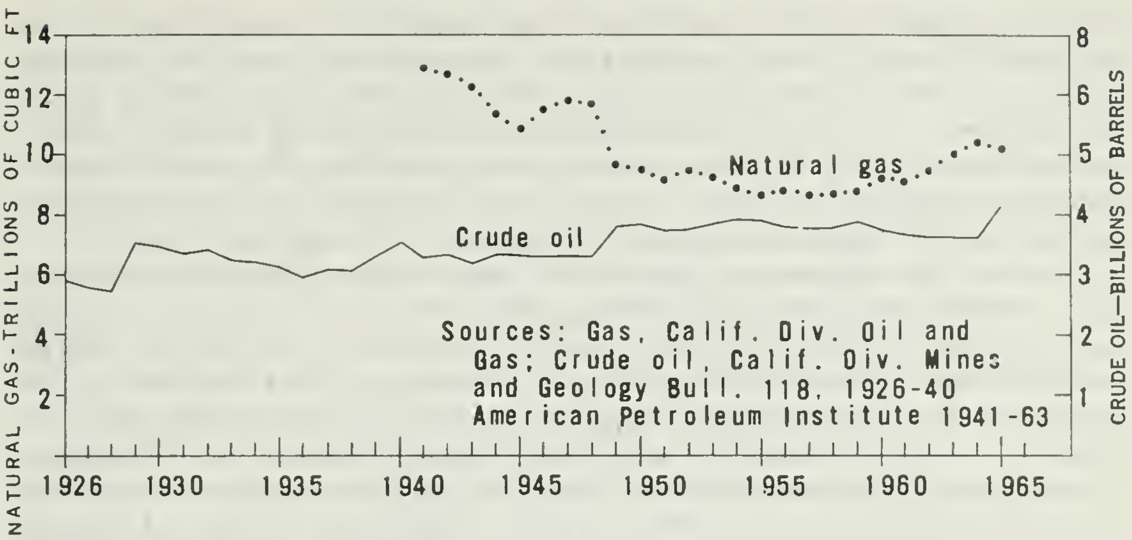

FIGURE 60. Estimated proved reserves of crude oil and natural gas in California, on January 1 of each year.

discoveries near Los Angeles and McKittrick may approach the "giant" class, if initially isolated discoveries prove to be single fields.

4. The two fields with the largest proved reserves are Elk Hills in the San Joaquin basin from which only a small amount of oil is produced at present because it is in Naval Petroleum Reserve No. 1, and the Wilmington field in the Los Angeles basin. To these might be added the largest known, but undeveloped, reserve of at least 1.2 billion barrels in the East Wilmington field.

The proved reserves of natural-gas liquids in California on January 1, 1965, were estimated at 270.8 million barrels (table 35).

The estimated proved reserves of natural gas in the United States on January 1, 1965, were 290 trillion cubic feet according to the Oil and Gas Journal. The reserves in California (fig. 60) on that date were 10.2 trillion cubic feet according to estimates by the California Division of Oil and Gas, or about 15 times the annual net withdrawals (production less amount reinjected). The reserves in the State have increased about 1.5 trillion cubic feet since the middle 1950's.

Approximately 60 percent of the gas reserves in California are wet, or oil-well gas. The largest reserves of wet gas are in the San Joaquin sedimentary basin, followed by the Los Angeles and Ventura basins. By far the largest reserves of dry gas are in the Sacramento basin, followed by the Ventura and San Joaquin basins.

Potential resources

Onshore.—Conjectures concerning the potential resources onshore in California suggest that they are large. It is generally believed that the most favorable localities for new discoveries are in areas of proved oil generation within the principal productive sedimentary basins (figs. 47, 48). Also favorable are some smaller sedimentary basins and other areas underlain by sedimentary rocks; minor amounts of oil and gas have been produced in several localities outside of the principal basins, especially in the California Coast Ranges.

The complex geologic structure and statigraphy in California forms innumerable traps in which oil and gas may have accumulated. Practically all the obvious traps in the principal basins were tested by the drill long ago, but very many obscure traps have been found in the past and certainly many more exist. Obscure traps are very difficult to find, but the discoveries in recent years show that they can be found in the already highly explored areas of California by creative thinking in exploration. With some exceptions, for example in the Salinas-Cuyama sedimentary basin, it may be said that any trap in the principal productive basins has a good chance of yielding oil or gas.

Parts of the principal productive basins are relatively untested. Many additional concealed stratigraphic traps may be present, especially on the flanks of known anticlinal structures and on the deeply buried flanks of the deepest parts of the basins. Not all of the known structural traps have been completely tested by drilling through all possible reservior rocks at adequately spaced locations. The area of the principal productive sedimentary basins is about 20 million acres, of which about 475,000 acres have yielded oil or gas. Approximately 5.5 million acres of unproductive land in the State are under lease for oil and gas; a large part of this leased land is within the principal productive basins.

The 13.25 billion barrels of oil already produced in California plus the 4.1 billion barrels of proved reserves of recoverable oil totals 17.4 billion barrels. If it is assumed that this is 25 percent of the oil originally in place, about 52 billion barrels of oil will not be recovered by the primary methods of production. Some of this remaining oil is being recovered now by the use of secondary recovery methods.

The Interstate Oil Compact Commission and several individuals (Supplies, costs, and uses of the fossil fuels, Energy Policy Staff, U.S. Department of the Interior, 1962) have made some estimates of the petroleum resources of California in addition to the proved reserves of 4.5 billion barrels. These estimates include (a) 1 billion barrels of oil that can be expected to be recovered by established secondary recovery operations, (b) 4.1 billion barrels that may be recovered as a result of changed economic conditions or improved technology, and (c) 1.3 billion barrels that could be recovered from known reserves of presently nonfluid oil in bituminous rocks or shale at a cost that is not now competitive with oil from wells.

In eastern California, the Salton Trough, the Mojave Desert, the Great Basin, and the Modoc Plateau provinces (fig. 47) do not yield oil at present, and except in the Salton Trough, few wells have been drilled. Only one surface evidence of oil seems to be a verified seep, but petroliferous rocks are known in Nevada to the east, and oil seeps have been reported south of the border in Mexico. The southeastern part of the Great Basin province in California contains thick Paleozoic and Mesozoic marine sedimentary rocks which may be worth testing for oil and gas.

Only a few very small showings of gas have been found in some 20 exploratory wells in the major sedimentary basin in the Imperial Valley region of the Salton Trough province. Marine sedimentary rocks that crop out in the hills west of the valley have not been found to depths of more than 12,000 feet in the central part of the valley, but may be present at even greater depths.

Offshore.—The potential resources of oil and gas off the coast of California, not only within the boundaries of the State but also on Federal lands outside the 3-mile line, are believed to be large. More than 6 years ago, it was estimated that fields on the mainland within 3 miles of the coast would ultimately yield about 3.9 billion barrels of oil. Also, it was suggested that, if the offshore geologic province is similar to the onshore province, a like amount might ultimately be obtained from the offshore area inside the 3-mile line within the boundaries of California. It was pointed out that 50 percent of the prolific Los Angeles and Ventura sedimentary basins are believed to lie offshore, and that the Santa Maria basin extends offshore. The Santa Cruz and Eel River basins also probably extend offshore (figs. 47,48).

The amount of oil estimated to be recovered from the onshore fields can probably be increased to approximately 4.2 billion barrels largely because of the increased estimates for the Wilmington field. Nearly 0.8 billion barrels of oil has been produced offshore to 1965, so according to these estimates some 3.4 billion barrels may be produced offshore from within the 3-mile line in the future. Probably 1.5 billion barrels of that amount can be expected from presently known fields, including East Wilmington. The remaining 1.9 billion barrels may represent an allowable amount for the potential offshore resources of other areas inside the 3-mile line within the State's boundaries on the basis of the foregoing estimates.

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PHOSPHATE

(By H. D. Gower, U.S. Geological Survey, Menlo Park, Calif.)

Phosphate rock is the principal industrial source of phosphorous, an element essential in sustaining all life. Plants extract phosphorous from the soil, and animals in turn obtain phosphorous by consuming plants. Extensively farmed soil soon becomes depleted and unproductive unless additional phosphorous is added. Man has used phosphatic material for fertilizer for more than 2,000 years, but it was not until the middle of the 19th century that he learned to produce fertilizers from phosphate rock. Before then bones, fish, and guano were the main sources of phosphate fertilizer. Today most phosphate fertilizers are made from phosphate rock. About 70 percent of the world's production of phosphate rock is used for the production of fertilizer. Phosphorous has many other uses in industry. A few of the more important uses are in the manufacture of detergents and soaps, animal feed supplements, baking powders, metallurgical alloys, water softening agents, petroleum refining agents and additives, drugs, and military devices (including incendiary bombs and smoke screens).

In 1963 the world production of phosphate rock was slightly over 50 million tons (Lewis, 1964). The United States accounted for 39 percent of the world's total production. Florida produced 74 percent of the United States total, followed by the Western States (Idaho, Montana, Utah, and Wyoming) with 14 percent, and Tennessee and Arkansas with 12 percent. Sixty percent of United States production in 1963 was used in agriculture, 19 percent in the chemical industry, and 21 percent was exported (most of this was also used in agriculture) (Lewis, 1964). No phosphate rock has been produced in California.

Phosphate is precipitated under certain marine environments and nearly all of the world's important deposits of phosphate rock occur in rocks of marine origin. Several times during the Miocene Epoch conditions were such that phosphate was precipitated over much of the southwestern part of California. Although phosphate rock was deposited over a wide area only in certain places were conditions suitable for the accumulation of concentrations of phosphate of sufficient amounts to be of potential economic value. After the phosphatic strata were formed they were buried and compacted under thick accumulations of younger sediments and later deformed by folding and faulting. Subsequent erosion removed the phosphatic strata from many areas, and only part of the original phosphatic strata remains.

The principal phosphate mineral of marine phosphate rocks is a variety of apatite called carbonate-fluorapatite. In California it occurs as light-gray to dark-brown pellets (0.1 to 2.0 mm in diameter), nodules (more than 2 mm in diameter), and laminae of very finely divided phosphate. Most California phosphate rock is thin bedded and closely associated with siliceous shale and bentonite.

Phosphate content is usually expressed as percent phosphorous pentoxide (P_2O_5) or less commonly as percent BPL (bone phosphate of lime) which is tricalcium phosphate, $Ca_3(PO_4)_2$. One percent P_2O_5 equals 2.18 percent BPL. In the western phosphate field high-grade rock must contain a minimum of 31 percent P_2O_5, and low-grade rock must contain at least 16 percent P_2O_5 (Service and Popoff, 1964). Very little is yet known about the California phosphate deposits, but all of the known deposits appear to be below the minimum standards for low-grade rock in the western phosphate field. However, close proximity to markets and possible ease of beneficiation may allow production from lower grade deposits in California. The only detailed chemical analyses of phosphatic sections in California that are currently available are for one measured section in the central part of the Indian Creek deposit of San Luis Obispo County. At that locality, about 50 feet of strata average nearly 4½ percent P_2O_5 and the main 21-foot-thick phosphatic section averages about 6½ percent P_2O_5. The thickness and concentration of phosphate varies from place to place and in other parts of the area the phosphate may be greater or less than at the section analyzed.

Occurrences in California

The occurrence of phosphate in sedimentary rocks in California has been known for several decades, but it was not until about 1960 that its potential economic value was actively explored. By mid-1965 four deposits of potential economic value had been examined in considerable detail by commercial interests; these, as shown on figure 61, are the Chico-Martinez Creek deposit of Kern County, the Indian Creek deposit of San Luis Obispo County, the Cuyama Valley Deposit of Santa Barbara County, and the Pine Mountain deposit of Ventura County. None of these deposits have yet been proven to be of commercial grade, but exploration work is continuing on the latter three deposits. There has also been some interest in the occurrence of low-fluorine nonmarine phosphate near Hyampom in Trinity County.

Phosphate has been reported over a wide area of California (Gower and Madsen, 1964), but most of the occurrences are concentrated in the southern Coast Ranges, western Transverse Ranges, and southwestern Great Valley (fig. 61). Nearly all of these occurrences are in rocks of Miocene age. Most occurrences shown on figure 61 are small and of no economic importance. However, they are important in pointing out areas for future prospecting, for the thickness and grade of phosphatic sections can vary greatly over a short distance. A slightly phosphatic horizon in one area may grade laterally into a significant phosphate deposit only 2 or 3 miles away.

Hyampom prospect

Low-fluorine nonmarine phosphate rock interbedded with siliceous and tuffaceous shales of the Oligocene (?) Weaverville Formation (Lydon, 1964) has been prospected by L. D. Cartwright near Hyampom in Trinity County. Because of the low fluorine content, this material could be readily used in animal feed supplements and in lime and ammonium fertilizers. Very little exploration work has been done on this occurrence, but it is questionable that it contains enough phosphatic rock to be of economic significance.

Indian Creek prospect

Phosphate rocks in the upper part of the Monterey Formation in the Indian Creek area, about 10 miles east of Creston in San Luis Obispo County, have been extensively prospected by Nicol Industrial Mineral Corp. The prospect is still under study. The phosphate rocks occurs in thin pellet beds interbedded with siliceous shale and bentonite. Phosphate occurs throughout about 70 feet of section, but the main phosphatic zone is about 21 feet thick.

Chico-Martinez Creek prospect

Pelletal phosphate rock in the lower part of the Temblor Formation in the vicinity Chico-Martinez Creek in Kern County was pros-

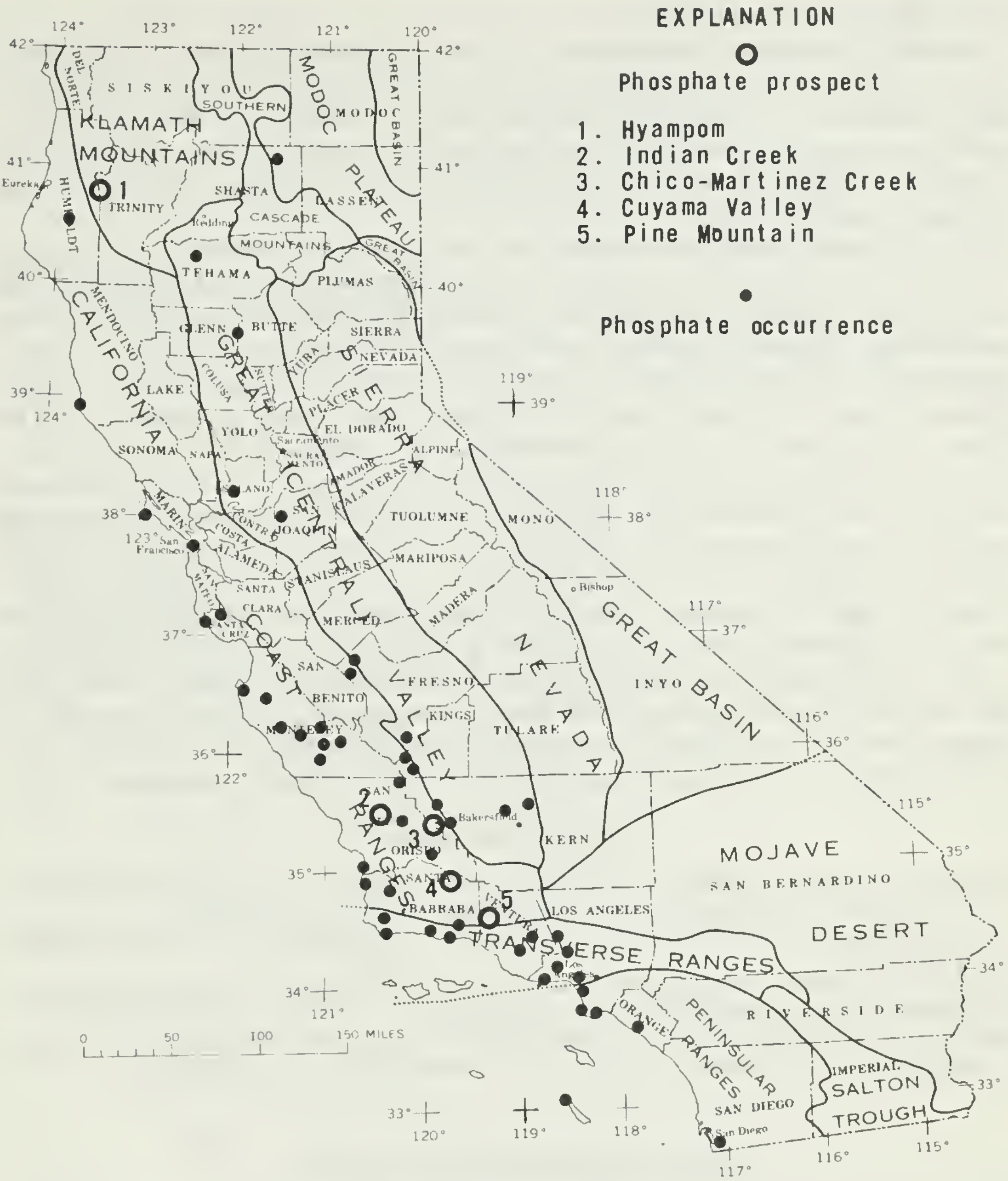

FIGURE 61. Phosphate in California.

pected by Nicol Industrial Mineral Corp. The phosphate-bearing strata were exposed and studied in five trenches. Phosphate is concentrated in three major zones ranging from about 30 to 65 feet in thickness. The deposit was not considered economic under current conditions and was abandoned.

Cuyama Valley prospect

Pelletal phosphate rock in the upper part of the Santa Margarita Formation on the south side of the Cuyama Valley near New Cuyama is currently being examined by Nicol Industrial Corp. under a Federal phosphate prospecting permit. The phosphate zone has been exposed in 8 trenches. Where best developed the main phosphate zone is about 100 feet thick.

Pine Mountain prospect

Pelletal phosphate rock in the upper part of the Santa Margarita Formation south of Pine Mountain in Ventura County is currently being studied by United States Gypsum Co. under a Federal phosphate prospecting permit. The phosphate section has been exposed in 3 trenches. Where best developed the main phosphate zone is about 100 feet thick.

The pelletal phosphate rock of middle and late Miocene age appears to offer the most promise for economic deposits of phosphate rock in California. Pelletal phosphate strata in the Santa Margarita Formation of late Miocene and early Pliocene(?) age extending in a southeast-trending belt through eastern San Luis Obispo, eastern Santa Barbara, and Ventura Counties looks particularly promising. The Monterey Formation of middle and late Miocene age in Monterey and San Luis Obispo Counties also holds promise of containing commercial deposits of pelletal phosphate. The pelletal phosphate horizons in the lower part (lower Miocene) of the Temblor Formation along the southeast border of the Coast Ranges and southwest border of the Great Valley also deserves further attention. The nodular and laminar finely divided phosphatic shales of Miocene age in Santa Barbara, Ventura, and western Los Angeles Counties are in places more than 200 feet thick and, although of low grade, contain a great amount of phosphate. If an effective means of beneficiating these shales could be developed, they could offer significant phosphate resources.

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PLATINUM GROUP METALS

(By W. B. Clark, California Division of Mines and Geology, Sacramento, Calif.)

The platinum group of metals includes platinum, palladium, iridium, osmium, rhodium, and ruthenium. Platinum is the most abundant and most important member of this group. All of these metals are essential in modern industry and are among the strategic and critical materials held in the national stockpile. United States production of platinum metals is small; most is imported from foreign sources.

Although platinum is the most important member of the group, each of the metals has important industrial uses, and each metal except palladium commands a price much higher than gold. In May 1965, the average prices per troy ounce were as follows: iridium, $92; osmium, $250; palladium, $33; platinum, $98; rhodium, $183; and ruthenium, $58. The uses of platinum and its alloys are based on: their resistance to corrosion, heat, and oxidation; electrical conductivity; and superior catalytic properties. The major uses are: (1) catalysts in the production of high-octane gasoline and various chemicals such as sulfuric acid; and (2) alloys for jewelry, dentistry, and electrical apparatus. Platinum is used in laboratory apparatus and ware, in equipment used in the manufacture of glass and synthetic fibres, and in certain delicate sensing instruments. Palladium has uses similar to platinum, as well as in electrical contacts and in nonmagnetic watches. The other platinum metals are used principally to improve the hardness and other properties of platinum and palladium. Osmium and ruthenium are used in hard alloys for phonograph needles, fountain pen tips, and fine machine bearings.

In California the platinum-group metals have been found only in stream placers, chiefly in the Sierra Nevada and Klamath Mountains (fig. 62). Thus far, no primary platinum-bearing deposits have been

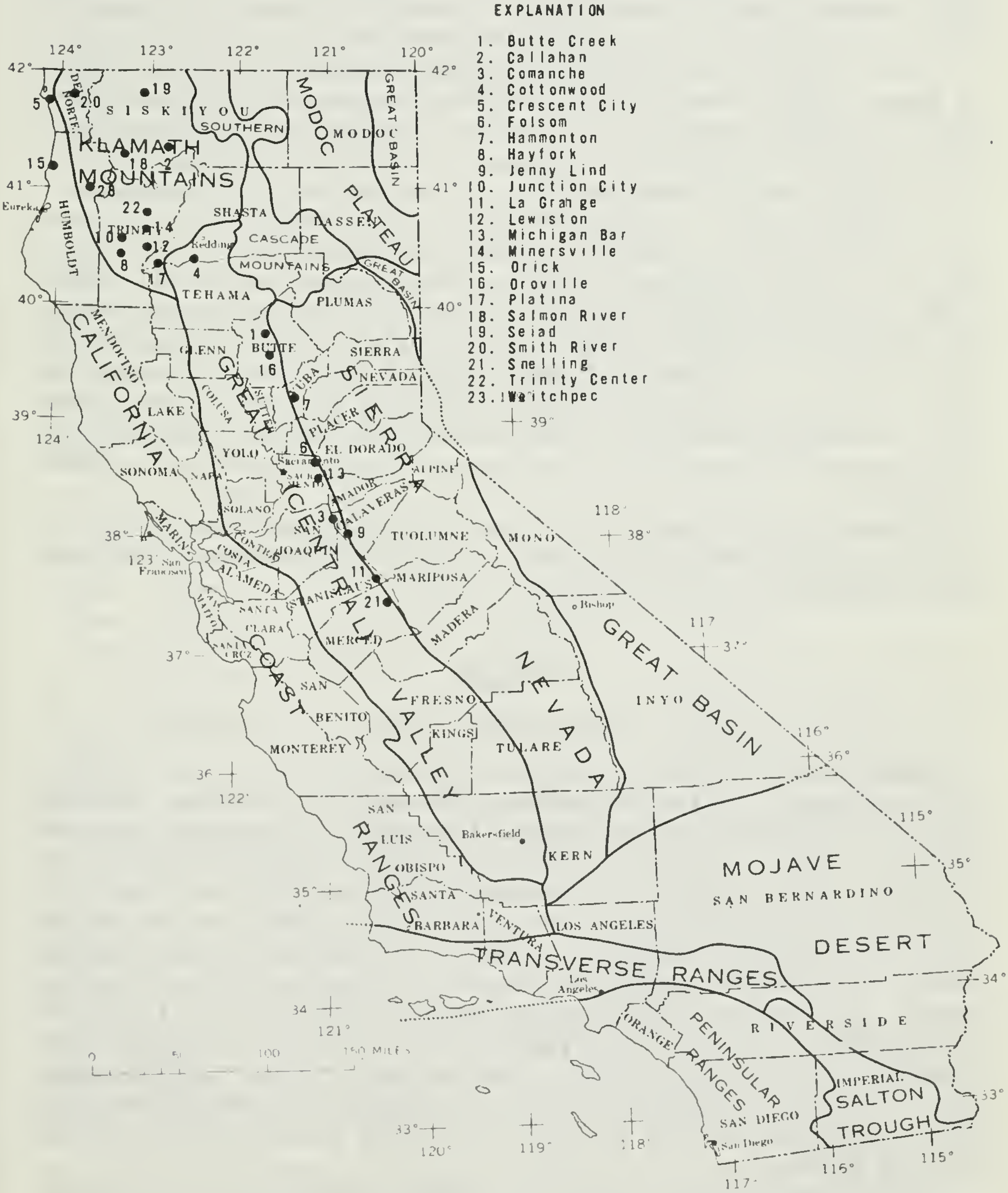

FIGURE 62. Locations where platinum has been recovered in California.

found in the State. Platinum alloyed with the other metals of the group occurs as small flakes, rounded grains, and irregular lumps in the placer deposits associated with gold and other heavy minerals at or near bedrock. The amount of platinum present in placer deposits in California is small; the average often is one ounce or less per 100,000 cubic yards of gravel.

Platinum and allied metals have been recovered in California as a by-product of placer gold mining since the days of the gold rush. The output of the State since 1850 is estimated to be about 28,000 ounces. The most productive periods were from around 1910 to the early 1920's, when the annual output averaged more than 500 ounces, and from the middle 1930's to the early 1940's, when production ranged from 700 to more than 1,000 ounces annually. An all-time high of 1,358 ounces was produced in 1940. Some platinum is produced by the three gold dredges in the Hammonton district in Yuba County.

World production of the platinum-group metals in 1963 amounted to about 1,530,000 ounces. Russia was the source of approximately 800,000 ounces; Canada, 340,000 ounces; and South Africa, about 300,000 ounces. Other sources included the United States with a production of 49,000 ounces and Columbia, which yielded 28,000 ounces.

During the early days of mining in the State, most of the platinum was recovered from hydraulic mines. Later nearly all of it was recovered by gold dredges. In the Klamath Mountains, the dredge fields were in the Klamath-Trinity River system or in tributaries of the upper Sacramento River. The hydraulic mines are on terrace gravel deposits adjacent to these rivers. In the Sierra Nevada, the hydraulic mines are located chiefly on Tertiary channel gravel deposits (see also section on Gold). Very small amounts of platinum have been recovered from beach placers in Del Norte and Humboldt Counties.

Because all of the platinum metals in California are produced as a by-product of placer gold mining, the output of these metals will continue to decrease as gold dredging declines.

POTASH

(By G. I. Smith, U.S. Geological Survey, Menlo Park, Calif.)

Potash is a term that means potassium oxide, but it is used widely to denote several other potassium salts as well. It is an essential ingredient of fertilizers, and about 94 percent of the potash delivered to points within the United States is destined for agricultural use. The bulk of this went to States east of the Mississippi River; less than 1 percent of this amount went to California. The 6 percent of national production destined for chemical or industrial uses was also mostly delivered to eastern states; about 5 percent of that fraction went to California. In 1963, production of all potassium salts in the United States was about 4,867,000 short tons which were equivalent to about 2,865,000 short tons of potassium oxide. Their value was estimated to be about $109,000,000, or an average of about $22.40 a ton for all potassium salts, equivalent to $38.00 a ton of potassium oxide (Lewis, 1964).

Potash production in the United States was started in the early 1600's. A marketable product was made from wood ashes (thus the name, pot-ash), and by 1635, appreciable quantities were being exported. Around 1860, potash was found essential to plant growth, and, in 1862, the Stassfurt deposits in Germany began significant production. Those deposits dominated the world supply until shortly after 1900 when minable deposits were found in Alsace (then in Germany, later in France) and in Spain.

Just prior to World War I, the United States started intensive exploration for domestic sources of potash to replace the threatened European suplies. One of the areas studied intensively was Searles Lake, California, which in 1916 became a major domestic source. At the close of World War I, at least 127 other plants were also producing potash in the United States, but only the one at Searles Lake survived the postwar decrease in price. In 1925, potash was discovered in the Carlsbad district of New Mexico, and in 1931 production started. The large deposits in Saskatchewan, Canada, were discovered in 1943, and production started in 1958 (Ruhlman, 1960a, 1960b).

At present, production from the United States supplies about 24 percent of the world total. Other major producing areas of today lie in West Germany, East Germany, France, Spain, U.S.S.R., and Israel-Jordan. These supply most of the markets of Europe, Africa, and west Asia. East Asia, Australia, and New Zealand, though, import large quantities of potash salts from the United States. In 1963, U.S. exports of potash materials to all countries was 722,000 tons, almost half of which went to Japan. During the same period, the United States imported 1,041,000 tons of potash materials, over half of which came from Canada (Lewis, 1964).

About 92 percent of United States production comes from the late Paleozoic marine deposits in New Mexico. Other production comes from underground late Paleozoic marine deposits and late Quaternary brine deposits in Utah, and from a late Quaternary brine deposit in California. Some by-product potash material is marketed from Michigan and Maryland (Lewis, 1964). A possible new source of potash consists of recently discovered deposits in eastern Arizona (Chem. Eng. News, 1963; Pierce and Gerrard, 1965).

The only producing deposit in California is Searles Lake. This deposit, described in more detail in the chapter on Sodium carbonate, lies in a closed depression in the southwestern part of the Great Basin of California. It consists of several saline layers that are permeated with brines containing the equivalent of between 3 and 5 percent potassium chloride (table 44, section on Sodium carbonate). Potassium compounds, along with six other products, are extracted from these brines by means of a complex process at the plant of the American Potash & Chemical Corp. In 1951, that plant's annual capacity was reported to be equivalent to 150,000 tons of potassium oxide, and in 1958, it was reported to be 170,000 tons (Ryan, 1951; Ruhlman, 1960b); these capacities are equal to about 6 percent of national production.

Speculation has existed about the possibility of extracting potash from the geothermal brines in the Salton Sea area of California. In 1963, five companies were actively exploring the area, primarily as a source of geothermal power. However, the hot brine contains up to 25,000 ppm potassium (analysis 5, table 10, section on Calcium chloride), and one company has announced plans to experiment with the extraction of potasium salts from it (Lewis, 1964; Chem. Eng. News, 1965). Production from this source, however, must await successful development of first the geothermal power and then the mineral resources, both of which involve solutions to complex engineering problems.

In the near future, potash production in California will probably remain about the same. Production from the Searles Lake deposit is not likely to change greatly, and in terms of its share in the national market, might decrease. This is partly because the production of potash from this deposit must remain coördinated with the demand for its coproducts, and partly because increased potash production in other areas will tend to increase the supply available to California and other nearby markets. The significant production from other areas consists of the producing deposits in New Mexico which will continue to dominate the domestic supply for many years, the more recently developed deposits in Utah which may increase production in the future, the area being explored for potash in Arizona which may someday provide additional supplies, and the enormous deposits in Saskatchewan which may reasonably be expected to develop rapidly into a major source for the Western Hemisphere.

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PUMICE, PUMICITE, PERLITE, AND VOLCANIC CINDERS

(By C. W. Chesterman, California Division of Mines and Geology, San Francisco, Calif.)

Pumice, pumicite, and volcanic cinders are products of explosive volcanic activity. Pumice is a very cellular, pale-gray to white volcanic glass that occurs in fragments greater than one-eighth inch in diameter and in masses as much as 10 feet across. Pumicite, also known as volcanic ash, consists of finely divided angular glass particles, less than one-eight inch in diameter. The distinction between pumice and pumicite is one of particle size rather than structure or composition.

Perlite, strictly defined, is a glassy volcanic rock characterized by an "onion skin" fracture, and which breaks into minute spherical fragments. Perlite, as well as many other siliceous volcanic glasses, will, when subjected to rapid controlled heating, expand into a white, frothy material that resembles pumice. In an industrial sense, all expansible volcanic glasses may be referred to as perlite.

Volcanic cinders (scoria) resemble furnace clinkers and consist of small crystals of plagioclase and pyroxene enclosed in a mesh of still smaller crystals of these minerals and subordinate dark-colored volcanic glass.

Pumice is used principally as aggregate in the production of lightweight concrete, and as an abrasive. Although some pumicite is used as a pozzolan in the production of concrete and as an abrasive, its principal usage is as a pesticide carrier for agricultural sprays.

About 40 percent of the perlite produced and expanded in the United States is used as aggregate in plaster. Other uses for expanded perlite include concrete aggregate, foundry sand, filter aid, filler, wallboard, and soil conditioning.

Volcanic cinders find their greatest use in highway and railroad building. Minor, yet substantial, amounts of volcanic cinders are used as aggregate in concrete building blocks, monolithic concrete construction, stucco, roofing granules, decorative stone in gardens, and as a conditioner of soils.

Pumice, pumicite, perlite, and volcanic cinders commonly occur together and exist in California in regions underlain by Tertiary and Quaternary volcanic rocks. Pumice rarely forms seperate rock masses and is generally the major constituent of tuff and tuff-breccia. Massive pumice, however, can be found as tops of flows and domes of obsidian. Pumicite generally occurs as layers interbedded with fine-grained sediments.

Since most of the pumice and pumicite mined in California is obtained from tuffs, tuff-breccias, and pumice breccias, their deposits may be classified, on the basis of their mode of deposition and origin as follows: (1) subaerial deposits—those deposited on dry land, (2) subaqueous deposits—those deposited in standing water, (3) Nuée ardentes deposits—lack bedding and show wide range in grain size, and (4) reworked deposits—show graded bedding, cross-bedding, and rounded fragments.

The bulk of the pumice and pumicite produced in California has been from subaqueous and subaerial types of deposits. Deposits of subaerial pumice range in thickness from a few feet to 50 feet, and have an aerial extent of several square miles; subaqueous deposits range in thickness from a few feet to 30 feet, and are of considerable aerial extent.

Volcanic cinders are mined from cinder cones which formed around central openings or along fractures during explosive volcanic activity. Cinder cones are, in general, nearly circular in plan, range from a few hundred feet to several thousand feet in diameter, and are as much as 500 feet high. The cones are stratified and consist largely of fragments that range from a fraction of an inch to several inches in diameter.

Although perlite has many modes of occurrence, most commercial production has come from flows associated with thick accumulations of tuffs and lava flows, and from domes. In many places, flows of perlite-bearing rock are so recent that they are nearly flat-lying, but locally they are deformed. Individual flows of perlite range in thickness from a few feet to several tens of feet, and may be traced along their outcrop length for thousands of feet. Perlite domes range in size from several hundred feet to more than a mile in diameter, and frequently extend as much as several hundred feet above their base.

The early known uses of pumice and pumicite date back to the days of the Roman Empire when pumicite was mixed with burned lime and used in the construction of the Pantheon and harbor installations on the Tiber. Many buildings in Belgium and France were built of pumice concrete during the 19th century. Ground pumice has been used as an abrasive for many years in the United States. Although only a limited amount of pumice was used as concrete aggregate prior to 1930, by the mid-1930's the demand for lightweight aggregate materials for military and domestic consumption had increased substantially, and consequently the production of pumice increased accordingly.

It has been known since about 1886 that perlite would expand, when properly heated, into a white, lightweight material. During the 1930's and early in the 1940's, research was conducted on the expansion of perlite, and by 1945 a new industry was established and a new product—popped or expanded perlite—was introduced to the construction world. A wide variety of furnaces were designed, ranging from inclined stationary and rotary to vertical stationary. In each case, the purpose was to produce a consistently lightweight material (8 to 10 pounds per cubic foot) with a minimum of fines.

The early use of volcanic cinders, undoubtedly, dates back several hundred years, but accurate records concerning where and when they were first used are scarce. The mining of volcanic cinders in California was started about 1916 on a small scale, and the early uses were for concrete aggregate and as track ballast in railroad construction.

The United States ranks third among the nations in the production of pumice, pumicite, and volcanic cinders, and first in the production of crude perlite.

The annual production of pumice and pumicite in California has increased markedly from about 50 tons in 1909 to about 160,000 tons in 1964, as compared with the total United States production of over 1,000,000 tons. California's peak production of pumice and pumicite was approximately 260,000 tons, attained in 1951.

California ranks first in the United States in the production of volcanic cinders, and was the source of about 300,000 tons in 1964 as compared to a total United States production of about 1,600,000 tons.

Crude perlite processed in the United States is mined from deposits in New Mexico, California, Arizona, Nevada, Colorado, Utah, and Idaho. New Mexico produces approximately 75 percent of the total United States production, and California is among the other important producing states.

In 1964, there were 14 perlite expanding plants operating in California. Eleven of these plants are located in southern California and provide a wide range of expanded perlite products to consumers in this part of the State. There is one plant at Fresno and two in the San Francisco Bay area, at Antioch and Sausalito.

Most of the pumice and pumicite deposits in California are in areas underlain in part by Tertiary and Quaternary volcanic rocks. Although considerable pumice and pumicite have been produced from tuffs of late Pliocene age, the bulk of California's output of these materials, as well as volcanic cinders, has come from tuffs and tuff-breccias of Pleistocene and Recent age.

The distribution of the principal deposits, deposits from which there has been commercial production, or deposits which warrant further consideration are shown in table 37 and figure 63.

TABLE 37.—*Summary of the features of pumice, pumicite, perlite, and volcanic cinder deposits of California*

Index No. on fig. 63	Commodity	Name of deposit	Remarks
1	Pumice	Thompson	Pumice for aggregate purposes is mined from extensive layer, 10 to 40 feet thick, of loosely consolidated tuff-breccia.
2	do	Boorman	Pumice for aggregate purposes is mined from extensive layer, 3 to 6 feet thick, of loosely consolidated tuff-breccia.
3	do	U.S. Pumice and Supply Co., Inc.	Pumiceous obsidian is quarried from top of Glass Mountain and used in the production of scouring bricks.
4	do	Skoria Star Brick Co	Pumiceous obsidian is quarried from top of Glass Mountain and used in the production of scouring bricks.
5	do	Pumice Stone mines	Pumice occurs as loosely consolidated tuff covering the ground and ranging in thickness from a few inches to 10 feet.
6	Pumice and pumicite.	Weisman	Pumicite and pumice were mined from an extensive layer of white tuff which ranges in thickness from a few feet to 20 feet, and used as sand in cattle cars.
7	Volcanic cinders	Kegg	Volcanic cinders mined from a cinder cone and used as ballast in railroad construction and repair.
8	do	Great Northern Railroad	Volcanic cinders produced from East Sand Butte, an extinct cinder cone. Material used principally as railroad ballast and bank widening.
9	do	Porcupine Pit	Volcanic cinders produced from cone at Porcupine Port, Siskiyou County. Material used in railroad construction.
10	do	Shastalite	Volcanic cinders produced from extinct cinder cone 1 mile east of Hotlum. Cinders used as aggregate for making building blocks.
11	Pumice	Long Haul Claims	Pumice is mined for aggregate purposes from extensive tuff-breccia layer that ranges in thickness from 5 to 10 feet.
12	Volcanic cinders	Sanford Cinders	Red and black volcanic cinders are quarried from eroded cinder cone and used as concrete aggregate.
13	do	Poison Lake Cinders	Dark red and black volcanic cinders are quarried from cinder cone and used as concrete aggregate.
14	do	Bowen Cinder	Do.
15	Pumice	William Silva	Pumice mined from 20-foot-thick layer of tuff and used as concrete aggregate.
16	do	Basalt Rock Co. pumice deposit.	Pumice for aggregate purposes was produced from massive tuff of unknown thickness.
17	Volcanic cinders	Cinder Products	Red volcanic cinders are quarried from eroded cinder cone and used as concrete aggregate.
18	Pumice	Coleman	Coarsely vesiculated obsidian is quarried for use as aggregate in plaster and concrete.
19	do	Volcanic Ash Pit	Sand from coarsely vesiculated obsidian is mined from extensive deposit and used as fill and in construction.
20	do	Sierra Placerite Corp	Firm consolidated, yellowish- to buff-colored rhyolite tuff is quarried and sold as flagstone, ashlar strips, garden stone, and used in the making of terrazzo.
21	Pumice and pumicite.	Red Rock pumicite	Beds of grayish-white pumicite of variable thickness are interbedded with beds of silt and tuffaceous sand. Some pumicite produced and sold under trade name of "Lassenite".
22	Pumice	U.S. Pumice and Supply Co., Inc.	Vesiculated obsidian is quarried from tops of volcanic domes and used in the manufacture of scouring bricks.
23	do	Victory	White pumice for aggregate purposes is mined from a 20-foot pumice bed.
24	do	Van Loon "Fine" west	Pale pink pumice was mined from several quarries and used as aggregate for making building blocks.
25	do	Snoeshoe	Several pumice beds with aggregate thickness of 30 feet were mined by benches and the pumice used as aggregate for making building blocks.
26	do	Brewster	Layer of pumice 20 feet thick, containing pink to white pumice fragments, is mined and the pumice used as aggregate.

TABLE 37.—*Summary of the features of pumice, pumicite, perlite, and volcanic cinder deposits of California*—Continued

Index No. on fig. 63	Commodity	Name of deposit	Remarks
27	do	Van Loon "Fine"	Pale pinkish pumice for aggregate purposes is mined from an extensive layer of unknown thickness and used in making building blocks and precast slabs.
28	do	Insulating Aggregates, Inc.	Extensive layer of grayish-white pumice is mined by open cut and the material is ground and made into plaster aggregate.
29	do	Ray Gill and Donna	Extensive layers of pumice are being mined for aggregate pumice.
30	do	Inyo Pumice Corp.	Creamy-white pumice has been mined for aggregate purposes from a layer of tuff about 30 feet thick.
31	do	Lucky Lager	Creamy-white pumice has been produced from a tuff bed of unknown thickness and used as aggregate in the manufacture of building blocks.
32	do	Calsilco Corp.	Pumice for aggregate and abrasive uses is being produced from a bed of pumice lapilli tuff about 20 feet thick.
33	Pumicite	Cudahy Packing Co., "Seismotite".	White, fine-grained pumicite was mined from a 9-foot bed in the Ricardo Formation (Pliocene).
34	do	Shoshone volcanic ash (pumicite).	Flat-lying layer of grayish-white pumicite, about 12 feet thick interbedded with lacustrine sediments has been mined intermittently and the pumicite used in the manufacture of scouring soaps and cleansing compounds.
35	Volcanic cinders	Redlite Aggregates	Volcanic cinders produced from Red Cinder Mountain, cinder cone, for aggregate purposes.
36	do	Splane	Volcanic cinders for aggregate, roofing granules, and agricultural purposes.
37	Pumice	Kleen-Gro	Pumice for aggregate and abrasive uses is being obtained from a thick tuff layer interstratified with other tuffs that rest upon deeply eroded granite.
38	do	Superlite	Pumice for aggregate uses mined from tuff layers associated with sands and gravels.
39	Volcanic cinders	Mount Pisgah	Volcanic cinders used for aggregate.
40	do	Dish Hill	Volcanic cinders for aggregate and roofing granules.
41	do	Pinto Cinders	Volcanic cinders quarried from cinder cone and used as concrete aggregate, stucco, and soil conditioner.
42	do	Cima Cinders	Do.
43	Pumice	Pumice and Pumicite Mining Co.	Pumice for aggregate purposes is produced from a layer of tuffaceous sandstone which has a maximum thickness of 30 feet.
44	Pumicite	California Industrial Minerals Co.	Buff-colored pumicite is produced from a 20-foot bed of pumicite and used as insecticide carrier, in scouring soaps, manufacture of cement, and polishing agent.
45	Perlite	Perlite Aggregates	Medium-gray, dense perlite has been quarried from an extensive flow that ranges in thickness from a few feet to 100 feet, and overlain by tuff.
46	do	Anadel Farm	Medium-gray, dense perlite has been quarried from an extensive flow that ranges in thickness from 25 to 50 feet, and overlain in part by basalt flow.
47	do	Cougar Butte	Extensive area underlain by a glassy flow composed of perlite and obsidian.
48	do	Fish Springs	Light-gray perlite is quarried from an elongated dome of pumiceous perlite that measures ½ mile wide and 1 mile in length.
49	do	Glassy Rock	Medium-gray, dense perlite has been quarried from an extensive, gently southward-dipping flow that ranges in thickness from a few feet to 50 feet, and interbedded with tuff and tuffaceous sediments.

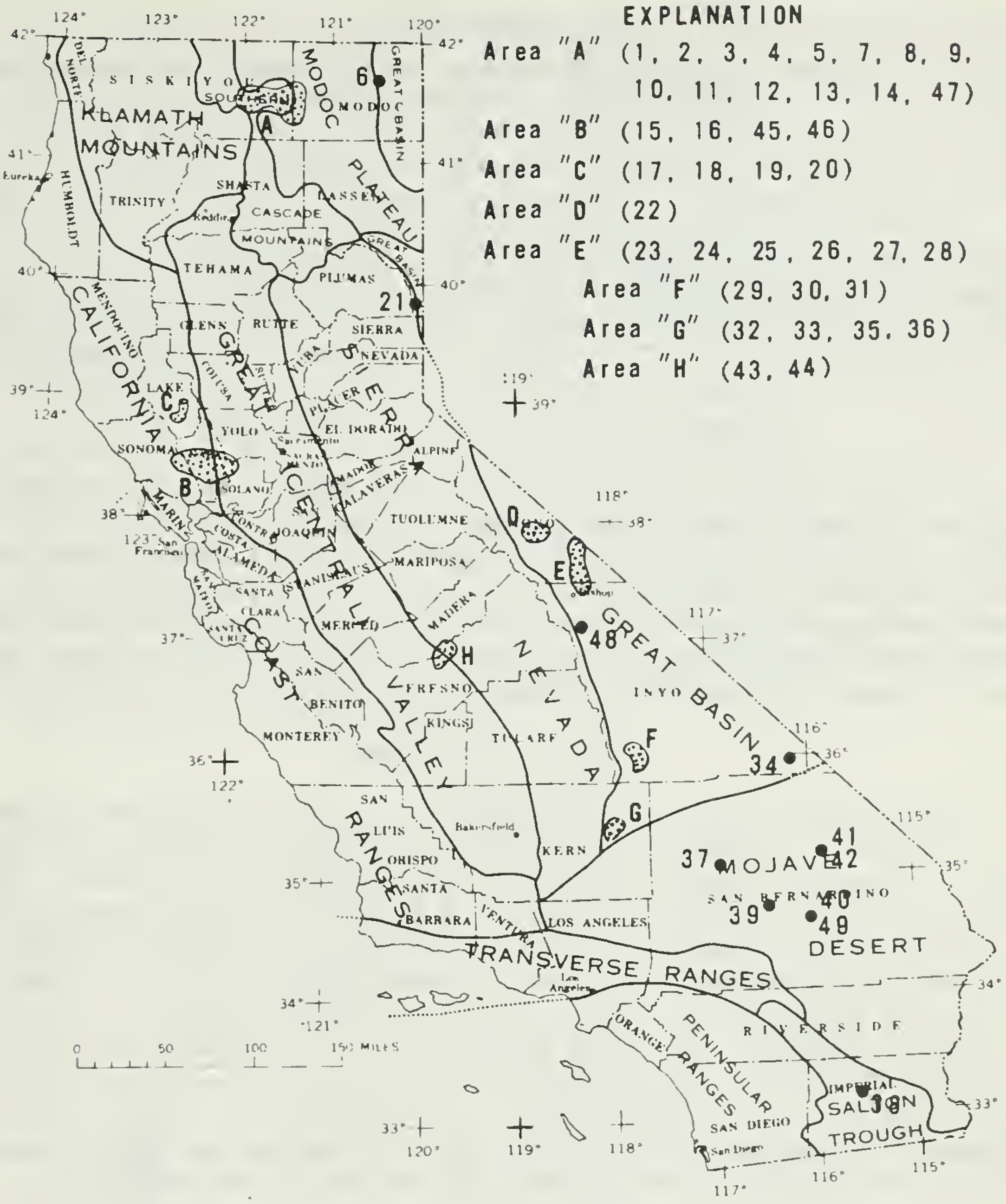

FIGURE 63. Pumice, pumicite, perlite, and volcanic cinder deposits in California (numbers refer to table 37).

Resources potential of pumice, pumicite, perlite, and volcanic cinders is extremely great in California. No attempt is made to indicate reserves of these materials, because many of the deposits have never been examined carefully, and, as in the case for perlite, any reserve data would be meaningless unless such factors as uniformity and a definition of acceptable quality are known.

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PYROPHYLLITE

(By L. A. Wright, Department of Geology and Geophysics, The Pennsylvania State University, University Park, Pa.)

USE AND ECONOMIC IMPORTANCE

Pyrophyllite ($Al_2Si_4O_{10}(OH)_2$), like the mineral talc, is very soft, micaceous in habit, soapy to the touch, and chemically inert. It is thus difficult to distinguish from talc. As industrial minerals, they share most of the same uses and are competitive for the same markets. If sufficiently white in the ground state and free of impurities, pyrophyllite is useful as a paint extender. White-firing pyrophyllite is employed in the manufacture of ceramic products and of wall tile in particular. Pyrophyllite that grinds relatively dark is extensively marketed as an insecticide carrier and as a filler in various products, including asphalt and rubber (Chappell, 1960, p. 84–85). In 1963 an estimated 20,000 tons of pyrophyllite was mined in California and was marketed mainly within the State. About 25 percent of this output was used in paints and ceramics. As most of the pyrophyllite that has been mined in California has proved too dark in color for these uses, it has been marketed principally as an insecticide carrier and filler.

GEOLOGIC OCCURRENCE

Concentrations of pyrophyllite that are large enough to be of commercial interest occur in terranes of metamorphic rocks. Most of them can be shown to represent alterations of silicic volcanic rocks. The pyrophyllite of commerce consists of a schistose rock composed of a fine-grained mineral aggregate in which the mineral pyrophyllite is the most abundant constituent, but which commonly also contains abundant quartz and sericite. This rock occurs in tabular to highly irregular deposits. The most productive of the domestic sources of pyrophyllite are in North Carolina where bodies as much as 1,500 feet long and 150 feet wide have been developed. Most of these deposits are lenticular in plan and appear to be best developed where the enclosing volcanic rocks have been thoroughly sheared.

HISTORY OF DISCOVERY AND DEVELOPMENT

The formal mining of pyrophyllite in California began in the early 1940's with the opening of the Pioneer deposit near San Dieguito, west-central San Diego County (Jahns and Lance, 1950). This deposit was most actively worked in the middle and late 1940's. It and several nearby deposits have been intermittently operated in recent years.

The most productive pyrophyllite deposits in California are along the lower part of the west face of the White Mountains of Mono

County (Wright, 1956, p. 455). These were opened in the mid-1940's and have been almost continuously worked since then, first at the Pacific mine and, in recent years, at the Colton mine.

A third pyrophyllite-bearing area in California lies 12 miles northeast of Victorville in San Bernardino County. There the Victorite deposit (Wright and others, 1953, p. 243–244; Bowen, 1954, p. 158–160), has been worked intermittently beginning about 1950.

The only domestic sources of pyrophyllite are in North Carolina and California. In recent years the two states have yielded about 150,000 tons annually. The output of North Carolina is several times that of California.

Geologic Occurrence in California

The pyrophyllite deposits near San Diguito, San Diego County, and those near Victorville, San Bernardino County (figure 64), occur in volcanic rocks of Mesozoic age and are alterations of them. The bodies of pyrophyllite-bearing rocks are lenticular in shape. The mineable bodies are characteristically a few feet to a few tens of feet wide and as much as a few hundred feet in length. They form parts of much larger masses composed mostly of partially pyrophyllitized rock of no present commercial value.

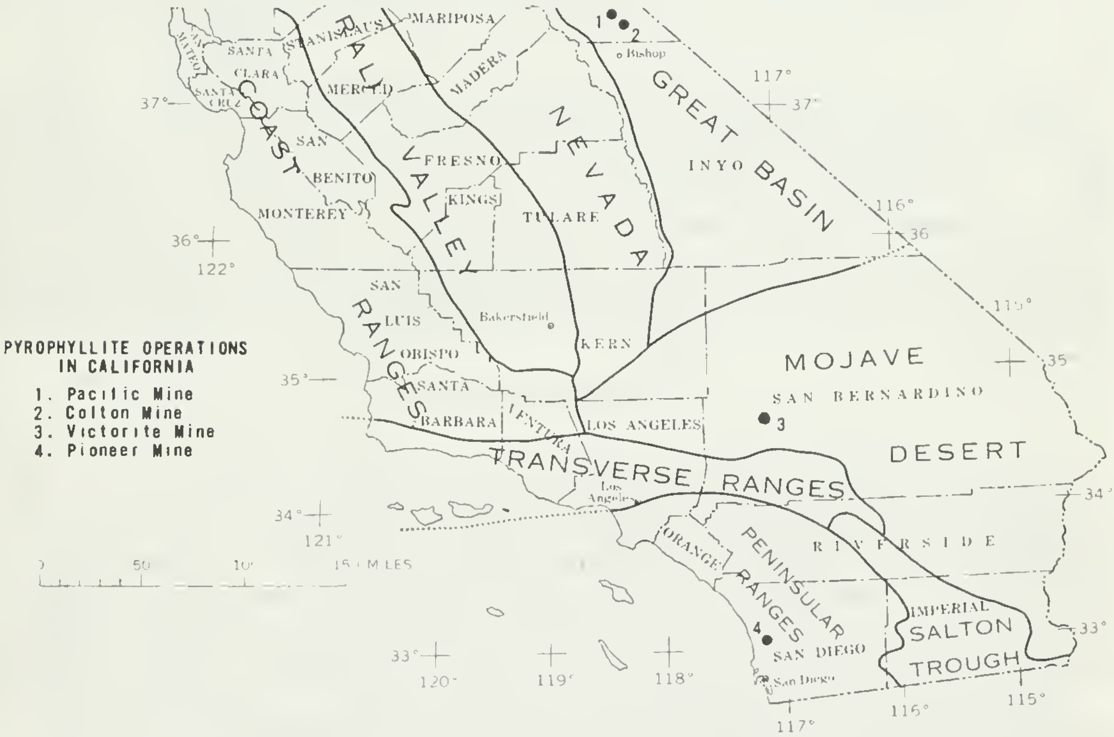

Figure 64. Pyrophyllite operations in California.

The deposits in the White Mountains occur in a belt of highly metamorphosed volcanic and sedimentary rocks of pre-Cretaceous age. These deposits are bordered by mica schist and quartzite and commonly contain highly quartzose layers of waste rock. The deposit at the Pacific mine appears to be the largest of the pyrophyllite bodies discovered to date in California. It is about 200 feet wide at the main quarry and appears to extend laterally for 1,000 or more feet. The commercial pyrophyllite is a friable schistose rock most of which is stained various shades of red, yellow or orange. Some of it is white or nearly so and is mined selectively. The Colton mine is about 2 miles south of the Pacific mine and in the same pyrophyllite-bearing belt. It has yielded relatively white pyrophyllite from a deposit that is about 100 feet in maximum exposed thickness and at least several hundred feet long.

RESOURCE POTENTIAL

Meaningful estimates of the pyrophyllite resources in California are as yet unavailable because the deposits of the White Mountains and those near Victorville remain to be studied in detail. The three areas already noted contain many millions of tons of rock that is sufficiently rich in pyrophyllite to be of commercial interest. But the proportion of this tonnage that ultimately will prove salable and that can be mined at a profit will depend on future use patterns, future industrial specifications, and mining costs, as well as upon the size of the deposits. The resources of pyrophyllite in the White Mountains appear to be especially large and capable of sustaining the present rate of production for several tens of years and probably much longer.

Deposits of pyrophyllite in California, in addition to those already mined or prospected, appear most likely to be discovered within the known pyrophyllite-bearing belts. The most obvious prospecting sites at present are at localities where the known mineralized zones extend beneath shallow covers of alluvium or talus. The principal problem in such exploration is the delineation of bodies of commercial pyrophyllite within much larger bodies of marginal or subcommercial material.

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QUARTZ CRYSTAL

(By Cordell Durrell, Department of Geology, University of California, Davis, Calif.)

Quartz crystals are used principally as oscillator plates for frequency control in electronics. Other uses are for lenses and prisms in optical devices, for the production of silica glass which has many scientific and industrial uses, and for ornamental purposes including jewelry.

World production of quartz crystal in 1963 exceeded 1,500 tons, nearly all of which came from the alluvial deposits of Brazil. Countries with small production include Japan, Peru, the Malagasy Republic, and other countries. Production in the United States is virtually nil. In 1963 the United States imported 141 tons and consumed 162 tons of quartz. The latter figure includes reworked scrap and manufactured crystal which amounted to 35 tons. Manufactured crystal is made from scrap and lower grade quartz crystal.

Quartz crystals occur in veins, often associated with ores, in rocks called pegmatite, and secondarily in alluvial deposits that have originated mostly through the action of streams. Practically all of the world production is from alluvial deposits.

Quartz crystal is present in innumerable places in California. It is found in pegmatites, especially in San Diego County and in Kern County in the southern Sierra Nevada; it is present in tactite also in the southern Sierra Nevada; in veins in the northern Sierra Nevada; and it is present in the ancient river channels of the central Sierra Nevada. Few occurrences are reported from the Klamath Mountains and the Mojave Desert and Great Basin, and significant occurrences are lacking in the Coast Ranges and the Modoc Plateau.

Most of the known occurrences contain, or contained, crystals too small and too flawed for industrial use, although many of them have yielded crystals useful for mineral specimens, jewelry, or other ornamental purposes. Crystals exceeding 2 inches in diameter are decidedly uncommon.

Only one California deposit has produced important quantities of quartz crystal for industrial purposes. This is an occurrence of crystals as boulders in an ancient river bed known as the Tunnel Ridge Channel, 2½ miles southeast of Mokelumne Hill (fig. 65, no. 1). The two adjacent underground mines from which the crystal was obtained were known variously as the Green Mountain, McSorley, Calaveras Crystal Mine, and the Rough Diamond Mine. They are in the SE¼ sec. 24 and NE¼, sec. 24, T. 5N., R. 12E., M.D.

Crystals here were first reported in 1897 and 1898, and were produced during World War I and World War II, and once in between. More than two tons of crystals were taken out during World War II. The total production is unknown but is probably several times that. Single crystals weighed as much as 200 pounds, and one was reported to weigh a ton. Clusters of two to a dozen crystals recovered during the latest operations weighed as much as 600 pounds. Only a small part—on the order of 10 percent—of each crystal was unflawed and useful. Although the crystals did not travel far as is evidenced by the total absence of wear, the primary source has not been found.

The probability of again establishing commercial production from any known deposit in California is small, but one other occurrence would merit investigation in case an emergency need for crystals should arise (fig. 65, no. 2). Crystals, and cobbles worn from single crystals, are present on the dump of the Pigeon mine which penetrated an ancient river channel on the ridge between Dry Creek and Big Indian Creek, about 1½ miles northeast of Fiddletown. Similar

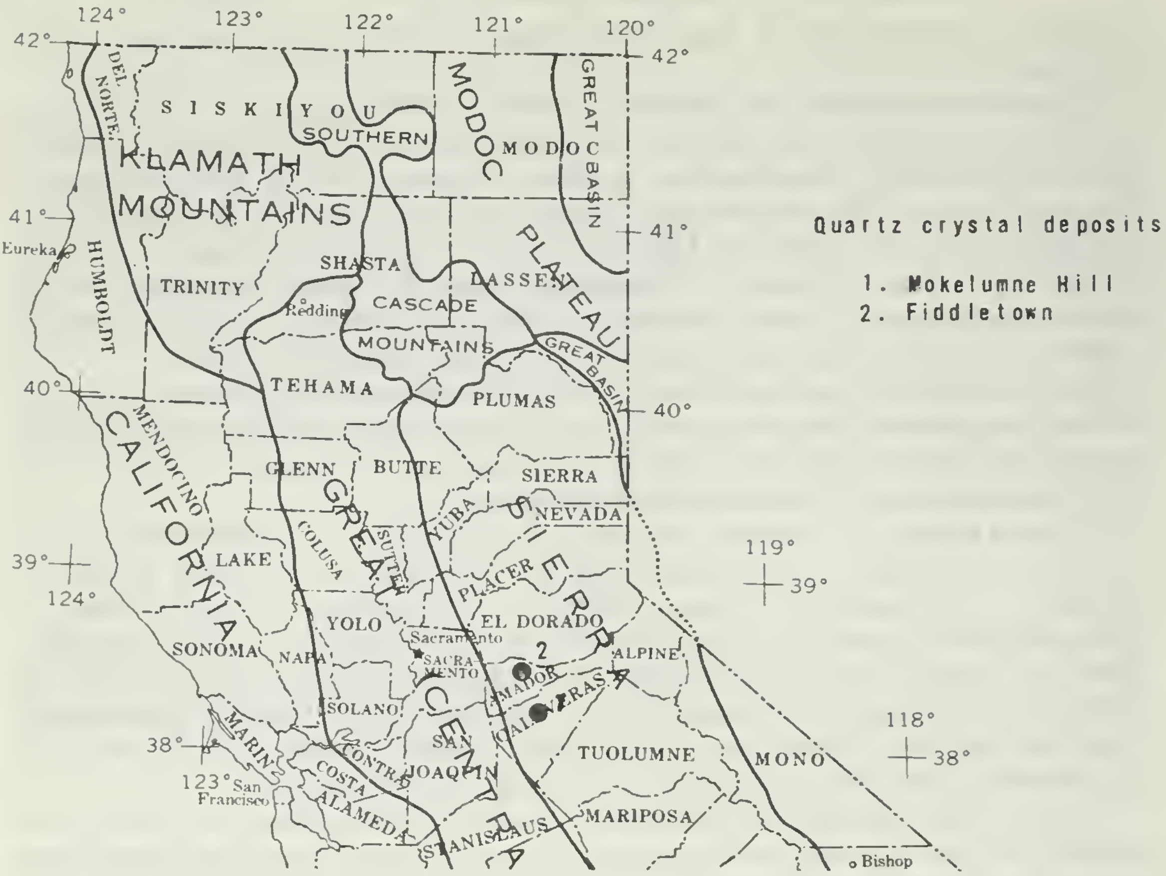

Figure 65. Quartz crystal deposits in California.

materials are reported to be present also in the Sharp Mine, three-fourths of a mile east of the Pigeon mine. The channel between these two mines possibly contains quartz crystal of commercial value, but of undetermined amount.

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QUARTZITE AND QUARTZ[1]

(By D. C. Ross, U.S. Geological Survey, Menlo Park, Calif.)

Quartz is the most common form of silica (SiO_2), one of the most abundant compounds in the earth's crust. Tightly cemented aggregates of quartz grains or aggregates that have been subjected to heat and pressure make up a common rock known as quartzite. Quartz, and rocks composed of quartz, have many diversified uses in industry and the arts because they are: (1) common and in large, easily exploited

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[1] Largely abstracted from Clark and Carlson (1957).

deposits, and consequently cheap to produce; (2) hard; (3) resistant to ordinary chemical action and weathering; and (4) highly resistant to heat (refractoriness).

Sand and gravel, which are used mostly for construction purposes, even though they are commonly quartz-rich, are excluded from this section as are specialty sands such as glass sands and foundry molding sands (see Sand and gravel chapter). Likewise quartz crystals are treated separately (see Quartz crystal chapter). This chapter is limited to quartz as used for industrial silica, which is widely used in abrasives, silica firebricks, metallurgical fluxes, filters, ferrosilicon, as a mineral filler and in ceramics and portland cement. Quartz and quartzite must be quite pure, easily mined, and near transportation facilities, however, to be of commercial interest. Silica from quartzite, vein quartz, quartz-rich gravel, and pegmatite quartz have been produced commercially from several California areas—quartzite is mined most abundantly, and is used principally in the manufacture of silica bricks and as a source of silica in portland cement.

Geologic Occurrence

The mineral quartz, next to the feldspars, is the most abundant mineral in the earth's crust, it makes up about 12 percent of the crust. It occurs as crystals and crystal aggregates as well as in massive and granular forms. It is quite hard (7 on the Mohs' hardness scale), generally colorless to white, and highly resistant to chemical weathering. Crystals of quartz are common in many granitic igneous rocks and in some volcanic rocks. Quartz is also common in veins as the gangue (waste material) of many ore deposits. Largely because of its resistance to chemical weathering and alteration, quartz tends to concentrate in the weathering cycle, and sedimentary rocks composed almost entirely of quartz grains (quartz sandstone) are abundant. Cementation of these quartz sandstones with silica cement or the application of heat and pressure changes sandstones to the tough, resistant rocks known as quartzite. The name "ganister" is sometimes used commercially for pure quartzite.

Quartz veins most commonly occur in granitic igneous rocks or in the wall rocks near granitic rocks. These veins range in size from small stringers an inch or less wide and a few inches long to massive, resistant bodies many tens of feet wide and miles long. Many quartz veins are pure, but some contain sulfide minerals such as pyrite, native gold, calcite, and many other minerals. Quartz-rich river gravels are common in areas where quartz veins are abundant.

Granitic pegmatites are another common source of quartz. Most pegmatite bodies occur in granitic rocks and are a coarse-grained intergrowth of principally feldspar and quartz. Quartz crystals several inches or even a few feet in diameter are not uncommon in large pegmatite pods.

Occurrence in California

Quartzite, vein quartz, and quartz gravel are abundant and widespread in California; quartz in pegmatite is more restricted in occurrence. Quartzite occurs most abundantly in the Great Basin and the Mojave Desert, and also in the Klamath Mountains, Coast Ranges, Sierra Nevada, and Peninsular Ranges. Quartz veins are most common in the western foothills of the Sierra Nevada, but also are locally abundant in other mountainous regions of the State. Quartz gravels derived largely from quartz veins are common in Recent and Tertiary stream channels in the Sierra Nevada. Quartz in granitic pegmatite is mostly found in the Peninsular Ranges.

The principal source of quartzite production in California has been from quartzite layers in the Oro Grande Formation of Carboniferous(?) age near Victorville. The silica content ranges from 98.5 to 99.1 percent in this tough, massive, pink rock that is used chiefly for portland cement and for silica refractories (silica brick).

In the Great Basin and Mojave Desert provinces of California, several pure quartzite formations are widespread. The Stirling Quartzite of late Precambrian age crops out over a large area in the Death Valley region and contains some remarkably pure parts. In the same region the Zabriskie Quartzite of Early Cambrian age is also present. Though not so thick as the Stirling, it is widespread and exceptionally pure. Within the Harkless Formation of Early Cambrian age in the Inyo Mountains thick pure quartzite is exposed over large areas. The Eureka Quartzite of Ordovician age is remarkably pure quartzite, a few hundred feet thick, which is exposed extensively in the Great Basin. These occurrences represent an almost inexhaustible supply of pure quartzite, but they are, for the most part, a considerable distance from population centers and many outcrops are far away from suitable transportation at present. In the southern Inyo Mountains, however, the Eureka Quartzite has been quarried to some extent and the quartzite utilized in the manufacture of silica brick and other industrial uses.

Massive quartz veins are widespread in the western foothills of the Sierra Nevada. These veins are most common in the Mother Lode belt, a system of linked quartz veins extending for more than 100 miles. Many of the veins contain gold and sulfides, but some barren veins have been a source of silica. One vein at White Rock in western Mariposa County, west of the Mother Lode, crops out for a distance of 300 feet and is 150 feet wide. This white "bull" quartz was quarried in the 1940's and 1950's and used to manufacture ferrosilicon. Mostly in the 1920's and 1930's vein quartz was mined in the foothills of Tuolumne, Calaveras, El Dorado, Fresno, and Placer Counties, and used for fluxing material in steel furnaces, and as abrasives and scouring powder. A massive quartz vein of the Mother Lode belt south of Jacksonville is quarried, crushed, bagged and sold as turkey grit. Vein quartz was also mined to a lesser extent in the Transverse Ranges of Los Angeles County, in the Coast Range in Stanislaus County, and in the Klamath Mountains. For the past few years quartz gravels have been mined from the Bear River and sent through a grinding plant at Colfax. The quartz is crushed and then fine ground for use in scouring powder.

Quartz from pegmatite deposits comes chiefly from the Peninsular Ranges of San Diego and Riverside Counties, though some has been produced from Kern and Imperial Counties. The largest operations were near Murrieta in Riverside County, where quartz was used in abrasives and ceramics in the 1920's and 1930's; much of the pegmatite quartz is a byproduct of feldspar mining. Other pegmatite quartz production has come from near Nuevo and Winchester in Riverside County, and from the Jacumba and Live Oak Spring areas in San Diego County. Some pegmatite quartz production also comes from near Rosamond in Kern County.

RESOURCE POTENTIAL

The supply of high-quality quartzite is virtually unlimited for the foreseeable future in the Great Basin and the Mojave Desert. Vein quartz material is extremely abundant in the western Sierra Nevada foothills. Quartz gravel is likewise abundant in some Sierra Nevada river channels, but not too common elsewhere in the State. Pegmatite quartz in quantity is mostly limited to the Pennisular Ranges and at present its production depends on feldspar mining. Quartzite and quartz are at a disadvantage to quartz sand for uses that require a fine-grained source of silica. The crushing and grinding required to reduce quartzite and quartz to fine-grain size are expensive and measures to reduce the hazard of silicosis also add to the cost of crushing and grinding.

The present pattern of production consists of relatively small producers and a somewhat stable, but small market. Some of the production of silica for industrial uses is esentially a by-product of quartzite and quartz production for construction uses.

Future production is not dependent on raw material so much as on mining and marketing costs. Many large bodies of pure quartzite are now amenable to quarrying but they are not commercial because they are long distances from adequate road and rail transportation. The major California market for quartzite is the Los Angeles metropolitan complex and other mushrooming urban areas. Commercial growth and development in these areas means increasing needs for industrial silica. The quartzite deposits of the Great Basin and the Mojave Desert are a readily available source to suppy these future needs.

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RARE EARTHS

(By J. W. Adams, U.S. Geological Survey, Denver, Colo.)

The rare-earth metals comprise the 15 elements having atomic numbers 57 to 71. They include lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu). One of these elements, promethium, has been known only as an artificially produced isotope until its recently reported discovery as a trace constituent of the rare earths recovered from apatite in a phospate plant in Finland (U.S. Bur. Mines, Mineral Trade Notes, 1965). Yttrium (Y), with atomic number 39, is also classed with the rare earths because of its chemical similarities and geochemical affinities.

The first seven elements listed above (La through Eu) are included in the cerium group of rare earths, so called because cerium is their most abundant member. The remaining eight elements (Gd through Lu), together with yttrium, are called the yttrium group. The two groups are also referred to, respectively, as the "light" and "heavy" rare earths.

The properties of the members of the two groups of rare earths are sufficiently distinct to cause one group to predominate over the other in most minerals, even though all or nearly all are ordinarily present (Olson and Adams, 1962). The rare earths are found in a large number of minerals, only a few of which have been found in sufficient concentration to be used as ores. The most widely used source material is monazite, a rare-earth phosphate, that is also an important ore mineral of thorium (See Thorium section). Bastnaesite, a rare-earth fluocarbonate that is less common than monazite, is now being actively mined from a very large deposit at Mountain Pass, in San Bernardino County.

Commercial monazite commonly contains 55 to 60 percent combined rare-earth oxides and 3 to 10 percent thorium oxide (Kelly, 1962, p. 5). Bastnaesite has a slightly higher rare-earth content than does monazite, but contains little or no thorium. Both monazite and bastnaesite contain predominently cerium group rare earths, but during the processing of these minerals, notably monazite, there is a recovery of yttrium and the heavy rare earths that has so far met much of the demand. Increased applications of yttrium and the heavy rare earths may, however, require other sources, so there is a growing interest in deposits containing minerals in which yttrium group elements predominate. Such minerals include xenotime—an yttrium phosphate, and euxenite—a multiple oxide of yttrium, niobium, and titanium. Minable deposits of these minerals are uncommon, but xenotime has been obtained from monazite placers at Aiken, South Carolina, and euxenite has been recovered on a large scale, primarily for its niobium content, from placers at Bear Valley, Idaho.

The rare-earth industry is developed largely around the cerium group elements obtained from monazite and bastnaesite. Concentrates of these minerals containing nearly 2,350 short tons of rare-earth oxides were apparently processed in the United States in 1963 (Parker, 1965). The rare earths contained in the ore minerals are converted into a variety of products, including cerium oxide, salts of the elements in varying degrees of purity, and *misch metal*, which is a mixture of the rare earths in their metallic state.

For most industrial uses, materials containing several of the rare earths in partly purified compounds are satisfactory. Products equivalent to about 1,800 tons of rare-earth oxides are used each year in these bulk applications (Chem. Eng. News, 1965) which include glass polishes, cores for arc-light carbons, catalysts, and the manufacture of misch metal which is used for sparking alloys and in metallurgical applications.

The development of ion exchange techniques for the separation of rare-earth elements has made high-purity metals and compounds available at greatly reduced cost and has thus stimulated research as to applications where their individual properties may be useful. A small but growing part of the industry is concerned with meeting the demand for these purified materials, both for further research and for newly discovered uses, which so far have been largely in the fields of nuclear energy and electronics. Two of the more promising applications are the manufacture of synthetic yttrium-iron garnets for electronic use, and the recently publicized development of new red phosphors employing europium-doped yttrium-vanadium compounds for use in color television tubes (Chem. Eng. News, v. 43, no. 19, 1965). Other actual and potential uses are discussed by Parker (1965, 1965A) and Mandle and Mandle (1964).

The marketing of rare-earth ores is difficult, particularly in small lots, and prices are generally determined by negotiation between buyer and seller. The prices paid for imported monazite depend on the thorium oxide and rare-earth oxide content and have ranged in recent years between 10 and 20 cents per pound (Parker, 1965).

Occurrences in California

California contains the free world's largest known concentration of rare-earth minerals in the Mountain Pass district in San Bernardino County (No. 6). Since the discovery of bastnaesite in the area in 1949, the district has been intensively studied (Olson and others, 1954) and deposits of rare earths and thorium were found to occur in a belt about 6 miles long and 1½ miles wide. This belt, which consists of Precambrian metamorphic and igneous rocks, is bounded on the east and south by alluvium, and on the west and north by major faults. The metamorphic complex within the belt has been intruded by potash-rich rocks, considered to be of Precambrian age, that range from shonkinite through syenite to granite. Dikes of probable Tertiary age are also found in the complex.

Rare-earth minerals, chiefly bastnaesite, occur locally in carbonate-rich veins and in the very large Sulfide Queen carbonate body that is now being mined by The Molybdenum Corp. of America. This deposit, which is 2,400 feet long and as much as 700 feet wide is estimated to contain 10 percent rare-earth fluocarbonate minerals, 20 percent barite, 10 percent quartz and silicate minerals, and 60 percent carbonate minerals, chiefly calcite (Olson and others, 1954, p. 29–30). According to Kruesi and Duker (1965), there are "4 billion pounds of rare-earth oxides in proven ore with the deposit still not delineated in depth." The Sulfide Queen carbonate mass as well as the many smaller carbonate bodies in the area presumably were derived from the same source as the somewhat older potash-rich rocks in the area; such carbonate-rich intrusive rocks, or *carbonatites*, are relatively uncommon, but are of increasing worldwide interest as sources of niobium, thorium, and the rare earths.

The bastnaesite in the Mountain Pass ore is recovered by flotation and then is leached with hydrochloric acid to remove remaining admixed carbonate minerals, giving a product containing 72 percent rare-earth oxides. By roasting the purified bastnaesite to remove fluorine and carbonate, the content of rare-earth oxides is raised to over 90 percent (Parker, 1965). In July, 1965, a new plant was put in operation at Mountain Pass for the separation of europium and other individual elements present in the ore (Mining Engineering, 1965).

Although the bastnaesite-bearing carbonatite body at Mountain Pass is the only rare-earth deposit being mined in California, many other occurrences of rare-earth minerals are known in the State. Some of these are shown in figure 66 and are listed in table 38 together with literature references. These deposits are of two principal types.

TABLE 38.—*Rare-earth mineral occurrences in California*

Index No. on fig. 66	Locality	Mineralogy and type of deposit	References
1	Little Nell mine	Brannerite in albitite dike	Pabst and Stinson, 1960.
2	Dean's mine	Brannerite in quartz vein	Pabst, 1954.
3	Hunter Mountain	Allanite in pegmatite	McAllister, 1956.
4	Lemon Cove	Allanite, minor monazite in pegmatite.	D. F. Hewett, oral comm., 1960.
5	Kern River area	Euxenite, allanite, xenotime(?) in pegmatites.	MacKevett, 1960.
6	Mountain Pass area	Bastnaesite, parisite, monazite, cerite, sahamalite in carbonatite and veins.	Olson and others, 1954; Glass, Evans, Carron, and Hildebrand, 1958.
7	Rainbow Group	Monazite in pegmatite	Walker and others, 1956.
8	Marl Springs area	Monazite(?) in metasediments cut by pegmatites and granite.	Olson and Adams, 1962.
9	Hoerner-Ross	Betafite and cyrtolite in pegmatite	Hewett and Glass, 1953.
10	Roll Prospect	Allanite in granitic detritus	Walker and others, 1956.
11	Gorman area	Monazite(?) in shear zones in granite; also in biotite-rich layers and pegmatite zones.	Olson and Adams, 1962.
12	Hope prospect	Rare-earth minerals in contact metamorphic rocks.	Chesterman and Bowen, 1958; Southern Pacific Co., 1964.
13	Lokey prospect	Allanite in gneiss	D. F. Hewett, oral comm., 1960.
14	Old Woman Springs	Brannerite and euxenite in gneiss	Hewett, Stone, and Levine, 1957.
15	Pacoima Canyon	Allanite in pegmatite	Neuerburg, 1954.
16	Little Tajunga Canyon	Monazite in biotite schist	G. J. Neuerburg, oral comm., 1965.
17	Gillespie prospect	Monazite in quartz lenses in schist	D. F. Hewett, oral comm., 1960.
18	Lucky Seven and Birthday No. 4.	Allanite, and monazite disseminated in biotite-rich pods in granite.	Walker and others, 1956.
19	Rock Corral area	Allanite, xenotime(?) and monazite(?) in quartz monzonite. Euxenite, allanite, and monazite at Pomana Tile Quarry pegmatite.	Moxham and others, 1955; Hewett and Glass, 1953.
20	Steiner prospect	Allanite(?) and monazite in biotite schist.	Walker and others, 1956.
21	Copper Mountain area	Monazite and allanite in biotite-rich parts of gneissoid granite.	Walker and others, 1956.
22	Alger Creek	Allanite and uranothorite in pegmatitic zone in gneiss.	Hewett and Stone, 1957.
23	Music Valley	Monazite and xenotime in metamorphic rocks and migmatite.	Evans, 1964.
24	Southern Pacific Silica Quarry.	Xenotime, monazite, multiple oxides in pegmatite.	Patchick, 1960.
25	Winchester	Xenotime and monazite in pegmatites.	Murdoch and Webb, 1956.
26	Desert View	Monazite in gneiss, associated chiefly with biotite schist.	Walker and others, 1956.
27	Eureka prospect	Monazite in biotite schist	Olson and Adams, 1962.
28	Pala district	Allanite, monazite in pegmatites	Murdoch and Webb, 1956.

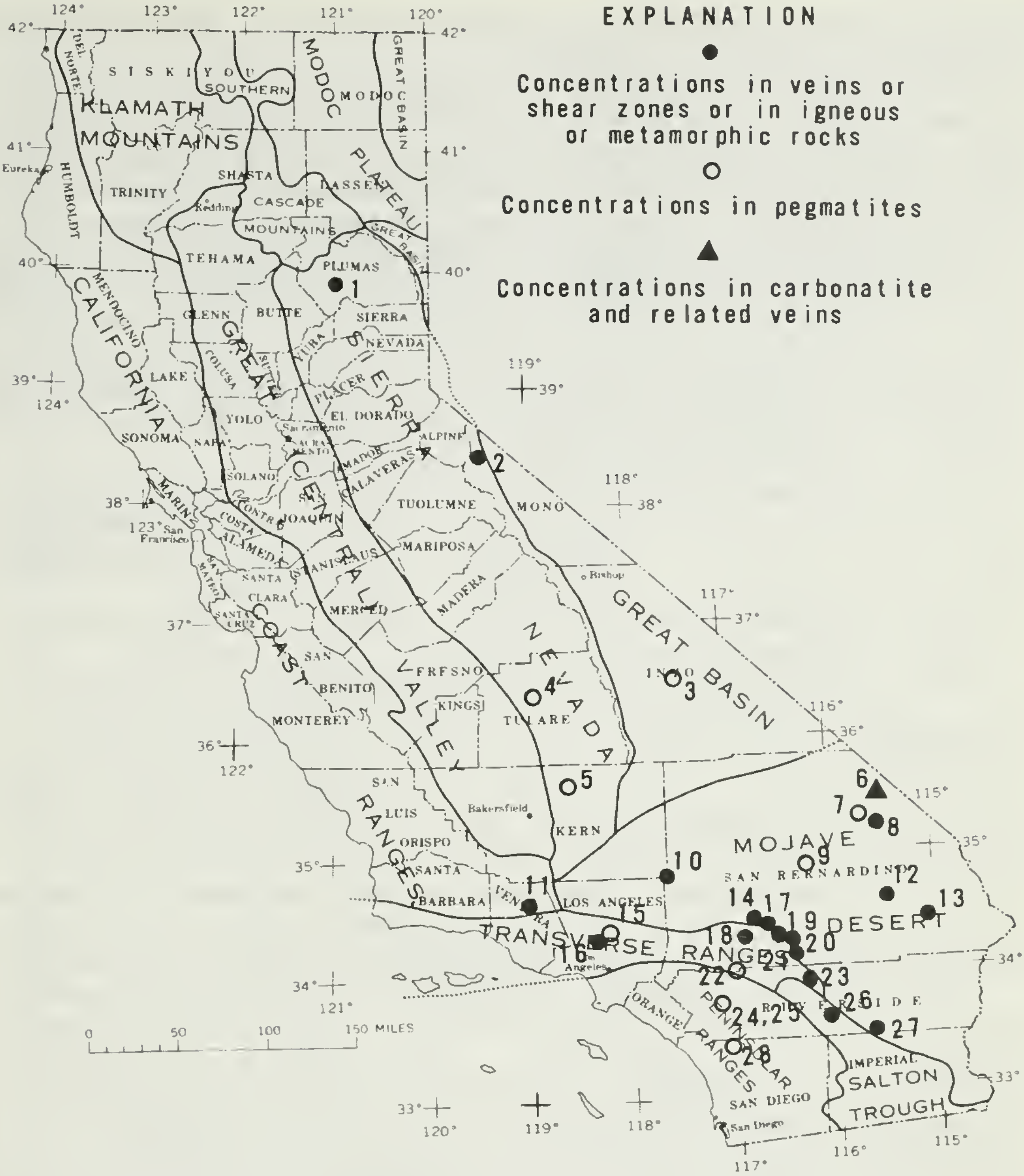

FIGURE 66. Rare-earths in California (number refers to table 38).

Deposits of the first type are pegmatites. These are commonly dike-like bodies that range from a few inches to thousands of feet in length. They are found in crystalline rocks and are characterized by large, but extremely variable, grain size. Most pegmatites are granitic in composition, having as their dominant minerals quartz, feldspar, and mica, which are the minerals found in ordinary granite. A large number of minerals containing rare earths have been found in pegmatites, but of these monazite and allanite, a silicate of calcium, iron, and the rare earths, are probably the most common. A notable pegmatite ocurrence is the Southern Pacific silica quarry near Nuevo (No. 24), in which monazite, xenotime, and samarskite have been reported. Pegmatites, in general, are not an economic source of the rare earths as the small quantity of rare-earth minerals found in any one pegmatite, and the diverse mineralogy commonly represented, make marketing of these ores difficult or impossible.

Deposits of the second type are segregations of rare-earth minerals in metamorphic rocks or in biotite-rich zones in igneous rocks. Several such deposits were found during the period of intensive search for uranium, as all show some degree of anomalous radioactivity due largely to thorium. Most commonly, deposits of this type contain only monazite, but in the southern Music Valley (No. 23) concentrations of xenotime with subordinate monazite are found in biotite-rich zones in gneiss in a northwest-trending belt about 3 miles wide and 6 miles long (Evans, 1964). An unusual occurrence of euxenite and brannerite, the latter a multiple oxide of uranium and titanium containing rare earths, was found in granite gneiss near Old Woman Springs in San Bernardino County (No. 14).

Brannerite, together with gold, was found in an albite-rich dike at the Little Nell mine in Plumas County (No. 1), and with molybdenite and other sulfides in a quartz vein at Dean's mine in Mono County (No. 2).

Rare-earth minerals are reported to occur in a contact metamorphic deposit at the Hope mine in San Bernardino County (No. 12).

Placer deposits, in which monazite and other heavy minerals have been concentrated in sands formed by the weathering of igneous and metamorphic rocks, are the source of rare-earth minerals in many parts of the world. No important placer deposits of these minerals appear to have been found so far in California, although minor amounts of allanite, monazite, xenotime, and euxenite occur locally in coastal beach sands (Hutton, 1959), and monazite has been reported among the heavy mineral assemblage in the sands of streams at several localities in the State (Chesterman, 1950; Stinson, 1957).

Many additional deposits of rare-earth minerals undoubtedly remain undiscovered in California. This is particularly true of concentrations in metamorphic rocks, which easily can be overlooked unless their generally high anomalous radioactivity is detected. The recognition of some rare-earth minerals can be facilitated by the use of a hand spectroscope by which characteristic absorption bands produced by certain rare-earth elements can be seen when the mineral is examined in strong white light (Mertie, 1960; Adams, 1965).

With the notable exception of the Mountain Pass deposits most of the rare-earth occurrences in California are at present of unknown potential or of mineralogical interest only. An increased demand for yttrium, or any of the other heavy rare-earth elements, could possibly make the xenotime-bearing gneiss deposits minable, providing sufficient tonnage is available for sustained operation.

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SALT

(By G. I. Smith, U.S. Geological Survey, Menlo Park, Calif.)

Salt is one of the basic commodities of man. For centuries it has been used almost universally as an element of diet and as preservative, although it was probably unobtainable to most primitive tribes that were remote from oceans, saline lakes, and salt springs. However, as trade routes became established, and as man began to cook his food, it became a virtual necessity to most groups and an important item of trade. Because of its importance, some cultures endowed salt with religious significance, others affixed a tax to it, and still others used it as a form of currency.

The earliest recorded use of salt in California was by the Indians who occupied this area for thousands of years before the arrival of white settlers. Their supply came chiefly from salty grass, seaweed, saline waters, and solid deposits. Virtually every tribe in the State used one of these forms of salt routinely, although those tribes that lived to the north apparently used none (Heizer, 1958).

Most of the early white settlers in California lived near its coast or along the edges of its bays, and they obtained salt from tide pools. Salt was first "manufactured" in 1856 by a settler who built levees around tide pools along the edge of San Francisco Bay to improve their capacity. This was the beginning of the salt industry in California, and, as indicated by the data in table 39 and figure 67, it grew rapidly from that time on.

TABLE 39.—*Estimated production capacity, sea water-evaporation plants in California*

Company	Source of sea water	No. on fig. 67	Areas of crystallization ponds (acres)	Estimated production capacity [1] (tons per year)
Leslie Salt Co	San Pablo Bay	1	[2] 180	[3] 100,000
Do	San Francisco Bay	3, 4, 5	[4] 2,300	1,265,000
Western Salt Co	San Diego Bay	9	[5] 100	55,000
Do	Newport Bay	8	[5] 8¼	4,500
Oliver Bros. Salt Co	San Francisco Bay	3	[5] 24	13,200
Western Salt Co	Monterey Bay	6	[5] 7	3,800
Total (rounded)				1,450,000

[1] Except as indicated, estimated from crystallization pond area, using factor of 550 tons per year per acre (See, 1960, p. 100).
[2] Approximate, estimated from data on production in Ver Planck, 1958, p. 43, and factor of 550 tons per acre per year (see 1960, p. 100).
[3] Ver Planck, 1958, p. 43.
[4] Approximate, estimated from U.S.G.S. topographic maps.
[5] Ver Planck, 1958, chap. 2.

A few years later, in 1862, the Comstock Lode was discovered in Nevada, and, because salt was one of the raw materials needed to process the ores, a major increase in production from the San Francisco Bay area took place. The steady population increase in California during and after this period further increased the demand for salt for table use and food curing. Because of quality differences, imports supplied most of these needs until well into the 1870's, but by 1880, the quality of domestic evaporated salt had improved to a point where imports ceased, and salt began to be exported. By this time, many small plants had been developed around San Francisco Bay and else-

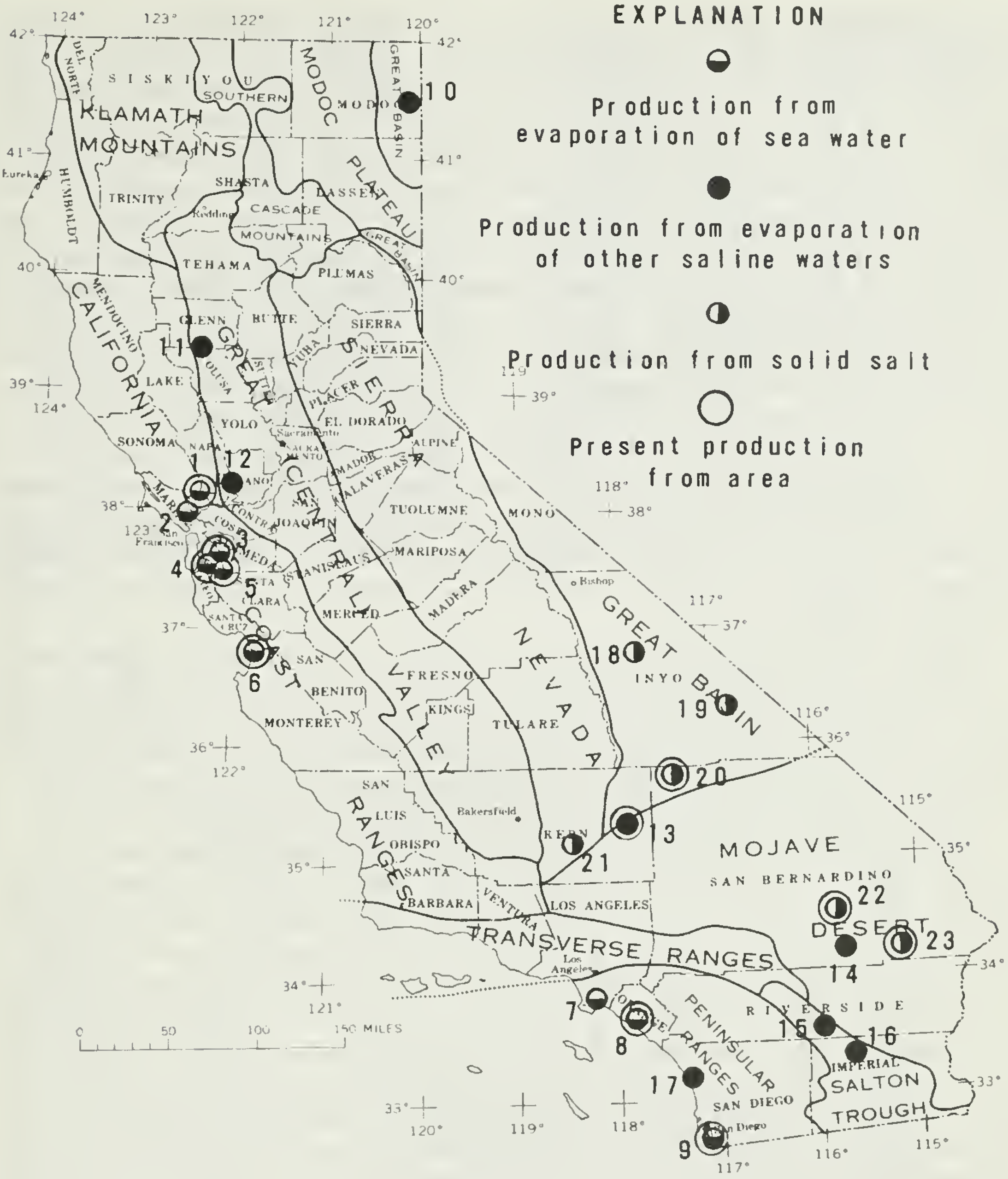

FIGURE 67. Salt deposits in California (numbers refer to table 40).

where in the State. Around 1900, there were about 20 plants in the San Francisco Bay area, and solar evaporation plants were being started in the San Pedro and San Diego Bay areas. Over the next 40 years, a series of company mergers in the San Francisco area took place, and, by 1940, only three companies remained, the Leslie Salt Co., the Oliver Bros. Salt Co. (started in 1937), and the American Salt Co. (Ver Planck, 1958). Of these, only the first two are still in production.

Production of salt from inland sources began in the 1880's and became significant in the early 1900's. Some of these deposits consisted of brine, others of solid salt. Almost all of these have had a history of intermittent production as a result of purification difficulties and high transportation costs. Four deposits are still in production, Koehn Lake, Searles Lake, Danby Lake, and Bristol Lake.

The geologic occurrences of salt are varied. Besides the almost unlimited quantities available from the oceans, it is found in the United States as rock salt and brines in marine sedimentary deposits of all ages and in nonmarine deposits of late Cenozoic age. The major deposits of rock salt in the United States are of marine origin. Most current production comes from those of Silurian age in the New York-Pennsylvania-Ohio-Michigan area, and those found as salt domes in the Gulf Coast area. Other large marine deposits are of Permian age in the Kansas-Oklahoma-Texas-New Mexico area; of Devonian, Mississippian, Permian, and Jurassic ages in the North Dakota-South Dakota-Montana area; of Pennsylvanian age along the Utah-Colorado boundary area; and of Permian age along the Arizona-New Mexico boundary area (Lang, 1957; Landes, 1960; Bersticker, 1963). Extensive areas underlain by subsurface brines also occur in and around West Virginia and southeastern Illinois. Large nonmarine deposits of Pliocene age are known in southeastern Nevada (Mannion, 1963). Smaller deposits are found in the Western United States in the form of brine wells and springs, outcrops, and saline lakes or salt flats.

Many of these smaller deposits occur in California. Brine wells and springs having diverse geologic settings occur in the northern part of the State; salt outcrops are found in an area of deformed late Cenozoic (continental) nonmarine sediments at the south end of Death Valley; saline lakes and salt flats occur in many of the closed basins of the Great Basin, Mojave Desert, and Salton Trough provinces.

The deposits in closed basins are of Quaternary age and consist of saline lakes or dry playas underlain by saline brines. They are the results of climatic fluctuations that took place during the Quaternary Period; the wetter periods accelerated the introduction of dissolved saline material into these basins, and the drier periods caused these accumulations to precipitate on the floor of the lake. The compositions of these deposits are variable, though, because each basin was the site of a unique set of controls; among the significant compositional controls were the lithologies of the rocks in the drainage area, the abundance and character of the mineral springs, the hydrologic history of the waters entering the valley, and the character of successive climatic cycles. This variability has caused many of the commercial failures on such deposits because the extraction and purifying techniques used successfully on one cannot be adapted easily to another. The compositions of deposits precipitated from sea water were affected by some of these variables, but the chemical makeup of the starting water was much more uniform.

In 1963, over 100 million tons of salt was produced throughout the world. The United States produced over 30 million tons of this total, with a value of about $185,000,000. About 83 percent of this production came from plants in Louisiana, Texas, New York, Michigan, and Ohio. Eleven percent came from smaller plants in Virginia, West Virginia, Alabama, North Dakota, Oklahoma, Kansas, Colorado, Utah, New Mexico, Nevada, and Hawaii. California provided a little less than 6 percent (Kerns 1964).

Production of salt in California during 1963 was a little over 1,700,000 tons. Most of this came from solar evaporation plants along the coast. An estimate of the production capacity of these coastal plants (table 40) suggests that they may have provided as much as 85 percent

TABLE 40.—*Salt deposits with record of production in California*

[Data from Ver Planck (1957, 1958)]

No. on figure 67	Method of production	Description of deposit or source of salt	Dates of production from area	Other data
1	Solar evaporation	Sea water from San Pablo Bay	1954(?) to present	Operated by Leslie Salt Co.
2	do	Sea water from San Francisco Bay	1906	
3	do	do	1862 to present	Includes property owned by American Salt Co., and those operated by Oliver Bros. Salt Co., and Leslie Salt Co.
4	do	do	1901 to present	Operated by Leslie Salt Co., property in part being proposed as housing development.
5	do	do	ca. 1864 to present	Operated by Leslie Salt Co.
6	do	Sea water from Monterey Bay	1916 to present	Operated Monterey Bay Salt Works, by Western Salt Co.
7	do	Sea water from San Pedro Bay	1902 to 1945	Last operated by Long Beach Salt Co.
8	do	Sea water from Newport Bay	1936 to present	Operated by Western Salt Co.
9	do	Sea water from San Diego Bay	1901 (1870(?)) to present	Do.
10	do	Middle Alkali Lake, brines from well on shore	1912–42	
11	do	Brines from springs	1892–1908	
12	do	Brine from gas well	1907–1918	
13	do	Koehn Lake, brine from surface and wells	1911 to present	Do.
14	do	Dale Lake, brine from wells	1950	Salt harvested from solar ponds built by Dale Chemical Industries, producers (1939–48) of sodium sulfate.
15	Collection of surface crusts and solar evaporation.	Salt crusts on surface and brine from Salton Sea.	1884–1905, 1929	Earlier production mostly from salt crusts; later production (1,500 tons) from solar evaporation of brine.
16	Solar evaporation	Brine from Salton Sea, springs, and wells	1919, 1935–47	
17	do	Brine from shallow wells near coast	1901–02	
18	Collection of crusts	Saline Valley, salt crusts on floor	1903–04, 1913, 1915–18, 1920, 1926–30, 1954.	Salt purified by recrystallization, shipped to railroad siding by 13½-mile aerial tramway.
19	do	Death Valley, salt crusts, near Badwater	1942	
20	Stripping from surface	Searles Lake, salt on surface	1921–26, 1933, 1951 to present	Operations by Pacific Salt and Chemical Company from land held by American Potash & Chemical Corp.
21	Collection of crusts	Proctor (Cameron) Lake, crusts on floor	Before 1888	
22	Stripping from surface and solar evaporation of brine.	Bristol Lake, salt on surface and brines from subsurface.	1909–1913, 1918 to present	Production mostly calcium chloride from brines; some salt produced from brines, the rest by stripping the surface.
23	Stripping and blasting, solar evaporation of brine from wells.	Danby Lake, lenses of salt interbedded with moist clay beneath surface, and brines porous salt beds.	1890–94, 1916–17, 1934–42, 1963	Production in 1963 by Metropolitan Water District of Southern California.

of the State's total and that inland sources may have provided only about 15 percent. Over 90 percent of the coastal production capacity lies in the San Francisco Bay area.

This predominance of salt production by means of solar evaporation is in marked contrast to the sources utilized throughout the rest of the United States; about 60 percent of national production comes from solution mining of underground deposits, 35 percent comes from underground mining of such deposits, and 5 percent comes from solar evaporation of sea and lake brines (MacMillan, 1960). It is evident, therefore, that California, with less than 6 percent of national production, has contributed most of the Nation's salt produced by solar evaporation.

The large consumers of salt in the United States are chemical industries. In 1963, manufacturers of chlorine and its coproduct sodium hydroxide consumed 39 percent of national production, manufacturers of sodium carbonate by the Solvay process consumed 21 percent, and manufacturers of other industrial chemicals consumed 2 percent; table and other household uses account for less than 3 percent (Kerns, 1964). Because of its geographic position and industrial balance, California's production is used somewhat differently; a slightly higher percentage is used for chlorine-sodium hydroxide production, none is used for sodium carbonate production, about the same percentage is used for other chemicals, and distinctly higher percentages are used for water treatment and refrigeration (Ver Planck, 1958, p. 95; 1957, p. 490).

Because salt is so plentiful and widespread, it is a relatively cheap substance. In 1963, the average value in bulk lots of solar-evaporated salt was quoted as $5.74 per ton; rock salt was quoted at $6.19 per ton (Kerns, 1964). However, the costs of transportation add substantially to the delivered price. For example, rail freight rates for salt in 1954 from salt plants near Newark (on the southeast side of San Francisco Bay) were $1.42 per ton to San Francisco, $7.83 to Los Angeles, and $8.86 to Seattle; rates from Searles Lake were $10.64 to San Francisco, $4.26 to Los Angeles, and $16.83 to Seattle (Ver Planck, 1958). These data make it evident that transportation costs account for over half the delivered price to all but the closest major markets.

Transportation by ship, though, is relatively cheap; for example, salt is transported from Louisiana to east coast markets for $12 per ton by sea train compared with $18 per ton by rail. In 1963, California imported nearly 50,000 tons of salt by ship from foreign countries, most of which probably came from Mexico (Kerns, 1964). New sources being developed in Mexico and other central and South American countries are likely to increase this imported tonnage.

The future supplies of salt to the United States and California are theoretically almost unlimited. Actually, though, an unlimited supply is of little use to those industries that require it unless the price remains low. Because of transportation costs, this means that salt production facilities must remain close to those industries. The bulk of California industry of this type depends on salt from solar evaporation plants along the coast, and in the future, with increasing population pressures, these sources of supply may be threatened. At present, thousands of acres of evaporating ponds in the San Francisco Bay area are being reclaimed for housing developments. If population pressures in California continue, this alternative use of such land may become more attractive to its owners, both around San Francisco Bay and in other areas—most of which also lie on reclaimable land near large and expanding population centers.

Thus, the long-term prospects for a continued supply of salt from these solar evaporation plants is uncertain. To maintain the present balance of supply and demand, it appears that unless reclamation of such land for real estate uses is found to be impractical, population pressures must decrease. Otherwise, the cost of salt to the nearby industrial users will have to increase, either because higher prices would be needed to justify production from these lands or because more distant suppliers would be used. The supplies of salt from these more distant areas are probably adequate, but the costs of transportation are likely to be higher. Transportation by ship from the gulf coast or foreign countries might minimize this added cost, but the economic pressure will encourage salt-consuming industries to locate nearer those sources in the future.

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SAND AND GRAVEL

(By H. B. Goldman, California Division of Mines and Geology, San Francisco, Calif.)

California's economic and population growth has been paralleled by the growth of one of its leading nonmetallic commodities—sand and gravel. The continued influx of population with resulting demands for homes, industrial buildings, highways, and public works projects has given impetus to this valuable industry. California has been the leading state in the nation since 1942 in sand and gravel production, and, within the State, that industry is exceeded only by production of petroleum products and cement.

In commercial usage "sand" applies to rock or mineral fragments ranging in size from three-thousandths of an inch to a quarter of an inch. "Gravel" consists of rock and mineral fragments larger than a quarter of an inch ranging up to 3½ inch maximum size. Approximately nine-tenths of the State's output is used as aggregate in mixtures of either portland cement or asphaltic compounds for use in construction or road building. The remaining tenth is special sand, mostly used in glass making, sandblasting, filters, and foundry processes.

The building industry uses sand and gravel as aggregate in portland cement concrete; the paving industry uses sand and gravel in both asphaltic mixtures and portland cement concrete. Aggregate is commonly designated as the inert fragmental material which is bound into a conglomeratic mass by cementing materials such as portland cement, asphalt, or gypsum plaster.

The principal markets for most commercial producers are within areas of greatest population density. Large volumes of aggregate are also used in public works and highway construction throughout the entire State. The present economic limit to the distance sand and gravel can be hauled differs through out the State; the maximum haul is about 40 miles. Little sand and gravel is sent out of the State except for a few producers near the State border.

Geologic Occurrence

In California, sand and gravel is obtained commercially from rock units of many types and ages. Quaternary stream deposits in channels, floodplains, terraces, and alluvial fans; and Recent beach and dune sands are the common sources. In some areas in California, sand and gravel is obtained from pre-Quaternary formations.

Stream deposits

The bulk of California's aggregate is obtained from the natural sand and gravel in stream deposits. California's rugged mountains are drained by streams which transport, in flood stage, huge volumes of sand and gravel which is deposited in channels, floodplains, and terraces. These deposits are the most favorable sources of aggregates for many reasons. Most source streams are dry a large part of the year, most of the deposits are easily accessible, and mining operations are commonly relatively simple. In some streams, excavated material is replenished during flood stage so that decrease in reserve is slight. The sand and gravel in stream deposits are most suitable for aggregate, because the natural abrasive action of stream transport grinds up and removes soft, weak rocks, and concentrates the hard and firm particles. Streams also exercise a sorting action so that the sand and gravel are often obtained in the size gradations necessary for aggregate. Individual particles undergo some degree of rounding and range from subrounded to very well rounded. Rounding is desirable in aggregate for portland cement concrete work, as rounded particles give a more workable mix with less cement and care than concrete made with angular particles.

In spite of the advantages, some stream deposits are not exploited due to such economic factors as inaccessibility, excessive distance to market, insufficient tonnage of materials available, and restrictive civic legislation. In addition, some deposits are unsuitable beause they contain harmful ingredients such as physically unsound or chemically reactive rocks. The nature of the material in a stream bed is determined by the nature of the source rocks within its drainage area. The different geologic formations drained by the stream contribute many varieties of rock types which show a wide range in chemical composition, physical soundness, and degree of weathering. Thus, there is danger of encountering unsound or chemically reactive rock in a deposit if such rocks occur anywhere within the drainage basin. Some thick deposits may contain severely decomposed material at shallow depths beneath seemingly fresh and durable materials. In some older stream deposits, such as stream terraces, undesirable coatings may be present on the grains, or the materials may be partly decomposed.

Alluvial fan deposits

Alluvial fan deposits also are widely exploited for aggregate. An alluvial fan is a gently sloping fan-shaped mass of loose rock material deposited at the mouth of a canyon where a stream leaves the mountains and enters an adjacent plain. Fan deposits ordinarily contain lenticular beds or tongues of poorly sorted sand and gravel interbedded with varying proportions of silt and clay. Suitable aggregate is obtained from these deposits in areas where excessive amounts of clay are not present.

Beach and dune sand deposits

About two percent of California's total output of sand and gravel is produced from beach and dune deposits. The deposits consist almost entirely of sand, which is used as concrete and plaster sand, or as a specialty sand.

Pre-Quaternary formations

Pre-Quaternary formations, particularly partly consolidated, poorly cemented marine sedimentary beds of sandstone and conglomerate, also are sources of aggregate. Most formations of this nature are inaccessible, have heavy overburdens, are too well cemented, or contain too much clayey material to be economically processed for aggregate through normal washing and screening operations.

History of Production

Records of sand and gravel production in California date back to 1893. In 61 years, from 1893–1964, almost two billion tons of sand and gravel valued at about 1.8 billion dollars were produced in the State. In the ten years from 1954–1964, about one billion tons were produced (fig. 68). Thus, more than half of the total recorded production for 71 years was produced since 1954. Sand and gravel production in California has constantly risen since 1900, with minor recessions during post-World War I years and the depression years of the 1930's. Since 1942, California's production has risen from 28 million tons valued at 15 million dollars to the 112,995,000 tons, valued at $129,333,000, produced in 1964.

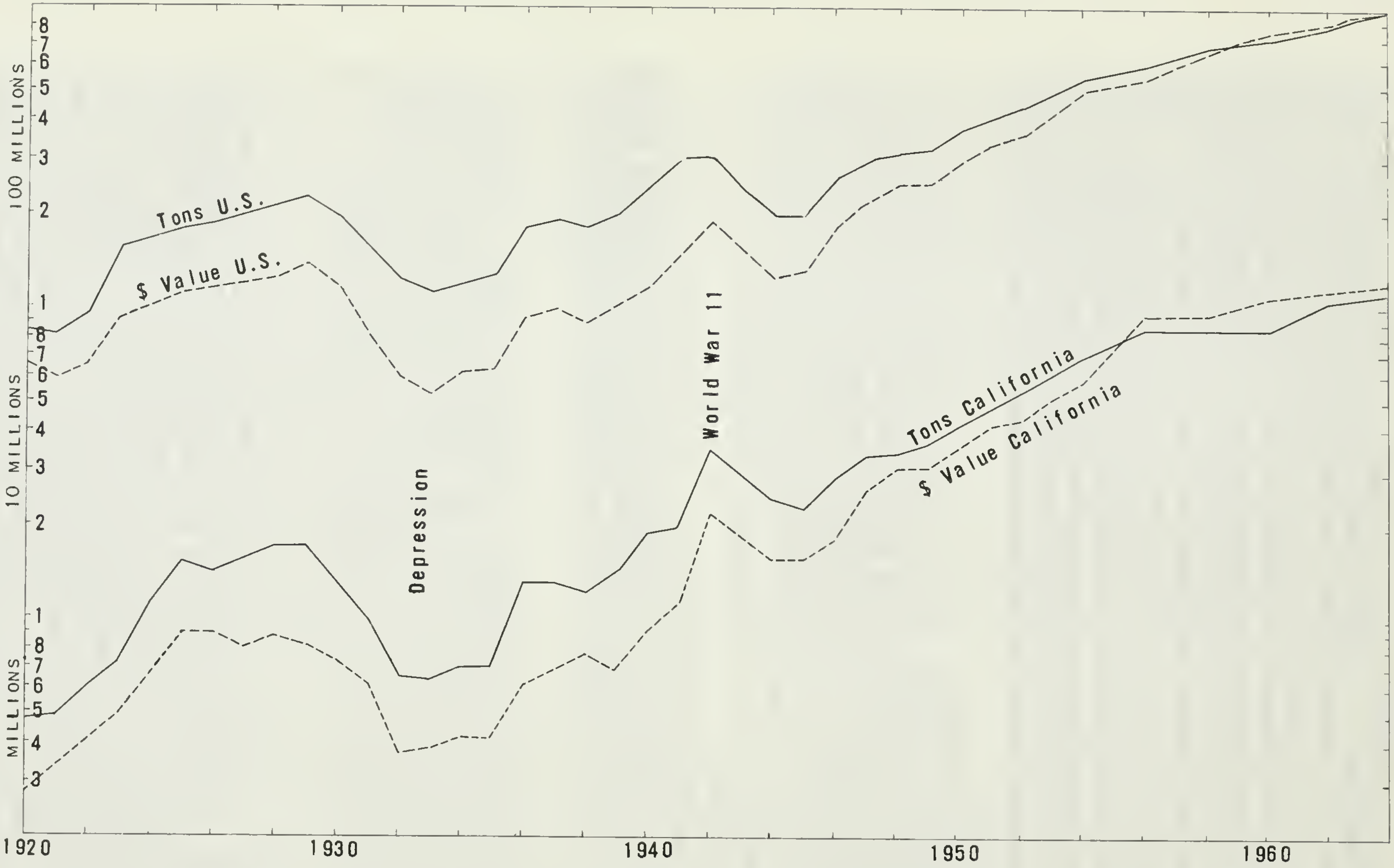

FIGURE 68. California and U.S. sand and gravel production, 1920–1964 (U.S. Bureau of Mines Minerals Yearbooks).

Occurrences in California

Usable stream deposits occur throughout the State (fig. 69 and table 41), and the northern one-third of the State contains large resources of sand and gravel. Under present economic conditions, only the deposits nearest to centers of population are of commercial value.

In northwestern California, deposits along the Smith River supply the Crescent City area, Del Norte County, and deposits along the Mad and Eel Rivers supply the Eureka area, Humboldt County. In the Sacramento Valley, deposits along the Sacramento River, and its tributary creeks and rivers, provide sand and gravel aggregate for consumption at Redding, Shasta County; Red Bluff, Tehama County; and Chico, Butte County. On the west side of the Sacramento Valley, stream deposits along Cache Creek provide aggregate for the Woodland area, Yolo County. On the east side of the Sacramento Valley, deposits are exploited along Dry Creek and Butte Creek, near Oroville, Butte County; the Yuba River, near Marysville; the American River, near Sacramento; and the Mokelumne River, near Clements, San Joaquin County.

In central California, deposits along the Russian River yield sand and gravel near Ukiah, Mendocino County; and Healdsburg, Sonoma County. The large tonnages of sand and gravel consumed in the San Francisco Bay area are obtained mainly from shallow alluvial cone deposits of ancestral Alameda Creek in the Niles-Centerville area, and from valley-fill alluvium along Arroyo del Valle and Arroyo Mocho in the Livermore-Pleasanton area. Other stream deposits that supply a portion of the San Francisco Bay area market are located along Sunol Creek, Alameda County and Coyote, Guadalupe, and Uvas Creeks near San Jose, Santa Clara County.

In the San Joaquin Valley, the principal stream deposits of sand and gravel occur along the San Joaquin River and its tributaries. On the east side of the valley, active deposits occur along the Stanislaus River near Riverbank, Stanislaus County; the Tuolumne River east of Modesto, Tuolumne County; the Merced River near Cressey, Merced County; the Kings River near Sanger; the San Joaquin River between Herndon and Friant, Fresno County; the Kaweah and Tule Rivers near Porterville, Tulare County; and the Kern River near Bakersfield, Kern County. Few stream deposits are worked on the west side of the valley, the main ones being along Orestimba Creek near Newman, Stanislaus County; Los Banos Creek near Los Banos, Merced County; and Corral Hollow Creek near Tracy.

In southern California, stream bed and alluvial fan deposits yield most of the sand and gravel aggregate for the principal consuming area, the Los Angeles area. Tujunga Creek in the San Fernando Valley, about 15 miles northwest of Los Angeles, and the San Gabriel River, about 15 miles east of Los Angeles are the principal sources. Stream-laid deposits along the lower reaches of the Santa Clara River provide sand and gravel for use in Ventura and Santa Paula, Ventura County. The Sisquoc River provides aggregate for the Santa Maria area. The Santa Ana River and its tributary, Lytle Creek are the principal sources of sand and gravel for San Bernardino, San Bernardino County and Riverside, Riverside County.

TABLE 41.—*Principal sand and gravel producing areas (exclusive of specialty sand operations)*

Index No. on fig. 69	Nearest city	Type of deposit	Rock types in deposit and source
1	Crescent City	Recent stream deposits of Smith River	Metavolcanic, mafic igneous, and granitic rocks with lesser amounts of graywacke derived from the western Klamath Mountains.
2	Eureka	Recent stream deposits of Mad and Eel Rivers	Chiefly graywacke and greenstone with some chert derived from the northern Coast Ranges.
3	Redding	Recent stream deposits of Sacramento River	Chiefly metavolcanic with graywacke, diorite, and quartzite derived from the Modoc Plateau, eastern Klamath Mountains, and Cascade Ranges.
4	Red Bluff		
5	Orland	Recent stream deposits of Stony Creek	Graywacke, greenstone, vein quartz, and chert derived from eastern portion of northern Coast Ranges.
6	Chico	Dredge tailings in Butte Creek	Greenstone, metachert, basalt, andesite, granite, and gabbro derived from northern Sierra Nevada.
7	Marysville	Recent stream deposits of Yuba River	Milky vein quartz, granite, quartzite, greenstone, and schist derived from northern Sierra Nevada.
8	Ukiah	Recent stream deposits of Russian River	Chiefly graywacke, greenstone, chert, vein quartz, and serpentine derived from northern Coast Ranges.
9	Healdsburg		
10	Madison and Yolo	Recent stream deposits of Cache Creek	Meta-sandstones, sandstones, cherts, metavolcanic rocks, and vein quartz derived from southeastern portion of northern Coast Ranges.
11	Sacramento	Recent stream deposits of American River and Pleistocene stream deposits of Victor Formation.	Quartzitic metasediment, greenstone, vein quartz, and granitic rock derived from western flank of the central Sierra Nevada.
12	Tracy	Recent alluvial fan of Corral Hollow Creek	Metagraywacke, vein quartz, chert, mafic igneous rocks, and andesite derived from eastern flank of southern Coast Ranges.
13	Livermore	Recent stream deposits of Arroyo Del Valle	Graywacke, greenstone, chert, and vein quartz derived from southern Coast Ranges.
14	Niles	Ancestral alluvial fan of Alameda Creek and stream bed Calaveras Creek.	Do.
15	San Jose	Recent stream deposits of Coyote, Carnadero, and Guadalupe Creeks.	Varying proportions of graywacke, chert, vein quartz, and greenstone derived from southern Coast Ranges.
16	Felton	Poorly consolidated marine sandstone in Miocene Santa Margarita Formation.	Sand size quartz and feldspar with minor amounts of chert and granitic particles.

17	Modesto	Recent stream deposits of Tuolumne, Stanislaus, and Merced Rivers.	Varying proportions of granitic rocks, greenstones, quartzitic metasediments, metavolcanic rocks, and vein quartz derived from western flank of the central Sierra Nevada.
18	Merced		
19	Fresno	Recent stream deposits of San Joaquin River	Granitic rocks, metavolcanic rocks, quartzite, basalt and andesite porphyry, and schists derived from western flank of southern Sierra Nevada.
20	Sanger	Recent stream deposits of Kings River	Granitic rocks, metavolcanic rocks, greenstone, quartzite, and schist derived from the western flank of the southern Sierra Nevada.
21	Bakersfield	Recent stream deposits of Kern River; and Kern River Formation (Pliocene to Pleistocene).	Granitic rocks, quartzitic metasediments, metavolcanic rocks, and schist from the western flank of the southern Sierra Nevada.
22	Tulare	Recent stream deposits of Kaweah and Tule Rivers	Greenstone, quartzite, granitic rocks, schist and gneiss derived from the western flank of the southern Sierra Nevada.
23	Sisquoc	Recent stream deposits of Sisquoc River	Chiefly sandstone, with granitic rocks, volcanic rocks, shale, and chert derived from the southern Coast Ranges.
24	Solvang	Recent stream deposits of Santa Ynez River	Chiefly sandstone, granite, gneiss and some volcanic rocks, shale, and chert derived from the Santa Ynez and San Rafael Mountains
25	Saticoy, Santa Paula	Recent stream deposits of Santa Clara River	Chiefly sandstone, granite, gneiss, and some volcanic rocks, shale, and chert derived from the Transverse Ranges.
26	San Fernando	Recent stream deposits of Big Tujunga	Chiefly granitic rocks, granitoid gneiss, and some schist derived from San Gabriel Mountains.
27	Monrovia	Recent stream deposits of San Gabriel River	Granitoid gneiss, granitic rocks, and some mica schist derived from the San Gabriel Mountains.
28	Claremont	Recent stream deposits of San Antonio River and Cucamonga Creek.	Granitoid gneiss, granitic rocks, and some mica schist derived from the San Gabriel Mountains.
29	San Bernardino and Colton	Recent stream deposits of Santa Ana River and the tributary Lytle Creek.	Chiefly gneiss, granitic rocks and some mica schist derived from the San Bernardino Mountains.
30	Orange	Recent stream deposits of Santa Ana River, and Santiago Creek.	Chiefly granitic rocks, gneiss, quartzite, and sandstone derived from San Bernardino and Santa Ana Mountains.
31	San Diego	Eocene Poway Conglomerate and Recent stream deposits of Otay and San Diego Rivers.	Chiefly andesite, rhyolite, and quartzite from Peninsular Ranges.

FIGURE 69. Major sand and gravel deposits in California (number refer to table 41).

Alluvial fans are the principal sources of sand and gravel for communities of Barstow and Victorville in San Bernardino County, and Indio and Palm Springs in Riverside County.

Several geologically older formations also provide significant amounts of aggregate. The Pliocene to Pleistocene Kern River Formation is mined near Bakersfield in Kern County; a thriving industry near San Diego, San Diego County is based upon the Eocene Poway Conglomerate; the Pleistocene Victor Formation is an important source for Sacramento, Sacramento County; the Pliocene and Pleistocene Santa Clara Formation is worked near San Jose in Santa Clara County; and the ancient beach deposits along the Salton Sea provide material for the Imperial Valley at the southern end of the State.

Miocene sandstones are important sources of concrete sands near Felton, Santa Cruz County, and Torrance in Los Angeles County.

Minor proportions of the beach and dune sand obtained in the Monterey Bay area, Monterey County are used for plaster and concrete sand, in addition to its prime use as a specialty sand.

Resource Potential

The market for sand and gravel will continue to expand as California continues its remarkable growth. However, there are no undiscovered deposits near the metropolitan areas that can be developed to meet the demand. Indeed, the State faces depletion of its major sources within the next three decades unless sand and gravel deposits can be set aside as natural resource zones for future use.

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SANDS, SPECIALTY

(By H. B. Goldman, California Division of Mines and Geology, San Francisco, Calif.)

In 1964, California produced 1,482,000 tons of specialty sands valued at $6,051,000. About 65 percent of the specialty sand tonnage was used in glass making, 13 percent for sandblasting, 6 percent for grinding and polishing, 4 percent for engine sand, and 12 percent for other specialty uses.

The special sands used in California are obtained mostly at localities within the State and consist largely of material from Recent beach and dune deposits and early Tertiary sandstones.

Nature of Specialty Sands

The term "specialty sand" (or "special sand") is applied to sand used for purposes other than for aggregate, ballast, or fill. Specialty sands generally have rigid physical and chemical specifications, and are used in much smaller quantities than ordinary sand. Some specialty sands include particles of gravel size (larger than a quarter of an inch).

Most specialty sands are obtained from the purest available sand deposits that can be economically worked. A high content of quartz makes the sand physically durable and chemically inert, and also provides silica as an ingredient of glass and soluble silicates.

For most uses, the physical properties of specialty sands are more important than chemical properties. The chemical composition is held to rigid specifications only in the production of glass and soluble silicates. For use in sandblasting, hardness and durability are the essential characteristics; in others, such as filter media, close size grading is essential.

Clay is generally undesirable, mainly because it coats sand grains and interferes with the usefulness of sand. Only in naturally bonded foundry sands is clay a desired admixture. Both clay and iron-bearing minerals constitute chemical impurities in sands for use in the manufacture of glass and soluble silicates.

Sand from most specialty sand deposits can be used in several ways. A single deposit, for example, could yield sand suitable for sandblasting sand, engine sand, or foundry sand. Sands from some deposits are especially suited to a single use, and hence command relatively high prices. The purest quartz sands are most prized for use in glass. Some clay-rich sands are used only as naturally bonded foundry sands, and "ganister".

Uses such as glass and soluble silicate manufacture require sand so clean that rigorous cleaning and beneficiation ordinarily are required. Sand to be used for less exacting purposes, such as for sandblasting and engine sand, commonly require little or no washing. Sand from some deposits is clean enough and of the right size for these uses without any processing.

Although nearly all clay-free special sand is suited for use as aggregate sand (concrete and plaster sand), the sands of higher quality are more valued as specialty sands.

Occurrences in California

In California, as well as elsewhere, deposits from which specialty sands can be mined are much less common than the deposits that contain aggregate-grade material. Most of the specialty sand is obtained from Recent beach and dune deposits, and from Tertiary sedimentary rocks as shown in figure 70 and table 42; relatively minor quantities of Recent alluvial sand are processed for specialty uses.

Recent beach and dune sands along the Pacific Ocean, in general, contain a lower proportion of quartz, and a higher proportion of feldspar, dark mineral grains, and rock fragments than the Tertiary sandstones that are mined for high-silica specialty sands. Beach sands, therefore, are used mostly for sandblasting, engine, and foundry sand, and for minor applications that do not require high-purity silica sand. Most beach sand deposits are measurable in many millions of tons, have little or no overburden, and can be mined inexpensively.

Most of the beach and dune sand that is mined in California for specialty uses is obtained from two areas in Monterey County; one is immediately southwest of Pacific Grove, and the other is along the shore of Monterey Bay, north of Monterey. The deposits southwest of Pacific Grove are unlike other beach sand deposits in California because of their uncommonly white color, and general lack of clay, iron-bearing minerals, and rock fragments. They consist of about 53 percent quartz grains; 46.5 percent feldspar, and 0.5 percent other minerals, including biotite, ilmenite, garnet, zircon, and monazite

(Valentine, P. C., oral communication, 1954). Nearly all sand grains pass a 20-mesh sieve, and 1 or 2 percent pass a 100-mesh sieve.

The east shore of Monterey Bay is formed entirely of dune sands, which consist largely of feldspar grains and have appreciably higher iron content than the Pacific Grove sand, both as ferromagnesian minerals and as ferruginous coatings on the quartz and feldspar grains. This sand is sold mainly for use as sandblasting and foundry sand, and for plaster and concrete sand.

At Oceano Beach, San Luis Obispo County, a dune area several square miles in extent yields clean feldspathic sand that is unusually fine grained, and closely graded in grain size; about 90 percent of the grains are retained on the 100- and 140-mesh sieves. This sand is sold unprocessed, mainly for use as foundry sand.

At El Segundo, Los Angeles County, ordinary feldspathic dune sand is obtained for use as foundry sand.

Most of the beach and dune sands in northern California contain large proportions of dark mineral grains and dark rock fragments, and have been much less extensively used as specialty sands than those from Monterey Bay and southward.

In 1963 all the specialty sand recovered from the beaches of California was obtained in seven operations; two at Pacific Grove; three on Monterey Bay; one at Oceano Beach; and one at El Segundo.

In California, some of the highest quality silica sands are obtained from sedimentary sandstone formations of early Tertiary age. Although less pure than the silica sands mined in Illinois and Missouri, they form the principal source of supply for the glass industry of California. Tertiary deposits that have yielded sand for specialty uses include Paleocene deposits south of Corona, Riverside County, and in the Trabuco Canyon area, Orange County; and Eocene deposits near Ione, Amador County; Oceanside, San Diego County; Tesla, Alameda County; and in the Nortonville-Somersville and Brentwood areas, Contra Costa County.

These deposits consist essentially of quartz grains and clay, with a low percentage of partly decomposed feldspar, and very small proportions of heavy, resistant minerals such as garnet, epidote, zircon, magnetite, and ilmenite. They are exposed in belts that range from several thousand feet to several miles long, are ordinarily about 25 to 200 feet thick, and dip gently to moderately. They have been mined mostly by open-pit methods. If it is to be used for glass sand, the mined material requires beneficiation to remove clay and iron-bearing minerals. The high-quality clay recovered from the beneficiation of these sands in the Ione and Trabuco Canyon areas is valued for ceramic uses. Sand from these deposits also is used, with relatively minor treatment, for foundry sand and less common uses.

In 1963, six operations were active in these high-silica sandstones of early Tertiary age. One was at Ione, Amador County; one near Corona, Riverside County; two in the Trabuco Canyon area, Orange County; one near Oceanside, San Diego County; and one near Antioch, Contra Costa County. Those near Ione, Corona, and Oceanside produced sand mainly for use in glass; those near Trabuco Canyon and Antioch mostly produced foundry sand.

Post-Eocene Tertiary sandstones are very widespread and abundant in California, but they have not been extensively mined as sources

TABLE 42.—*Specialty sand deposits in California*

Index No. on fig. 70	Name and location	Description of deposit	Uses
1	Monterey Bay beach and dune sand, Monterey County, near Monterey.	Present beach and Quaternary dune sands extend for about 10 miles from the Salinas River to Monterey. The dunes average about one-fourth mile wide and about 50 feet high. Sands are well-sorted, sub- to well-rounded, and in the medium- to coarse-size range.	Blast, engine, filtration, grinding and polishing sand.
2	Monterey Peninsula dune sand, Monterey County, near Pacific Grove.	Dunes occur on the west side of the Monterey Peninsula in two strips: one is 1½ miles long by about ¼ mile wide. The other covers an irregular area of about one-fourth square mile. The dunes range from a few feet to about 30 feet in depth. The sands are well-sorted, subangular, and in the medium-size range.	Glass, molding, pottery, foundry, filler sands.
3	Recent dunes, San Luis Obispo County, near Oceano.	Unconsolidated sand dunes extend for several miles along the shore south of Pismo Beach and as much as 1 mile inland. Sand is in the fine to medium size and is highly feldspathic.	Molding, engine sand.
4	Recent dunes, Los Angeles County, near El Segundo.	Unconsolidated, highly feldspathic dune sands extend about 10 miles along Santa Monica Bay, and about 2 miles inland.	Molding, blast, engine sand.
5	Bear River, Placer County, near Colfax	Stream bed of present Bear River contains sand and gravel. Sand contains high proportion of quartz fragments derived from Tertiary channel deposits that have been reworked by the Bear River.	Molding sand.
6	Torrance deposit, Los Angeles County, near Torrance.	Unconsolidated, flat-lying sediments in the Quaternary alluvium are exposed in the hills separating Torrance ad Redondo Beach. Approximately 4 feet of overburden overlies dark, reddish-brown, naturally bonded silica sand which overlies clay-free sand.	Do.
7	Ione Formation, Amador County, near Ione	Poorly consolidated, gently dipping, nearly massive, 70-foot-thick bed of Eocene Ione Formation, yields about 60 percent quartz sand, 35 percent clay, 5 percent heavy minerals.	Glass sand.
8	Tesla Formation, Alameda County, near Tesla	Poorly consolidated bed of fine-grained thinly cross-bedded, white sandstone of middle Eocene marine Tesla Formation contains 70 to 95 percent quartz sand, 5 to 30 percent feldspar. Visible sand bed is 15 to 20 feet thick, and dips 60° between coal seam and clay bed.	Glass, foundry sand.
9	Domengine Formation, Contra Costa County, near Antioch.	Sandstone beds of the middle Eocene Domengine Formation crop out to the northeast of Mount Diablo in a milewide belt extending from Concord to Byron, a distance of 20 miles. Suitable material is present in a white sandstone member that ranges in thickness from 75 to 400 feet. The sandstone is massive, compact, and relatively uncemented, containing angular, well-sorted medium-sized grains of quartz (80 to 90 percent) and feldspar (10 to 20 percent).	Glass, molding sand.
10	Silverado Formation, Riverside County, near Corona; and Orange County, in Trabuco Canyon.	Poorly consolidated, coarse-grained, nearly flat-lying, thin-bedded white sandstone that forms basal unit of Paleocene Silverado Formation, contains about 60 percent quartz sand, 40 percent clay, silt and scattered pebbles.	Glass pottery, fire and furnace sand.
11	Tejon Formation, San Diego County, near Oceanside.	Poorly consolidated, white, gently dipping marine strata of Eocene Tejon Formation include layers of usable sandstone as much as 40 feet thick interbedded with lenses of silt and clay. Usable material consists of about 65 percent quartz, 15 percent feldspar, 20 percent clay and silt, with minor amounts of heavy minerals.	Glass, molding, blast, oil, filtration, and engine sand.
12	Pleistocene sandstone, Ventura County, near Ventura.	Unconsolidated, clay-rich Pleistocene marine sandstones; usable bed, 100 feet thick, dips 47°, interbedded with clay-poor sandstone. Sand is very fine grained, tan and unconsolidated.	Molding sand.

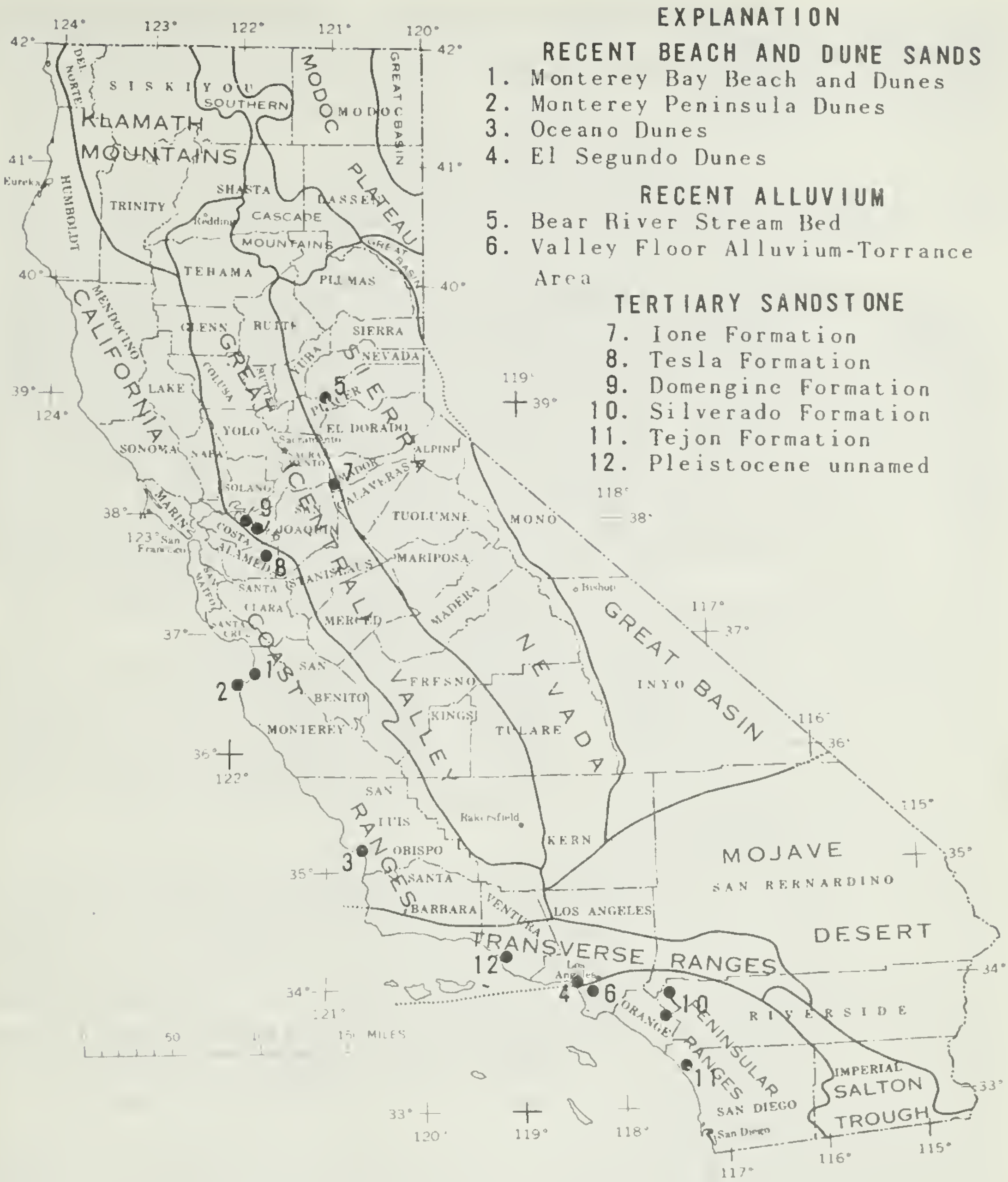

FIGURE 70. Specialty sand deposits in California.

of specialty sands. Their characteristically high-feldspar content and the low quality of their contained clay prevent them from competing with early Eocene sandstones as sources of high-quality silica sands.

Their relatively high degree of consolidation, and consequent high expense of preparation, makes them less desirable than dune sands as sources of sandblasting and engine sands. One of the higher quality later Tertiary sandstones is the upper Miocene and lower Pliocene(?) Santa Margarita Formation, which is quarried near Felton, Santa Cruz County, mainly for aggregate use. Pleistocene beds in Ventura County are sources of foundry sand.

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SHALE, EXPANSIBLE

(By J. L. Burnett, California Division of Mines and Geology, Redding, Calif., and C. T. Weiler, U.S. Bureau of Mines, San Francisco, Calif.)

Expansible shale is a raw material used to manufacture lightweight aggregate for concrete. The aggregate is produced by rapidly heating certain types of common shale in a high-temperature kiln. When the particles of shale reach temperatures in the vicinity of 1,800° to 2,000°F, they partially melt, forming a slag-like shell around the exterior of the particle. The gas, generated within the particle, is sealed in by the viscous glass that results from melting. The entrapped gas expands to form closed pores which enlarge the volume of the particle and decrease its apparent specific gravity. The expanded aggregate particle is frothy and cellular on the inside and is surrounded by a dense, hard shell on the surface.

Expanded shale aggregate combines the desirable features of low weight with relatively high strength, making it especially useful in special-purpose lightweight concrete applications such as concrete block, structural concrete for multi-story buildings, and a variety of specialized concrete products such as pre-cast and prestressed panels and beams, and storage tanks.

As construction costs continue to increase and technological improvements are made, higher strength lightweight concrete will undoubtedly replace concrete made with natural aggregate for many applications, even though natural aggregate may be less expensive. The lesser weight of the lightweight concrete will materially lessen design load factors and thus afford substantial savings in cost of construction. As utilization of lightweight concrete increases and it becomes more a general use item, the cost will decrease and the use become more widespread.

Expansible shale is used in this discussion as a commodity name and includes three lithologic types: shale, claystone, and slate. These three types of rock are fine grained, and all have been deposited in water—either the ocean, a bay, or an inland lake. Although these rocks have a similar origin, they differ in the amount of compaction that they have sustained, and this is reflected in their structure. Shale is a moderately hard, laminated rock; claystone is a softer, poorly compacted rock which is massive to poorly laminated; slate is harder than shale, has been compacted more, and displays such perfect lamination that the rock can be split into thin sheets.

Typical expansible shale is a fine-grained argillaceous rock of marine origin. The minerals usually found in shale include those of the clay group, quartz, and feldspar, with minor amounts of organic carbon, pyrite, calcite, and gypsum.

Undesirable materials are often associated with expansible shale in a deposit. Weathered shale is normally found at the surface of a deposit and is undesirable because the process of weathering eliminates those properties which permit the shale to expand (White, 1959).

Sandstone, siltstone, and other coarse-grained sediments do not expand and will increase the average weight of the aggregate if they are included with the raw material. Limestone becomes highly reactive when subjected to intense heating because it is converted to calcium oxide or "quick lime". Calcium oxide is actively harmful to concrete structures due to expansion and resultant cracking of the structure. Any or all of these materials may be found in a shale deposit, and, although small quantities can be tolerated, they should be avoided through selective mining or removed during processing.

The expansible shale industry in California began in 1932 with the completion of the McNear Co. plant near San Rafael. Added incentive for a northern California expansible shale industry was created when specifications for the San Francisco-Oakland Bay Bridge called for expanded shale aggregate in the construction of the roadbeds on the bridge deck. The McNear Co. supplied part of this aggregate, and the remainder was produced from a quarry and plant at Point Richmond in Contra Costa County. Both of these plants used shale quarried from the Franciscan Formation.

The first plant in southern California was established in 1940 near Ventura. The raw material is a bentonitic claystone from the Mudpit Shale. After the United States entered World War II, lightweight aggregate was produced near Casmalia, Santa Barbara County for use in the hulls of ships made with reinforced concrete.

During the years following the end of World War II, commercial and residential construction increased at a tremendous rate and so did the demand for lightweight aggregate as shown in figure 71. Production capacity in the existing plants was enlarged, and several additional plants were put into operation. In 1952, a plant was opened near Frazier Park in Ventura County which used bentonitic claystone of Miocene age from the Lockwood Clay. In the following year, the largest plant in California was established by the Basalt Rock Co. south of Napa. This plant used marine shale of Cretaceous age from a quarry near Vallejo and later (1962) opened another quarry west of Oakville, Napa County. A shale deposit in the Yorba Member of the Puente Formation (upper Miocene) was opened near Chino, San Bernardino County in 1958 by the Shale-Lite Corp., although this operation closed in 1962 due to unsolved problems in product quality control. In 1962, a plant was opened in San Clemente to supply the growing market in Orange and San Diego Counties. This plant is operated by Crestlite Division of Susquehanna-Western, Inc., and uses shale from the Capistrano Formation of late Miocene and early Pliocene age.

Occurrences in California

At the present time (1965), expanded shale aggregate is being produced from five operations in California which are located near San Rafael, Napa, Ventura, Frazier Park, and San Clemente, and a sixth plant near Casmalia is producing lightweight aggregate from sintered diatomaceous shale (fig. 72). Several companies are planning to build additional plants in the San Francisco Bay Area. Port Costa Clay Products Co., a subsidiary of Homestake Mining Co., is enlarging their facilities on Carquinez Strait to produce expanded shale as well as brick. The Henry J. Kaiser Co. has optioned property near

FIGURE 71. Annual production of expanded shale aggregate in California (figures prior to 1953 are approximate due to incomplete statistics).

Sunol in Alameda County and plans to produce lightweight aggregate from shale of Cretaceous age. In southern California, the Pavolite Division of Pacific Vegetable Oil Corp. purchased the plant and quarry near Chino, formerly operated by the Shale-Lite Corp., renovated the plant, and has resumed production.

Deposits of expansible shale in California that are potentially suitable for industrial use occur in marine sedimentary formations of Jurassic, Cretaceous, Eocene, and Pliocene ages. Some shale of Miocene age is suitable, but that in the Monterey Shale and equivalent

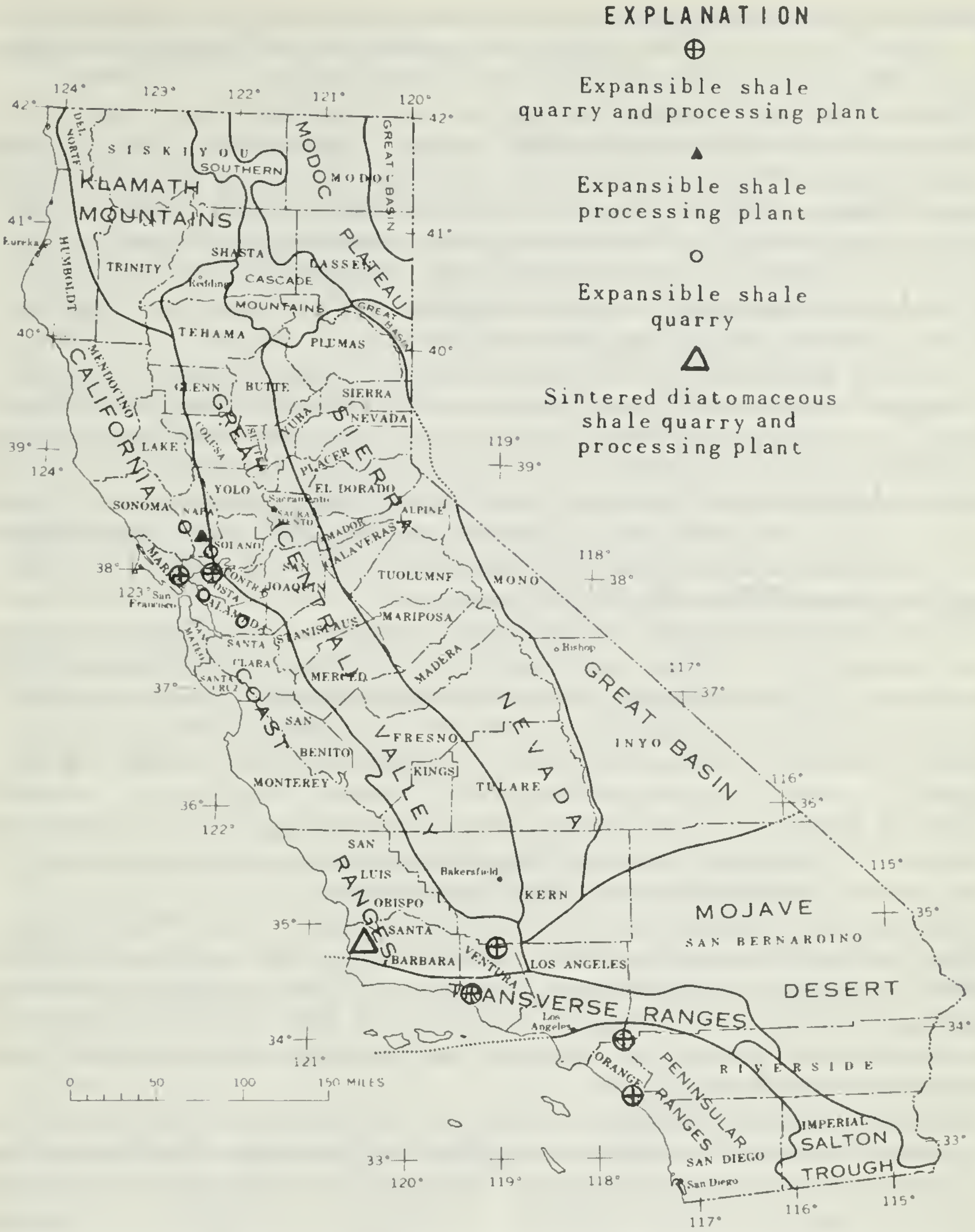

FIGURE 72. Expansible shale in California.

formations ordinarily contains too much silica to permit suitable expansion. The Quaternary sedimentary units of California generally consist of course nonexpansible detritus, although clay being deposited in the bays along the coastline of California is usable.

In the northern Coast Ranges, formations of Jurassic and Cretaceous age contain shale of potential commercial interest (Jennings and others, 1958–1965). The shale is most abundant in two north-trending belts. One belt is 10 to 20 miles wide and lies along the west side of the Sacramento Valley from Redding to Fairfield. The Knoxville Formation, which lies on the western side of this belt, contains shale-rich rocks which are thousands of feet thick. Minable deposits are present which are many hundreds of feet thick and thousands of feet in exposed length. The other belt extends from Eureka to Santa Rosa and contains shale-rich rocks of Cretaceous age.

Shale of Early Cretaceous age also is abundant along the south and east flanks of Mount Diablo, Contra Costa County, and on the southern side of Carquinez Strait near Port Costa. In the central Coast Ranges, along the east side of the Santa Clara Valley, shale-bearing units of Late Jurassic to Early Cretaceous age form belts as much as 4 miles wide and 10 miles long. Although the shale is interlayered with sandstone, minable deposits are as much as 1,000 feet thick and a half a mile in exposed length.

In many places in the California Coast Ranges, Lower Cretaceous rocks are overlain by Upper Cretaceous units that also are partly shale. The Upper Cretaceous shale, however, is commonly interbedded with standstone so that the shale bodies are generally less than 10 feet thick and would be difficult to mine. In Solano County, however, an Upper Cretaceous shale body about 70 feet thick is mined by the Basalt Rock Co. Another deposit, several hundred feet thick, is mined by the same company west of Oakville, Napa County.

The Franciscan Formation of Late Jurassic to Late Cretaceous age also contains expansible shale, but this is commonly interbedded with sandstone. The Franciscan Formation is the source of the raw material expanded by the McNear Co. at McNear Point in Marin County. Here the shale is removed from a deposit approximately 150 feet thick.

In the southern Coast Ranges, Transverse Ranges, and Peninsular Ranges of southern California, expansible shale occurs in deposits of Cretaceous, Eocene, Miocene, and Pliocene ages.

The Espada Formation (Upper Jurassic and Lower Cretaceous) occurs in belts as much as three miles long on the north side of the Santa Ynez Mountains, between Buellton and Santa Barbara, in Santa Barbara County. The shale is interbedded with sandstone, but the sandstone layers are thin and sparse, and individual bodies of shale are 100 feet or more in thickness.

The Holz Shale Member of the Ladd Formation (Upper Cretaceous) crops out on the southwestern slopes of the Santa Ana Mountains in belts as much as one mile long. The shale is interbedded with sandstone and minor limestone layers. A shale body 1,000 feet thick and of possible commercial interest occurs in Silverado Canyon, Orange County. Other exposures of shale-bearing rocks of Upper Cretaceous age occur near Carlsbad in San Diego County. Although the shale is interbedded with sandstone and limestone, shale zones are found which are commonly 25 to 50 feet thick and contain 80 percent shale. Rocks of Late Cretaceous age form a large part of the Simi Hills, which lie in Los Angeles and Ventura Counties, west of Chatsworth. These rocks consist mostly of sandstone and conglomerate, but a body of shale about 150 feet thick and as much as two miles in exposed length lies near the summit of Santa Susana Pass.

The Cozy Dell Formation is extensively exposed in a wide belt of Eocene rocks that underlies much of the Santa Ynez Mountains, from Point Conception eastward for about 70 miles, in both Santa Barbara and Ventura Counties. The shale of the Cozy Dell Formation is interbedded with sandstone, but minable bodies hundreds of feet thick are common in both the Ojai and Santa Barbara areas.

Exposures of the Lockwood Clay (Miocene or younger) are found in an area of about four square miles, near Frazier Park, in the northeastern part of Ventura County. This clay is mined and expanded by Ridgelite Products Co. The deposit is at least 120 feet thick in the quarry. The Capistrano Formation (Miocene and Pliocene) underlies an area of 40 to 60 square miles, near San Juan Capistrano, Orange County, and contains bodies of shale that are hundreds of feet thick. A deposit in the city of San Clemente is being mined and processed by Crestlite Aggregates. The Sycamore Canyon Member of the Puente Formation crops out extensively in the Chino Hills between the city of Puente and Prado Dam. In this member, shale is interbedded with sandstone, but bodies of shale 300 or more feet thick and many hundreds of feet in exposed length occur north and west of Prado Dam. Shale from the Yorba Member of the Puente Formation was expanded at a plant near Chino from 1958 to 1962.

Large areas north of the Santa Clara Valley in Ventura County are underlain by the Pico Formation (Pliocene) which contains large quantities of shale. A shale deposit in the Mudpit Shale is quarried by the Rocklite Co. near the city of Ventura.

Many of the lagoons and bays along the coastline of California contain recent clay deposits which can be dried and expanded into a suitable product. The most noteworthy is San Francisco Bay, where clay deposits averaging 60 feet in thickness cover its entire floor. Limited testing indicates that much of this material can be expanded, although drying the clay may be a difficult and expensive process.

Expanded shale is a commodity that must be produced in high volume at a low cost. The initial cost of establishing an expanding plant is high, usually 1 to 3 million dollars. As with many other nonmetallic minerals and construction materials, the marketing situation in the intended sales area, and the probable cost of mining and transporting the product to this market, is of equal or greater importance than an optimum quality raw material. For these reasons, prospecting should not be carried on solely for the purpose of finding the raw material with the best ceramic properties but is best carried on in several stages, the initial steps determining the course of action in each successive step.

A most important early step is to learn where the major sales area will be and to determine the volume of sales that can reasonably be expected. Once the region of major interest has been determined, the next step is to appraise the sedimentary materials within this area. In order to be considered, a deposit should be large and uniform so that inexpensive mining methods can be used, and it should be readily accessible so that transportation to the market will be inexpensive. Processing the shale requires rather large quantities of fuel, so proximity to a fuel source also is important. All these factors, plus the probable cost of constructing and operating a plant, must be considered to determine whether a commercial operation would be profitable if a suitable deposit of raw material was economically available.

When it has been determined that commercial exploitation is feasible, the prospector should look for the best raw material within the area of interest. Although firing in a ceramic kiln is the final test of expansibility, many ceramic properties can be estimated by inspection of the raw material (Burnett, 1964).

The quantity of usable raw material in California is measurable in terms of cubic miles of shale, but the annual production will, for some years to come, be measurable in terms of one to several millions of tons. It would seem, therefore, that no raw material shortage could ever exist, but, in practice, this is not the case. There are a limited number of economically minable deposits which are located close to both the sales area and inexpensive transportation. Urban expansion is normally accompanied or preceded by zoning ordinances which tend to strictly control or exclude heavy industrial operations such as an expansible shale plant.

Outlook

The future for expansible shale will be defined by urban growth more than by any other single factor. In the next few years, existing plant capacities will be sufficient to supply the Los Angeles and San Francisco Bay areas, and, therefore, any additional facilities in these areas will have to depend on active competition with established producers rather than from large increases in consumption of the product. If other urban areas increase in size, they will create local markets of sufficient size to support other plans. The Fresno area is foremost among these areas, because it is equidistant from the existing expanding plants and close to some of the largest urban growth centers in the Central Valley.

There is need for additional research in the technology of shale expansion. Many areas in California have raw materials of marginal quality or waste products from other industrial operations which could be used for the production of lightweight aggregate, if more flexible techniques of processing were known. If a high degree of flexibility could be designed into a single plant, the degree of expansion of the raw material might be adjustable, so that both a light, relatively weak product and a relatively heavy but strong product could be supplied. This would allow the producer to meet varying customer needs and improve his competitive position.

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SILVER

(By H. K. Stager, U.S. Geological Survey, Menlo Park, Calif.)

Silver has been searched for, treasured, and fought over since ancient times. Along with gold it is one of the precious metals and has found wide use as a measure of wealth and a medium of economic exchange for about four thousand years. It is a durable and easily worked metal of beauty and is widely used in the arts and industry.

The United States has almost 2 billion troy ounces of silver in coinage and consumed 203 million ounces for this purpose in 1964. Industrial use of silver in 1964 amounted to about 123 million troy ounces, of which the photographic industry alone consumed about 40 million ounces. Other major uses were for sterling silverware and jewelry, electrical and electronic uses, in brazing alloys, and for dental and medical purposes.

Silver is found in many types of rocks and environments but the major deposits are veins in the more acidic volcanic rocks and replacements in limestones and dolomites. Silver rarely occurs alone in nature and usually accompanies other metals such as gold, copper, lead, or zinc. Thus the prices of these metals have a greater influence on the production of silver than do fluctuations in the price of silver alone.

Silver was probably first discovered in California about 1800, although no reliable records are known to exist. Some early reports mention that a silver mine on the Alisal Ranch, east of Salinas, on the flank of the Gabilan Range was worked about 1801. The gold and silver lode mines of the Mother Lode were discovered about 1850. In 1856 silver was discovered in the South Fork mining district of Shasta County (No. 5 on fig. *73*), followed by Bodie (No. 30) in 1860, Blind Spring (No. 46) in 1862, Cerro Gordo (No. 49) and Clark Mountain (No. 63) in 1865, Darwin (No. 51) in 1874, California's largest silver producing district, West Shasta (No. 6) in 1879, the rich silver mines of Calico (No. 62) in 1881, Mojave (No. 59) in 1894, and the deposits at Randsburg (No. 60) in 1919.

The United States has been the leading consumer of silver for many years but ranked third in silver production (after Mexico and Peru) in 1963 and 1964. United States production was 35 million troy ounces in 1963 and 36 million troy ounces in 1964. California ranks seventh among the states in total silver production, having produced about 120 million troy ounces since 1848. During 1964, California was seventh in yearly production with a total of 174,000 troy ounces, valued at $225,000. This was an increase of almost 18,000 ounces over the 1963 production of 156,528 ounces valued at $200,000.

About 90 percent of the silver produced in California in 1964 was a by-product of base-metal mining and came from three mines in Inyo County. The Pine Creek mine (No. 47 on fig. *73*) of Union Carbide Nuclear Co. was the leading producer in the State, followed by the Santa Rosa (No. 50) and Jubilee (near No. 55) mines. The only deposit mined primarily for silver, with significant production, was the Zaca mine (No. 27) in Alpine County. Some silver was also produced as a by-product of gold mining in Yuba and Sierra Counties.

The distribution of silver deposits is shown in figure 73 and listed in table 43.

Silver occurs in all of the geomorphic provinces of California (fig. 73) but the major deposits are in the Mojave Desert, Great Basin, Klamath Mountains, and Sierra Nevada. The most common silver minerals found in California ores are cerargyrite ($AgCl$, mirargyrite ($AgSbS_2$), freibergite ($Ag_{12}Sb_4S_{13}$), and electrum ($Au{:}Ag$). However, there are few districts in which silver is the chief metal of value and much of the silver produced comes as a by-product from the mining of argentiferous galena, tetrahedrite, tennantite, enargite, chalcopyrite, and gold. Most of the native gold from the Mother Lode contains 10 to 20 percent silver. Only 3 of the 10 major districts (Calico, Clark Mountain, and Blind Spring) produced silver in greater value than the other metals. Of the 72 mines or districts shown on figure 73 only in 11 is silver the primary metal of value. In 36 districts it is a by-product of gold mining; in 14 a by-product of

FIGURE 73. Silver in California (numbers refer to table 43).

TABLE 43.—*Silver in California (data from McKnight and others, 1962)*

MINES IN WHICH SILVER IS THE PRINCIPAL METAL OF VALUE

Index number on fig. 73	*District or region*
5	South Fork (Chicago mine).
20	Calistoga (Silverado, Palisade mine).
27	Monitor (Zaca mine).
28	Mount Patterson (Silverado and Kentuck mines).
43	Boot Jack.
46	Blind Spring.
61	Grapevine (Waterman mine).
62	Calico.
63	Clark Mountain (Ivanpah in part).
64	Cima (Death Valley mine).
66	Lava Beds.

MINES IN WHICH SILVER IS A BY-PRODUCT OF COPPER MINING

1	Squaw Creek (Blue Ledge mine).
3	Island Mountain (Island Mountain mine).
6	West Shasta.
7	Bully Hill.
9	Lights Canyon (Engels, Superior mines).
10	Genessee (Walker mine).
24	Ione (Newton mine).
25	Campo Seco (Penn Mine).
32	West Belt (Quail Hill area).
33	Copperopolis (Keystone-Union, North Keystone mines).
47	Bishop Creek (Pine Creek tungsten mine).

MINES IN WHICH SILVER IS A BY-PRODUCT OF LEAD AND/OR ZINC MINING

8	Cow Creek (Ingot, Afterthought mine).
15	Yankee Hill.
41	Hunter Valley (Blue Moon mine).
48	Black Canyon.
49	Cerro Gordo.
50	Lee (Santa Rosa mine).
51	Darwin.
52	Modoc.
53	Panamint.
54	Carbonate (Queen of Sheba mine).
55	Resting Springs (Tecopa).
56	Slate Range.
71	Silverado (Santa Rosa, Blue Light).
72	Santa Catalina Island.

MINES IN WHICH SILVER IS A BY-PRODUCT OF LODE AND/OR PLACER GOLD MINING

2	Dillon Creek (Klamath River in part, Siskon mine).
4	French Gulch-Deadwood (Brown Bear, Washington, and Niagara Summit mines).
11	Sierra City (Sierra Buttes mine).
12	Washington (Graniteville, Spanish, Gaston mines).
13	Alleghany.
14	Slate Creek (La Porte).
16	Oroville.
17	Hammonton (Yuba River).
18	Nevada City.
19	Ophir.
21	Folsom.
22	Placerville.
23	Plymouth-Jackson.
26	Mokelumne Hill.
29	Masonic.
30	Bodie.

TABLE 43.—*Silver in California (data from McKnight and others, 1962)*—Con.

MINES IN WHICH SILVER IS A BY-PRODUCT OF LODE AND/OR PLACER GOLD MINING—con.

Index number on fig. 73	*District or region*
31	Angels Camp.
34	Carson Hill (Carson Hill mine).
35	Columbia Basin.
36	Sonora.
37	Soulsbyville-Tuolumne.
38	Jamestown.
39	Shawmut (Eagle-Shawmut mine).
40	Groveland-Big Oak Flat.
42	Hites Cove.
44	Mammoth Lakes.
45	Chidago.
57	Cove.
58	Amalie.
59	Mojave.
60	Randsburg.
65	Buckeye (Bagdad Chase mine).
67	Dale (Monte Negro).
68	Eagle Mountain.
69	Paymaster (Paymaster mine).
70	Cargo Muchacho.

lead and/or zinc mining; and in 11 it is a by-product of copper mining.

The geologic settings of silver-bearing deposits in California are many and varied. About one-third of the total California silver production has been mined as a by-product from large massive sulfide replacement bodies along axes of broad folds in Devonian rhyolitic rocks in the West Shasta district. Along the Mother Lode silver has been produced as a by-product from placer gold deposits and from quartz veins in slates, granodiorite, and serpentines of the Sierra Nevada. In the old Monitor district of Alpine County silver ore is being mined from braided fissure zones and impregnations of silver minerals in highly altered andesite. At Bodie it was mined as a by-product of gold from quartz veins in andesite. Veins along parallel faults in a Jurassic granitic stock yielded the silver ores of the Blind Spring district. In the Bishop Creek district silver is produced as a by-product from tungsten-copper-molybdenum ores in contact metamorphic deposits in Paleozoic marble. Replacement bodies near the axis of a plunging anticline in Devonian limestone yielded silver as a by-product of lead-zinc ore at Cerro Gordo. At the Santa Rosa mine silver is produced as a by-product of lead mined from veins in tactitic Permian limestone and ore shoots along bedding fractures in Mississipian limestone. The Darwin district has yielded silver as a by-product of lead mined from replacement bodies along and near faults in tactitic Pennsylvanian limestone adjacent to a granodiorite stock. Mines in the Randsburg district have produced silver and gold from intersecting vein systems in Precambrian biotite schist, amphibole schist, and quartzite in the footwall of a large flat fault. In the Mojave district veins along faults in Miocene dacite flows and plugs, and on the contact between flows and underlying Upper Jurassic quartz monzonite have yielded silver as a by-product of gold mining. At Calico high-grade silver ore was mined from veins along or near faults and from disseminated deposits in shattered Miocene volcanic rocks and lake beds. Replacement bodies in Mississippian limestone and Devonian dolomite, in part localized by fractures near a quartz monzonite sill, yielded the silver ores of the Clark Mountain district.

California's greatest silver resource potential probably still lies in undiscovered, or unmined, copper ore bodies in the Klamath Mountains, gold veins of the Sierra Nevada, and lead-zinc ore bodies in the Darwin and Cerro Gordo areas. Silver-rich epithermal veins in Tertiary volcanic rocks in the Great Basin and Mojave Desert will probably also yield additional silver ore.

Geophysical exploration followed by drilling is probably the most effective method for finding silver-bearing copper ore bodies in the Klamath Mountains. Extensive geochemical prospecting in the Great Basin, Mojave Desert, and Sierra Nevada regions is warranted, particularly in the areas of Tertiary andesitic and rhyolitic rocks.

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SODIUM CARBONATE

(By G. I. Smith, U.S. Geological Survey, Menlo Park, Calif.)

Sodium carbonate, known industrially as soda ash, occurs in nature chiefly where concentrated by evaporating lake waters. It is used in large quantities in the manufacture of glass and chemicals, and in smaller quantities for paper products, soda and detergents, nonferrous metals, and water softeners.

Sodium carbonate has been used since the time of early Egyptian cultures, when efflorescences composed of it were collected from the edges of saline lakes in that area. In early European and American civilization it was obtained by burning marine plants, such as seaweed, which formed an ash from which sodium carbonate could be extracted. The name "soda ash" is inherited from this process. In 1791, an industrial process was developed in France which ended production by this method. In 1860, the Solvay method was developed in Belgium, and this process, which uses salt, ammonia, and limestone as raw materials, provides most of the sodium carbonate used in the world today (MacMillan, 1960).

In 1963, the annual production capacity of sodium carbonate products in the United States were estimated to be 7,050,000 short tons (Chemical and Engineering News, 1963). Products manufactured by the Solvay process account for 5,730,000 short tons (81 percent), and natural deposits provided the balance. California's share in this production capacity from natural deposits was 370,000 short tons (5 percent), and Wyoming's was 950,000 short tons (14 percent). The total value of 1963 production from natural sources was $27,600,000 (MacMillan, 1964). Individual capacities of California producers were reported as follows (Garrett and Phillips, 1960):

	Short tons
American Potash & Chemical Corp	150,000
Stauffer Chemical Co	150,000
Pittsburgh Plate Glass Co	70,000

Two producers, FMC Corp. and Stauffer Chemical Co., provided the indicated Wyoming production by mining beds of the mineral trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). In 1965, an additional four companies were developing or actively exploring Wyoming properties (Engineering and Mining Journal, 1965). Production capacity from that state can therefore be expected to increase, and this will provide additional competition for available western markets.

Because sodium carbonate is a relatively inexpensive product—in 1963, it sold for $32 per ton in bulk lots (MacMillan, 1964)—a major percentage of its price comes from the cost of transporting it to the customer. Trucking and rail rates between sources and markets thus become important considerations in the economic practicality of a deposit. The natural deposits in Wyoming and California therefore have an advantage in capturing western markets. Within this area, though, the deposits in Wyoming generally have freight-rate advantages in supplying customers in the northwestern states where large quantities are used in the production of paper. The California deposits have comparable freight-rate advantages for markets in much of California and the southwestern states, but the demand for sodium carbonate in these areas is less.

The three producers of sodium carbonate in California operate on two deposits, Searles Lake in San Bernardino County (fig. 74, loc. A), and Owens Lake in Inyo County (loc. B). American Potash & Chemical Corp. and Stauffer Chemical Co., West End Division, produce from brines pumped from Searles Lake. Pittsburgh Plate Glass Co. produces from brines from Owens Lake. All three plants extract sodium carbonate from the impure brines by complex processes that involve carbonation, evaporation, and cooling. The plants at Searles Lake produce other products as well; the plant at Owens Lake produces sodium carbonate or sodium sesquicarbonate as its only products (Ver Planck, 1957).

Prior to the full development of these operations on Owens and Searles Lakes, sodium carbonate was produced in small quantities by other plants on these deposits (Garrett and Phillips, 1960). The earliest operations were on Owens Lake in the years following 1886. In these operations, trona was precipitated in evaporation ponds, and then calcined to produce sodium carbonate. Similar operations were attempted on both Owens and Searles Lakes, but interest was sporadic until about the time of World War I. Then, the accelerated requirements for both soda ash and potash (which was also found to occur in dry lakes) prompted several attempts to establish large-scale production from both deposits. It was not until 1926, though, that the American Potash & Chemical Corp. began successful production of sodium carbonate on an industrial scale from Searles Lake. In 1927, it was first produced from this deposit by the West End Chemical Co. (now a division of the Stauffer Chemical Co.). In the period since

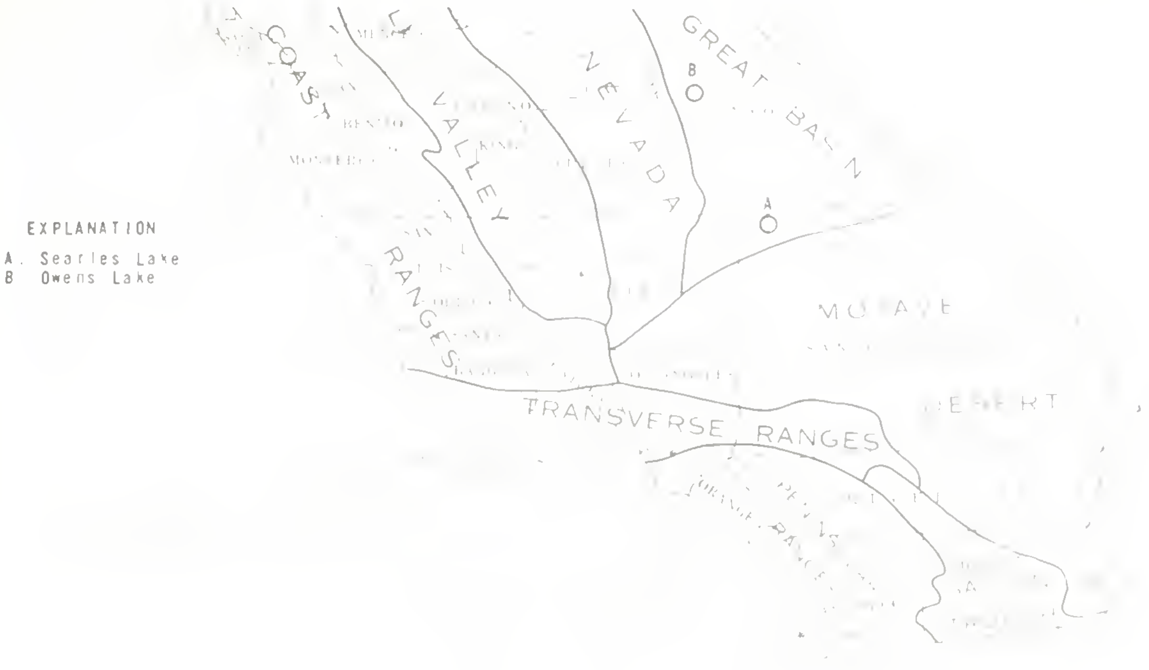

FIGURE 74. Location of sodium carbonate producers in California.

World War I, several smaller plants also produced from the Owens Lake deposit, but only the relatively modern plant of the Pittsburgh Plate Glass Co. is still in operation.

The geologic settings of Searles and Owens Lakes are similar. Both deposits were formed by the drying up of large saline lakes that formed during late Quaternary time in closed basins. These lie in the southwest part of the Great Basin, and during the wetter periods they contained large lakes that were integrated into a chain (Gale, 1914). Owens Lake was the first lake in this chain, and it received most of its water from the east side of the Sierra Nevada. When Owens Lake was about 200 feet deep, it overflowed southward, first into Indian Wells Valley to form China Lake, and then into Searles Valley to form Searles Lake which reached a maximum level 640 feet above the present valley floor. At these times Searles and China Lakes coalesced into one large body of water and overflowed into Panamint Valley. The lake in Panamint Valley, in turn, overflowed into Death Valley.

For long periods during the later parts of Quaternary time, the chain of lakes ended with Searles Lake. During these periods the more soluble components dissolved in the waters became concentrated in Searles Lake. When climatic changes caused it to become dry, or nearly so, the dissolved salts were deposited on the valley floor.

Such changes in climate were repeated many times during late Quaternary time. In Searles Lake, each cycle produced a layer of mud (formed during the time a large lake occupied the valley) and an overlying layer of salines (formed during the subsequent period of dryness). These saline layers differ in composition. The major differences are the result of changes in the composition of the saline materials dissolved in the tributary waters; the smaller differences are the results of the specific climatic characteristics of successive drying episodes.

The saline deposits being exploited in Searles Lake are among those that differ slightly as a result of minor climatic differences at the time of deposition. The deposits are grouped into two zones, both of which extend over areas of about 40 square miles (Flint and Gale, 1958; Haines, 1959; and Smith, 1962). The upper zone, formed during the post-Wisconsin dry period, is generally 70 to 80 feet thick in the areas being used for commercial purposes. The lower zone, formed during the middle Wisconsin dry period, is 30 to 40 feet thick in these areas. It is separated from the upper layer by a mud layer 12 to 14 feet thick. Brines occupy the interstices of both saline layers, and they are estimated to account for about 40 percent of their total volume. These brines are pumped to the chemical plants on the edge of the lake where they are processed to extract the valuable saline components. Chemical analyses of brines representative of those being pumped from these two zones are given in table 44.

TABLE 44.—*Chemical analyses of brines*

	Searles Lake [1]		Owens Lake [2] (in percent)
	Upper zone	Lower zone	
Na_2CO_3 (percent)	4.8	6.1	8.6
$NaHCO_3$	.1	0	0(?)
Na_2SO_4	6.8	6.7	4.6
NaCl	16.2	16.2	16.8
KCl	4.9	3.2	.7
$Na_2B_4O_7$	1.6	1.7	.5
Total dissolved solids (percent)	34.6	34.5	------------

[1] Garrett and Phillips, 1960, table 3; values in grams per liter unless indicated as weight percent.
[2] Dub, 1947, table 3, analysis of April 1940.

Owens Lake never dried up during these periods. Saline waters that collected in the basin during periods of nonoverflow were later washed downstream. However, since the last overflow (probably 2 to 4 thousand years ago), salines have accumulated in the basin, and in about 1913, when the Owens River was diverted into the Owens Valley aqueduct (which leads to Los Angeles), the lake began to dry up. By 1921, a layer of salines had formed, and brines from this provide the raw material of present operations. A typical analysis of these brines is listed in table 44.

Future sources of natural sodium carbonate in California appear to be limited to the Owens Lake and Searles Lake deposits. Their reserves have been estimated as more than 58 million tons and 150 million tons, respectively (Garrett and Phillips, 1960). At current plant capacities, this supply would last over 500 years. Although demand in the Western States will increase, the continued development of the enormous resources in Wyoming will tend to limit the role of California producers in supplying this demand.

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SODIUM SULFATE

(By G. I. Smith, U.S. Geological Survey, Menlo Park, Calif.)

Sodium sulfate, known industrially as salt cake, is produced in the United States both from natural deposits and as by-products of several chemical processes. About 70 percent of production is used in pulp and paper industries; the remaining 30 percent is used by manufacturers of glass, ceramic glazes, detergents, stock feeds, dyes, textiles, medicines, and other assorted chemicals (MacMillan, 1964).

Natural deposits of sodium sulfate are common in many parts of the world, especially arid regions. Significant production from foreign deposits has come from Spain, Rumania, Italy, Russia, Argentina, Chile, Mexico, and Canada (mostly Saskatchewan). At present, United States production from natural sources comes from California, Wyoming, and Texas, but deposits that might be utilized also occur in Colorado, Idaho, Nevada, New Mexico, North Dakota, Oregon, and Utah (Goudge and Tomkins, 1960). In 1963, these active deposits provided 36 percent of the Nation's total output, or about 435,000 short tons, having a value of $8,392,000 (MacMillan, 1964).

During the same period, industrial sources provided 64 percent of the Nation's total, or about 770,000 short tons. Processes that make sodium sulfate as a by-product include those that manufacture hydrochloric acid, rayon, phenol, sodium bichromate, boric acid, and cellophane. Industrial sources in California are the U.S. Borax and Chemical Corp., and the Stauffer Chemical Co., which produce sodium sulfate during the conversion of borax to other products (MacMillan, 1964).

In 1963, bulk lots of domestic salt cake sold for $28 per ton at the works (MacMillan, 1964). Inasmuch as it is a fairly inexpensive product, transportation costs account for a significant part of the ultimate price to the consumer. Producers close to large markets thus have a potential advantage. For this reason, markets in the Eastern United States are chiefly supplied from industrial by-product sources, and those in the Western States depend more heavily upon natural deposits in California, Texas, Wyoming, and Canada.

Two companies in California, the American Potash & Chemical Corp. and the Stauffer Chemical Co. (West End Division) with plants at Searles Lake (fig. 75), provide much of the United States production from natural sources. In 1951, the annual plant capacity of American Potash was reported to be about 220,000 short tons (Ryan, 1951), and in 1958, Stauffer was reported to have an annual capacity of about 145,000 short tons (Chilton, 1958). Both companies extract sodium sulfate (among other products) from complex brines pumped from the interstices of the late Quaternary saline deposits of Searles Lake. This deposit and its geologic setting are described in the section on sodium carbonate. Descriptions of the industrial processes used to extract the product are given by Ryan (1951), Ver Planck (1957), Chilton (1958), and Goudge and Tomkins (1960).

Other potential sources of sodium sulfate in California are listed in table 45. All deposits except one in the Durmid Hills—are late Quaternary to Recent saline bodies formed in closed basins. Owens lake, in the Great Basin, is predominantly a carbonate saline body. Dale and Danby Lakes, in the Mojave Desert, lie in an area characterized by sulfate and chloride saline bodies. Soda Lake, in the California Coast Ranges, lies in a sag pond along the San Andreas fault: its composition suggests that this is a province with sodium sulfate-rich water, although most of it drains to the sea. The deposit in the Durmid Hills is in late Cenozoic lacustrine deposits that have been steeply folded by displacements along the nearby San Andreas fault.

Some of these deposits consist chiefly of sodium sulfate in brine; others contain high percentages in the solid minerals. Relatively simple extraction and refinement methods produce a marketable grade of sodium sulfate from either type of material; these methods generally depend upon the uncommonly large decrease in the solubility of sodium sulfate with decreasing temperature. In some instances, a

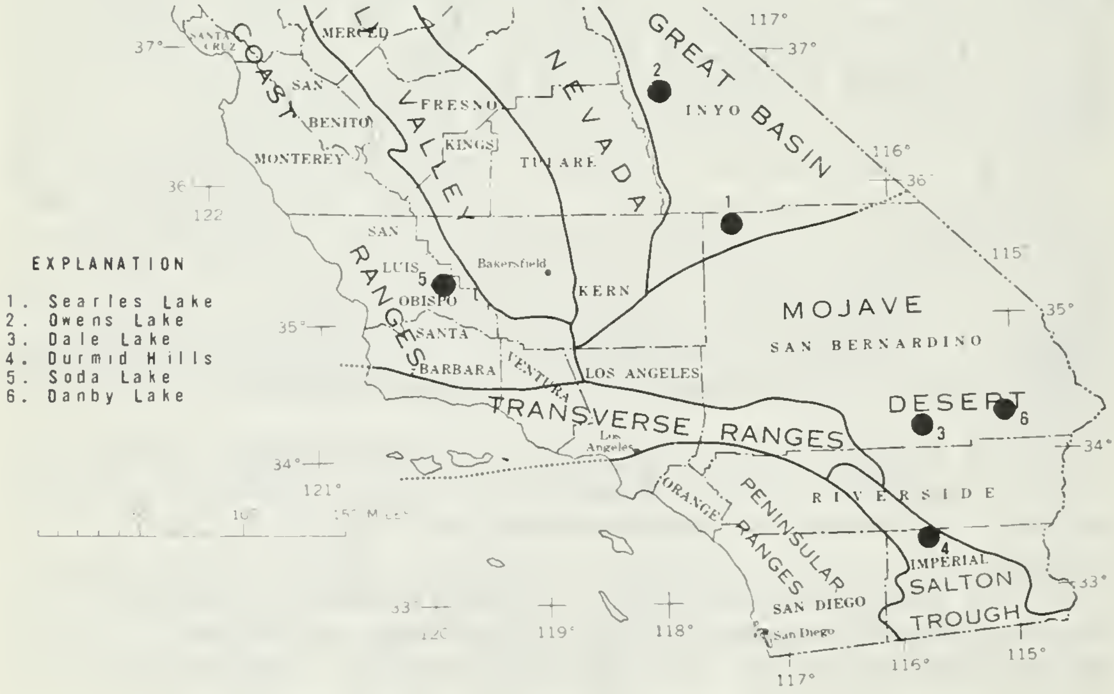

FIGURE 75. Sodium sulfate deposits in California.

TABLE 45.—*Sodium sulfate deposits in California*

Occurrence	No. on fig. 75	Type of occurrence [1]	Record of production
Searles Lake [2]	1	Brine-filled saline body (see table 44 for brine analyses). Major sulfate minerals: thenardite, burkeite, hanksite, and aphthitalite.	Production from brine, 1926 to present.
Owens Lake [3]	2	Brine-filled saline body (see table 44 for brine analyses). Major sulfate minerals: burkeite, thenardite, mirabilite.	No production.
Dale Lake [4]	3	Brine-filled saline lenses. Major sulfate mineral: thenardite.	Production 1937–48, from brines; several attempts to produce from solids.
Durmid Hills [4]	4	Thenardite and bloedite in deformed upper Cenozoic shale and sandstone.	Some past production from opencut mines.
Soda Lake [4]	5	Mirabilite crust, some bloedite	Some past production from crusts.
Danby Lake [4]	6	Disseminated mirabilite crystals	Minor past production.

[1] Mineral compositions: Thenardite, Na_2SO_4; Mirabilite, $Na_2SO_4 \cdot 10H_2O$; Burkeite, $2Na_2SO_4 \cdot Na_2CO_3$; Hanksite, $9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$; Aphthitalite, $K_3Na(SO_4)_2$; Bloedite, $Na_2Mg(SO_4)_2 \cdot 4H_2O$.

[2] Smith and Haines, 1964.

[3] Dub, 1947.

[4] Ver Planck, 1957.

marketable grade has been produced solely by spraying the sodium sulfate-bearing brine into cool air. This technique is used on Searles Lake by the American Potash & Chemical Corp. to produce sodium sulfate decahydrate (mirabilite) for use in the plant cycle, but a more complex process is used in the production of anhydrous sodium sulfate (thenardite) for shipment. Whenever mirabilite is produced from other deposits by these methods, it is generally dehydrated to thenardrite prior to shipment because 56 percent of the weight of mirabilite is water. Dehydration is difficult on an industrial scale, though, because at normal drying temperatures, the solubility of sodium sulfate decreases with increasing temperature so that crystallized material tends to form an insulation on the heating surface.

The presently known resources of sodium sulfate in California are probably adequate to maintain present production for many years to come. Estimates of the quantities in Searles Lake have not been published, but calculations based on published data indicate that many years' supply exists in the brines, and that a much larger quantity is potentially available from the solution or mining of the enclosing saline minerals. To a large extent, the life of this deposit also depends on the reserves of other marketable products because all are co-products of the present plants. Other deposits in the State might become economically feasible in the future. Of these, Owens Lake is probably the largest and has been estimated to contain 24,000,000 short tons of sodium sulfate (Dub, 1947); only part of this would be recoverable, though, and the lack of past production suggests that engineering or marketing problems exist which might limit the recovery to a relatively low percentage. The other deposits in California might supply material at present rates for a few years.

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STONE, CRUSHED AND BROKEN

(By H. B. Goldman, California Division of Mines and Geology, San Francisco, Calif.)

Stone production is one of the oldest and most extensive mineral industries in California. In the late 1800's, dimension stone was produced in the State in much greater volume than crushed stone. During the past 50 years the output of dimension stone has dwindled, while the production of crushed stone has increased many fold. Greatly increased use of crushed stone for aggregate, especially in asphalt concrete for paving, and the marked decrease in use of dimension stone for building stone, paving blocks, or curbing is largely responsible for this trend.

In 1964, California ranked third among the states in stone production, with a total output of approximately 45,710,000 short tons, valued at $61,391,000. Crushed stone ranked in value only behind petroleum products, cement, and sand and gravel, among California's mineral commodities.

Although the terms "rock" and "stone" commonly are used synonymously, they have different meanings when strictly applied. "Rock" has been defined variously by geologists, but in the stone industry it is applied to any mass of mineral aggregate as it exists in its natural state and in place. "Stone" refers to individual blocks, masses, or fragments that have been broken or quarried from bedrock exposures, and are intended for commercial use.

Most deposits of economic minerals have formed under relatively uncommon geologic conditions, but stone is obtained from the ordinary rocks that constitute the earth's crust. The materials that can be classed as stone are numerous, widespread, and of a wide range of geologic ages and modes of origin.

Stone has many industrial applications, but these can be divided into two general classifications by usage: (1) crushed and broken stone, and (2) dimension stone. Crushed and broken stone includes all stone in which the shape is not specified, such as that used as aggregate, railroad ballast, and riprap. Dimension stone is produced to specified dimensions, and includes stone employed as building stone, monumental stone, curbing, and flagstone (see section on Dimension stone in this volume).

For most uses, crushed or broken stone should be durable, dense, sound, hard, strong, able to withstand high temperatures, and tend to break into suitably shaped fragments. In almost all uses, stone must resist the chemical action of weathering. Stone to be used for certain special purposes, such as the limestone used in agriculture, glass manufacture, or the sugar refining industry, must be chemically suited to these applications.

Crushed and broken stone commonly is further subdivided, on the basis of use, into (1) crushed stone, (2) riprap, (3) furnace flux, (4) refractory stone, (5) agricultural stone, and (6) stone used for other purposes. Crushed stone is mainly used as aggregate in asphalt concrete for paving purposes, railroad ballast, aggregate base, and fill. Riprap consists of large broken stone used without a binder, principally for jetties, breakwaters, and seawalls which are intended primarily to resist the physical action of water. Furnace flux consists of limestone and marble used for chemical purposes in the refining of iron ores and in other metallurgical practices. Refractory stone, such as quartzite, mica schist, dolomite, and soapstone is used in the manufacture of refractory brick, and for furnace and ladle linings. Agricultural stone includes any type of stone that is added to soil, either as a fertilizer or a soil-conditioner. The category "other purposes," includes crushed stone used as a filler, poultry grit, roofing granules, stone sand, and terrazzo granules; in the production of mineral wool, stucco, artificial stone, and mineral food; in coal mine dusting; and for various chemical applications.

Many materials, that by definition can be classified as stone are considered as separate commodities. Dolomite, limestone, vein quartz and quartzite, sand and gravel, and specialty sands, as well as such stone-like nonmetallic materials as diatomite, pumice, perlite, volcanic cinders, and soapstone are described more completely elsewhere in this volume.

Rocks used as crushed and broken stone in California

The stone industry recognizes the following stone classification based mainly on composition and texture: (1) granite; (2) basalt and related rocks; (3) limestone; (4) marble; (5) sandstone; and (6) miscellaneous stone (including conglomerate, greenstone, shale, mica schist, and tuffaceous volcanic rocks). Most of these types are abundant and widespread in California, as shown on Figure 76, and listed in table 46.

TABLE 46.—*Principal crushed and broken stone quarries in California*

[Locations shown on fig. 76]

GRANITE

1. Union Granite Co., Rocklin, Placer County.
2. Guy F. Atkinson, Riverside, Riverside County.
3. J. B. Stringfellow, Riverside, Riverside County.
4. Granite Rock Co., Watsonville, San Benito County.
5. Hansen, Silvey, and Sinnott, Felton, Santa Cruz County.

SANDSTONE

6. Blake Bros., Richmond, Contra Costa County.
7. Quarry Products, Inc., Point Richmond, Contra Costa County.
8. Sweetser Bros., Rosamond, Kern County.
9. Basalt Rock Co., McNear Point, Marin County.
10. Hutchinson Co., Greenbrae, Marin County.
11. Pacific Cement and Aggregate, Inc., Brisbane, San Mateo County.
12. Guy F. Atkinson, Rincon, Santa Barbara County.
13. Rancho Guadalasca, Camarillo, Ventura County.

TABLE 46.—*Principal crushed and broken stone quarries in California*—Continued

BASALT (AND RELATED VOLCANIC ROCKS)

14. Gallagher and Burk, Inc., Oakland, Alameda County.
15. A. C. Goerig, Orinda, Contra Costa County.
16. Basalt Rock Co., Inc., Novato, Marin County.
17. Basalt Rock Co., Inc., Napa, Napa County.
18. Don Weaver, Jucumba, San Diego County.
19. J. M. Nelson, Cordelia, Solano County.
20. Hein Bros. Basalt Rock Co., Petaluma, Sonoma County.

LIMESTONE

21. California Rock and Gravel Co., Cool, El Dorado County.
22. El Dorado Limestone Co., Inc., Shingle Springs, El Dorado County.
23. Premier Marble Products, Lone Pine, Inyo County.
24. Kaiser Aluminum and Chemical Corp., Natividad, Monterey County.
25. Industrial Rock Products, Wrightwood, San Bernardino County.
26. C. K. Williams, Cushenbury, San Bernardino County.
27. Eaton and Smith, Paso Robles, San Luis Obispo County.
28. Marks Materials, Inc., Rockaway Beach, San Mateo County.
29. Kaiser Cement and Gypsum Corp., Los Altos, Santa Clara County.
30. Sonora Marble Aggregates, Sonora, Tuolumne County.

MISCELLANEOUS STONE

31. La Vista Quarries, Hayward, Alameda County.
32. San Leandro Rock Co., San Leandro, Alameda County.
33. Ry-lite Corp. of California, Altaville, Calaveras County.
34. Henry J. Kaiser, Clayton, Contra Costa County.
35. Pacific Cement and Aggregates, Clayton, Contra Costa County.
36. Gravelle and Gravelle, Trinidad Quarry, Humboldt County.
37. Desert Rock Milling Co., Randsburg, Kern County.
38. Connolly-Pacific Co., Catalina Island, Los Angeles County.
39. Riverside Cement Co., Catalina Island, Los Angeles County.
40. Minnesota Mining and Mfg. Co., Corona, Riverside County.
41. Brubaker-Mann Co., Barstow, San Bernardino County.
42. Canyon Rock Co., San Diego, San Diego County.
43. Kenneth H. Golden Co., San Diego, San Diego County.
44. Robert Guerra, Morro Bay, San Luis Obispo County.
45. Mirassou Bros., Los Gatos, Santa Clara County.

SLATE

46. Placerville Slate Products, Placerville, El Dorado County.

Granite

The term "granite" is commonly applied to medium- to coarse-grained igneous rocks that consist mainly of feldspar and quartz, with subordinate amounts of ferromagnesian minerals. In the stone industry, and in the following discussion, the terms "granite" and "granitic rock" are used even more broadly to refer to various intrusive igneous rocks with granitoid textures, and to some metamorphic rocks with gneissic textures.

Most unweathered granitic rocks are hard, strong, tough, and resistant to abrasion, impact, and chemical attack. These properties make granitic rock well suited to use as building stone, riprap, and aggregate.

Granitic rocks occur mainly in large bodies, known as batholiths, which are exposed over many square miles. In California, granitic rocks occur mostly in the Sierra Nevada and southern California batholiths and in smaller masses in the Klamath Mountains and the

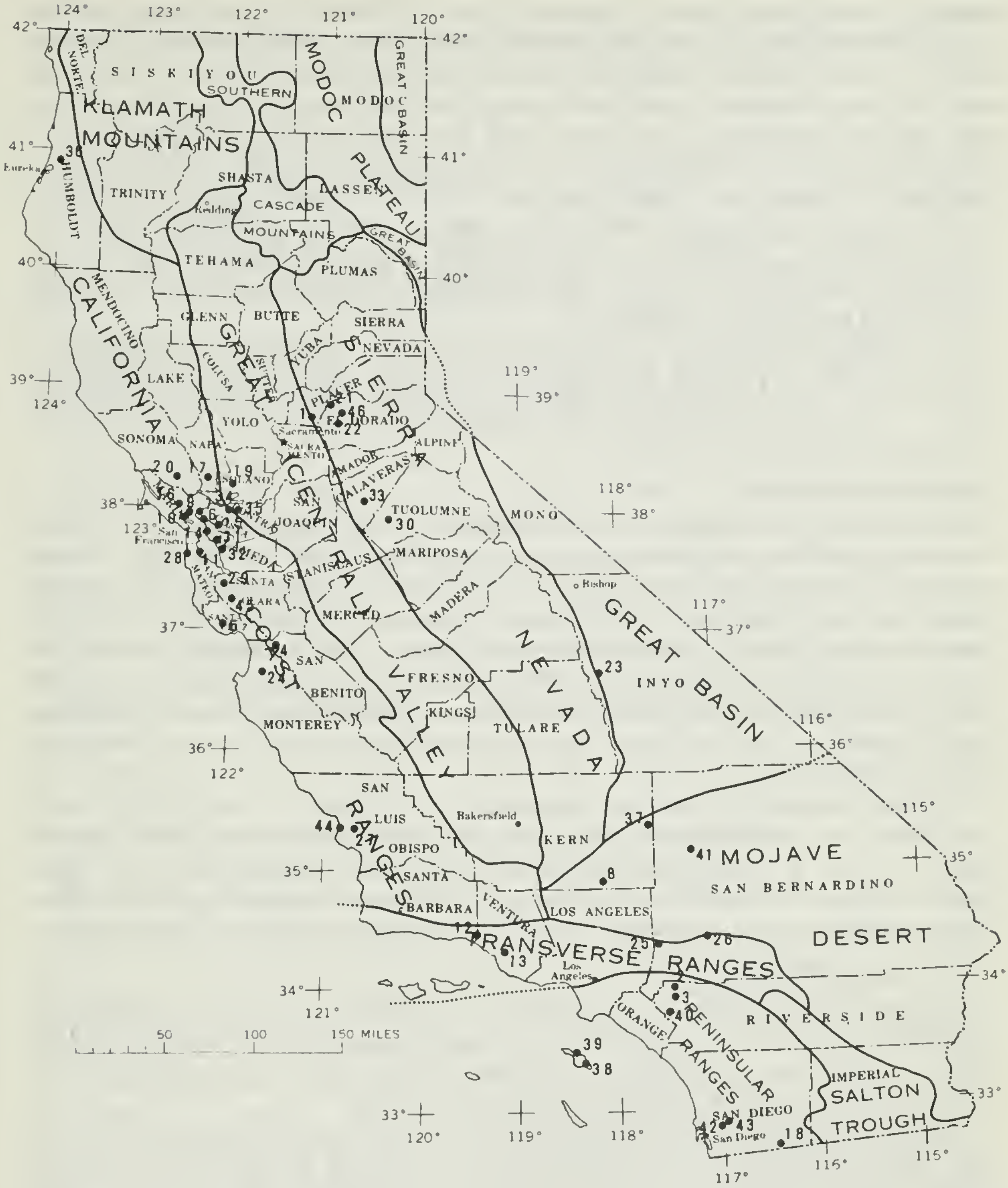

Figure 76. Principal crushed and broken stone quarries in California; numbers refer to table 46.

desert regions of eastern and southern California. These bodies together underlie about 40 percent of the State's area and are largely or wholly of Mesozoic age. Batholiths commonly consist of numerous individual bodies of various granitic rock types, with contrasting colors, textures, and mineral composition. The two great batholiths of California are exposed mostly in mountainous areas, but the main granite quarries lie about their peripheries or in outlying smaller masses, so that the quarries are as close as possible to major transportation routes to centers of consumption. Over wide areas of the State, the exposed granitic rocks are so deeply weathered or highly fractured as to be unsuited to the purposes outlined above. In the Los Angeles area, for example, little or none of the granitic rock exposed in the nearby Santa Monica or San Gabriel Mountains is sufficiently unshattered or unweathered to be quarried as crushed stone in large tonnages, and all granitic stone must be brought to the Los Angeles area from quarries in Riverside, San Diego, and San Bernardino Counties, 45 to 100 miles away. Disintegrated and shattered granitic rock, known commercially as decomposed granite, or "DG" is much used in southern California as aggregate base, low-quality paving material, and fill.

In California, granitic rock, has been quarried mainly for use as dimension stone and riprap, but the quarry waste has been a source of crushed stone for local uses.

The following granite quarries were active in 1964: near Rocklin, Placer County; Logan, San Benito County; the Jurupa Mountains and vicinity, Riverside and San Bernardino Counties; and near El Cajon, San Diego County.

Decomposed granite

Weathering may decompose the feldspar and ferromagnesium minerals in granitic rock, and convert once-sound rock in situ to a weak, relatively friable mass of quartz grains, clay, and partially decomposed grains of feldspar and ferromagnesian minerals. Granite that has been shattered by fault action is particularly susceptible to decomposition by weathering. Weathering in sedimentary deposits of granitic debris may render the stone unsound for use as aggregate and if sufficiently advanced, convert the deposit to the equivalent of decomposed granite.

As an extremely low-cost material employed in relatively nonexacting uses, decomposed granite can rarely be economically hauled farther than a few miles to the site of use. Therefore, it is used extensively only in those sections of California where it occurs near metropolitan areas, especially the Los Angeles and San Diego areas.

Basalt and related rocks

In commercial usage, and in this discussion, the term "basalt" is applied to any of the dense, fine-grained, dark-gray or black volcanic rocks. The term ordinarily includes rock types that geologists classify as dacite, andesite, basalt, trachyte, or latite.

Basaltic rocks are characteristically hard, tough, and durable, so are best suited for use as aggregate, railroad ballast, and riprap. Some types of crushed basaltic rock are well suited for use as artificially colored roofing granules.

Basaltic rocks are extensively exposed in many localities in California. In the northeastern part of the State, Tertiary and Quaternary basaltic rocks are exposed for hundreds of square miles in the Modoc Plateau and form the most extensive occurrences. A number of smaller areas, measurable in tens of square miles or less, occur scattered in the Sierra Nevada and Mojave Desert provinces in the northeastern portion of central and southern California. Little basaltic stone is obtained from these areas because of their remoteness from the main centers of use, but some has been quarried for local construction projects and for railroad ballast.

Less extensive occurrences in the Coast and Peninsular Ranges are the sources of most of the basaltic stone produced in the State. Notable quantities of basaltic stone are produced near Napa, Marin County; Novato, Marin County; Orinda, Contra Costa County; Cordelia, Solano County; and Jucumba, San Diego County.

Limestone and marble

Carbonate rocks are abundant and commercially important in California (see section on Limestone, dolomite, and lime products, including cement).

In the stone industry the term limestone is applied to many types of rock that contain a high percentage of calcium carbonate, although large proportions of other substances also may be present. They also commonly contain clay, silt, and sand grains. A high percentage of clay commonly weakens carbonate rock, and makes it unfit for use as stone; a high content of sand grains or silica may make carbonate rock too hard to be prepared for use economically.

The term "marble" is applied to any carbonate rock that will take a high polish and includes various dense types of limestone and dolomite. The term is also loosely applied to coarsely crystalline carbonate rocks. The classification of carbonate rock either as limestone or marble therefore is determined largely by its use. Stone from many California deposits, for example, has been used both as limestone (e.g., in the sugar industry) and as marble. Nearly all of the crushed carbonate stone produced in California is classified as limestone.

For use as stone, carbonate rock should be physically sound, dense, and relatively pure. Carbonate stone that is strong, tough, and durable is well suited for use as concrete aggregate, road metal, railroad ballast, and riprap. A pure-white color also is desirable in carbonate stone to be used for granules in built-up roofing, and various colors are desirable in granules to be used for terrazzo.

Most of the carbonate stone produced in California in recent years has been used primarily for its chemical properties, and has been consumed in the cement, lime, agricultural, and various other process industries. Relatively smaller tonnages have been produced for use as crushed and broken stone primarily as by-products of cement company operations.

Occurrences of carbonate rocks are extensive and widespread in California. Deposits are especially numerous in the western Sierra Nevada province, the northeastern portion of the Klamath Mountains province, the Great Basin, and Mojave Desert provinces in southeastern California; in the Coast Ranges, mainly south of San Francisco, and in the Peninsular and Transverse Range provinces of southern California. The ages of these deposits range from Precambrian to Miocene.

Sandstone

Sandstone is a clastic sedimentary rock composed of particles mainly in the size range of about one-fourth to one-hundredth of an inch in diameter. Some sandstones consists almost wholly of quartz grains, but most sandstones are feldspathic and some contain a high proportion of ferromagnesian minerals. The strength and durability of sandstone are mainly determined by the type of material that cements the grains together. Only well-indurated sandstone, cemented with silica or calcite (rather than with the weaker cements, clay or iron oxide), is suited for use as crushed and broken stone.

Most of the sandstone that occurs in California is very friable, but some is sufficiently durable to be used for riprap, railroad ballast, portland cement, concrete aggregate, and bituminous aggregate.

Virtually all of the sandstone in California occurs in formations that lie within the age range of Jurassic to Quaternary. Commonly, the older sandstones are harder and stronger than the younger ones, hence are better suited to use as crushed and broken stone.

Sandstone is extensively exposed in most of the western and central parts of the State, but sandstone for use as crushed and broken stone has been produced mainly in the San Francisco Bay area at quarries in Marin and Contra Costa Counties.

Miscellaneous stone

In addition to the four main categories described previously, many varieties of rock types have been quarried throughout California and are grouped under the heading of "Miscellaneous stone". Significant production is obtained from conglomerate, greenstone, slate, tuff, and metavolcanic rocks.

Conglomerate is clastic sedimentary rock containing abundant fragments of pebble size or larger in a matrix of sand and finer-grained materials. Conglomerates show various degrees of induration which depend largely on the nature and amount of cementing material—clay, calcium carbonate, iron oxides, or silica—in the matrix.

In California, the principal source of conglomerate for use as crushed and broken stone is a body of well-indurated conglomerate within the Mesozoic or older Catalina Schist at Pebbly Beach, Santa Catalina Island, Los Angeles County. This deposit has been worked for many years, and considerable tonnage has been hauled by barge to the mainland for use as riprap and harbor stone in the Long Beach area.

Greenstone is a general term applied by geologists to basic or intermediate volcanic rocks that contain abundant green secondary minerals. In the stone industry, the term is applied also to a variety of fine-grained green rocks, including arkosic sandstone, graywacke, impure quartzite, and various pyroclastic rocks.

Rocks classifiable as greenstone in this broader sense are moderately abundant in many parts of California, but relatively small tonnages are used as crushed and broken stone. Many occurrences of greenstone are outside the range of economic haulage to main centers of use, and much of the more readily available greenstone is of inferior quality.

Much of the crushed greenstone is employed for uses in which a green color is specifically desired, such as for naturally colored roofing granules. Physically sound greenstone also may be used for aggregate, ballast, riprap, or fill, if it is available economically.

Some of the most extensive occurrences of greenstone in California are in the Franciscan Formation, in the northern and central Coast Ranges, and in the upper Palezoic Calaveras Formation and the Jurassic Amador Group along the west flank of the Sierra Nevada. Much of the green pyroclastic sedimentary rock quarried in Kern County since World War II for roofing granules could be classed as greenstone.

Slate is a thinly foliated metamorphic rock composed essentially of muscovite (sericite), quartz, and graphite, all in grains of microscopic or submicroscopic size. Slate is formed by compaction and partial recrystallization of shale, is commonly dark colored and moderately hard.

Slate is desired mainly for use as dimension stone (see section on Dimension stone). Its chemical inertness, resistance to weathering, and flat particle shape make crushed slate a desirable material for roofing granules and filler dust.

Extensive exposures of slate of the Jurassic Mariposa Formation occur along the western flank of the Sierra Nevada. Minor bodies of slate, mostly of low quality, occur in pre-Tertiary metamorphic rocks at several scattered localities in the State.

The State's principal source of crushed and pulverized slate is the Chili Bar mine, El Dorado County, which has been active since 1962. Here the slate is mined in extensive underground workings and is used for roofing granules and filler dust.

The term "*tuff*" embraces pyroclastic volcanic rocks, most of which would be classed as rhyolite or dacite tuffs or tuffaceous sediments. Most tuffaceous rocks are only moderately hard, although on exposure to air they commonly harden appreciably. As many tuffs are attractively colored and workable, they have been extensively used for building stone (see section on Dimension stone). Because of its softness, tuffaceous rock is unsuited to most uses of crushed and broken stone but it is extensively used in the production of colored roofing granules.

Extensive bodies of light-colored tuffaceous rocks occur in the Tertiary volcanic section at many localities in California. Pink and buff-colored tuff in the Valley Springs formation along the west flank of the Sierra Nevada, and highly colored Miocene tuffaceous sedimentary rocks near Randsburg in Kern County, are quarried and crushed for use as naturally colored roofing granules.

Dark dense *metavolcanic* rocks are excellent sources of riprap, crushed stone and roofing granules. Quarries are active in San Diego, San Diego County; Corona, Riverside County; and Clayton, Contra Costa County.

RESOURCE POTENTIAL

The market for crushed and broken stone will continue to grow in California to keep pace with the growth of the State. The demand has been primarily for stone used in public works and, therefore, can fluctuate widely from year to year. While it appears that reserves are adequate at developed sources, the press of urbanization threatens many a quarry. Sources of stone for riprap are constantly being sought by contractors.

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STONE, DIMENSION

(By H. B. Goldman, California Division of Mines and Geology, San Francisco, Calif.)

Dimension stone production is among the oldest and largest of the mineral industries of California; commercial quarries were operated as early as 1854 at Monterey and Point Reyes. Until the early 1900's the production of dimension stone, mainly for use in buildings, paving, and curbing, greatly exceeded that of crushed stone, but, since then, the dimension stone output has dwindled while production of crushed stone has increased many fold. The development of steel-frame buildings, which require comparatively little stone, and the introduction of concrete, which is much less expensive and more conveniently used than stone, combined to cause this decline.

The term "dimension stone" is applied to natural stone that is cut to definite size and shape and includes cut, carved, and roughhewn blocks of building stone, paving blocks, curbing, flagging, and cut and polished monumental stone.

The recorded production of dimension stone in California from 1887 to 1964, totals approximately 58 million dollars, as shown in fig. 77. In 1964 dimension stone valued at approximately 2.1 million dollars was produced in the State. This stone was used principally for monumental and building stone. Rock types quarried in 1965 were granite, light-colored volcanics, siliceous limy shales, mica schist, slate, and quartzite.

Dimension stone is subdivided by uses into building stone, monumental stone, paving stone, curbing, and flagging. One of the principal uses of dimension stone is as a construction material. Included in this category is stone in any form that constitutes a part of a structure. Whereas building stone formerly was a basic construction material, its present function is largely ornamental. Building stone is marketed as rubble, rough building stone, ashlar, and cut or finished stone.

SPECIFICATIONS OF ROCK USED FOR DIMENSION STONE

Only a small portion of the rock that comprises the earth's crust can satisfy the exacting specifications for most dimension stone. Freedom from cracks and lines of weakness is essential. Uniform texture and grain size together with an attractive color are generally required. The rock must be free from such minerals as pyrite, marcasite, and siderite, which oxidize upon weathering to cause deterioration or surface staining. A rock that splits easily in 1 or 2 planes is desirable. Many rocks, particularly granites and sandstones, split in some directions with greater ease than in others.

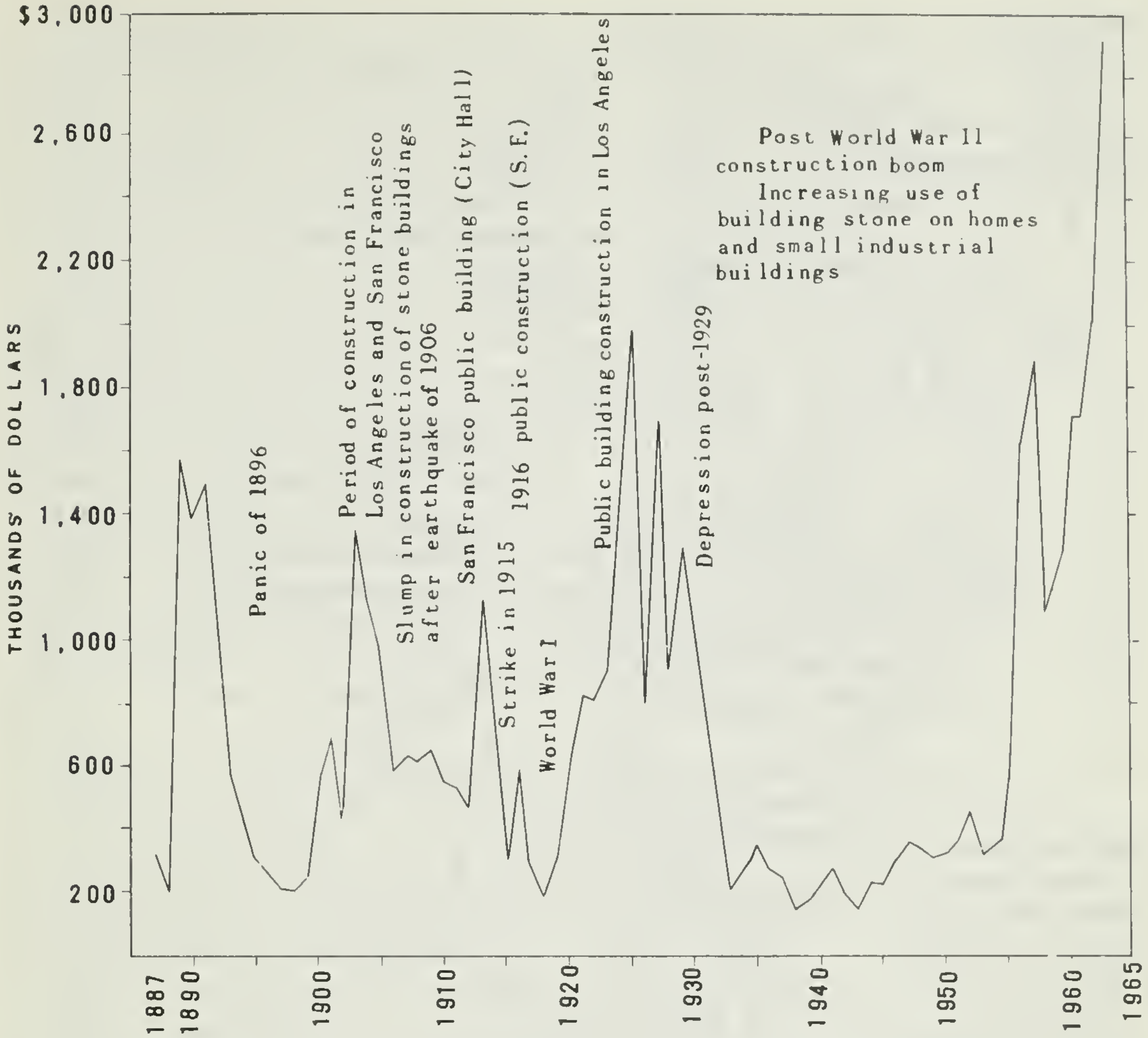

FIGURE 77. California dimension stone production, 1887–1963.

ROCK USED AS DIMENSION STONE IN CALIFORNIA

Granite and related rocks

Granite, defined geologically, is a medium- to coarse-grained crystalline rock that consists essentially of potassium feldspar, subordinate sodic feldspar, and quartz. In the stone industry the term "granite" is used more broadly to refer to various intrusive igneous rocks with granite textures, and even some metamorphic rocks with gneissic textures. Such igneous rocks as syenite, granite, granodiorite, quartz monzonite, diorite, and gabbro, which range in color from light to dark and in composition from acidic to basic, commonly are referred to commercially as "granites".

Granite has comprised approximately 75 percent of the total dimension stone produced in California. In 1963, dimension stone granite valued at $1,564,271 was produced in the State. Principal sources of this and other dimension stone types are shown on figure 78.

Granitic rock underlies about 40 percent of California's land area and occurs mostly in the large bodies known as the Sierra Nevada and Southern California batholiths, and in smaller bodies exposed in the Klamath Mountains and in the desert regions of the State.

FIGURE 78. Principal sources of dimension stone in California.

Quarries in the Sierra Nevada batholith.—Quarries in the Sierra Nevada batholith have yielded approximately half of the granite dimension stone, and about 40 percent of all the dimension stone produced in California. The most productive districts have been at Raymond, Madera County; Rocklin, Placer County; and Academy, Fresno County. Smaller areas were active at Folsom, Sacramento County; Porterville, Tulare County; Nevada City, Nevada County; and Susanville, Lassen County. The quarries have been located mainly on low rounded outcrops in the foothill area where the granite was exposed at the surface, or as residual boulders. The periods of greatest activity were 1889–1895, 1903–1905, and 1920–1930.

The principal source of granite in California has been the Raymond district in Madera County. This district which was active mainly from 1888 to about 1943, has a total production valued at about 10 million dollars. Granite is quarried from a broad exfoliated dome about 700 feet in diameter. The oldest and most productive of the quarries, that of the Raymond Granite Co., was acquired in 1953 by the Cold Spring Granite Co. of Minnesota and was still active in 1965.

Granite similar to that quarried at Raymond has been quarried in Placer County from an area that extends from Rocklin to Newcastle. Since 1863, granite valued at well over 3 million dollars has been produced from this district. Quarrying has been confined to the gently rolling plain, approximately 6 miles long and 1 to 2 miles wide, that extends from Rocklin to Penryn. In 1965, the Union Granite Co. operated a quarry near Loomis.

Granite dimension stone valued at more than $650,000 has been produced in the Sierran foothills 1 mile northeast of Academy in Fresno County. In this district a dark-colored augite gabbro-diorite crops out as residual surface builders and as massive ledges underlying low rounded hills. Nine quarries in all have been worked in a 100-acre area. In 1964 the Raymond Granite Co. operated a quarry in this area.

Granite valued at $740,000 has been produced in Tulare County from three quarries in the foothills east of Porterville and Exeter.

Quarries in the southern California batholith.—In San Diego, Riverside, and San Bernardino Counties the various bodies of granitic rock, known collectively as the southern California batholith, are sources of dimension stone. The production of granite in San Diego County from 1898–1963 amounted to approximately 3 million dollars. Two types of granite have been quarried in the country, a pale-gray granodiorite and a "black granite," which includes such rock species as hornblende gabbro, norite, and quartz-biotite gabbro. The "black granite" is in demand for use in monuments and building fronts because of its pleasing black color, fine-grained texture which permits a high polish, and its resistance to weathering. However, the "black granite" is unusually hard and tough and therefore more costly to quarry and finish than most other California granites.

Most of these "black granite" quarries are in residual boulder deposits, whereas the light-gray granite is quarried mainly from massive rock. Distinct joint sets and a poorly developed sheeting structure characterize the massive exposures. The joints intersect at right angles and are spaced from 1 to 10 feet apart. The sheeting surfaces dip gently and generally are parallel to the slope of the land surface and are irregularly spaced from 6 inches to 6 feet apart. Such features are rarely observed in residual bouldery deposits. The boulders have formed chiefly from weathering through expansion and subsequent breaking apart by disintegration.

The principal dimension stone districts in San Diego County are near Lakeside, Escondido, and Vista. Since 1888, more than 40 quarries have been opened. Fifteen quarries have been active for various periods since 1953, and four were being worked in 1963. The most productive operations in 1963 were those of Escondido Quarries and National Quarries near Escondido. The stone is used for monuments and for making surface plates.

Sandstone

Sandstone is a consolidated sedimentary rock composed mostly of mineral or rock fragments that range in size from $\frac{1}{16}$ to 2 mm. The most common cementing materials are iron oxide, calcite, silica, and clay. The predominant mineral grains in most sandstones in California are quartz, feldspar, and mica. Some sandstones are composed almost entirely of quartz grains; other sandstones contain 33 percent or more of fragments of dark-colored rocks and minerals and are known as graywacke.

The usefulness of a sandstone as dimension stone depends largely upon the nature of the cementing material and degree of cementation. Permanence of color is desired in a sandstone. Uniformity in grain size, however, is a very desirable feature in sandstone. The ease with which sandstone can be worked, its variety of pleasing colors, and its ability to harmonize with brick and other building material makes it one of the most desirable of the building stones. The principal uses of dimension sandstone are for building stone, flagging, and curbing. An estimated 4 million dollars worth of sandstone has been produced as dimension stone in California since 1887 (Averill and others, 1948, p. 92).

Sandstone crops out predominantly in the Coast Ranges of northern and central California and the Transverse and Peninsular Ranges of Southern California. Almost all of the dimension sandstone has been produced from Cretaceous formations.

The principal centers of past production were located at Sites, Colusa County; Graystone, Santa Clara County; Chatsworth, Los Angeles County; and Sespe Canyon, Ventura County. The main period of sandstone production extended from 1888–1919.

The principal source of dimension sandstone in the State has been the Upper Cretaceous sandstones near Sites in Colusa County. From 1894 to 1914, these sandstones yielded about 1,186,000 cubic feet of dimension stone valued at $1,448,000. The Sites locality is in a belt of interbedded sandstone and shale that extends along the western margin of the Sacramento Valley from the northern boundary of Colusa County southward for 20 miles. In the vicinity of Sites massive sandstone beds, suitable for building stone, are exposed for a distance of 8 miles in a zone three-fourths of a mile wide. The beds range in thickness from 4 to 35 feet, dip approximately 50° to the northeast, and strike northwest. The stone has a blue-gray and buff color which weathers to light brown, is soft and has an even grain. In recent years small quantities have been quarried for use in the San Jose area in Santa Clara County.

Limestone and marble

To the petrologist, marble is a crystalline limestone, but in the stone industry and in the present discussion the term "marble" is applied to any calcareous rock capable of taking a polish. Some marbles are composed almost entirely of carbonate minerals; others contain such impurities as silica and silicate minerals, iron oxide and iron sulfide minerals, and organic matter. Marble is commonly white, but the iron oxides impart colors of tan, red, or brown, whereas carbonaceous matter causes a gray to black color. Verde antique is a greenish rock composed of serpentine mixed irregularly with calcite.

Uniform hardness and high resistance to abrasion are desirable qualities in marbles to be used for floor tile, sills, or steps. Marble for exterior purposes should have a low porosity to prevent infiltration of water which may dissolve or discolor the stone. Marble to be used for monuments should present a distinct contrast between chiseled and polished surfaces. The principal uses of dimension marble are as building stone and monumental stone.

Despite its widespread occurrence in California, marble has been produced commercially in only a few localities, principally in Tuolumne, San Bernardino, and Inyo Counties. From 1887 to 1963 the total recorded production of marble in California was valued at approximately 4 million dollars.

In 1965, minor amounts of limestone were produced at quarries in Tulare, Santa Cruz, and Solano Counties mainly for use as rubble.

The Columbia district near Sonora, Tuolumne County, has been the principal source of marble in California. From 1904 to 1942 this district yielded 255,000 cubic feet of marble valued at $700,000. In recent years, the marble has been used as crushed stone.

The marble in the Columbia district occurs as irregularly shaped masses of dolomite in metamorphosed limestones of the Calaveras Formation of late Paleozoic age. The limestones are exposed in a belt, approximately 25 miles long and 1 to 5 miles wide, trending roughly northwest. The bedding is generally indistinct and steeply dipping. The marble is a dense, fine-grained dolomite that takes a fine polish. The stone weighs 169 to 182 pounds per cubic foot and has a compressive strength of 25,000 pounds per square inch. The stone most commonly quarried is white with blue veining. A buff stone with reddish veining also was produced.

From 1896 to 1950, several localities in San Bernardino County yielded 185,388 cubic feet of dimension stone marble valued at $343,076. The main periods of activity were from 1902 to 1909 and 1936 to 1941. The bulk of the early production came from Slover Mountain, near Colton, where a recrystallized limestone of probable Paleozoic age occurs as roof pendants in granitic rocks. The poorly defined limestone strata which strike N. 70° E. and dip 45° E. are more than 2,000 feet thick. These beds are now quarried for use in cement.

Slate

Slate is a fine-grained rock produced by the regional metamorphism of clay or shale. Pressure and heat cause the shaly material to partly recrystallize to platy, micaceous minerals in parallel orientation. The cleavage thus produced is sufficiently well developed to allow easy splitting of the rock and is the feature of greatest economic importance. The predominant minerals in slate are muscovite, quartz, chlorite, and carbonaceous matter.

Approximately $700,000 worth of slate dimension stone has been produced in California since it was first produced in 1880. Peak years were in 1903 and 1906 when approximately one million square feet a year were produced. The output held firm through 1910, but since has been erratic. Small quantities of dimension slate are produced at Chili Bar and Mariposa in the Sierra Nevada.

Most of the slate production in California has been obtained from the Jurassic Mariposa Formation which is exposed in the western foothill belt of the Sierra Nevada in Mariposa, Tuolumne, Calaveras, Amador, El Dorado, and Placer Counties. The Mariposa Formation originally consisted of shales with minor amounts of interbedded sandstones and conglomerate. Near the close of the Jurassic Period, the formation was folded and locally intruded by granitic rocks, and the shaly material recrystallized into slates and phyllites. The productive slate quarries in California are in a slate-bearing belt that trends northwest from Calaveras to El Dorado County for approximately 65 miles, and ranges from 1 to 3 miles in width. The schistosity strikes northwestward and dips steeply to the northeast, irrespective of the attitude of the original bedding.

Basalt and related rock types

In commercial usage and in the discussion to follow the term "basalt" is applied to any of the dense, fine-grained, dark-gray or black volcanic rocks, including some that geologists refer to under the more specific names of dacite, andesite, latite, and trachyte, as well as basalt in the strict sense. All of them have similar physical properties. The light-colored volcanic rocks are discussed below with the miscellaneous group.

In California, basalt has been quarried for both paving block and building stone, and an estimated 3 million dollars worth of basalt paving block has been produced (Averill and others, 1948, p. 98). Basalts and related rocks are extensively exposed in many localities in the State. Tertiary and Quaternary basaltic rocks are exposed for hundreds of square miles in the Modoc Plateau, Sierra Nevada, Mojave Desert, Coast Ranges, and Peninsular Ranges provinces.

Past production of basalt centered about a score of operations in the counties immediately north of San Francisco—Marin, Sonoma, Napa, and Solano.

The periods of peak production years were 1887 to 1891 and 1906 to 1913. More than 50 individual quarries were active from 1864 to 1913. No dimension basalt is presently quarried in California.

Miscellaneous stone

Embraced in the general designation of "miscellaneous stone" is a wide variety of rocks, other than those already discussed, that commonly are attractive enough to be used as dimension stone. These include light-colored volcanic rocks, mica schist, and siliceous limy shale. The important characteristics of these rocks are color, natural appearance, durability, and workability. The colors ordinarily are pleasing shades of off-white, yellow, cream, buff, and pink. The stone should be easily quarried, soft enough to split by hand or by a block-splitting machine, yet durable enough to withstand weathering. Most of the rocks in this group occur as layered rocks with natural partings along bedding planes or along planes of schistosity.

In California, the principal uses of these miscellaneous stones are as building stone (ashlar, rough block, and rubble) and as flagging. The Pelona Schist in Los Angeles County, and siliceous shale of the Monterey Formation near Carmel in Monterey County were quarried as early as 1927. These and other operations were active intermittently on a minor scale until about 1950, when the building boom created a new demand for stone. By 1963, the value of the annual production of miscellaneous dimension stone in California had increased to $1,109,980. The bulk of production has been from the sedimentary rocks of the Monterey Formation and from the Pelona Schist.

Monterey "Shale".—Fine-grained siliceous limy sediments of the Miocene Monterey Formation crop out in the southern Coast Ranges, the Transverse Ranges, and the Peninsular Ranges. The rocks are thinly bedded, dip at low angles in many places, and range from off-gray to buff-brown in color.

In 1965, the most productive building stone operation in California was at the site of a former diatomaceous earth operation of the Great Lakes Carbon Corp. in the Palos Verdes Hills of Los Angeles. The Palos Verdes Stone Division of this company has directed activities on their 1,000-acre holdings since 1953 when the building stone production began.

In Tepesquet Canyon east of Santa Maria in Santa Barbara County, a light-buff to cream, thinly-bedded limy siltstone member of the Monterey Formation has been quarried since 1939. A buff-colored siliceous shaly limestone has been quarried since 1927 near Carmel in Monterey County, but by 1964 production had ceased.

Pelona Schist.—A dark-gray, iron-oxide stained quartz-mica schist of the Precambrian(?) Pelona Schist has been quarried since 1927 at several localities north of Saugus, Los Angeles County.

Light-colored volcanic rocks.—Rhyolite tuff of the Miocene Valley Springs Formation has been quarried in the foothills of the Sierra Nevada since the early 1850's. A buff-colored rhyolite tuff has been quarried at several localities near Placerville, El Dorado County, since 1948.

Banded, light-gray and purple flow rocks of the Pliocene Sonoma Volcanics have been quarried at several localities near Glen Ellen in Sonoma County since 1928. The rock is a banded riebeckite rhyolite that splits readily along well-defined and closely spaced parting planes which are usually stained with brown limonite.

Quartzite.—A red, iron-oxide stained quartzite is quarried intermittently in small tonnages at Suncrest, San Diego County.

Field stone.—Throughout the State, an undetermined amount of rock is picked off the ground without any quarrying or other treatment. These rocks are used for garden landscaping and occasionally as veneer. Among the rocks thus used are schist, mariposite, pumice, wollastonite, and basalt.

RESOURCE POTENTIAL

The outlook for expansion of the dimension stone industries is fair. The market for monumental stone has been growing, and the merits of using natural building stone are being increasely recognized by architects, builders, and the general public. However, future development of deposits in California will continue to be restricted by the competition from foreign and eastern United States sources.

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STRONTIUM

(By Cordell Durrell, Department of Geology, University of California, Davis, Calif.)

Strontium and strontium compounds are used in many ways in small amounts. Among these are caustic soda refining, ceramics, depilatories, desulfurizing steel, dielectrics, well-drilling muds, getter alloys, greases, luminous paint, plastics, rubber fillers, coatings for welding rods, chemicals, and in the production of red pyrotechnics as in signal flares, tracer bullets, fireworks, and warning fuses.

Strontium occurs in only two minerals of commercial importance—strontianite ($SrCO_3$), and celestite ($SrSO_4$). The former is most desired because of ease in processing it.

Many countries produce strontium minerals in small quantities. U.S. imports come principally from Mexico and Great Britain. Free-world production in 1963 was 16,800 tons. The United States is reported to have imported 16,232 tons in the same year. California deposits have been worked from time to time but their total contribution has been small compared to U.S. consumption.

The strontium minerals commonly occur in veins associated with other valuable minerals, but mostly they are found in association with sedimentary rocks, notably limestone and dolomite. In California they occur in the sediments of long extinct lakes, mostly in association with clay rocks and volcanic ash deposits.

Occurrences in California

Five of the six known strontium deposits in California are in San Bernardino County and the other is in San Diego County. All are in the desert regions. Four, including that in San Diego County, are celestite. The remaining two, both near Barstow, are strontianite. Their locations are shown in figure 79.

South end of Death Valley

Celestite occurs as lenses and concretions in middle Tertiary sedimentary rocks at the north end of the Avawatz Mountains; salt and gypsum are associated minerals. The geologic structure is complex, and the steeply dipping celestite-bearing beds occur at intervals for several miles along the strike. Most of the celestite rock is quite impure. The largest celestite body is 2,000 feet long and has a maximum thickness of 12.7 feet. Numerous other bodies are very much smaller. Access to the region is difficult.

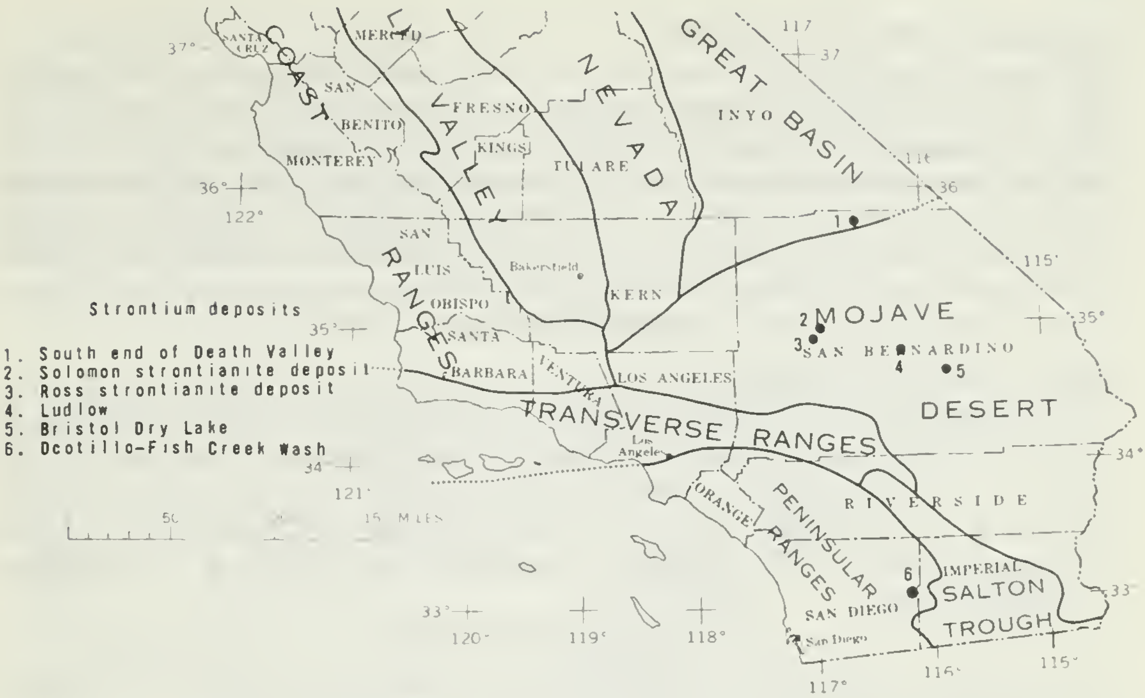

FIGURE 79. Strontium in California.

Bristol Dry Lake

Concretions of celestite occur in the upper 3 feet of the playa sediment along the south margin of the Bristol Dry Lake west of the Amboy to Twentynine Palms road. They are most abundant in sec. 6, T. 4 N., R. 12 E., S. B. where about 18 acres were exposed by ploughing in 1942. Concretions exposed by deflation are also present east of the road, and are also reported along the north shore of the playa. The celestite concretions may occur elsewhere around the playa.

Ocotillo-Fish Creek Wash

Celestite-bearing rock occurs capping hills 9½ miles south of Ocotillo, just north of Fish Creek Wash and by the road to the gypsum mine. The pure celestite occurred as a lens or lenses in gypsum but now consists only of remnants on the hill tops. Much of the original bodies have been mined, and no continuation or extension of this deposit in any direction is to be anticipated.

Ludlow

Celestite rock occurs as concretions and beds in lacustrine clays, volcanic ash, and limestone of Tertiary age in secs. 29 and 30, T. 8 N., R. 7 E., S.B. at the south base of the Cady Mountains, 8 miles northwest of Ludlow, San Bernardino County. The celestite is exposed in a number of isolated outcrops that extend along the strike of the sedimentary beds for a distance of 6,300 feet. The maximum reported thickness of celestite-bearing rock is 112 feet distributed through a total thickness of 350 feet of beds. Single celestite beds range up to 2 feet in thickness and zones up to 30 feet thick are as much as 25 percent celestite rock. The beds dip about 50° S. so that most of the deposit is concealed. Some celestite has been mined.

Solomon strontianite deposit

A strontianite deposit known as the Solomon deposit is in the east end of the Mud Hills, north of Barstow, in sec. 20, T. 11 N., R. 1 W., S.B. Strontianite occurs principally in bedlike deposits in two stratigraphic units one of which is 10 to 15 feet thick, and the other 20 to 30 feet thick. It also occurs in veins and concretions. The deposits are in clay and volcanic ash, and the geologic structure is complex. The strontianite rock is distributed over half a square mile and is disseminated in such a way that no significant concentrations occur.

Ross strontianite deposit

Another deposit known as the Ross strontianite deposit is about a half mile from the Solomon deposit, in the NE¼ sec. 30, T. 11 N., R. 1 W., S.B. Strontianite occurs in nodular concretionary beds 0.1 to 1.5 feet thick and is distributed over about 7 acres. The beds dip to the north at 20 to 40°. The deposit extends eastward where it is concealed by younger rocks.

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SULFUR

(By A. R. Kinkel, Jr., and G. N. Broderick, U.S. Geological Survey, Washington, D.C.)

Sulfur is a nonmetallic element that is found widespread in nature in both the free state and in combination with other elements. Its largest single source is from deposits of native sulfur associated with salt domes. Other sources include metallic sulfides, hydrogen sulfide gas associated with natural gas and petroleum, concentrating plants and smelters treating sulfide ores, oil refineries, coal-burning plants, and deposits of gypsum and anhydrite.

Sulfur has many and varied uses. Its principal use is for the production of sulfuric acid, an acid that is used so extensively by modern industry that it is considered an index of a nation's economic activity. The largest sulfur consuming industry in the United States is the fertilizer industry. Sulfur is also used in large amounts by the chemical, paint and pigment, iron and steel, rayon and film, and petroleum industries. These consumers use the sulfur in acid form. The paper industry uses large quantities of sulfur for sulfite pulp, and the insecticide and rubber industries use large amounts of elemental sulfur. The consumption pattern of sulfur and sulfuric acid in California is complex because of the diversified agricultural and industrial enterprises.

United States production of sulfur in all forms in 1964 amounted to 7.1 million long tons, of which 5.2 million long tons came from deposits associated with salt domes in Texas and Louisiana mined by the Frasch hot-water process. Free-world production in 1964 totaled an estimated 20.85 million long tons, an increase of 8 percent over 1963 production.

Moderate quantities of sulfur have been produced intermittently from sources in California. The State's total production, however, is insufficient to meet the needs of its numerous sulfur-consuming industries, and out-of-state sources (Frasch sulfur from Texas and Louisiana) supply most of the elemental sulfur consumed in California. Production in California has come from the following sources: native sulfur, pyrite, smelter gases, and from sour-natural and refinery gases as a by-product of petroleum refining. Locations of these sources are shown on figure 80.

NATIVE SULFUR

The Leviathan mine in Alpine County has been by far the largest producer of native sulfur in California. Sulfur occurs as veins and as an impregnation of completely opalized fine-grained andesite tuff of

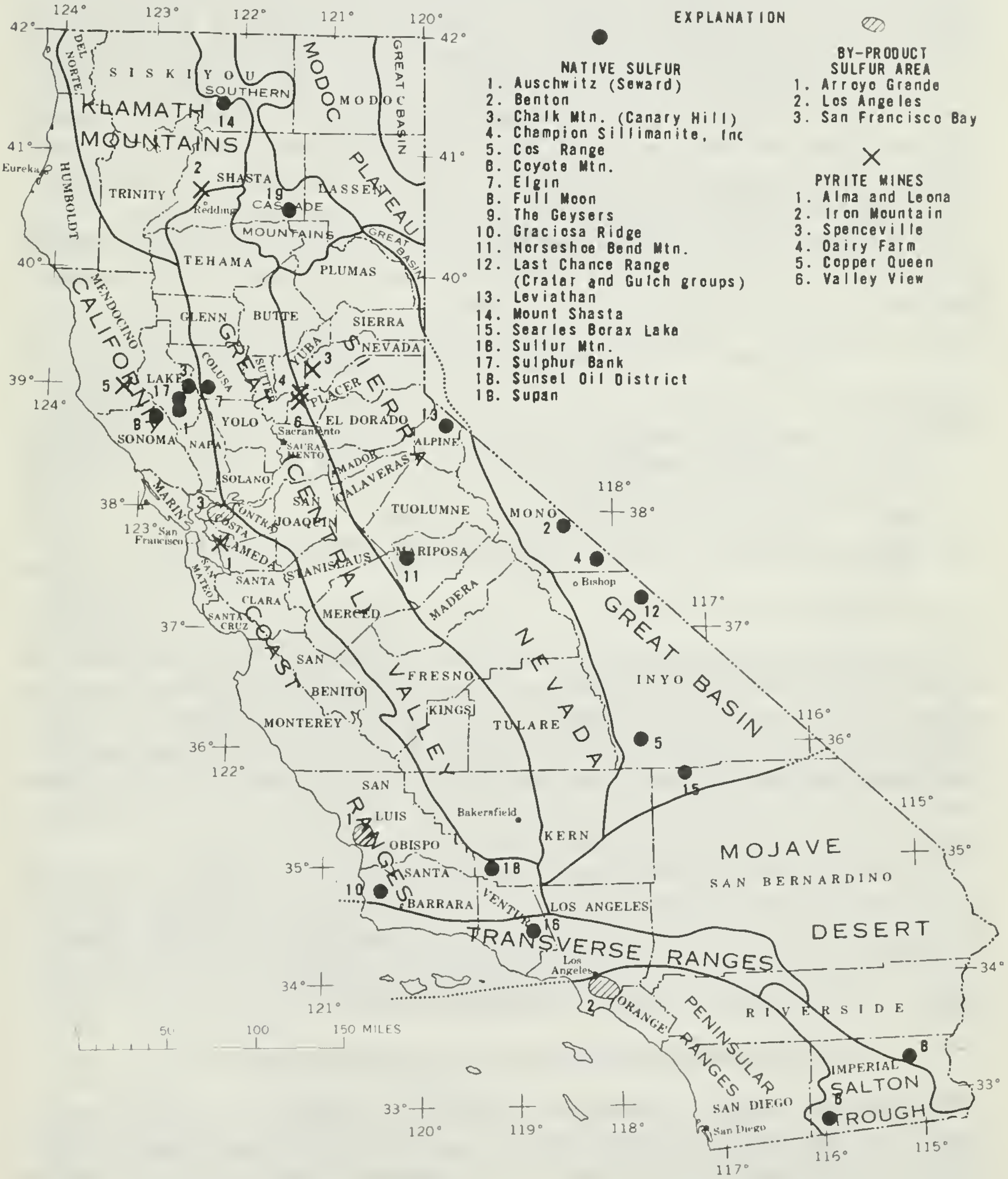

FIGURE 80. Sulfur in California.

Tertiary age about 100 feet thick. The tuff is enclosed in andesitic mud flows and breccias. Sulfur was introduced along faults together with considerable pyrite (Pabst, 1940). A small but rich copper deposit was mined in the upper part of this sulfur deposit in the 1860's.

Some early production for sulfur was recorded from the Leviathan mine, but the main production was from 1953 to 1962 to supply sulfuric acid for recovery of copper at Yerrington, Nevada.

Smaller amounts of native sulfur have been produced from mines in Inyo, Colusa, Kern, Lake, and Imperial Counties, and from a few other counties (Branner, 1959).

SULFUR FROM PYRITE

Pyrite has been mined to produce sulfur at several mines in California, and sulfur has been an important by-product recovered in treating low-grade massive sulfide copper ore. The principal producer of sulfide ore has been the Iron Mountain mine of the Mountain Copper Co. in Shasta County. The Alma and Leona mines in Alameda County and the Spenceville mine in Nevada County produced smaller amounts. Sulfur was not recovered in treating most of the copper-bearing massive sulfide ores in California.

Production of sulfur from sulfide ore up to 1964, as far as records are available, is shown in table 47, furnished by the U.S. Bureau of Mines.

TABLE 47.—*Pyrite and pyrrhotite production from which sulfur was recovered*

Location:	*Long tons of sulfide ore*
Iron Mountain mine, Shasta County	4,500,000
Alma mine, Alameda County	156,500
Leona mine, Alameda County	87,600
Spenceville mine, Nevada County	150,000
Others (Dairy Farm mine, Copper Queen mine, Valley View mine)	90,000
Total	4,984,100

In treating low-grade pyritic copper ores it has been economic in some cases to roast the ore first to remove the sulfur, and to leach the copper from the residue (calcines). The copper is recovered as copper sulfate, which is a readily marketable product. The iron residues contain some sulfur after roasting, and it is a finely ground product that would have to be sintered before further treatment. Both of these features have made the residue unattractive as an iron ore.

In recent years it has been more economical for sulfur users in California to buy Frasch process (native) sulfur. Although most of the copper mines contain large amounts of sulfur in sulfides, there is thus little probability that sulfide deposits in California can be mined for their sulfur content in the foreseeable future.

BY-PRODUCT SULFUR AND SULFURIC ACID

By-product sulfur production from oil refineries in California began in 1937 when Standard Oil Co. of California reported production of hydrogen sulfide from its El Segundo refinery in Los Angeles

County. Elemental sulfur production from hydrogen sulfide was first reported in 1949 by the Hancock Chemical Co., Los Angeles County. By 1954 more than half of the sulfur-equivalent produced in California was derived from the treatment of sour or sulfurous crude oils and gases, and waste-acid sludges from petroleum refineries (Lydon, 1957). With the exception of the Union Oil Co. of California refinery in the Arroyo Grande area, which began production in 1955, the refineries in California are centered in the Los Angeles and San Francisco Bay areas. In 1963, according to the U.S. Bureau of Mines, six California plants (two in Contra Costa County, three in Los Angeles County, and one in San Luis Obispo County) recovered elemental sulfur from sour-natural and refinery gases as a by-product of petroleum refining.

Sulfur compounds are recovered from stack gases at the American Smelting & Refining Co. smelter at Selby in Contra Costa County, where sulfur dioxide has been converted to sulfuric acid since 1937, and liquid sulfur dioxide production was first reported in 1953.

RESOURCE POTENTIAL

Production of native sulfur and of pyrite in California is feasible only when it can compete profitably with Frasch sulfur. Oil refineries will continue to yield increasing amounts of by-product sulfur. Liquid sulfur dioxide and sulfuric acid will continue to be obtained from smelter gases by the American Smelting & Refining Co. at Selby, but the possibility of production from other smelters in California does not seem promising at the present time.

Gypsum, a sulfur-bearing mineral that is abundant in California, is sold for agricultural use. It is not likely, however, to become a significant source of sulfur in the near future.

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TALC AND SOAPSTONE

(By L. A. Wright, Department of Geology and Geophysics, Pennsylvania State University, University Park, Pa.)

Use and Economic Importance

The term "talc" is applied to a mineral species and also to various commercially valuable aggregates of magnesium silicate minerals. The mineral talc ($Mg_3Si_4O_{10}(OH)_2$), is extremely soft, flaky in habit, soapy to the touch, chemically inert, and difficult to fuse. This combination of properties distinguishes it from most other common minerals and contributes to its usefulness. Most commercial talcs contain the mineral talc as a prominent constituent, but they commonly also contain one or more other minerals among which are tremolite ($Ca_2Mg_5H_2(SiO_3)_8$), serpentine (a hydrous magnesium silicate), chlorite (an alumino-silicate of iron and magnesium), anthophyllite ($(Mg,Fe)_7Si_8O_{22}(OH)_2$), olivine ($(Mg,Fe)_2SiO_4$), carbonate minerals, and quartz. Depending upon the intended use of the commercial material, these other minerals may be beneficial or may constitute impurities.

About 50 percent of the talc now being mined in California is used as a ceramic raw material and about 20 percent is used as a paint extender. The remaining 30 percent is marketed for a wide variety of uses, especially as an ingredient in the manufacture of paper and rubber, a polishing and coating agent in the preparation of rice, sizing in the preparation of textiles, a powder for toilet and pharmaceutical preparations, a filler in asphalt, and a carrier for insecticides. For most of these uses, whiteness of color, both in the ground and fired state, is required. The degree to which the ground talc will absorb certain types of greases and oils, contributes to its usefulness as a paint extender (Lamar, 1952).

Some of the talc that is used for ceramic purposes, particularly the manufacture of wall tile, consists almost wholly of the mineral tremolite. In the production of high-frequency insulators, which must have low-electrical conductivity, material composed essentially of the pure-mineral talc is desired. If suitable for this purpose, the talc is designated as "steatite." Talc of steatite or near-steatite grade commonly is specified for uses that require a soft, smooth, and inert material. For use as ordinary fillers and insecticide carriers, dark-grinding talcs that contain several percent iron oxide are acceptable. The most commonly mined material of this type is a blocky, talc-rich, but generally impure material known as "soapstone."

Most of the talcs that are sold commercially consist of mixtures of two or more types of crude materials, and are especially ground and blended for specific industrial applications. High-quality talcs mined in California, ground, and sold at the mill are valued in the range of $34 to $40 per ton. Talcs ground to very fine sizes are marketed at about $80 per ton.

Geologic Occurrence

Talc deposits typically occur in highly deformed terranes in which bodies of igneous rocks are abundant (Chidester and others, 1964; Engle and Wright, 1960). Most talc deposits of commercial interest are associated with magnesium-rich rocks, particularly the magnesian carbonate rocks, dolomite and dolomitic limestone, and the ultramafic igneous rocks. Mineable concentrations also have altered from other types of rocks including quartzite, granite, schist, and limestone. In California, as well as in the United States in general, talc has been mined mostly from bodies that represent alterations of carbonate rocks (Wright, 1954). These deposits characteristically contain less than 1.5 percent iron oxide, reflecting a low iron content of the original rock. On the other hand, deposits that have altered from the ultramafic rocks, principally serpentine, ordinarily contain several percent of iron oxide, enough to appreciably discolor the product in either the ground or fired state. Much of such talc can be classified as soapstone. Talc that is associated with ultramafic rock, therefore, is generally of less commercial interest than talc that is associated with carbonate rocks.

Talc bodies of commercial interest are ordinarily tabular to lenticular in shape. They range in length from a few tens of feet to several thousands of feet and in width from a few feet to a few hundred feet. Because most talc-bearing terranes are highly deformed, steep dips are common. Some deposits consist of commercial material from wall to wall, but masses of waste rock cause many deposits to be difficult to mine or prohibit their commercial development.

History of Discovery and Development

Talc was first mined in California by prehistoric Indians who carved it into utensils and ornaments. As early as the mid-1800's, white settlers were mining soapstone from deposits along the western foothills of the Sierra Nevada and were using the material in linings and foundations of furnaces and for building and ornamental stone. Talc-bearing areas that lie east of the Sierra Nevada and that are now major domestic sources, were opened in the period 1912 to 1918. Of special importance was the development of the Talc City mine, near Darwin in Inyo County (Page, 1951; Gay and Wright, 1954), which for many years was the nation's principal source of steatite-grade talc. Much of the talc mined in this deposit has been blocky enough to be machined into insulator bodies, but such bodies are now manufactured by molding or extruding ground steatite mixed with a binder. Steatite from the Talc City mine was much in demand particularly during World War I, when foreign sources of high-priority, blocky talc were cut off.

From 1916 to the mid-1930's, the Talc City mine. together with the Western mine in southern Inyo County (Wright and others, 1953; Wright, 1954a) and the Silver Lake mine in northern San Bernardino County (Wright, 1954b) were the principal sources of talc in California. During this period, the total production of talc in the State rose from about 9,000 to about 20,000 tons per year. This output was used mainly in the paint, cosmetic, and insulator industries.

During the period 1933 to 1943, the use of talc as a major ingredient in the manufacture of wall tile became widespread. In this period, also, steatite-grade talc was found to be a necessary ingredient in the manufacture of high-frequency electrical insulators for certain types of electronic equipment. Because this grade of talc was then again in short supply, it was classified as a critical mineral for a several-month period in 1942 and 1943. Spurred by these two uses and by the growth of industry and population on the Pacific Coast, talc production in California had reached 65,000 tons per year in 1943. This output was obtained mainly from mines in the region that extends from the Inyo Mountains southeastward through the Death Valley area to the Nevada line. The Talc City, Western, and Silver Lake mines continued in operation, and numerous other mines were expanded or placed in production. Of these others, the White Mountain mine in the Inyo Mountains (Page, 1951), the Death Valley, Grantham (Warm Spring), Eclipse, Monarch, Superior, Tecopa (Smith), Acme, and Excelsior mines in the southern Death Valley-Kingston Range region (Wright, in press, 1966), and the Yucca Grove mine north of Baker, San Bernardino County (Wright, and others, 1953), have been the most productive and continuously worked.

The post-war building boom, and the resulting demand for paint and wall tile, caused a continued increase in talc production in California. Production of about 120,000 tons was reached in 1951. Since then the production rate has been in the general range of 100,000 to 130,000 tons. Several additional mines have been opened in the post-war period. These are widely scattered through the State, but most of them lie east of the Sierra Nevada in the established talc-producing areas. The most productive of these more recently developed mines are the Eureka mine in the northern Inyo Mountains, the Omega mine in the central Kingston Range, and the Rainbow and Sheep Creek mines in the southern Death Valley area (Wright, 1966, in press).

The mining of soapstone in the western foothills of the Sierra Nevada has continued, on a small scale, to the present. About 20 properties have been worked, but most operations have been short-lived.

In 1963 about 114,000 tons of talc and soapstone was mined in California to bring the overall production to nearly 3 million tons since the early 1900's. The 1963 output of high-quality talc was obtained from 12 properties in San Bernardino County, and 11 in Inyo County. Most of the established mines continued in operation. Soapstone was quarried from two properties in Amador County, one in El Dorado County, and one in Los Angeles County (U.S. Bureau of Mines, Minerals Yearbook for 1963).

UNITED STATES AS A SOURCE OF TALC

Since the beginnings of the talc mining industry, the United States has constituted the principal source and market of the material. In 1963, a total of 671,000 tons of talc was mined in the United States. This was nearly one-fifth of the world's total output. About 92 percent of the domestic product was consumed within the United States, and about 26,000 tons of talc was imported mainly from Italy and France and used in the cosmetic and pharmaceutical trades.

CALIFORNIA'S RANK IN U.S. PRODUCTION OF TALC

For many years California has ranked second to New York State in tonnage of talc produced. Until the early 1950's, the State was the source of almost all of the steatite-grade talc produced in the

United States, but now Montana far outranks California in both production and reserves of such talc. The decline, in California, of the production of steatite-grade talc has been dwarfed by the increase in the production of other types of talcs, particularly those that supply the building industry of the Western States. For these markets, the talc produced in California can be supplied at a lower cost than talc from most other domestic sources. Thus a continuing and growing market seems assured for these products.

Occurrences in California

Southern Death Valley-Kingston Range region

The largest and presently most productive source of high-quality commercial talc in California is a group of deposits that occurs in a belt about 75 miles long that, as shown in figure 81, extends from southern Death Valley eastward to the Kingston Range near the California-Nevada line (Wright, 1966, in press). These deposits occur in an ancient (Precambrian) unit termed the Crystal Spring Formation which consists of marine strata and the dark igneous rock, diabase. The latter was introduced, mostly as sills, soon after the strata were deposited. Most of the talc bodies have formed along the margins of a single, very extensive sill and are alterations of carbonate strata. The mineralized zone, thus formed, originally extended over 2,000 square miles or more, but severe and much later deformation has caused the talc-bearing terrane to be thoroughly faulted, and much of the talc has been removed by erosion following uplifts. Thus, the talc bodies are now very discontinuous. They commonly constitute zones of weakness along which faulting has been localized, so that deposits pinch and swell abruptly.

The talc body at each of the more productive mines is 1,000 or more feet long. Some are as much as 5,000 feet long. Most of them are 10 to 20 feet in average width. As nearly all of the mining has been done within 500 feet of the surface, the down-dip extent of much of the larger deposits remains undetermined. The commercial talc in these bodies ranges in composition from mostly talc to mostly tremolite. Individual bodies commonly contain two layers, one talcose and one tremolitic.

Inyo Mountains and northern Panamint Range

The talc deposits in the Inyo Mountains and northern part of the Panamint Range, both in Inyo County, have yielded nearly all of the steatite-grade and pharmaceutical-grade talc mined in California. These deposits generally are much smaller and more irregular than those in southern Death Valley-Kingston Range region. The largest bodies are about 500 feet long and 50 feet in maximum width; most of them are only a few tens of feet long and a few feet wide. Most are lenticular to very irregular in shape.

They occur as replacement bodies in Paleozoic sedimentary rocks and, locally, in granitic rock of Mesozoic age. Most of the talc in these deposits is an alteration of dolomite, but some has altered from quartzite, limestone, and quartz-rich igneous rocks. The commercial talc in most of these deposits consists almost wholly of the pure

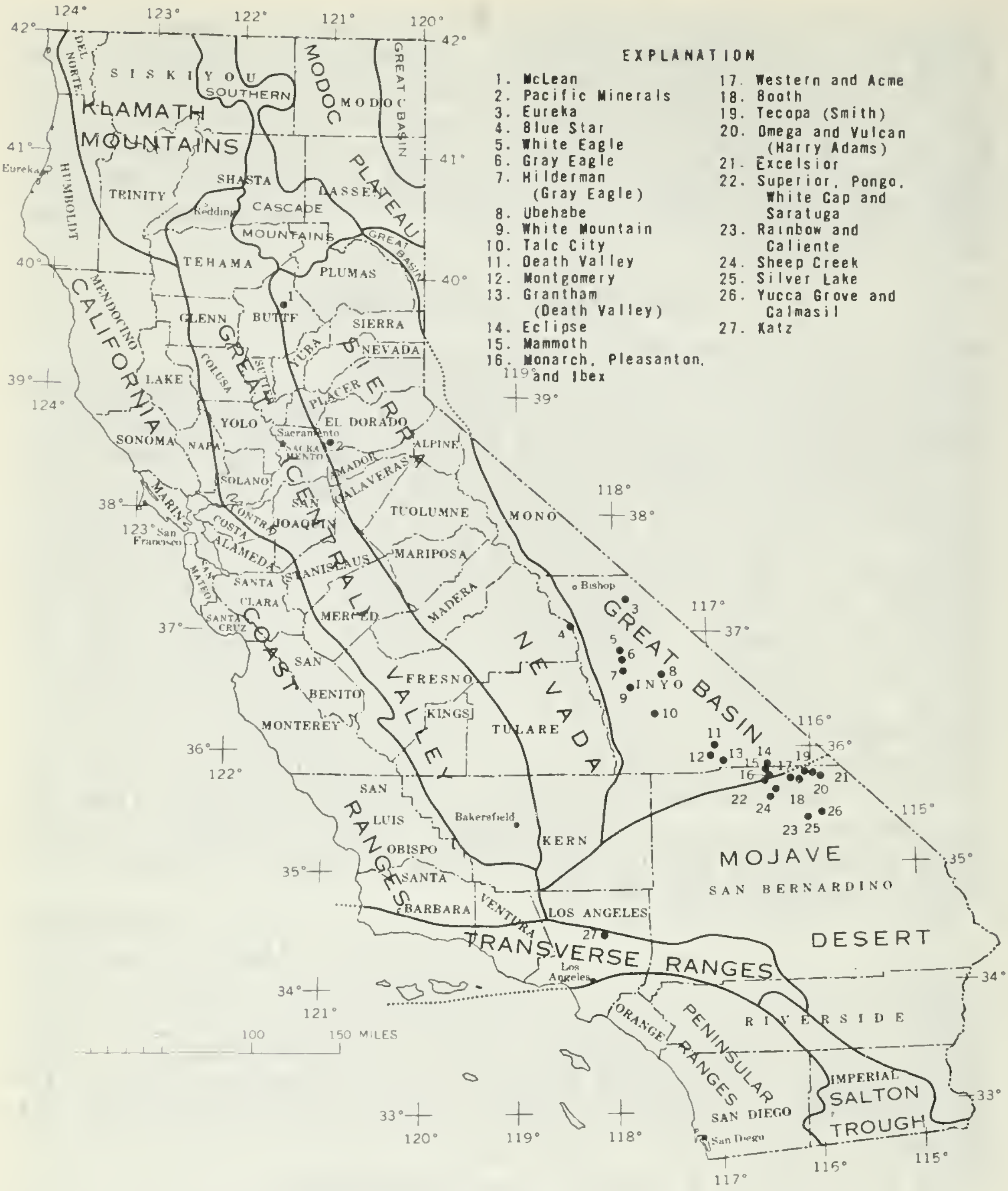

Figure 81. Talc mines in California.

mineral. Chlorite, the only other magnesium silicate present, is abundant in deposits that have altered from igneous rocks.

Silver Lake-Yucca Grove area

A small group of deposits, including those at the Silver Lake mine and occurring in the Baker-Yucca Grove area of north-central San Bernardino County, form part of a complex of metamorphic and igneous rocks which is presumed to be of Precambrian age. These deposits apparently represent layers and lenses of dolomite that have been thoroughly altered to rock composed mostly of talc and tremolite. These deposits also are very discontinuous. Those that have been mined average about 10 feet in width; two such bodies commonly parallel each other and are separated by a 15-foot thickness of waste rock. The largest of these deposits are about 500 feet long and most or all of them appear to bottom within 300 feet of the surface. Although the mined material is coarser grained than that obtained from the southern Death Valley area, it is marketed for the same general uses.

Western foothills of the Sierra Nevada

The talc deposits that occur in the western foothills of the Sierra Nevada and that have altered from bodies of ultramafic rock are probably much more numerous than the deposits east of the Sierra Nevada. But, they have been mined much less extensively, because the talc typically contains several percent of iron oxide and thus cannot be used for most of the purposes to which the low-iron talcs are put. The talc bodies in the Sierra Nevada foothills are characteristically lenticular and rarely exceed 50 feet in width and 400 feet in length. Only deposits that can be mined by open-pit methods and lie close to rail facilities have proved profitable, as the mind material is much lower in value and much less in demand than the low-iron talcs from the deposits described above.

RESOURCE POTENTIAL

The tonnages of high-quality talc that remain to be mined in California are difficult to estimate. By far the largest resources exist in the deposits of the southern Death Valley-Kingston Range region. Although in most mines only a few tens of thousands of tons are blocked out in advance of mining, studies of the geologic environments indicate that many millions of tons of talc remain in this region. The tonnage that will be eventually recovered will depend upon the maximum depths to which individual mines can be worked at a profit, the efficiency of the mining operations, and the prices that these talcs will command in the future. Conservatively estimated, at least 2 million tons of talc or about 20 year's supply at the present rate of production appears to be recoverable. The eventual recovery may well exceed this figure by 2 or 3 times.

The talc resources in the Inyo Mountains-northern Panamint Range region and in the Silver Lake-Yucca Grove area are much smaller than those of the southern Death Valley-Kingston Range region. Most of the deposits have been mined, both laterally and downdip, to points where they pinch out or are too thin to be mined profitably. Deposits, comparable in size to those already mined, are certain to exist at shallow depths and unexposed, but discovering them will be difficult and expensive.

The resources of relatively dark, high-iron talcs in California appear to be measurable in many millions of tons. Although these deposits remain to be studied in detail, they seem capable of supplying the markets for this type of talc indefinitely.

Future explorations for talc in California should center about the known talc-bearing areas and be aimed at the discovery of extensions, either downdip or lateral, of known deposits or mineralized zones. As the main talc-bearing zone in the southern Death Valley-Kingston Range region is everywhere at about the same stratigraphic position, drilling programs could be planned on a stratigraphic basis and in areas where the Crystal Spring Formation, which contains the talc, is believed to lie beneath a thin cover of younger rock.

The deposits in the Silver Lake-Yucca Grove area also seem to lie at a uniform stratigraphic position. Here, too, drilling for extensions of the known deposits is recommended if economically feasible.

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THORIUM

(By J. R. Evans, California Division of Mines and Geology, Sacramento, Calif.)

Thorium is a heavy, soft, ductile, and radioactive metal. It was discovered by Berzelius in 1828 on analyzing a mineral (thorite) from Lovo Island, opposite Bevik, Norway, and named for Thor, the Scandinavian god of thunder.

The metal has not been produced in California, and the State needs, as well as that of the United States, as a whole, are fulfilled mainly by imports of monazite from Australia and Malaysia. Monazite-bearing black sand from Florida provided about 20 percent of domestic consumption in 1964. Only 1,800 tons of monazite, valued at $155,000, were imported in 1964, as compared with 6,434 tons, valued at $777,000 in 1963. The reason for the decrease in imports was the closing of the monazite mine at Steenkampskraal, Cape Province, South Africa in mid-1963, after completion of an 8,000 short ton (of 5 percent+ ThO_2 monazite) contract with American Potash and Chemical Corp. From 1961 to 1963 this mine provided 78 percent of United States imports of monazite.

By far the most important use for thorium is as a 3 percent additive to magnesium in order to form a low-density, high-temperature, high-strength alloy for high-speed aircraft and missiles. Thorium nitrate is used in incandescent gas mantles in lanterns for camping and by our armed services and accounts for about 30 percent of thorium consumption. Roughly 10 percent of thorium consumption is for catalysts in the petroleum and chemical industry, in tungsten electrodes for inert arc-welding, and as nonconsumable electrodes in vacuum arc-melting of refractory metals. A very small amount of thorium is used in nuclear reactors for power plants, but there may be increased consumption in the near future, possibly in California.

The California Department of Water Resources and the Atomic Energy Commission are considering a seed-blanket reactor, using a thorium fuel cycle, as a source of power for transporting and pumping water long distances and over mountain ranges with as much as 2,000 feet of relief. If the reactor is located near the coast, it may include a sea-water to fresh-water conversion unit.

Monazite is a cerium group rare-earth metal phosphate containing as much as 10 or 12 percent thorium oxide. There are several other thorium-bearing minerals such as thorite (thorium silicate), pyrochlore (niobate of cerium group rare-earth metals, calcium and sodium, with some titanium, fluorine, and thorium), and thorianite (oxide of thorium and uranium), but at present monazite is more abundant and can be mined at lower costs than the other minerals.

Because monazite is physically durable, chemically stable, and has a fairly high specific gravity, it is a typical detrital mineral common in placer deposits of beach and river sand. It is particularly abundant in local alluvial material adjacent to, or underlain by biotite-rich granitic and metamorphic rocks in which monazite occurs as a minor constituent. Thorium-bearing minerals also occur in veins cutting some granitic and metamorphic rocks, such as those in Idaho, Montana, and Colorado.

At Mountain Pass, San Bernardino County, monazite occurs in dolomite-rich areas along the borders of the intrusive Sulfide Queen carbonate body adjacent to its contact with Precambrian schist and gneiss. The monazite also is Precambrian. The thorium oxide content of monazite ranges from 1 to 3 percent. Thorite is found with hematite, goethite, sericite, chlorite, quartz, and carbonate minerals in shear zones, and also in some carbonate veins in the Mountain Pass area. Analyses of some vein material show as much as 6 percent ThO_2.

In the Music Valley area, Riverside County, thorium-bearing xenotime (yttrium group rare-earth metal phosphate) and monazite occur in biotite-rich areas in the Precambrian Pinto Gneiss. Semiquantitative spectographic analyses of samples of gneiss show that ThO_2 content is mostly below 0.50 percent, but one sample contained 1.2 percent of ThO_2. A highly radioactive sample of xenotime and monazite-bearing gneiss from the U-Thor deposit was analyzed chemically. It showed a 0.5 percent ThO_2 content, and a 7.3 percent ThO_2 content after mechanical concentration of xenotime and monazite.

Nearly all the rare-earth metal-bearing minerals in California contain some thorium, and the reader who is interested in more information about the geologic occurrence of thorium should refer to the rare-earth section in this bulletin.

Under present marketing conditions, most deposits of monazite and other thorium-bearing minerals generally are not of high enough grade to compete with imports from foreign deposits. However, foreign deposits may be depleted and/or imports cut off because of war or other factors, and exploration for monazite should continue, particularly in California where thorium fuel cycle reactors may be used. Granitic and metamorphic rocks that show a radioactive anomaly should be sampled and examined for thorium oxide content. Beach sand and dune sand, as well as gruss derived from weathering of granitic rocks should also be examined, because placer deposits such as those in Florida and Idaho appear to be a major source of thorium (monazite) in the United States.

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TIN

(By C. H. Gray, Jr., California Division of Mines and Geology, Los Angeles, Calif.)

The usefulness of tin is based upon its easy fusibility, malleability, resistance to corrosion, readiness to alloy with other metals, and its attractive silver color. No completely adequate substitute has been found for its major use as a protective coating for other metals. Most of the tin consumed in the United States is used in the production of tinplate, solder, bronze, brass, and babbitt, and in tinning; small quantities are used in metallic forms, miscellaneous alloys, and chemicals.

Cassiterite (SnO_2), is the principal tin-bearing mineral of commercial importance, but, in a few localities, tin has been recovered from lode deposits that contain the complex sulfides stannite, cylindrite, and teallite. Tin minerals are widely distributed throughout the world, but in only a few areas are the deposits large enough to be profitably mined.

Primary tin deposits show a characteristic genetic relation to silicic igneous rocks, particularly to granite pegmatites. Bolivian deposits are associated with quartz monzonite. Most tin veins are high-temperature hydrothermal deposits and are believed to have formed under high pressures. Wood tin, a nodular variety of cassiterite, occurs in rhyolite flows. As cassiterite is extremely resistant to alteration and has a high specific gravity, it is easily concentrated in placer deposits.

Tin was first discovered in California in the Temescal district, Riverside County, probably in 1853. In 1869, a 15.34-ton shipment of ore to San Francisco was said to have yielded 6,895 pounds of tin (Page and Thayer, 1945, p. 1). However, the first production of record was in 1891. Ore was mined during 1891–1892 and in 1928–1929. Estimates of total production from the district range from 113 long tons of tin (Segerstrom, 1941, p. 543) to 130 long tons (Page and Thayer, 1945, p. 2).

A property in Trabuco Canyon, Orange County, was explored in 1916 in search of tin, but no production was recorded (Segerstrom, 1941, p. 534). Cassiterite was identified in 1940 in ore from the Evening Star copper-tungsten prospect, San Bernardino County, and extensive underground prospecting was done from early 1941 through late 1944, when the mine was closed. Several small shipments of ore and concentrates were made, with a probable total tin content slightly less than 2 tons.

Tin was discovered in the Gorman district, Kern County, in 1940, and during the period 1943–1945, the Meeke-Hogan mine yielded 6.70 short tons of ore equivalent to 2.64 tons of tin. Tin mining was renewed in July 1963 and has continued on a small scale to date (July 1965). According to the operator, this operation has yielded about 47 short tons of concentrates ranging from 35 percent to 65 percent metallic tin and averaging about 58 percent.

During 1964, free-world mine output was about 146,000 long tons of tin, while consumption of primary tin was about 168,000 long tons. The gap between production and consumption was offset by 29,000 tons sold by General Services Administration during 1964. United States consumption in 1964 was estimated as 59,000 tons of primary tin and 23,000 tons of secondary tin; some observers believe consumption will be 100,000 tons by 1975. Although the United States consumes about 40 percent of the free-world tin output, the production from its few scattered tin deposits is insignificant. In 1964, United States production consisted of small quantities of tin in concentrate produced at the Meeke-Hogan mine in California and as a by-product of molybdenum mining in Colorado.

The total California tin production that has been reasonably well documented is equivalent to about 140 long tons of tin metal, calculated on the basis of 100 percent recovery from concentrates.

OCCURRENCES IN CALIFORNIA

Cassiterite, the only tin-bearing mineral of commerical importance known to occur in California, has been reported at numerous localities in 15 counties, but in only about half of these localities has its presence been substantiated. Most of the localities are in southern California (Segerstrom, 1941, p. 549–552; Bedford and Johnson, 1946). Stannite (Cu_2FeSnS_4) occurs at the Pacific Limestone Products quarry near Santa Cruz and at the Thompson lead-silver mine, Darwin district of Inyo County. Three mines in the State, representing three geologic-geomorphic provinces, have recorded production of tin.

The Temescal mine and several neighboring properties, which together constitute the Temescal tin district, are confined to an area of approximately 15 square miles within the Peninsular Ranges province, about 11 miles southwest of Riverside. Mesozoic quartz monzonite contains tourmaline-quartz veins and pipelike masses in which cassiterite occurs as disseminations and as bunches and stringers, and in a few of which recoverable amounts of cassiterite have been found. Tourmaline veins in Mesozoic quartz latite porphyry also contain traces of tin.

According to Page and Thayer (1945, p. 8), the average width of the veins, including spotted tourmaline rock and silicified rock, probably is 1 to 2 feet; in places a few are 15 to 20 feet wide. Most of the veins are less than 1,000 feet long and are discontinuous, although one vein system is about 4,800 feet long. Their downward extent is not known, but the Cajalco vein was followed to a depth of 690 feet and was not bottomed.

Maps of the mine indicate that two cassiterite-bearing ore shoots in the Cajalco vein yielded the entire production; one was about 70 feet and the other 160 feet in strike length. The larger one had a dip length of about 240 feet (Page and Thayer, 1945, p. 15–16, figs. 8, 11). Assays indicate that almost all of the veins contain 0.03 to 0.1 percent tin; the Cajalco vein averages about 0.15 percent of tin. The ore that was milled is reported to have averaged in the range of 2 to 5 percent SnO_2 (Page and Thayer, 1945).

The Meeke-Hogan mine and several neighboring tin-bearing properties are in the Gorman district of southern Kern County, near the boundary of the Sierra Nevada and Mojave Desert provinces, at the southwest end of the Tehachapi Mountains. These deposits consist of small cassiterite-bearing iron-rich bodies associated with tactite bodies which apparently have replaced limestone near the borders of an intrusive mass of granitic rock. The cassiterite occurs as scattered grains within the tactite, which is composed principally of limonite, magnetite, and various contact-metamorphic minerals.

The largest deposit, the Meeke-Hogan, is composed chiefly of two bodies of tin-bearing limonite gossan. The west gossan is about 200 feet in length and has a maximum exposed width of 40 feet, and lenses out at either end. The east gossan is 100 feet long and as much as 30 feet wide.

According to Wiese and Page (1946, p. 37) the Meeke-Hogan mine was extensively explored in 1942–1943, including core drilling. Most of the high-grade ore was obtained from residual boulders exposed at the surface. Some was mined, by means of shallow pits, from pockets in limestone. The average grade of these small shipments was about 40 percent tin. However, exploratory work indicated that reserves of ore in place carried only from 0.1 to 2.0 percent tin (Wiese, 1950, p. 46). During 1963–1965, mining has been from near-surface, narrow, high-grade cassiterite zones in limestone between the former west and east shafts at the Meeke-Hogan mine.

Since mid-1964, the California Division of Mines and Geology has been engaged in a geochemical, geophysical, and geologic study of the area. In June and July 1965, the U.S. Bureau of Mines in cooperation with the Division core-drilled two sites.

The Evening Star mine, and other nearby tin-bearing properties, are about 8 miles north of Cima in the Mojave Desert province in northeastern San Bernardino County. These are small contact-metamorphic replacement deposits in dolomite and dolomitic limestone, near an intrusive body of quartz monzonite. The mine has explored, to a depth of 100 feet, a hematitic pipelike ore body formed in limestone at the intersection of two fractures. Cassiterite occurs as disseminated grains, euhedral crystals, and massive aggregates in tremolite-serpentine-calcite rock together with scheelite, chalcopyrite, sphalerite, pyrite, and magnetite.

Properties other than those in the districts mentioned above, and at which tine has been noted in quantities greater than one pound per ton of rock sample, include the following: The Lucky Three, Jeanette Grant, Black Jack, Rocky Point, and Big Blue properties in the Isabella district, Kern County; the Greenback Copper and Iron Mountain properties in the Woody district, Kern County; the American Flag and Monarch mines in the Elsinore district, Riverside County; and the Atolia tungsten mines, San Bernardino County (Bedford and Johnson, 1946).

The tin occurrences in California that have been worked or have attracted attention as possible commercial sources are primary deposits. The absence of known concentrations of placer tin in California is evidence against the former or present existence of exposures of large vein deposits. There remains the slight possibility of segregations at depth and of sufficient size to be economic. Should such deposits exist, it seems likely that they will be found in areas of silicic granitic rocks. The fact that tin occurs at several localities in California near contacts of quartz monzonite or granite with metamorphic rocks, or in quartz monzonite, points to such areas as possible prospecting targets. Tin resources in California have not been quantified, although relatively minor reserves apparently exist in the Meeke-Hogan mine area.

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TITANIUM

(By Norman Herz, U.S. Geological Survey, Washington, D.C.)

Introduction

Titanium comprises 0.6 percent and is the ninth most common element of the continental crust. Its greatest application is as titanium dioxide in pigments, but its use as a structural metal is increasing at a much greater rate. The United States consumed about 1.1 million tons of TiO_2 in 1962 and 1963, divided (in 1962) as follows: 96.8 percent in pigments, 1.5 percent welding rod coatings, 1.4 percent as metal, and 0.3 percent for other purposes, including as a ferroalloy and carbide, and in plastics and ceramics (Peterson, 1965).

An increased consumption of about 4 percent a year for the period 1960–1985 is seen for TiO_2 and about 13 percent a year for 1963–1985 for Ti metal (Fulkerson and Gray, 1964). By the end of 1985, the domestic consumption of TiO_2 pigment is expected to be 1.3 million tons and Ti metal 100,000 tons.

Titanium dioxide was developed as a pigment for paints because of its high opacity, its chemical and physical stability, and its low specific gravity. In 1960, 96 percent of the white paint coverage in the United States utilized a titanium dioxide base (Fulkerson and Gray, 1965).

Titanium is the fourth most abundant structural metal, has the highest strength to weight ratio of any of them, shows little change in physical properties from minus 300°F to 1,000°F, and has the greatest resistance to corrosion of any common metal or alloy (Schlain, 1964). These properties explain its increasing use in supersonic jet aircraft, rockets, submarines, desalinazation plants, and elsewhere in industry where extreme temperatures or corrosion are major problems.

Rutile (TiO_2), and ilmenite ($FeTiO_3$), are the most important economic minerals of titanium. Anatase (TiO_2), and alteration products of ilmenite are also recovered from some placer deposits. Both rutile and ilmenite are found in primary or lode deposits in igneous or metamorphic rocks and in alluvial or eluvial deposits, including placers, beach sands, saprolite, and bauxite. The principal ilmenite deposits, however, are primary, and are associated with anorthosite-gabbro complexes, whereas most of the world's rutile is obtained from beach sands. United States ilmenite production is from anorthosite deposits in New York, saprolite in Virginia, and beach sands in Florida and New Jersey. Rutile is produced from saprolite in Virginia and beach sands in Florida.

California and United States Production

The earliest attempt to mine titanium ore in California was from Russ Siding in Soledad Canyon, Los Angeles County, in 1906 and this failed because of the refractory nature of the ore (Oakeshoot, 1950, p. 354). The State's largest production was in 1927–1938 when 10,013 tons of ilmenite valued at $150,195 was mined in Los Angeles County from a beach deposit in Hermosa and a lode deposit in the San Gabriel Mountains for the manufacture of white pigment. Outside of Los Angeles County, ilmenite has only been mined in modern and ancient beach sands at Aptos, Santa Cruz County. Distribution of titanium deposits is shown in figure 82.

The total California production is estimated at 15,000 tons, and this is almost entirely from Los Angeles County (Lydon, 1957, p. 649). This figure is negligible compared to the United States total of 890,000 short tons of ilmenite and 11,900 of rutile for 1963 alone (Stamper, 1964).

Occurrences in California

California Coast Ranges

Ilmenite has been found in black sand deposits with magnetite, chromite, zircon, garnet, and monazite near Crescent City, Del Norte County, and in black sand layers near Aptos in Santa Cruz County. The Crescent City sands are similar to the occurrences in southern Oregon which have up to 8.3 percent ilmenite by weight and 0.5 per-

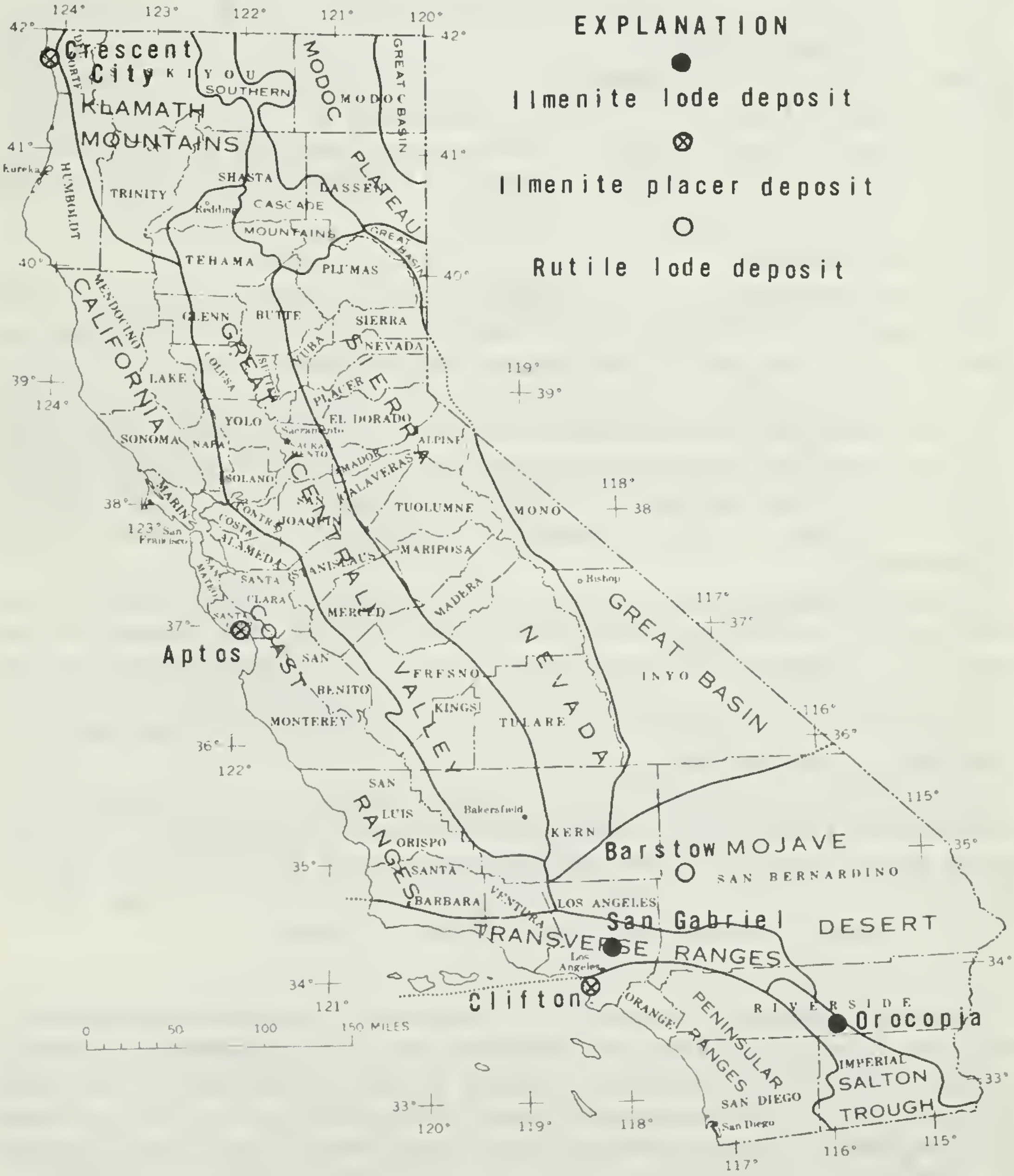

FIGURE 82. Titanium deposits in California and types of ore.

cent rutile (Griggs, 1945). The Crescent City black sand occurs in layers and lenses that vary in thickness from a few inches to 42 feet, in width from a few tens to more than 1,000 feet, and in length from a few hundred feet to more than a mile.

Black sands on the shore of Monterey Bay, near Aptos in Santa Cruz County, were worked unsuccessfully in 1926–1927 as a source of sponge iron, titanium, and chromium (Oakeshott, 1950, p. 353). The black-sand layers occur in long, irregular crescents up to 6 inches in thickness, 50 feet in width, and 100 to 200 feet in length, and contain up to 16 percent TiO_2 in the form of ilmenite. Economic minerals associated with the ilmenite are magnetite, chromite, garnet, zircon, hematite, and some gold and platinum minerals (Lydon, 1957, p. 650). Hutton (1959) found abundant ilmenite in black sands at Año Nuevo Creek about a mile to the northwest of Aptos and at the Pajaro River about 10 miles south.

Mojave Desert

The only known deposit of rutile in the State is west of Barstow and north of Hodge in San Bernardino County (Wright and others, 1953, p. 110 of table). The deposit is small and consists of disseminated rutile crystals that are locally concentrated in layers in a 200-foot long lenticular quartz body in schist. A test sample was found satisfactory for the manufacture of electric welding rods in 1942 but the deposit apparently was never worked.

Transverse Ranges

The most important titanium deposits in California are in Los Angeles County and include modern beach sands in the Clifton area and lode and sand deposits in the western San Gabriel Ranges. The lode ore consists of apatite and ilmenite-magnetite intergrowths in altered pyroxenite segregations in anorthosite. The ore bodies vary greatly in form and size, ranging from small irregular veins to large dikelike lenses, but all are lenticular in outline (Oakshott, 1948, p. 253; Higgs, 1954). Ore also occurs in placers derived from the weathering of the anorthosite.

About 12 million tons of titaniferous iron ore are estimated to be in anorthosite that ranges from 5 to 10 percent TiO_2 plus several million tons of 2 to 3 percent TiO_2 (Peterson, 1965). Placer deposits in Pacoima Canyon contain several million tons that range from 2.4 to 30.8 percent TiO_2; the placers in San Canyon average about 7 percent TiO_2 (Benson and others, 1962, p. 8).

Ilmenite-bearing beach sands between Redondo and Palos Verdes have been intermittently worked from at least 1927 to 1944. The sands along more than 3,000 feet of beach average 7 percent ilmenite, and the richer parts have as much as 60 percent ilmenite (Lydon, 1957, p. 650). No recent production is known from this area.

Salton Trough

An anorthosite-gabbro complex that may have once been continuous with the San Gabriel anorthosite, but was displaced about 130 miles to the southeast on the San Andreas fault, was discovered recently in the Orocopia Mountains, just north of the Salton Sea (Crowell and Walker, 1962). Several large lenticular or veinlike bodies of ilmenite-magnetite-apatite rock were found northwest of Salton Creek Wash.

in the contact area of anorthosite and gabbro. These had been prospected but not mined, and no information is available on the resources of the area (Crowell and Walker, 1962).

APPRAISAL

The titanium resources of the State are not fully known. Further geologic and geophysical work accompanied by drilling is needed for the ilmenite placer deposits of Aptos, Crescent City, and Los Angeles County and for the lode deposits of the San Gabriel and Orocopia Ranges. Inferred reserves in these deposits are probably sufficient to support both titanium pigment and metal plants of moderate size. The rutile of San Bernardino County is not economically exploitable under present-day conditions.

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TUNGSTEN

(By D. M. Lemmon, U.S. Geological Survey, Menlo Park, Calif.)

Tungsten is an important metal in industrial processes because the element, its alloys, and its compounds have unique physical and mechanical properties including strength, hardness, heat resistance, and electrical and thermionic qualities. Tungsten metal is light gray, heavy (specific gravity 19.3), and heat resistant (melting point 3,410°C, highest of the metals). Pure tungsten metal in wire form, is used in the filament of electric light bulbs and in other lighting and electronic devices. Much larger quantities of tungsten are used in combination with other substances, in alloy steels for high-temperature applications, in nonferrous alloys, in tungsten carbide for cutting tools, in armor-piercing shells, and in various chemicals for dyes, inks, and fluorescent lamps. Of the 10,516,000 pounds of tungsten consumed in the United States in 1963, approximately 40 percent was used in carbides, 27 percent in steel, and 12 percent in nonferrous alloys (Stevens, 1964).

In nature, tungsten does not occur as native metal, but is chemically combined in 14 known minerals, of which the commercially important ones are scheelite (calcium tungstate) and the gradational members of the wolframite group: ferberite (iron tungstate), wolframite (iron and manganese tungstate), and huebnerite (manganese tungstate). Most tungsten ores contain only small proportions of these minerals, which must be concentrated to 60 to 70 percent of WO_3 before utilization. The concentrate also must meet low tolerances of such impurities as tin, copper, arsenic, antimony, bismuth, molybdenum, phosphorus, sulfur, lead, and zinc, each of which may be injurious for particular uses. Scheelite forms a gradational series with powellite (calcium molybdate) and may contain varying proportions of molybdenum and tungsten. Some scheelite concentrates, especially from contact-metamorphic ore bodies, contain as much as 5 percent of molybdenum chemically combined in the scheelite. The molybdenum must be removed by chemical digestion if a molybdenum-free product is required.

The principal world sources of tungsten ores are veins, contact-metamorphic deposits, hydrothermal replacement deposits, stockworks, and placers. Vein deposits have been the most productive, followed by contact-metamorphic deposits; veins probably contain the largest known resources, although potentially very large resources are also present in the brines of Searles Lake. Pegmatites and deposits of tungsten-bearing iron and manganese oxide have been worked on a lesser scale than the other types.

The veins generally have a gangue of quartz and contain wolframite, huebnerite, or ferberite, usually with some scheelite, and some contain only scheelite as the tungsten mineral; some contain minor proportions of sulfides and other minerals that may yield by-products. The veins commonly are found in granitic igneous rocks or closely associated with granitic rocks, and range from thin seams to layers many feet thick. The content of WO_3 in ores mined has ranged from 0.25 percent to more than 10 percent and has perhaps averaged 0.5 to 1.0 percent.

The vertical range of tungsten-bearing ore shoots is shallow in many vein deposits; at Atolia, California, ore was followed to a maximum depth of only 1,100 feet.

Contact-metamorphic deposits contain scheelite in skarn (tactite) composed of garnet and other silicates formed at places along or near contacts of granitic intrusive rocks with invaded carbonate rocks. The ores are complex and may yield such by-products as molybdenum, bismuth, silver, copper, and fluorite. The content of WO_3 in exploited deposits has ranges from 0.25 percent to several percent. Some major deposits containing millions of tons have been worked to depth without reaching the bottom of the ore, and others have been worked out near the surface. Contact deposits have not been as important as veins in world output of tungsten, but some very large productive deposits of this type exist in the United States, Canada, Korea, and Tasmania.

The United States has traditionally been the largest consumer of tungsten, followed by other industrial nations, principally Great Britain, Germany, France, Sweden, Russia, and Japan. Consumption in Europe generally exceeds that in the United States. United States consumption reached a peak of 19 million pounds in 1943–1944; in the period 1957–1964, annual consumption ranged from 8.5 million (1957) to 13.6 million (1962) pounds (Stevens, 1964), and was approximately 11.5 million pounds in 1964 (Forbes, 1965).

Only the United States and Russia among the industrial nations obtain an appreciable portion of their tungsten requirements from domestic sources. The United States has always imported tungsten concentrates to meet part of its needs, although the domestic mining industry has long been sheltered by a tariff, currently $0.50 per pound of contained tungsten, equivalent to $7.93 per short ton unit of WO_3. Only in 1953–1956, under premium prices guaranteed by the United States Government, did domestic production exceed consumption (Holliday and Burke, 1958).

The price of tungsten concentrates fluctuates widely with supply and demand. Consumption increases markedly during periods of high industrial activity and of war, and decreases drastically during slack periods. The tungsten-mining industry is not instantaneously adjustable to such wide fluctuations, and the time lag leads to cyclic oversupply and undersupply and to price instability. Prices have ranged from a low of $2 a short ton unit [1] at the start of this century to $85 in 1916 during World War I. Following a postwar period of low demand and distress prices while excess inventories were consumed, quotations increased to $28 during World War II. From 1951 to 1955, in order to create a strategic stockpile, the United States bought domestic concentrates at $63 per unit of WO_3, thus stimulating the largest domestic production on record. Since 1958, most of the United States production has come from two mines: Pine Creek, California, and Climax, Colorado. These were the only producers in 1964 (Forbes, 1965), and their combined output was nearly half as large as that yielded by almost 600 mines in 1956 (Holliday and Burke, 1958, p. 1,227).

In June 1965, the price of foreign concentrates delivered in the United States had firmed to $27.75, plus tariff of $7.93 per unit, from a low of $7.75 plus tariff in mid-1963.

China, the leading producer of tungsten concentrates since 1915 when wolframite deposits were discovered there, has contributed about 27 percent of the world output from 1905 through 1964, and the United States, second largest producer, has contributed 13 percent.

Within the United States, California and Nevada each yielded about 30 percent of the total domestic output from 1900 to 1957, followed in order by Colorado, Idaho, and North Carolina. Some significant production (more than 0.1 percent of the cumulative total) has come from six other states. California reached first in cumulative

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[1] A short ton unit of WO_3 is 20 pounds (1/100 of a short ton) and contains 15.862 pounds of tungsten; 1 million pounds of tungsten are contained in 63,050 units of WO_3.

production since 1958 because of large production from the Pine Creek mine while most other deposits in the nation were idle. The cumulative production of the United States was derived from many mines, large and small, but a high percentage of the total came from relatively few deposits. In 1955 and 1956, when United States output was at its peak, 15 mines accounted for 82 percent (1955) and 90 percent (1956) of the total output (Holliday and Burke, 1957).

In 1962, the United States Government held in stockpile concentrates containing 161,464,000 pounds of tungsten (Wall Street Journal, March 26, 1962), an amount roughly equivalent to two-thirds of total shipments from mines in the United States since 1900 and more than 8 percent of all tungsten produced in the world to that time.

Shipments of concentrates from California from 1906 to 1957 are listed in table 48, with approximate value. Since 1957, production figures for California have been withheld to avoid disclosing data held in confidence, but the larger part of the 37,093 tons of 60 percent WO_3 produced in 1958 to 1963 in the United States came from California.

TABLE 48.—*Shipments of tungsten ore and concentrate from California mines, 1906–57, in short tons of 60 percent* WO_3

Period	Tons	Value (thousands)
1906–12	2, 226	[1] $800
1913–19	8, 882	11, 608
1924–38	4, 541	3, 735
1939–46	18, 652	25, 317
1947–57	26, 871	85, 808
1906–57	61, 162	127, 268

[1] Estimate.

Tungsten mining in California was started in 1905 with the discovery of vein deposits rich in scheelite at Atolia, San Bernardino County. The contact-metamorphic scheelite deposits west of Bishop were recognized in 1914 and were productive during World War I and intermittently to the present. Hundreds of tungsten occurrences have been found in California, mostly of the contact-metamorphic type associated with granitic rocks of the Sierra Nevada and southern California batholiths (Stewart, 1957; Bateman, 1965). In a summary review of tungsten deposits of the United States, Lemmon and Tweto (1962) listed 177 mines or districts in California. Of these, only 36 are known to contain more than 10 tons of metallic tungsten (1,261 short ton units of WO_3) in combined production and reserves; they are the ones shown on the map (fig. 83) and described briefly in table 49, keyed by numbers to the map.

Major tungsten resources of California are in the Sierra Nevada, the Great Basin, and the Mojave Desert geomorphic provinces. Minor deposits are present in the Transverse Ranges and in the lower California provinces. A few noncommercial occurrences are known from the Klamath Mountains and the California Coast Ranges.

Two areas have yielded the largest production: the Bishop district and the Atolia district. At Bishop, many mines have contributed, including those of the Pine Creek area, the Tungsten Hills (11), and the Black Rock mine (5). By far the largest is the Pine Creek mine

(10) which is opened in one of the world's largest contact-metamorphic ore deposits (Bateman, 1945; 1956). This mine has been worked from the highest outcrop at an altitude of 11,900 feet down to the Zero adit at an altitude of 9,430 feet. An adit under construction in 1965 from the mill level at an altitude of 7,900 feet will explore the ore zone 4,000 feet beneath the outcrop. The cumulative production is far greater than any other tungsten mine or district in the United States; the mine still has an outstanding potential. The ores are complex and yield other marketable products than scheelite, including molybdenum, copper, silver, and gold.

The quartz veins at Atolia (30) contained scheelite ore of high grade and were formerly important producers. The known deposits are now mostly worked out.

Scheelite has been produced profitably from four medium-sized contact-metamorphic deposits on the west slope of the Sierra Nevada, in Madera and Fresno Counties: Strawberry (6), Consolidated Tungsten (18), Tulare County Tungsten (20), and Tungstore (24). The only important known reserves are in the Strawberry mine. Darwin (21) and Starbright (31) were also medium-sized profitable producers that are now largely depleted.

Tungsten is present in solution in the brines of Searles Lake (28) in very small concentrations, only 0.005 to 0.008 percent of WO_3 (Carpenter and Garrett, 1959). The total amount contained in the brines is estimated at 8.5 million units of WO_3. Recovery methods have been developed but are not yet economic.

California appears assured of a leading rank in production of tungsten in the United States for a long time. The known resources are large and new discoveries are probable.

Tungsten deposits or districts that contain more than 10 short tons of W are shown on the map, fig. 83, next page) and are listed in table 49, keyed to the map. Deposits numbered 1, 22, 30, 32, and 36 are veins; 28 is brine, and the others are contact-metamorphic scheelite deposits.

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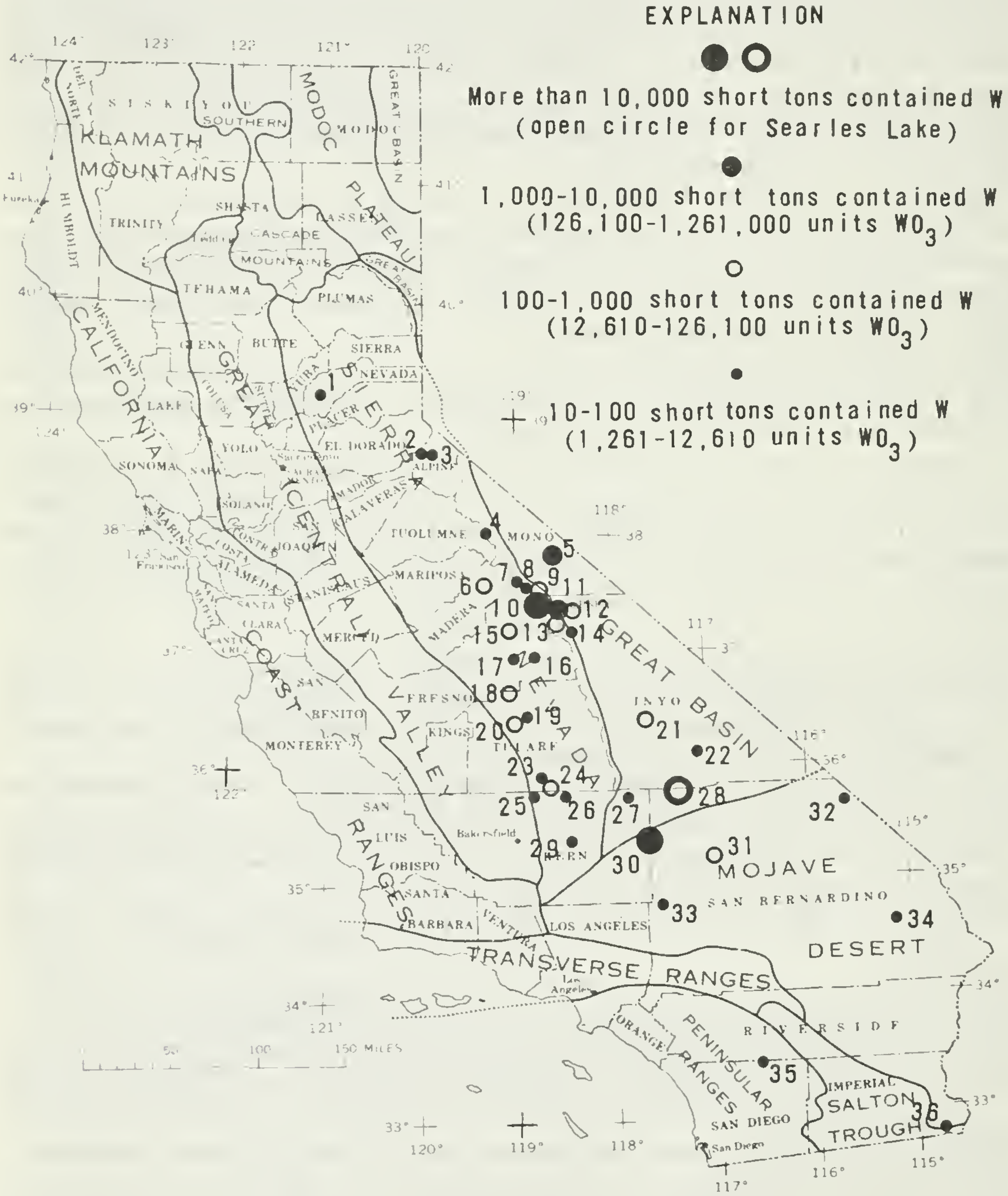

FIGURE 83. Tungsten in California, showing mines or districts with combined production and reserves containing more than 10 tons W (numbers refer to table 49).

TABLE 49.—*Tungsten mines or districts in California with combined production and reserves exceeding 10 tons tungsten*

Index No. on fig. 83	Name	Location	Reference
1	Grass Valley	Nevada County	Farmin, 1941.
2	Alpine mine	Alpine County, N. side Hope Valley, NE¼ sec. 11, T. 10 N., R. 18 E	
3	Valpine	Alpine County, Burnside Lake, secs. 9 and 16, T. 10 N., R. 19 E	
4	Saddlebag Lake	Mono County, 4 miles N. of Tioga Pass, sec. 6, T. 1 N., R. 25 E	
5	Black Rock mine	Mono County, S. of Benton, secs. 14 and 23, T. 3 S., R. 31 E	Rinehart and Ross, 1956.
6	Strawberry mine	Madera County, sec. 36, T. 4 S., R. 24 E	Krauskopf, 1953.
7	Hard Point	Mono County, Laurel Creek, sec. 29, T. 4 S., R. 28 E	Rinehart and Ross, 1964.
8	Scheelore	Mono County	Do.
9	Hilton Creek	do	Do.
10	Pine Creek mine	Inyo County, 18 miles W. of Bishop	Bateman, 1945, 1956.
	Adamson mine	Inyo County, N. of Pine Creek mine	Do.
	Brownstone mine	SW. of Pine Creek mill	Bateman, 1956.
	Tungstar mine	SE. of Pine Creek mill	Do.
11	Tungsten Hills (Aeroplane, Jackrabbit, Little Sister, Round Valley, Tungsten Blue, Western, and White Caps mines).	Inyo County, W. from Bishop	Do.
12	Rossi mine	Inyo County, 3 miles S. of Bishop	Do.
	Yaney mine	Inyo County, 3 miles E. of Rossi	Do.
13	Schober mine	Inyo County, Bishop Creek pendant, sec. 23, T. 8 S., R. 31 E	Do.
14	Marble mine	Inyo County, Shannon Creek, SE¼ sec. 31, T. 8 S., R. 33 E	Do.
15	Mud Lake	Fresno County, SW¼ sec. 30, T. 9 S., R. 27 E	Krauskopf, 1953.
16	Obelisk	Fresno County, SW¼ sec. 7, T. 12 S., R. 29 E	
17	Garnet Dike	Fresno County, NE¼ sec. 22, T. 12 S., R. 27 E	Do.
18	Consolidated (Harrel Hill)	Tulare County, sec. 11, T. 15 S., R. 26 E	Goodwin, 1958; Krauskopf, 1953.
19	Pioneer, Martin, Royal Tungsten mines.	Tulare County, sec. 27, T. 18 S., R. 29 E	Krauskopf, 1953.
20	Tulare County Tungsten mine (Big Jim).	Tulare County, sec. 11, T. 19 S., R. 28 E	Goodwin, 1958; Krauskopf, 1953.
21	Darwin district	Inyo County	Hall and MacKevett, 1958.
22	Panamint district	Inyo County, Panamint Mountains S. of Telescope Peak	
23	Tyler Creek mine	Tulare County, NW¼ sec. 35, T. 23 S., R. 30 E	Goodwin, 1958; Krauskopf, 1953.
24	Tungstore mine	Tulare County, SW¼, sec. 32, T. 24 S., R. 31 E	Do.
25	Woody mine	Kern County, NE¼ sec. 11, T. 25 S., R. 29 E	Troxel and Morton, 1962.
26	Cedar Creek district	Kern County, near Greenhorn Summit	Do.
27	Hi Peak mine	Kern County, sec. 10, T. 26 S., R. 38 E	Do.
28	Searles Lake	San Bernardino County	Carpenter and Garrett, 1958.
29	Tungsten Chief	Kern County, secs. 27 and 34, T. 28 S., R. 32 E	Troxel and Morton, 1962.
30	Atolia district	San Bernardino and Kern Counties	Lemmon and Dorr, 1940.
31	Starbright mine	San Bernardino County, secs. 19 and 20, T. 12 N., R. 1 E	Bateman and Irwin, 1954; Hazenbush, 1952; Wright and others, 1953.
32	Green mine	San Bernardino County, N. of Clark Mountain	Wright and others, 1953.
33	Shadow Mountains	San Bernardino County	Bateman and Irwin, 1954.
34	Old Woman Mountains	San Bernardino County, secs. 6, 8, and 9, T. 5 N., R. 17 E	Do.
35	Aguanga district (Pawnee mine)	Riverside and San Diego Counties	Do.
36	Cargo Muchacho district	Imperial County	Do.

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URANIUM

(By G. W. Walker, U.S. Geological Survey, Menlo Park, Calif., and A. P. Butler, Jr., U.S. Geological Survey, Denver, Colo.)

Uranium is a metallic element which consists of three semistable isotopes, U^{238}, U^{235}, and U^{234}. Heat released when a uranium atom fissions (splits) makes uranium an important source of energy for weapons and for generating power, its principal uses. The U^{235} isotope, constituting 0.7 percent of natural uranium, fissions readily whereas the abundant U^{238} isotope, constituting over 99 percent of natural uranium, must first be converted in a nuclear reactor to the readily fissionable plutonium isotope, Pu^{239}.

The principal nonenergy uses of uranium are in the ceramics and chemical industries.

Most of the uranium mined in the United States comes from stratiform deposits in continental standstones and conglomerates, principally in New Mexico, Utah, Colorado, and Wyoming. Less important deposits of uranium are found in lacustrine limestone and coal or carbonaceous sediments interbedded with continental sedimentary rocks. Vein and related fracture-controlled deposits are present in nearly all kinds of rocks widely distributed in the United States. Until about 1950 veins were the dominant world source of uranium (or radium), but they now represent only a subordinate source. Large, low-grade concentrations of uranium are present in marine black shales, phosphorites, and locally in some granitic rocks. Uranium minerals also have been reported from many pegmatites, but, in general, are not sufficiently abundant to be mined economically.

Although uranium minerals have been known in California at least since 1895 (Rickard, 1895, p. 239), the first uranium ore marketed from the State was shipped from the Thum Bum Claim near Big Bear Lake, San Bernardino County, in the early summer of 1954. Also in 1954, a railroad carload (about 48 tons) of uranium ore averaging 0.62 percent U_3O_8 was shipped from the Miracle mine in Kern River Canyon, Kern County. Since then about 9,000 tons of ore has been shipped from 17 different properties in the State,[1] and the uranium contained in this ore places California twelfth in rank among uranium-producing states. Only two deposits are recorded as having produced in 1964.

Uranium ores have been mined in California from several different kinds of deposits in widely separated parts of the State (Walker, Lovering, and Stephens, 1956; Troxel, Stinson, and Chesterman, 1957).

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[1] As compiled from information furnished by the Grand Junction Office, U.S. Atomic Energy Commission.

Nearly all the deposits are in the Sierra Nevada, Great Basin, and Mojave Desert psysiographic provinces (fig. 84) or parts of adjacent provinces.

Some of the deposits, for example, those at the Miracle and Kergon mines in the southern Sierra Nevada area fig. 84, (No. 7) and at the Northeast claim group in the southern McCoy Mountains area (No. 11), are readily identified as veins in which primary or secondary uranium minerals, or both, occur in faults and fracture zones. Disseminated primary uranium minerals along a contact between granite and schist is the ore at the Thum Bum claim in the San Bernardino Mountains area (No. 10) ; small vein deposits of uranium in limestone

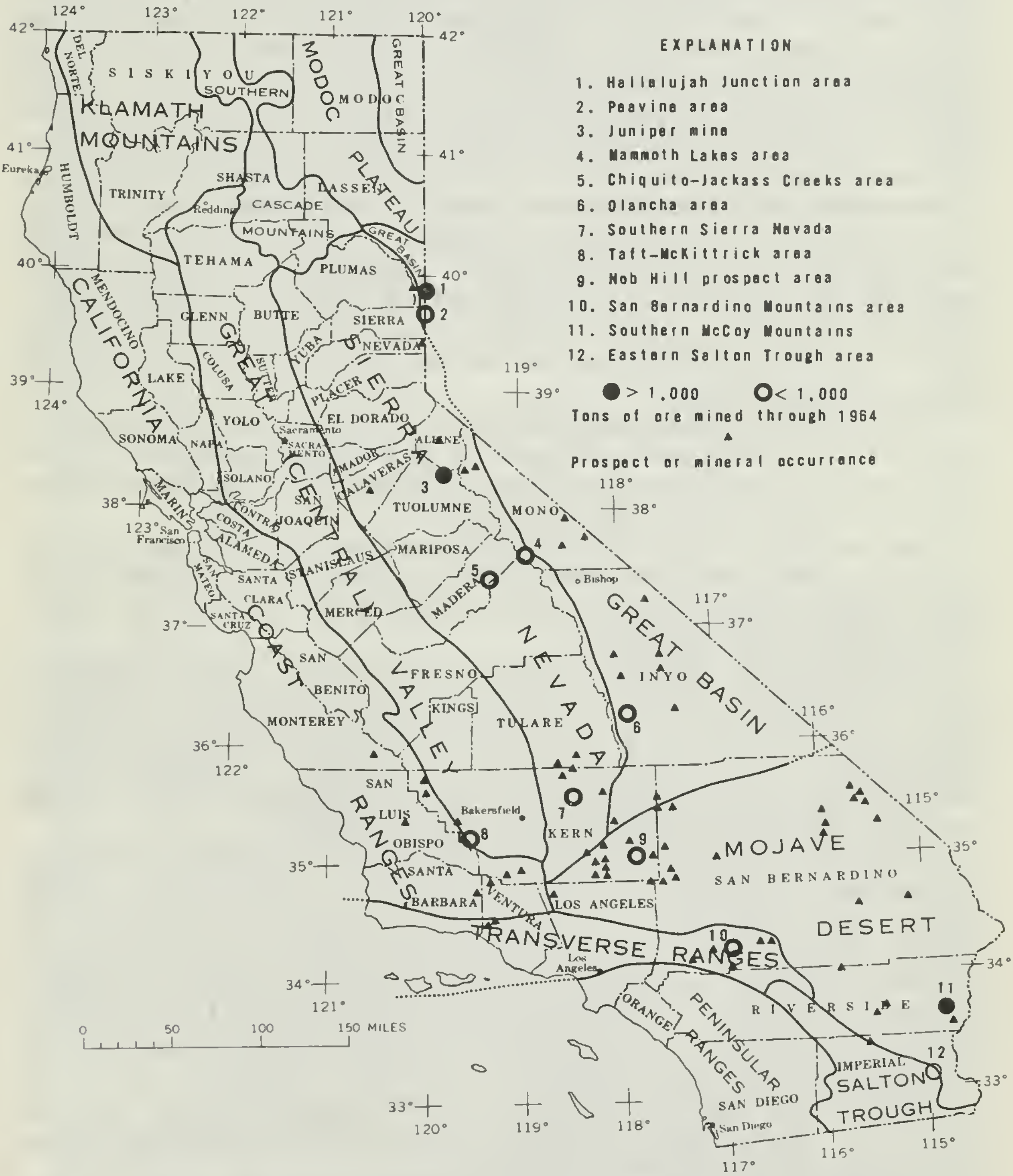

FIGURE 84. Uranium in California.

and schist, and one unusual allanite- and monazite-bearing vein in biotite gneiss are also present in the area. Secondary uranium minerals are locally abundant in quartz veins and shear zones cutting decomposed granitic rocks in Plumas County near the Hallelujah Junction area (No. 1); however, no ore has been shipped from these deposits. Deposits in the Mammoth Lakes area (No. 4) contain secondary uranium minerals, mostly as networks of tiny veinlets, and minor pitchblende in poorly sorted material thought to be either glacial till or the remnants of a talus apron (Rinehart and Ross, 1964, p. 100).

Another group of productive deposits, which are not so readily categorized, consists of fracture and bedding plane coatings or impregnations of brightly colored secondary uranium in rocks of Tertiary age. Some are in or near faults and commonly have been classed as veins; others are mainly stratiform. The host rocks include: (a) clayey and tuffaceous continental sedimentary rocks interbedded with volcanic rocks in northeastern Tuolumne County (No. 3), which is the largest single source of uranium ore mined in California to date (1965); (b) continental arkosic sandstone and bentonitic tuff that lie on an irregular surface on Jurassic granitic rocks in the Olancha area (No. 6); (c) volcanic and continental sedimentary rocks in the Hallelujah Junction area (No. 1); (d) fractured volcanic rocks in the Peavine area (No. 2); and (e) marine sedimentary rocks in the Taft-McKittrick area (No. 8). A large number of geologically similar deposits, with no recorded production, are present in the western part of the Mojave Desert province.

Small amounts of carnotite and possibly other secondary uranium minerals occur with pods or lenses of carbonaceous material in Tertiary sandstone beds in several places in western Ventura County, principally near Ojai (Troxel, Stinson, and Chesterman, 1957).

Sand and gravel of possible Pleistocene age containing some partly decomposed plant material are locally mineralized with uranium in the Chiquito-Jackass Creeks area in Madera County (No. 5). Some of this material has been mined.

Several peat bog deposits in the southern Sierra Nevada area composed of woody fragments, black carbonaceous matter, silt, and arkosic sands, contain an appreciable amount of uranium in some unidentified form, possibly absorbed in the peat. One deposit averages about 0.10 percent and another about 0.24 percent U_3O_8. No ore has been shipped from these deposits to date (1965).

Extensive marine phosphorites of Miocene age that are commonly radioactive are present in a number of places in the southern Coast Ranges and along the west side of the San Joaquin Valley (H. D. Gower, oral communication, 1965). The source of the anomalous radioactivity is not known but by anology with phosphorites elsewhere (Butler and Schnabel, 1956, p. 37–38) it can be assumed that it comes mostly from uranium. Ultimately, the uranium may be extracted as a by-product of phosphate mining.

Uranium also has been reported in some asphalt-bearing rocks in California(Hail, Myers, and Horr, 1956), but is insufficiently concentrated to be economically extracted.

Compared to the large economic deposits in other parts of the United States most of the uranium deposits of California are small, and none are thought to contain large reserves of minable uranium ore.

However, future prospecting undoubtedly will uncover many new occurrences of uranium minerals comparable to those in granitic rocks in Kern River Canyon, in metamorphic rocks in the McCoy Mountains, and in continental sedminetary rocks in Tuolumne County. Some may be rich enough to support mining on a small scale but are unlikely to contribute appreciably to total resources in the United States.

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VANADIUM

(By R. P. Fischer, U.S. Geological Survey, Denver, Colo.)

The consumption of vandium in the United States increased from about 1,900 tons in 1955 to about 3,500 tons in 1964, according to figures published by the U.S. Bureau of Mines. Of the total vanadium consumed, 75 to 80 percent has gone into special engineering, structural, and tool steels, where it is used as an alloy to control grain size, impart toughness, and inhibit fatigue. The other principal domestic uses have been in nonferrous alloys and chemicals (Busch, 1961).

Four geologic types of deposits have yielded most of the world's supply of vanadium. The bulk of domestic vanadium, and nearly half of the world supply, has come from deposits of vanadium- and uranium-bearing sandstone in southwestern Colorado and the adjoining parts of Utah, Arizona, and New Mexico. The other principal sources have been a deposit of vanadium-bearing asphaltite in Peru, vanadate minerals from the oxidized zones of some base-metal deposits in Africa, and vanadium-bearing iron deposits in Europe and Africa. These iron deposits and similar ones in many parts of the world contain very large resources of vanadium; probably they will become increasingly important as sources of vanadium in the future.

Of these four principal types of productive vanadium deposits, only two are known in California—vanadate deposits with base metals, and vanadium-bearing iron deposits. Accumulations of vanadium above trace amounts are known in only two other geologic types of occurrences in the State. These deposits and occurrences are shown on figure 85, and they are briefly described below. None of these are judged to be of significant commercial potential.

Minerals composed of the vanadates of lead, zinc, or copper have been found in the oxidized zones of several deposits in southern California, but only two have any recorded production. Hewett (1956, p. 134) states that about 40 tons of concentrates containing vanadates were recovered at the Leiser Ray mine (No. 1, fig. 85), San Bernardino County, in 1916–1917, and Brown (1923, p. 63) reports the recovery of some vanadium-bearing concentrates from the Eldorado mine (No. 2), Riverside County, in 1918. Similar occurrences are common in the oxidized zones of base-metal deposits in southwestern United Statese and in many other parts of the world where the climate is arid or semiarid. In most of these deposits the vanadate minerals occur only as scattered crystals or sparse powdery coatings, but in a few deposits these minerals are abundant enough in patches or bodies

FIGURE 85. Vanadium in California.

to yield ore by selective mining or mill concentrating. None of the deposits in California are known to have large bodies of rock containing vanadate minerals.

The ultramafic rocks of the San Gabriel Mountains (No. 3, fig. 85), Los Angeles County, contain vanadium-bearing titaniferous magnetite in small high-grade pods and larger low-grade disseminations, and along some of the stream valleys nearby are placer deposits of vanadium-bearing ilmenite and magnetite sand. Although a few samples from these deposits assay 0.5 percent or more V_2O_5, most samples contain much less vanadium (Benson and others, 1962; Oakeshott, 1948). Probably the vanadium content of these deposits is too low to encourage attempts to recover this metal, even if the deposits are worked for titanium and iron. Many similar titaniferous magnetite deposits in other parts of the world are larger and higher grade, and some contain 0.5 percent V_2O_5 or more.

Vanadium-bearing minerals occur in the uranium deposit at the Miracle mine (No. 4, fig. 85), Kern County (Bowes, 1957), but the average vanadium content of many samples from the deposit is only about 0.14 percent V_2O_5, which is too low to attempt vanadium recovery. Vanadium minerals are absent or inconspicuous in other uranium deposits in California. Many of the known uranium deposits in California are of the vein type, and probably of hydrothermal origin, and vanadium is not commonly abundant in deposits of this type.

Roscoelite, the vanadium-bearing mica, is a minor gangue mineral in some of the gold-quartz veins in El Dorado County (No. 5, fig. 85) (Murdock and Webb, 1956, p. 287). No assay data showing the vanadium content of the ore as mined have been found, but the content is assumed to be too low to consider vanadium recovery. Small amounts of roscoelite are common in gold-bearing veins, especially those containing gold-telluride minerals, in other parts of the world.

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WOLLASTONITE

(By B. W. Troxel, California Division of Mines and Geology, Los Angeles, Calif.)

California is endowed with large deposits of wollastonite and wollastonite-bearing rocks which, to date, have been utilized mostly as sources of ornamental building stone (field stone). Wollastonite has been produced from two sources in California; from deposits near Willsboro and Lewis, New York; from a deposit at Lappeenranta, Finland; and from a deposit near the Khor Dirbat well in the Red Sea Hills, Sudan.

Beneficiated wollastonite has proved satisfactory for use in floor and wall tile bodies, in porcelain fixtures, thermal insulation products, acoustical tile, frits for enamelware, glazes and dinnerware, electrical insulator products, as a paint extender, filler in asphalt-based floor tiles, in welding rod coatings, and mineral wool. It has certain applications as coating and filler for paper, as an abrasive, a bond for abrasive wheels, as filler for plastics and cement, and as a filter. Bonded and baked wollastonite products could be used for wall board and exterior sheathing (Amberg and McMahon, 1949).

Wollastonite ($CaO \cdot SiO_2$) ordinarily occurs as a contact-metamorphic mineral in siliceous limestone masses that have been metamorphosed near intrusive igneous bodies. Wollastonite commonly is associated with diopside, idocrase, garnet, epidote, calcite, and quartz. Locally, the rocks may be infused with metallic sulphides. In California, contact-metamorphic environments are most common on the borders of granitic rock masses in the Sierra Nevada, Great Basin, Mojave Desert, and Peninsular Ranges.

The first production of wollastonite in California, and possibly in the world, was in 1933 from a deposit near Code Siding, north of Randsburg, Kern County. Since 1955, wollastonite has been obtained from sources in the Blythe area, but most of these have yielded undisclosed quantities of field stone for use as ornamental building stone. A deposit near Blythe was explored about 1958 as a source of wollastonite for use as the principal raw material in mineral wool at a plant near Blythe, Riverside County; no significant quantity of mineral wool was produced or marketed. Since early 1964, several California deposits of wollastonite have been evaluated by ceramic producers but by mid-1965 none had been developed.

The United States ranks first in production of wollastonite. New York is the principal source in the United States, and California ranks second. Data on quantity and value of California production are undisclosed, but wollastonite production probably averages a few thousand tons each year, valued at less than $15 per ton, f.o.b. mine.

Occurrences in California

In the Big Maria Mountains, 16 miles northwest of Blythe, eastern Riverside County, pods of high-purity wollastonite occur in crystalline limstone (fig. 86). The pods range from a few inches in maximum dimension to as much as 1,800 feet in length. Mixed metasedimentary rocks associated with the limestone also contain wollastonite-bearing layers. These rocks appear to be as much as 500 feet thick and can be traced laterally for about 4 miles. The wollastonite-bearing rock is fine grained and is interbedded with fine-grained diopside and thin layers of limestone. Local beds are brownish-gray and appear to have a relatively high iron content. Other beds are nearly pure white. Similar wollastonite-bearing rocks occur in the Little Maria Mountains, the Arica Mountains, and probably elsewhere north of Blythe.

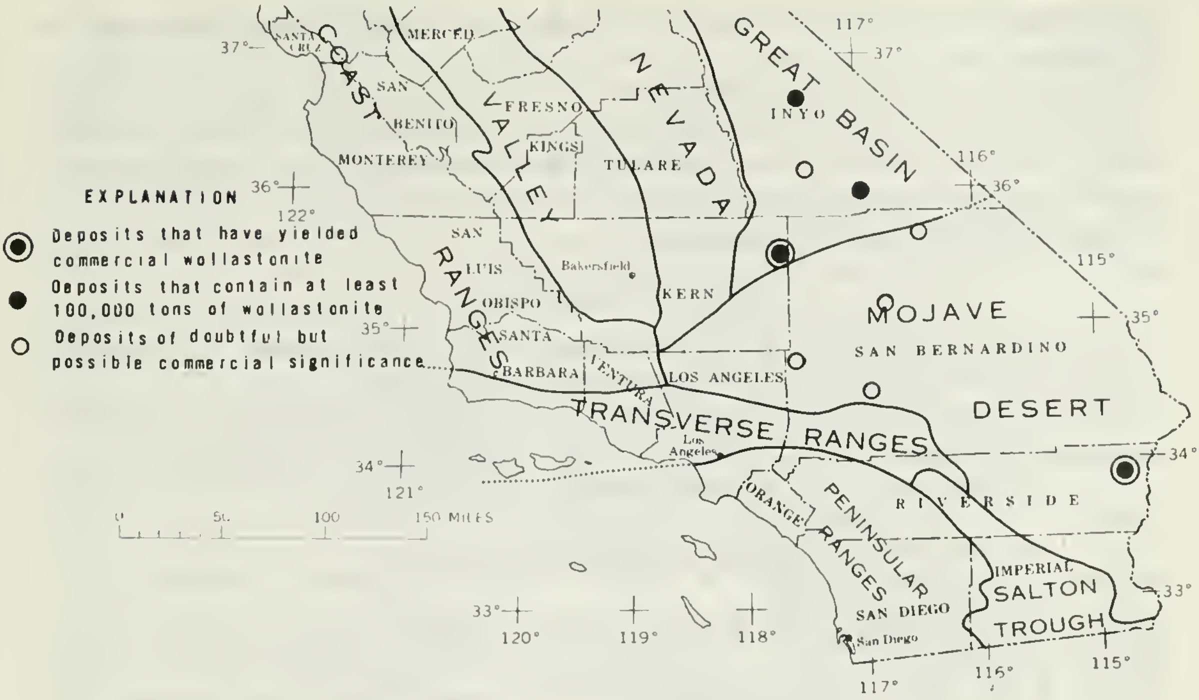

FIGURE 86. Wollastonite in California.

White, coarsely crystalline wollastonite occurs in Permian limestone in Warm Spring Canyon on the east slope of the Panamint Range, Inyo County. The largest body is an elongate lens about 750 feet long and 35 feet in average thickness. Most of the rock in the lens consists almost wholly of wollastonite, but siliceous and calcareous material forms local layers and irregular masses. Diopside, quartz, and calcite are minor constituents throughout the lens of wollastonite. Wollastonite occurs in recrystallized limestone at Striped Butte, several miles farther west up Warm Spring Canyon and probably elsewhere locally in the Permian strata.

Wollastonite-bearing metasedimentary rocks also occur in the northeastern part of the El Paso Mountains near Code Siding, north of Randsburg in Kern County. In these rocks the wollastonite occurs as intricately folded layers interstratified with nearly equal or greater amounts of diopside and garnet. The sequence is several tens of feet in total thickness. In 1933–1934, this deposit yielded an undisclosed amount of material for the manufacture of mineral wool.

Since 1957, wollastonite, of undetermined quantity and quality, has been modestly explored in a few masses of recrystallized limestone along the north edge of Hunter Mountain, Inyo County. Those deposits may contain large reserves of wollastonite or wollastonite-bearing rock. Metamorphosed limestone masses in Sheep Creek, Avawatz Mountains, San Bernardino County, may contain significant quantities of wollastonite but are as yet unexplored.

Several wollastonite occurrences also have been reported in crystalline limestone in the Mojave Desert, principally near Barstow and Victorville. Still other wollastonite deposits exist throughout the Sierra Nevada where the mineral has been found in metamorphosed limestone, especially in the vicinity of tungsten deposits. Wollastonite also occurs in metasedimentary rocks near Darwin, Inyo County, and has been noted in the north part of the Argus Range almost due east of Darwin.

Of the 37 occurrences of wollastonite in California, reported in Bulletin 173 of the California Division of Mines (Murdoch and Webb, 1956), only those described above appear to be capable of yielding commercial quantities of the relatively pure mineral, but not all of the occurrences have been investigated.

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ZINC

(By P. K. Morton, California Division of Mines and Geology, Los Angeles, Calif.)

Zinc has been utilized by man since the dawn of civilization. Metal artifacts dating back 2,000 years contain zinc, but it is thought that these early uses were largely the accidental result of crude smelting of complex copper-tin-zinc ores. Separate identity of zinc is not known before the 16th century, and recovery for commercial use did not occur until the 18th century. Utilization increased steadily thereafter, and, in 1963, only steel, copper, and aluminum outranked zinc in total production. Total world production in 1963 was 3,970,000 short tons of which the United States produced 529,250 tons or more than 13 percent. The primary sources of lead-zinc-copper deposits in the United States, in the order of total production, are Oklahoma, New Jersey, Missouri, Kansas, Montana, and Idaho. The leading states in 1963 were Tennessee, Idaho, New York, Colorado, and Utah.

The pricipal domestic uses of slab zinc in 1963 were zinc base alloys (die castings, alloy dies and rods, slush and sand castings), 42 percent; galvanizing, 38 percent; brass products, 12 percent; the remainder was used mainly for rolled zinc, zinc oxide, and other zinc compounds.

Mineable zinc occurs principally in the form of the sulfide, sphalerite, deposited as open-space filling and replacement bodies of hydrothermal origin in association with lead, copper, gold, and silver. These deposits commonly occur as complex ore masses in the form of veins, flat or gently inclined tabular bodies, or as lenticular to irregularly shaped bodies. Most of these deposits are believed to have originated through processes accompanying the late stages of intrusion of large igneous masses into the earth's crust.

Where zinc-bearing ore deposits lie near the surface, sphalerite oxidizes readily to form smithsonite (zinc carbonate), hemimorphite (hydrous zinc silicate), and other less common oxidation products. Smithsonite and hemimorphite are important ore minerals of zinc, but are much less abundant than sphalerite.

Although zinc-bearing ores have been mined in California since the 1860's, no zinc was recovered commercially until 1906, because it was not economically feasible. Total output for the State is about 308 million pounds. California's lead-zinc-copper industries have been crippled in recent years by a combination of factors including, poor reserves, increased mining and transportation costs, and depressed prices. Production during the 5-year period 1959–1963 was only 1,270 tons valued at $305,000, which amounted to less than one percent of the United States production during that period.

Occurrences in California

In California, the chief zinc-producing areas in order of total production are the Shasta district (42 percent), the Great Basin province (28 percent), and the Foothill Belt (15 percent). Other less productive areas noted on figure 87.

The *Shasta zinc-copper district* lies in Shasta County at the southeast corner of the Klamath Mountains province (fig. 87). It is divided into the East and West Shasta districts on the basis of lithologic and structural differences.

Ore bodies in the East Shasta district occur as massive sulfide replacement lenses which are localized along shear zones in Triassic Bully Hill Rhyolite and along fault contacts between Bully Hill Rhyolite and the Pit Formation (Middle and Upper Triassic). Ore bodies, which are as large as 400 feet in their largest dimension, commonly are closely grouped along shear zones (Albers and Robertson, 1961, p. 98).

Deposits of the West Shasta district also consist of massive sulfide replacement masses of lenticular shape, but they occur as flat-lying or gently inclined bodies in Devonian Balaklala Rhyolite. Ore controls as recognized by Kinkel, Hall, and Albers (1956, p. 137) are (1) stratigraphic control within Balaklala Rhyolite; (2) structural control by folds and foliation; and (3) by location of feeder fissures for ore solutions.

Mineralogy in the two districts is similar and it is probable that the source of mineralizing solutions for both districts was a subjacent igneous mass or masses of albite granite or quartz diorite.

Outlook for future exploration for hidden ore bodies in the Shasta district appears to be favorable in light of the studies by Kinkel, Hall, and Albers (1956) and Albers and Robertson (1961). More detailed geologic studies of favorable areas supported by integrated geophysical and geochemical techniques should yield profitable results. Of especial value in exploring for this type of deposits are electrical, magnetic, and gravity methods.

The *Great Basin* province occupies much of Nevada, Utah, and Wyoming and its southwestern corner extends across most of Inyo and Mono Counties, California. Approximately 28 percent of California zinc production as well as 94 percent of its lead, has come from this

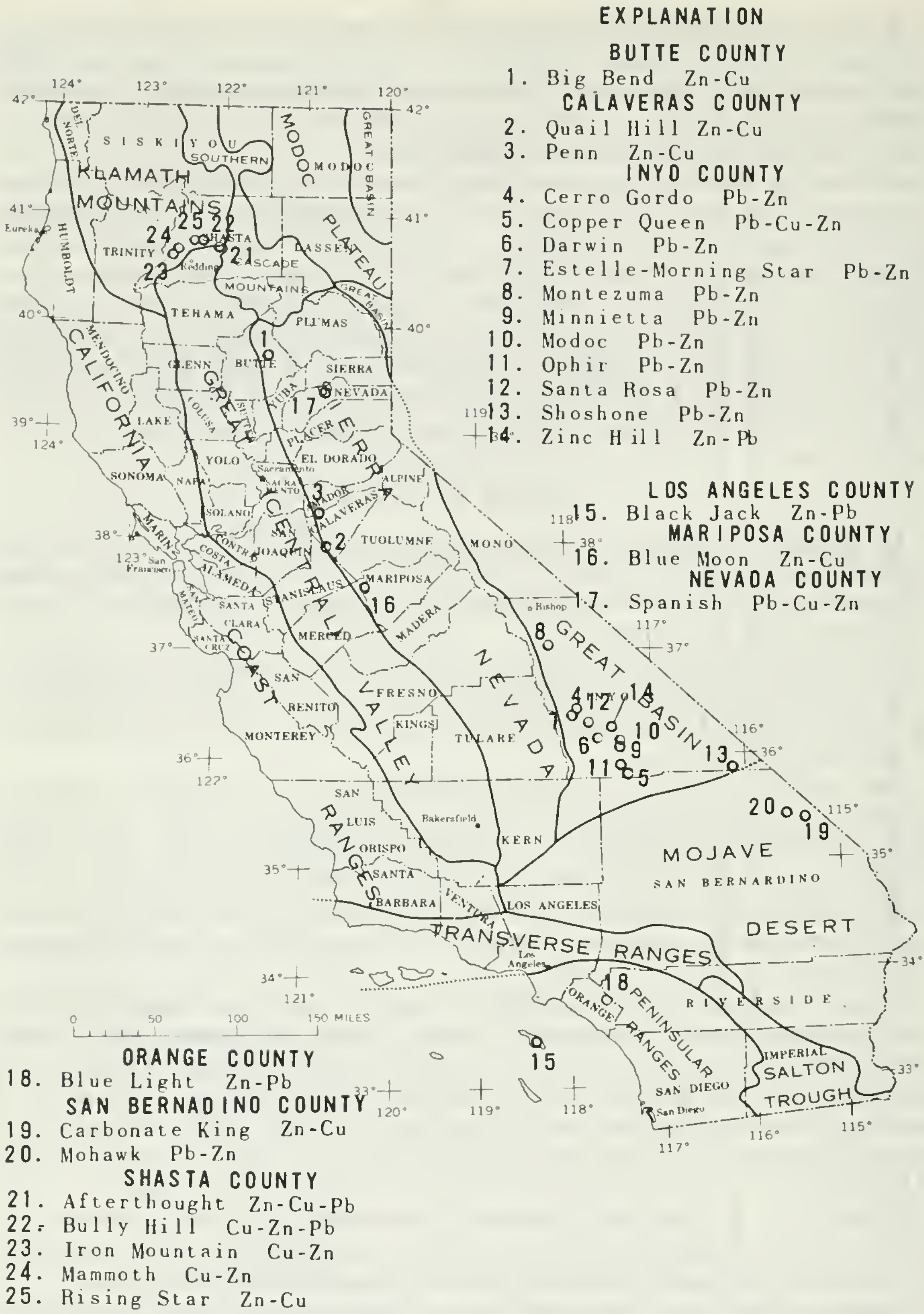

FIGURE 87. Principal zinc mines in California and types of ore.

province. The deposits are widespread within the province, but the great majority lie in a northwest-trending belt, several hundred square miles in extent, in the southern Inyo Mountains and the Argus Range. The geologic environments of lead-zinc deposits in the Great Basin province are diverse, but in general the deposits occur as replacement bodies along faults, as irregular replacement bodies in carbonate rocks, or as contact metasomatic deposits along the peripheral margins of plutonic rocks. The primary ores are composed typically of galena, sphalerite, and chalcopyrite, with minor tetrahedrite-tennantite and gold. Gangue minerals include pyrite, pyrrhotite, altered wall rock, quartz, calcite, jasper, fluorite, and barite. The controlling factors in this region appear to have been: (1) proximity to Cretaceous plutonic rocks of silicic to intermediate composition, (2) stratigraphic control in certain carbonate formations, and (3) faults to provide adequate channels for transport of mineralizing solutions and convenient loci for deposition.

Because of the widespread distribution of deposits in this province, exploration for new deposits constitutes a major problem; on the other hand it presents a better potentiality in that it offers more areas for investigation. Reconnaissance geochemical sampling may offer some solution to narrowing down the number of areas for future exploration. District studies employing coordinated geological, geochemical, and geophysical techniques are needed, and should, if undertaken, result in discovery of new deposits.

The *Foothill Belt* constitutes a narrow northwest-trending belt along the southwestern front of the Sierra Nevada from Fresno County northwestward to Butte County, a distance of about 250 miles. This belt lies along the western edge of Sierra Nevada geologic province.

The copper-zinc deposits within the Foothill Belt consist of lenticular sulfide replacement bodies lying along steeply dipping shear zones in Paleozoic and Jurassic metavolcanic and metasedimentary rocks. They are associated with zones of sericitization, silicification, pyritization, or chloritization developed by hydrothermal acton. The deposits have been divided into four groups by Heyl (1944, p. 11–29). Two are exclusively copper deposits; the remaining two are characterized by a composition of sphalerite, chalcopyrite, pyrite, pyrrhotite, milky quartz, calcite, and small amounts of gold and silver.

According to Heyl, ore deposition was largely controlled by structural features including (1) intersections of bifurcations of faults and shear zones, (2) changes of strike and dip of faults, (3) irregularities on contacts between rocks of markedly different competency, and (4) intersection of faults with such contacts.

The deposits of the Foothill Belt have contributed about 15 percent of the total State output, and will doubtless contribute more in the years to come. The mode of occurrence of the deposits is fairly well established but, as is also true of the deposits of the other two provinces, little is known of their origin, and further study is necessary. The orderly drainage pattern of the Foothill Belt and its uniform linear nature lends itself well to systematic geochemical reconnaissance. Anomalous areas can be studied by more detailed and coordinated geological, geochemical, and geophysical methods.

The potentialities of the three zinc provinces and many other smaller districts are great. The zinc-lead-copper resources of California have been largely neglected in recent years. Exploration and economic studies have not kept pace with the rate of development of new techniques in the earth sciences. With application of these techniques by both industry and government, California can become an important source.

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ZIRCONIUM AND HAFNIUM

(By M. C. Stinson, California Division of Mines and Geology, San Francisco, Calif.)

Zirconia (zirconium oxide) and zirconium compounds are made directly from the commercial source minerals, zircon and baddeleyite. Zircon is used in refractories and foundry sands. Stabilized zirconium oxide is used to insulate high-frequency induction furnaces and to line jet engines. Zirconium metal is used in nuclear reactors, in steel alloys, and in surgery. Hafnium is used in nuclear reactors.

Zirconium is more abundant in the earth's crust than nickel, copper, zinc, lead, tin, and mercury combined. The earth's crust contains approximately 0.03 percent zirconium and 0.004 percent hafnium. Hafnium occurs in nature only with zirconium-bearing minerals and has almost the same chemical properties as zirconium. Of the zirconium minerals, only zircon and baddeleyite are abundant enough to be of commercial interest. These ores always contain from ½ to 2 percent hafnium.

Zircon (zirconium silicate), the most widely distributed and abundant zirconium mineral, is a common constituent of many igneous and metamorphic rocks as well as sands resulting from the disintegration of these rocks. Many sedimentary rocks contain zircon because the mineral is hard and chemically resistant to weathering. In ultraviolet light, most specimens of zircon fluoresce a brilliant orange, red, or yellow.

Baddeleyite (zirconium dioxide), much less widely distributed than zircon, occurs in igneous rocks that are deficient in silica, and in sedimentary rocks derived from them.

The zirconium-hafnium content of igneous and metamorphic rocks rarely exceeds 0.06 percent. These elements are not known to be concentrated in veins, but the high-specific gravity of zirconium minerals leads to their concentration in placer deposits. As the expense of removing zirconium- and hafnium-bearing minerals from hard rocks is much greater than from placer deposits, and as placer deposits commonly are richer in such minerals, the commercial production of zirconium and hafnium has been limited to sands. Furthermore, other minerals of commercial value are often found associated with placer deposits of zirconium- and hafnium-bearing minerals and are recovered simultaneously and at little extra expense.

The bluish-violet mineral hyacinth (also called jacinth or jargon) has been known for many years as a semiprecious gem stone. Intaglios of zircon are common among ancient gems. In the 18th century, colorless zircons were supposed to be inferior or imperfect diamonds and were known as "Matera diamonds" because many were found in the Matera district of Ceylon. M. H. Klaproth, during the analyses of zircon from Ceylon, noted an oxide that had not been previously described. The results of his study were published in 1789. In 1824, J. J. Berzelius obtained a black impure zirconium powder, but nearly pure zirconium metal was not produced until 1914.

In 1922, zirconium was found to contain a small proportion of the element of atomic number 72. This element is so nearly identical to zirconium that no qualitative differences in chemical behavior between the two elements have been found up to the present time. In January 1923, von Henesy announced the discovery of element 72, and he called it hafnium. Until recently, only a small quantity of pure hafnium was produced. In recent years satisfactory, though still costly, large-scale separations of zirconium and hafnium have been made. Hafnium is not removed from the zirconium metal and zirconium compounds used by industry. For all purposes other than use in atomic reactors and research, the hafnium content is ignored because of the extreme similarity of the two elements.

The United States production of zirconium metal in 1963 was estimated at 850 short tons. The United States production of zirconium concentrates is confidential. There is no reported production of zircon from California.

Occurrences of zircon have been noted in many placer gold deposits in California (fig. 88), but only one has yielded zircon on a commercial basis. Small quantities of zircon were removed in a dragline gold dredging operation in 1937 near Lincoln in Placer County. The concentration of zircon in California sands generally is too low to permit

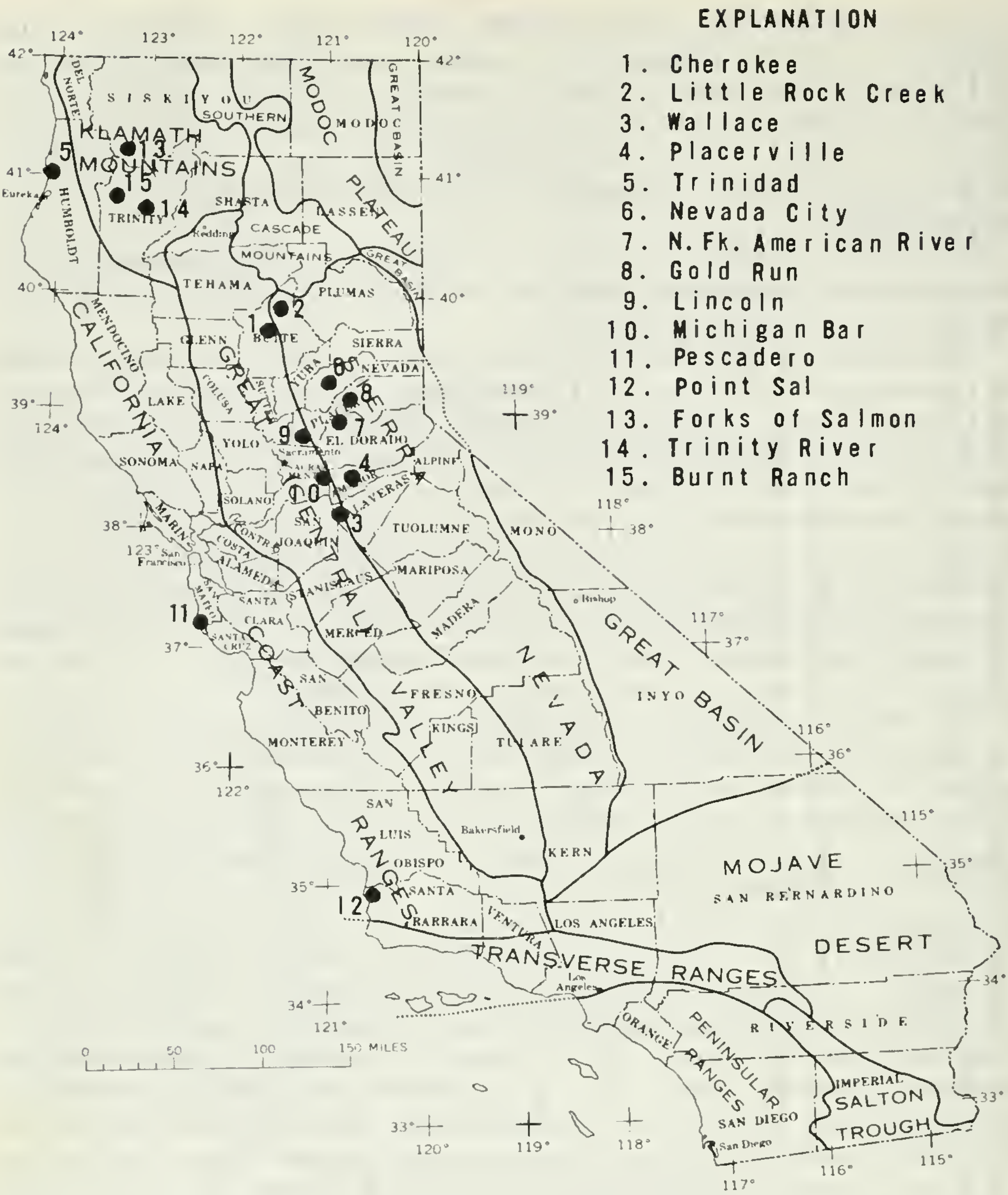

FIGURE 88. California placer deposits containing above average zircon concentrations (modified after Day and Richards).

the commercial recovery of this mineral at the current prices and with the limited western market.

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