GEMS & GEMOLOGY

TABLE OF CONTENTS

pg. 99

pg. 115

pg. 132

pg. 146

ABOUT THE COVER: *Although rhodochrosite had long been known to the gem and jewelry community as a massive, pink ornamental material, recently some attractive transparent orangy pink to red rhodochrosites have become available as faceted gems. Many of the transparent rhodochrosites in the gem market today are from the Sweet Home mine near Alma, Colorado. Current exploration and minig at this mine, as well as the gemological characteristics of—and cutting and setting guidelines for—Sweet Home rhodochrosite, are covered in the article by artist Kimberly Knox and Sweet Home Rhodo president Bryan Lees. A very soft material, rhodochrosite can still be worn in some jewelry if it is carefully set, as in this unusual necklace of rhodochrosites with enamel mounted in 18k gold.*

The necklace was designed by kimberly knox and manufactured by Ms. Knox and Zane A. Gillum of Golden Pacific Arts, San Diego, California. The rhodochrosites range from 1.50 to 14.06 ct. The loose rhodochrosites, which range from 6.50 ct. to 11.50 ct., are courtesy of The Collector's Edge, Golden, Colorado.

Photo © Harold & Erica Van Pelt—Photographers, Los Angels, CA.

Color separations for Gems & Gemology are by pacific color, Carlsbad, CA. Printing is by cadmus journal Service, Richmond, VA.

Carlsbad: A new home for GIA and Gems & Gemology

*A*bout 10 years ago, a new instructor called me and asked if he could visit the *Gems & Gemology* offices. A great fan of the journal, he wanted to see where it was produced and meet the people responsible. I will never forget his surprise when he saw our little office and reception area, in a comfortable, but small, corner on the ground floor of GIA's Santa Monica headquarters. "But," he said, "from the quality of the publication, I always imagined that *Gems & Gemology* occupied the better part of a three-story building . . . ."

I was delighted that he had that image of *Gems & Gemology*. Our goal 17 years ago, when I was asked to redesign and reformat the journal, was to use *G&G* as a springboard to enhance the professionalism of gemology both in the scientific community and with the trained gemologist. To this person, we had achieved that goal—too well, perhaps, because now he felt that *G&G*'s facilities did not reflect the role that the journal had assumed in the gemological community.

It was a refrain that was being heard worldwide about GIA and its subsidiaries in the late 1980s. Through its education, laboratories, instruments, research, and publications, GIA had established a unique leadership position in the world gemological community. Yet, while the facilities in Santa Monica were state-of-the-art when they were first built in the 1970s, they eventually became inadequate in terms of space and future planning to meet the needs of the industry.

Today, *Gems & Gemology* is in that three-story building—one of three buildings on the Robert Mouawad Campus. The new campus fulfills a dream and years of hard work under the guidance of GIA's president Bill Boyajian. Beautifully designed and constructed, the Carlsbad world headquarters sits on a hill overlooking the Pacific Ocean, about 30 miles (48 km) north of San Diego and only 100 miles (160 km) south of GIA's former home in Santa Monica. The spacious Carlsbad facility can comfortably accommodate 1,000 students and staff members. The new West Coast GIA Gem Trade Laboratory already employs more than 100 graders. The Education building has 19 classrooms and two student lounges with room for expansion. The new library and information center houses more than 20,000 publications, supported by an expanded staff. An auditorium and a gem museum are planned for the future. The new *Gems & Gemology* area, on the second floor of the administration building, looks out on the coastal mountains of Southern California from a wall of windows. With space for six employees and a number of visiting authors, the *Gems & Gemology* area is now truly a place to be proud of.

Do come visit us. Share our pride. Like *Gems & Gemology*, GIA's new world headquarters is dedicated to serving you and all members of the gem and jewelry community.

*A*s with all such moves, however, we have had to say good-bye to some old friends during this one. With this issue, C. W. (Chuck) Fryer, a former director of the West Coast GIA Gem Trade Laboratory, retires as editor of the Lab Notes section. Thank you, Chuck, for the years that you have devoted to making Lab Notes one of the most popular features of the journal.

Alice S. Keller

Alice S. Keller
EDITOR

UPDATE ON EMERALDS FROM THE SANDAWANA MINES, ZIMBABWE

By J. C. (Hanco) Zwaan, Jan Kanis, and Eckehard J. Petsch

Zimbabwe's Sandawana mines have been an important producer of emeralds for 40 years. Since the mines came under new ownership in 1993, consistent production has been established and, in addition to the small sizes for which Sandawana is known, greater numbers of polished stones as large as 1.50 ct have been produced. Currently, mining at the most active area, the Zeus mine, is done underground, with the ore processed in a standard washing/ screening trommel plant. Sandawana emeralds can be readily separated from emeralds from other localities. They have high refractive indices and specific gravities. Two amphiboles, actinolite and cummingtonite, are abundant inclusions; albite and apatite are common. Also found are remnants of fluid inclusions. Chemically, Sandawana emeralds typically have a very high chromium content.

ABOUT THE AUTHORS

Mr. Zwaan is curator at the Mineralogy Department of the National Museum of Natural History (NNM), Leiden, The Netherlands, and head of the Netherlands Gemmological Laboratory, Leiden. Dr. Kanis is a consulting geologist/gemologist specializing in gemstone occurrences; he resides in Veitsrodt near Idar-Oberstein, Germany. Mr. Petsch is president of the firm Julius Petsch Jr., Idar-Oberstein.

Please see acknowledgments at end of article.

*I*t is believed by some that the area now known as Zimbabwe was the fabled land of Ophir, which produced gold for King Solomon's temple. By the middle of the 10th century, the discovery of ancient gold workings in different parts of the country had led Arab geographers to speculate on Ophir in their writings (Summers, 1969). Although gold, and even diamonds, stimulated exploration in the 20th century, for gemologists the most important discovery was the large emerald deposit found in the mid-1950s at the area called Sandawana. For four decades, Sandawana has provided the jewelry industry with large quantities of fine, if typically small, emeralds (figure 1). Production was sporadic for much of this period, but new ownership in the mid-1990s has brought renewed attention to exploration and mining, with excellent results in terms of both the quantity and quality of the stones produced.

Although the Sandawana mines have been known for some time now, only short articles on the characteristics of Sandawana emeralds have been published to date. There has been little information about the mining area and the techniques used for exploration, mining, and processing. This article attempts to fill that gap. Not only does it provide some results of a detailed study on the geologic factors that contributed to emerald formation in this part of Zimbabwe, but it also offers new data on the distinctive properties of these emeralds.

HISTORICAL BACKGROUND

In 1868, German geologist Carl Mauch uncovered some of the ancient gold workings to which Arab geographers had referred—in the interior of what is now Zimbabwe, near Hartley (now Chegutu). Subsequently, after Cecil Rhodes's British South Africa Company obtained a charter to promote commerce and colonization in Zimbabwe in 1889, prospecting for gold became a major industry. The simplest surface indicator was an ancient working. In the nine years between 1890 and the outbreak of the South African Boer

Figure 1. The Sandawana mines are known for the small but fine emeralds that have been produced there for more than 40 years. This 16-strand necklace is composed entirely of Sandawana emeralds, more than 1,000 beads, which range from 4 to 7 mm in diameter. Courtesy of Fine Emerald, Inc., New York City; photo © Harold & Erica Van Pelt.

War in 1899, over 100,000 gold claims were pegged (Summers, 1969).

The search for gems in Zimbabwe appears to be more recent and can be dated only from H. R. Moir's 1903 diamond find in the Somabula Forest (Mennell, 1906). Some prospecting and minor mining for diamonds took place between 1905 and 1908, but these efforts faded as the results did not meet the expenses. Subsequently, several workers tried to make their fortunes in small mining operations, but interest waned and activity all but ceased (Wagner, 1914).

In 1923, Zimbabwe became a British colony under the name Southern Rhodesia. A sudden change in the fortunes of the nation's gemstone industry arrived in the mid-1950s, as a result of increased demand for beryllium and lithium minerals. On October 7, 1956, the first emerald was found in the Belingwe district (now Mberengwa) by Laurence Contat and Cornelius Oosthuizen, two former civil servants who had relinquished their posts to take up full-time prospecting. This first stone was recovered in the Mweza Hills about 5 km west-southwest of the confluence of the Nuanetsi (now Mwenezi) and Mutsime Rivers. They called their first claim "Vulcan" (Martin, 1962).

On May 17, 1957, after a rainstorm, a Vulcan worker named Chivaro found a deep green crystal protruding from a muddy footpath, some 2.5 km northeast of what eventually became the Vulcan mine. He reported the find to his employers, who rewarded him handsomely. Follow-up at the spot, which would later become known as the Zeus mine, revealed the presence of more such crystals in the "black cotton" soil, the popular name for a dark calcareous soil, relatively high in montmorillonitic

Figure 2. The Sandawana emerald mines are located in southern Zimbabwe, 65 km by gravel road from Mberengwa, the nearest village.

clay, that formed from rocks with a low silica content. Recognizing the superior quality of these crystals, Contat and Oosthuizen cautiously checked out the potential value through various renowned gemologists, including Dr. Edward Gübelin, before revealing the discovery to government officials and seeking security protection. Late in 1957, Contat and Oosthuizen sent the first parcel of rough emeralds to the United States. By February 1958, suitable regulations to control the mining and marketing had been promulgated; shortly afterwards, production formally began. The earliest processing consisted of simply washing wheelbarrow loads of soil (Böhmke, 1982).

When these rich-green stones came on the world market, Zimbabwe quickly established itself as a source of fine emeralds. By late 1959, after washing a mere 70 m^3 of soil, Contat and Oosthuizen made their fortune by selling out to a subsidiary of the large mining company RTZ (Rio Tinto Zinc) that was owned jointly by RTZ (53%) and the Zimbabwean public (47%).

The name *Sandawana*, which refers to the min-

ing area and the emeralds mined there, was derived from that of a mythical "red-haired animal." According to local African folklore, possession of one of this animal's red hairs would result in lifelong good fortune (Böhmke, 1982). Similarly, it was believed that possession of a Sandawana emerald should bring the owner good luck!

The discovery of large quantities of fine emeralds at Sandawana sparked further interest in emerald prospecting. Within a few years, determined prospectors were rewarded with new finds in the Filabusi and Fort Victoria (now Masvingo) districts (see figure 2).

Some of these occurrences have been described by Anderson (1976, 1978), Martin (1962), and Metson and Taylor (1977). A more recent (1984) discovery was at Machingwe (Kanis et al., 1991), about 12 km northeast of the Zeus mine (figure 3), also in the Mweza Hills. Because RTZ insisted on strict secrecy, Dr. Gübelin's initial article, published in 1958, was not followed by another paper until 24 years later: In 1982, resident geologist F. C. Böhmke published his lecture on "Emeralds at Sandawana."

In May 1993, RTZ sold the Sandawana company to a newly formed company, Sandawana Mines (Pvt.) Ltd., of which the Zimbabwean government is a minor shareholder. Co-author E. J. Petsch (Idar-Oberstein) was appointed chairman of the new board. He worked with a new technical team—consisting of Mr. P. J. Kitchen (Camborne School of Mines), co-author J. Kanis (consulting geologist), Dr. A. N. Ncube (mineralogist and director of the company), and Mr. A. H. F. Braunswick (who continued as general manager of the mine)—to revitalize all activities at Sandawana. Additional investment provided new mining equipment, transportation, housing, and important improvements to underground mining and ore processing.

In 1996, Mr. D. B. Siroya of Dubai became the chairman. The company, which is headquartered in Harare, currently employs about 400 workers at the mine, of which 60 are security officers. As is the case with most gem mines, security is a major concern.

LOCATION AND ACCESS
Zimbabwe is a landlocked country in south-central Africa, covering an area of 390,624 km^2. It is surrounded by Zambia, Botswana, South Africa, and Mozambique (again, see figure 2). Zimbabwe lies astride the high plateaus between the Zambezi and

Limpopo rivers. In the south and southeast of the country are the extensive Limpopo and Save basins, which form part of the Low Veld land below 3,000 feet (915 m).

The Sandawana mines are located in the Low Veld (coordinates roughly 20°55′S and 29°56′E, confirmed by global positioning satellite [GPS] readings), approximately 830 m above sea level. The temperature ranges from a high of 41°C in the summer (November) and a low of 6°C in the winter (May). The area has an average summer rainfall of 700 mm, with occasional light drizzle in winter. The natural vegetation is open savanna (Böhmke 1982).

Zimbabwe has a well-maintained road system, and the nearest villages to the Sandawana mines—Mberengwa and West Nicholson—can be reached from Masvingo, Gweru, or Bulawayo on good tarred roads (again, see figure 2). The exception is the last 65 km traveling via Mberengwa (or 68 km coming via West Nicholson), which are on gravel roads that, during the winter rainy season, are best traversed using a four-wheel-drive vehicle. When the weather conditions are good, however, the easiest way to reach the Sandawana area is by a small plane, as there is a good landing strip at the Zeus mine. The mine can be visited by invitation only.

The Sandawana mines have their own medical clinic, which is essential in this remote area, and a primary school. There is also a sports-clubhouse, a soccer club, a community hall, a general store, as well as regular bus service to the capital, Harare.

The mining lease and claim holdings cover a 21-km-long strip along the southern slope of the Mweza Hills. They are bordered on the north by the densely populated Communal Lands. On their southern flank, the Sandawana claims share a 16km-long electrified game fence with "The Bubiana Conservancy." This syndicate of seven different ranches, which covers an area of 350,000 acres, represents one of the largest private game reserves in the world and is supported by the World Wildlife Fund.

Figure 3. This simplified geologic map shows the location of both the currently producing emerald mines and the old emerald mines in the Mweza greenstone belt, near the major shear zone between the Zimbabwe craton and the Limpopo mobile belt. This map is mainly based on data from Robertson (1973) and Mkweli et al. (1995), and from satellite images.
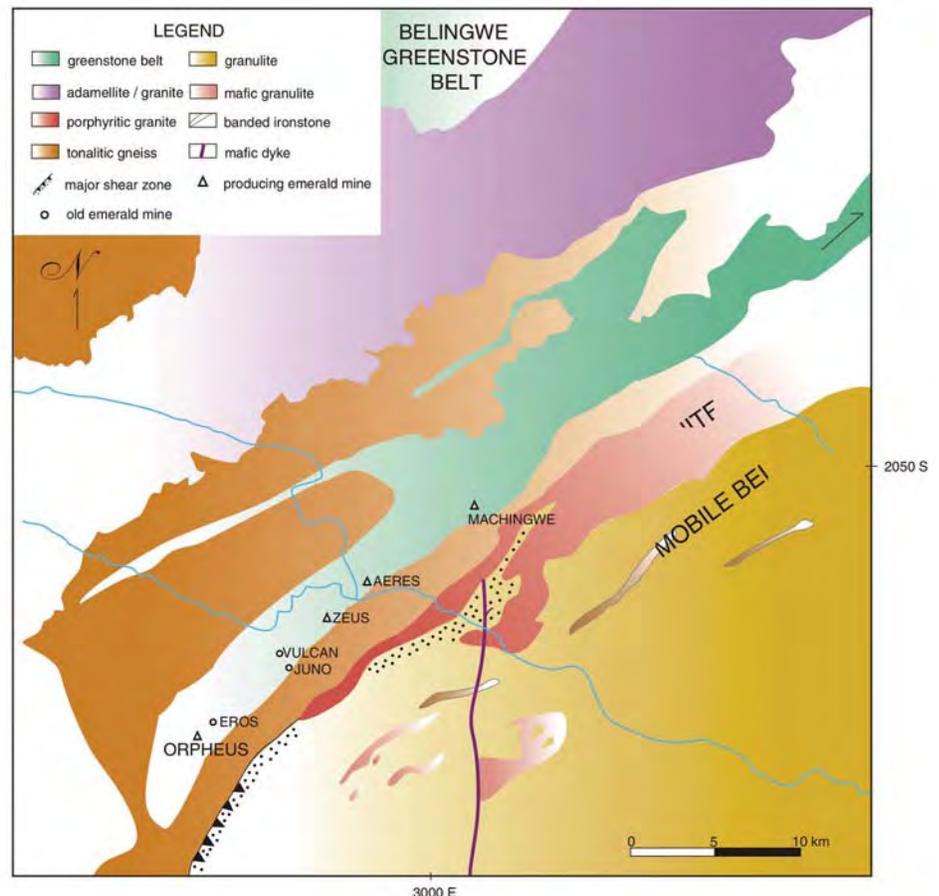
GEOLOGY AND OCCURRENCE

The Zimbabwe craton (a relatively stable part of the Earth's continental crust) covers a large part of Zimbabwe and consists of Archean greenstone belts and granite terrains. The greenstone belts are important producers of gold, but they also contain significant amounts of chromium and nickel. The Great Dike, 530 km long and up to 4 km wide, crosses the Zimbabwe craton from north to south and is a major source of chromium.

There are few early papers on the geology of the Sandawana region (Worst, 1956; Gübelin, 1958; Böhmke, 1966), but geologic research in this area has intensified recently, as evidenced by the detailed studies on nearby greenstone belts (e.g., Fedo et al., 1995; Fedo and Eriksson, 1996) and the adjacent Limpopo mobile belt (e.g., Rollinson and Blenkinsop, 1995; Mkweli et al., 1995).

These studies underline the important magmatic and tectonic processes in the area, which resulted in the emplacement of emeralds there, and include new data on the timing of these events. In addition, the petrologic and mineralogic aspects of the complex Sandawana occurrence will be published in the near future (J. C. Zwaan, in prep.). Such publications ultimately are possible because of the open attitude of Sandawana Mines (Pvt.) Ltd.

The Sandawana emerald deposits lie along the southern limb of the Mweza greenstone belt, which is located at the southern margin of the Archean Zimbabwe craton, close to the northern margin of the Limpopo mobile belt (again, see figure 3). The Mweza greenstone belt consists of a series of intensely deformed and moderately metamorphosed ultramafic-to-mafic volcanic rocks and metasediments. It also contains numerous relatively small pegmatite bodies that tend to be concentrated at the southern end of the belt. Emeralds occur near the pegmatites at the contact with (ultra)mafic lavas; they are concentrated in pockets at sites where the pegmatite is tightly folded and/or the rocks are sheared. These "ideal" locations are characterized by actinolite schist streaks in the pegmatite and pegmatitic stringers in the adjacent actinolite schist (figure 4).

An order of geologic events in the Sandawana region has been reconstructed from field evidence and geochronological data (Robertson, 1973; Rollinson and Blenkinsop, 1995; Mkweli et al., 1995; Fedo and Eriksson, 1996). About 2.6 billion years ago, the Northern marginal zone was uplifted over the Zimbabwe craton, accompanied by thrusting in a north-northwest direction. Associated with this at the southern border of the Mweza greenstone belt was a series of shear zones (planar zones of relatively intense deformation, resulting in crushing and brecciation or ductile deformation of the rock; such areas are often mineralized by ore-forming solutions). In response to the uplift and thrusting, crustal shortening occurred, which caused folding and metamorphism of the greenstone belt. The old greenstones consist of ultramafic lavas, which are

Figure 4. At Sandawana, emeralds are typically found in the zone (outlined in red here) at the contact of small pegmatite bodies and greenstone (left, in the Zeus mine, 25/28 stope, 200 foot [61 m] level). Schlieren (streaks) of actinolite and phlogopite in pegmatite are commonly seen in the "ideal" emerald-bearing pegmatite bodies (right, in the Zeus mine, 17/16 stope, 250 foot [76 m] level). Photos by J. C. Zwaan.

Figure 5. The open pit of the original Zeus mine was called the "Bank of England" because it was extremely rich in emeralds. Buildings in the foreground are the offices, workshop, and processing plant. The employees' village is visible in the background. Note also the granitic hills of the Northern marginal zone of the Limpopo belt at the horizon. Photo by E. J. Petsch.

"komatiitic" in composition (highly magnesium- and chromium-rich).

Widespread magmatic and hydrothermal activity occurred at the same time as the shearing, in the course of which beryllium-bearing granitic pegmatites intruded into the chromium-bearing ultramafic (komatiitic) rocks of the Mweza greenstone belt. Fluids present in the pegmatite/greenstone contact zone incorporated beryllium and chromium and migrated along local shear zones, in which the emerald crystals subsequently crystallized. The deformation in the area, the uplift of the Northern marginal zone, the intrusion of the pegmatites, and the metamorphism in the greenstone belt occurred so close in time that they cannot be resolved geochronologically. This would imply that the Sandawana emeralds formed during the main deformation event, around 2.6 billion years ago.

MINING

Since the discovery of the Sandawana deposits in 1956, an almost continuous exploration program has been carried out within the 21-km-long claim holding. Over the years, systematic trenching and surface drilling of profiles for structural studies has led to the discovery of many emerald-bearing sites, including: Eros, Juno, Aeres, and, more recently,

Orpheus. Nevertheless, since the earliest days, emerald exploitation has been concentrated mainly in the Zeus area (again, see figure 3).

The Zeus mine was an open-cast operation until the pit reached 15 m. It was so rich in emeralds that the location was nicknamed the "Bank of England" (figure 5). Subsequently, the Zeus mine was developed into a modern underground mine. Over a strike of 700 m, four vertical shafts have been sunk. The No. 3 shaft (figure 6) currently serves as the main production shaft, reaching levels as far down as 400 feet (122 m). Another almost vertical shaft serves the mine from 400 feet (122 m) to the 500 feet (152 m) level. Levels and sublevels are 25 feet (7.6 m) apart vertically and are connected by raises. Drifts (horizontal tunnels) are mined along the hanging and footwall contacts of the pegmatites, and mining of the emerald-bearing shoots is done by stoping methods. Ore is removed via small tunnels called ore passes. It is then transported in cocopans (ore carts) on rails to the haulage shaft.

More than 40 km of tunnels and shafts have been dug at the Zeus mine. All underground survey data are plotted on a composite mine plan, scale 1:1000. Since its inception, the survey department has maintained a three-dimensional model of the underground mine workings.

Figure 6. The main production shaft at the Zeus mine, the No. 3 shaft, serves as a haulage shaft down to 400 feet (122 m). Photo by E. J. Petsch.

After extensive trenching (figure 7, left), surface drilling (figure 7, right), sampling, and some open-pit mining, exploration shafts recently were sunk at the Aeres-3 and Orpheus sections. These prospects are 3 km northeast and 10 km southwest of the Zeus mine, respectively (again, see figure 3).

PROCESSING

Waste rock loosened by the blasting is dumped near the haulage shaft, and rock with any "green" in it taken from the (narrow) ore-zone is transported to the processing plant and batch processed. Exceptionally rich matrix with fine-quality emeralds visible is hand cobbed underground and treated separately from the normal run-of-mine material. Some of these pieces are selected for sale as collectors' specimens.

The processing plant is a standard washing/screening trommel plant with a capacity of approximately 300 tons of ore per month. About 42 people work there, eight hours a day, five days a week.

After the ore passes through a grizzly-grid (24 cm), it is broken by a jaw crusher. (Although some emeralds might be slightly damaged by the jaw crusher, there is no alternative for large tonnages.) The ore is then washed and sized, with the largest (over 20 mm) and smallest (under 3 mm) pieces separated out in a rotating trommel. Additional vibrating screens further separate the material into specific size ranges, so that larger and smaller pieces are not mixed (and the latter hidden by the former) during the next stage of sorting, on slow-moving conveyor belts. Under strict security, 30 hand-pickers scan this material for emeralds (figure 8). For emerald recovery from the 1.6–6 mm fraction, Sandawana has introduced innovative processing technology based on gravity separation. The DMS (dense media separation) module, which has a capacity of one ton of ore per hour, was originally designed for diamond processing. This technology enables the mine to recover those smaller emeralds that might be overlooked in the course of hand sorting (figure 9).
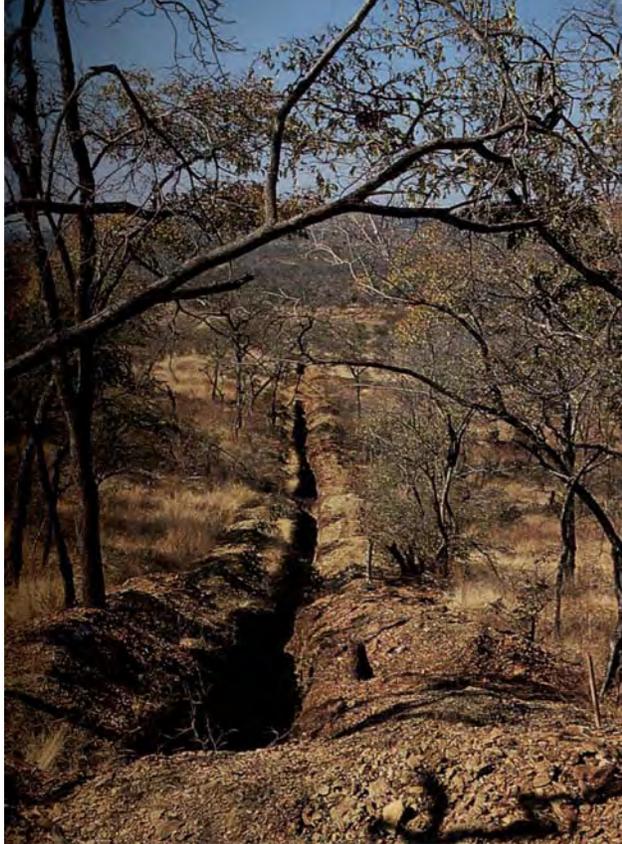
Next, "cobbers" use tungsten-tipped pliers and chipping hammers to liberate the emeralds from their matrix with a minimum of damage (figure 10). Some material needs additional tumbling for further cleaning. Last, all the rough emeralds are sorted according to size, color, and clarity to prepare parcels for the international market. The entire processing plant area is surrounded by a security fence, patrolled by security staff, and monitored by security officers using closed-circuit television.

THE SANDAWANA ROUGH

The majority of the rough emeralds are recovered as crystal fragments, most of which show a few crystal faces. Also seen are well-formed short-prismatic hexagonal crystals with pinacoidal terminations. In fact, most of the emeralds seen *in situ* to date have been either euhedral or subhedral, with prominent prismatic faces (figure 11). Many of the crystals contain fractures filled with fine-grained albite, which represent very weak zones. Consequently, these emeralds break easily when they are removed from the host rock or processed.

Most of the emeralds are medium to dark green. Although pale-green stones (perhaps more appropriately called green beryls) have occasionally been found, to date these have been seen only in the pegmatite, away from the contact with the schist.

Sandawana emerald crystals are typically small

Figure 7. Exploration activities at Sandawana include (left) cross-trenching at the Aeres-3 section to find new pegmatite bodies, and (top) surface drilling at Orpheus to locate new ore zones. Photos by J. C. Zwaan (left) and E. J. Petsch (top).

(most gem-quality material is between 2 and 8 mm, although opaque crystals as large as 12 mm are frequently seen), but some larger crystals were found recently. The largest crystal that one of the authors (JCZ) has seen was 1,021.5 ct, found at the Orpheus mine in 1995. It showed complex interpenetrant twinning and, in addition to the first-order prismatic faces, a small second-order bipyramidal face. Some of the larger crystals from Orpheus (figure 12) were found in "khaki"-colored altered schist near a pegmatite at the surface. These crystals represent the more common crystal habit for this size, showing prismatic faces and rounded-to-somewhat irregular terminations, with pinacoidal faces only partly developed. Most of these large crystals contain a substantial portion that is suitable for cutting, usually as cabochons. The average retention after cutting is 10%–20% of the original weight. The general manager of the mines recently reported that larger crystals, about 25 to 100 ct each, are now regularly extracted from the Zeus mine as well.

PRODUCTION AND DISTRIBUTION

Since 1993, when the mine changed management, monthly emerald production has improved considerably and become more consistent. As noted earlier, crystals in the 25–100 ct range are now produced fairly regularly (precise quantities are not available); a few exceptional crystal clusters, weighing around

500 ct, have also been found. Nevertheless, many polished stones weigh less than 0.25 ct, as previously described by Gübelin (1958), although a substantial number of polished stones weighing between 0.25 and 0.80 ct have entered the market. Additionally, stones weighing above 1 ct and even close to 2 ct are sometimes produced. Cut Sandawana emeralds of 1.50 ct or more are still rare (figure 13).

Although the quantity of emeralds produced varies somewhat from month to month, figures over the last three years show a production of at

Figure 8. Ore fractions on the slow-moving conveyor belts are carefully checked for emeralds by hand-pickers. Gem-quality pieces are deposited in safety boxes by each sorter. Photo by E. J. Petsch.

Figure 9. The high-efficiency DMS (dense media separation) module is used at Sandawana to separate emeralds in the 1.6–6 mm fraction of run-of-mine material from the other minerals that are present in the ore zone. This computer-controlled module can process about one ton of ore per hour. Photo by J. C. Zwaan.

least 60 kg of mixed grades of rough emeralds per month, of which 10% is usually transparent enough and of a sufficiently attractive color to be faceted or cut *en cabochon.*

As regulated by the government, part of the production is cut locally for export from Zimbabwe. However, the greater part of the rough material is sold to traditional clients and, in recent years, also

Figure 10. Tungsten-tipped pliers are used to free the emeralds from their matrix. Photo by E. J. Petsch.

at regular invitation-only auctions. Sales of all gem materials (rough and cut) in Zimbabwe are monitored by the Mineral Marketing Corporation of Zimbabwe (MMCZ). For those emeralds cut officially in Harare, the fractures are not filled with an oil or an artificial resin. When fractures in these stones are filled, this happens at a later stage "along the pipeline."

Although it is difficult to give a precise estimate of reserves, ongoing exploration in the Sandawana area indicates that current production can be maintained for many years to come.

GEMOLOGICAL CHARACTERISTICS

Materials and Methods. For this study, we examined a total of 68 emerald samples, of which 36 (ranging from 0.07 to 1.87 ct) were polished. Almost all of the rough samples were transparent to translucent, suitable for cutting. Some of the material was collected *in situ* during fieldwork. The rest was obtained from the mine run, but from material that was kept separate for each stope, so that we could identify from which mine or part of the mine it came. Most of the rough emeralds were found near the contact between pegmatite and schist, but we also studied one 2.5 cm pale-green gem-quality crystal that was recovered from the pegmatite 1.25 m from the contact.

A Rayner refractometer with an yttrium aluminum garnet (YAG) prism was used to measure the refractive indices and birefringence of all polished samples. We measured specific gravities on all samples—except the 11 from which thin sections were made (see below)—using the hydrostatic method. Inclusions were identified using a standard gemological (Super 60 Zoom Gemolite Mark VII) microscope, a polarizing (Leica DMRP Research) microscope, and a laser Raman microspectrometer (Dilor S.A. model Microdil-28). For the detailed study of fluid inclusions, we had polished thin sections made from 11 samples. Polarized absorption spectra of 10 representative medium- to dark-green samples were taken with a Pye Unicam PU 8730 UV/VIS spectrometer under room-temperature conditions.

Quantitative chemical analyses were carried out on some emeralds and some inclusions with an electron microprobe (JEOL model JXA-8800M). In total, 40 spot analyses were performed on four gem-quality medium- to dark-green rough emeralds and the one light-green emerald extracted from a peg-

Figure 11. Most of the emeralds seen in situ (here, in fine-grained, sugary albite) have been either euhedral or subhedral, with prominent prismatic faces. Photo © NNM, The Netherlands.

Figure 12. Note the crystal habits of these large emerald crystals found at the Orpheus mine, 103.58 ct (left) and 64.95 ct (right). Both have translucent areas from which cabochons or beads could be cut. Photo © NNM, The Netherlands.

matite, all from the Zeus mine, and one medium-green emerald from the Orpheus mine; 23 were performed on amphibole inclusions; and 20 analyses were done on other inclusions.

Both the Raman and microprobe analyses were performed at the Institute of Earth Sciences, Free University of Amsterdam.

Visual Appearance. Fashioned Sandawana emeralds are known for their attractive color. Most of the samples we examined were a vivid green with medium to dark tones (figure 14). It is striking that the darker tones are not restricted to the larger stones; for instance, one stone weighing only 0.10 ct had a medium dark tone. Sandawana emeralds typically show even color distribution and are slightly to heavily included. Eye-visible internal features such as minerals or (partially healed) fractures are quite common.

Physical Properties. The standard gemological properties of the Sandawana emeralds tested are given in table 1 and discussed below.

Refractive Indices. The measured values fell within a somewhat narrower range than was indicated by Gübelin (1958; n_ε =1.581–1.588 and n_ω =1.588–1.595), which only confirms that small variations exist. More than 70% of the stones tested showed n_ε = 1.585–1.586 and n_ω = 1.592–1.593, and 90% showed a birefringence of 0.007.

Specific Gravity. The measured values varied between 2.73 and 2.80. However, stones weighing 0.15 ct or more gave results between 2.74 and 2.77, and most stones (66%) showed values around

Figure 13. Although the row of calibrated emeralds (0.09–0.18 ct) is more typical of the emeralds routinely produced from the Sandawana mines, more larger stones, such as the approximately 0.80 ct pear shape, have been produced recently. Stones like the 3.67 ct Sandawana emerald in the ring are still extremely rare. The row of calibrated emeralds is courtesy of Edward Boehm, Joeb Enterprises, Atlanta, Georgia; the ring and pear-shaped emerald are courtesy of The Collector Fine Jewelry, Fallbrook and La Jolla, California. Photo © Harold & Erica Van Pelt.

Figure 14. These stones, which range from 0.28 to 1.87 ct, are part of the group of 36 cut Sandawana emeralds examined for this study. Like most of the polished samples studied, they are medium to dark in tone. Photo © NNM, The Netherlands.

Figure 15. The "tremolite" needles and laths that are a well-known hallmark of emeralds from Sandawana were conclusively identified as actinolite and cummingtonite. Darkfield illumination, magnified 50×; photomicrograph by J. C. Zwaan.

2.75–2.76. These numbers are consistent with earlier reports by Gübelin (1958) and Böhmke (1966). Note that the smaller stones with higher specific gravities contained many (predominantly amphibole) inclusions. Thus, the scattering of values between 2.73 and 2.80 can be attributed in part to

TABLE 1. Physical properties of 36 cut emeralds from Sandawana, Zimbabwe.

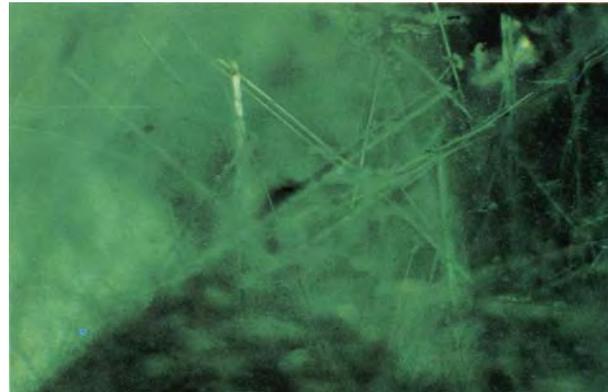| Color	Saturated colors ranging from medium to dark green. Color is evenly distributed; only weak color zoning is seen in some crystals and polished stones.
Clarity	Slightly to heavily included
Refractive indices	n_ε = 1.584–1.587, n_ω = 1.590–1.594
Birefringence	0.006–0.007
Optic character	Uniaxial negative
Specific gravity (samples 0.15 ct)	2.74–2.77
Pleochroism	Dichroism: yellowish green (ω) and bluish green (ε)
Fluorescence	Usually inert to long- and short-wave ultraviolet radiation. Sometimes faint green to long-wave UV.
Reaction to Chelsea filter	Light pink to pinkish red; the majority of the material shows pink
Internal features	• Mineral inclusions: actinolite and cummingtonite needles and long-prismatic laths, randomly oriented; albite and apatite, both showing various morphologies; phlogopite, calcite, dolomite, quartz, ilmenorutile • Partially healed fissures • Decrepitated primary fluid inclusions, typically rectangular in shape • Weak, if any, color zoning; complex zoning roughly parallel to the prismatic crystal faces seen in some clean crystals

inaccuracy due to the small size of the stones and the greater influence of the inclusions at these sizes.

Internal Features. *Mineral Inclusions.* The most abundant inclusions in the Sandawana emeralds examined are fibrous amphibole crystals (figure 15), which were previously described by various authors (e.g., Gübelin, 1958; Böhmke, 1982) as tremolite needles or fibers. In this study, we identified two amphiboles. Actinolite (a series with tremolite and ferro-actinolite) was identified by optical microscopy with transmitted light and by electron microprobe analyses. Tremolite and actinolite have the same basic chemical formula, $Ca^2(Mg,Fe^{2+})_5$-$Si_8O_{22}(OH)_2$, but they have different $Mg/(Mg + Fe^{2+})$ ratios. Tremolite contains very little iron and is extremely rich in magnesium ($Mg/(Mg + Fe^{2+})$ = 1.0–0.9). Actinolite, however, contains significantly more iron ($Mg/[Mg + Fe^{2+}]$ = 0.50–0.89; e.g., Leake, 1978; Fleischer and Mandarino, 1995). The analyses gave a $Mg/(Mg + Fe^{2+})$ ratio of 0.69–0.74, which is well within the actinolite field.

The other amphibole, identified with these same techniques, is cummingtonite, which occurs both as fibers and as somewhat thicker prismatic crystals. It is as abundant as actinolite and sometimes (where the fibers are large and thick) can be distinguished from it by its slightly higher relief in transmitted light and the presence of lamellar twinning in polarized light (figure 16).

Using the electron microprobe, we observed that the thicker actinolite crystals are zoned and often show a rim of cummingtonite; in contrast, the cummingtonite crystals are not zoned. In many thinner amphibole needles, actinolite is intergrown
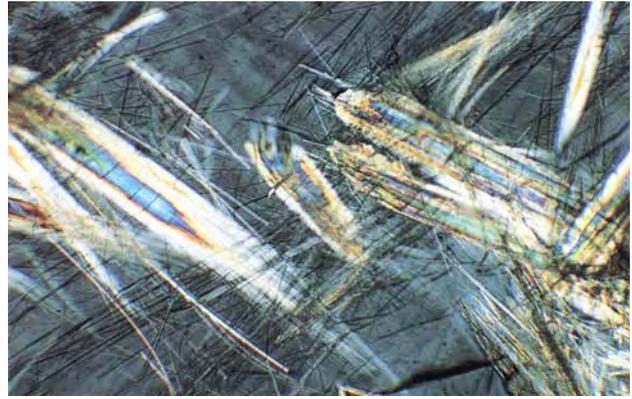
Figure 16. Long-prismatic crystals of the amphiboles actinolite and cummingtonite were identified in the Sandawana emeralds studied. In transmitted light (left), the cummingtonite laths (here, on the right of the photomicrograph) show a slightly higher relief. Between crossed polarizing filters (right), these same cummingtonite laths show lamellar twinning. Photomicrographs by J. C. Zwaan; magnified 35×.

with cummingtonite. Therefore, it will not come as a surprise that it is virtually impossible to distinguish between actinolite and cummingtonite with a normal gemological microscope, using either transmitted or darkfield illumination.

Another fairly common mineral inclusion is albite. It most frequently occurs as large tabular fragments (figure 17) or as small, slightly rounded, colorless crystals (figure 18). It also occurs in the form of a whitish, rectangular crystal surrounded by minute grains of (probably) albite, which give it the appearance of a snowball (figure 19).

Apatite is a common inclusion, too, but the apatite crystals are often very small and show various morphologies. Apatite may occur in clusters of small colorless-to-light green crystals, or as isolated,

idiomorphic crystals, sometimes brownish green but also colorless (figure 20). In addition, apatite frequently occurs as rounded crystals with an irregular surface (figure 21). This illustrates that, in some gem materials, the same mineral can have a variety of appearances, which makes these inclusions difficult to identify by using only the microscope. In many cases, Raman spectroscopy helped reveal the true nature of an inclusion (see, e.g., Pinet et al., 1992; Hänni et al., 1997); in some, it easily distinguished between albite and apatite, which may look very similar.

Phlogopite is abundant in the ore zone where the emeralds are found, but it was only occasionally present in the samples we studied. The distinctive orangy brown plate-like crystals are easy to identify

Figure 17. Large colorless to milky white tabular albite crystals, such as the one shown here near the surface of the stone, frequently occur in Sandawana emeralds. Oblique illumination, magnified 60×; photomicrograph by J. C. Zwaan.
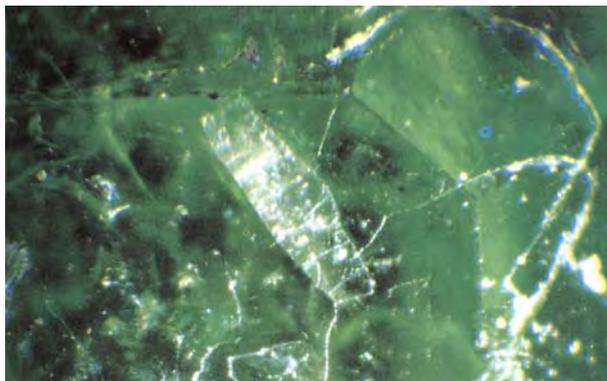
Figure 18. Many Sandawana emeralds of various qualities were also seen to contain small, rounded, colorless albite crystals. Transmitted light, magnified 125×; photomicrograph by J. C. Zwaan.
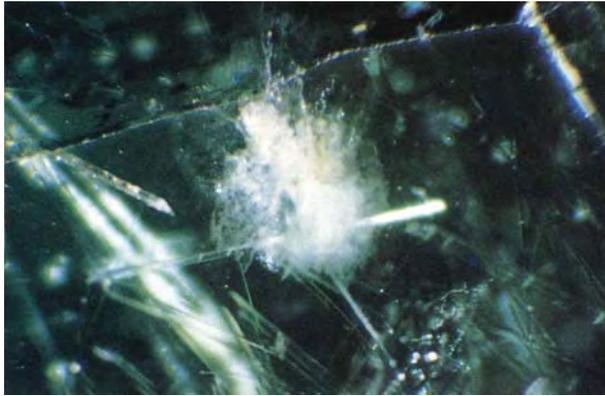
Figure 19. This albite crystal, which is surrounded by minute inclusions (probably also albite), looks like a snowball. Oblique illumination, magnified 60×; photomicrograph by J. C. Zwaan.

Figure 20. A cluster of small apatite crystals lies near a larger brownish green apatite in this Sandawana emerald. Transmitted light, magnified 100×; photomicrograph by J. C. Zwaan.

visually (figure 22; identification confirmed by microprobe). Inclusions also identified visually (and confirmed by microprobe) were calcite and a dolomite-group carbonate, emerald, quartz (very small, elongated, and rounded crystals), and zircon (minute crystals). Large black crystals of chromium-bearing ilmenorutile were found in one cut emerald, but they cannot be considered common inclusions. Gersdorffite, another opaque mineral, also was identified by microprobe analysis, but it is only present as extremely small grains. In the reaction rim of a medium-green emerald that was found in the pegmatite near a streak of amphibole schist (only 10

cm away from the contact with the greenschist), the lithium amphibole holmquistite was tentatively identified (from electron microprobe analysis and calculation of the chemical formula) but no cummingtonite or actinolite. This was confirmed by optical microscopy: The amphiboles analyzed showed straight extinction under crossed polarizing filters, which is characteristic for holmquistite. We did not encounter any of the resorbed garnet inclusions that had been previously described (Gübelin, 1958; Gübelin and Koivula, 1992); similar-appearing inclusions (figure 23) were investigated with Raman spectroscopy but could not be identified as garnet

Figure 21. In a classic "Sandawana scene" of long actinolite and cummingtonite crystals, lie three small, rounded apatite inclusions with slightly corroded surfaces—very different in appearance from those apatites shown in figure 20. Transmitted light, magnified 160×; photomicrograph by J.C. Zwaan.
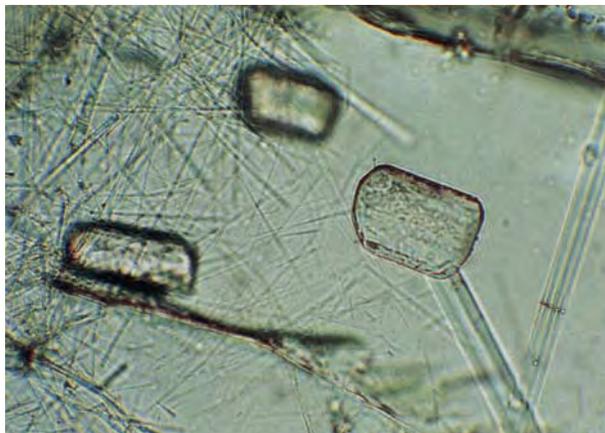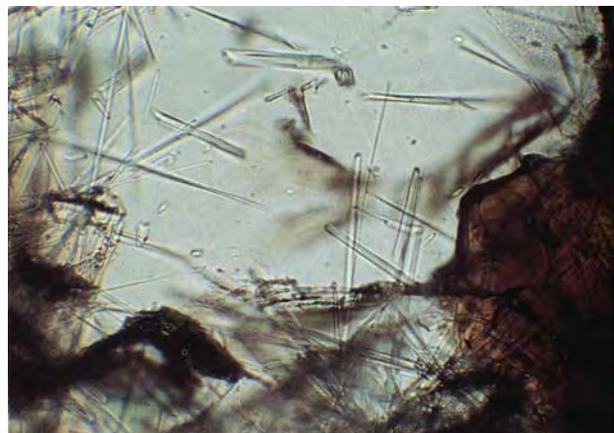
Figure 22. Seen here at the edge of a piece of gem-quality rough, this orangy brown plate-like crystal is phlogopite, which is somewhat rare in Sandawana emeralds. The black inclusion at the lower left was tentatively identified as a metamict zircon. Transmitted light, magnified 100×; photomicrograph by J. C. Zwaan.
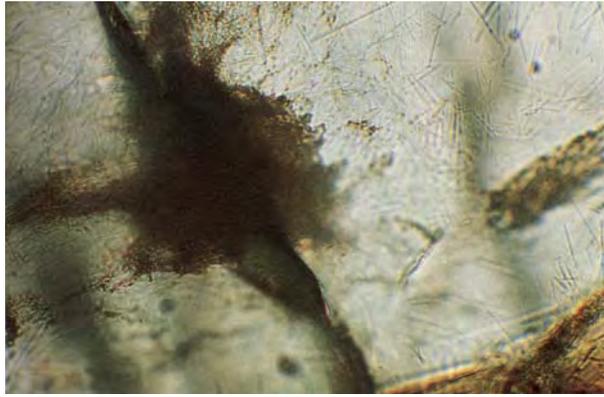
Figure 23. Although similar in appearance to previously described garnet inclusions with brownish haloes, the inclusion shown here is probably a mixture of limonite (on the basis of visual appearance) and amphiboles (as identified by Raman spectroscopy). Garnets were not identified in any of the Sandawana emeralds studied for this report. Transmitted light, magnified 160×; photomicrograph by J. C. Zwaan.

(which should be easily identified by that method; see Pinet et al., 1992).

Fluid Inclusions. Much more difficult to investigate than the solid inclusions, the fluid inclusions seen in the samples we investigated are very different from the well-known brine inclusions present in, for example, Colombian emeralds. In our search for fluid inclusions, we did find partially healed fractures with minute inclusions to be quite common (figure 24). However, most of these inclusions were so small (less than 6 μm in diameter) that they could not be analyzed by Raman spectroscopy. Some of the slightly larger inclusions in a partially healed fracture were found to be empty, and quite a few contained minerals that were identified as carbonates (figure 25).

Slightly larger isolated inclusions (approximately 35 μm long) were seen to occur as small, dark, comma-like features oriented parallel to the c-axis (figure 26). These inclusions, too, were empty and carbonate has been identified near them. Carbonate is often found near decrepitated inclusions that may have contained CO_2 (J. Touret, pers. comm., 1996). These isolated inclusions thus can be interpreted as the remnants of primary CO_2 inclusions.

In addition to these partially healed fissures and isolated decrepitated inclusions, straight trails with decrepitated inclusions were also a common feature in the emeralds from Sandawana (figure 27).

Tube-like two-phase, liquid and gas, inclusions were seen in one sample, but they were difficult to
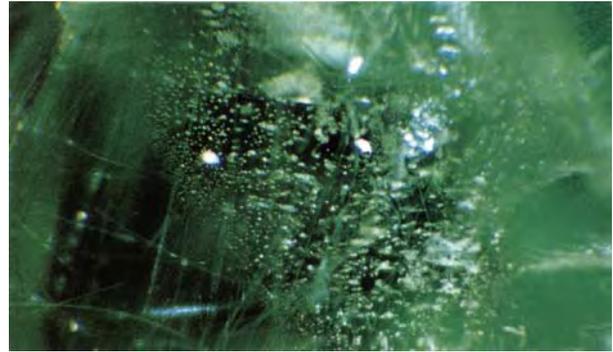

Figure 24. Partially healed fractures containing minute inclusions were often present in the Sandawana emeralds examined. Darkfield illumination, magnified 60×; photomicrograph by J. C. Zwaan.

identify with a standard gemological microscope because there were so few of them and they were extremely small.

Growth Zoning. In most of the samples, the color was evenly distributed. Occasionally, we saw a very weak and broad medium to medium-dark green color zoning , which was straight and parallel to the prismatic crystal faces. Some clean idiomorphic crystals with an even color distribution actually showed complex deformation twinning when viewed with crossed polarizers (figure 28). This pattern, together with anomalous birefringence, indicates considerable directional stress during crystal growth.

Figure 25. A closer look at the minute inclusions in a partially healed fracture reveals that the doubly refractive minerals are carbonates. Transmitted light, crossed polarizers, magnified 175×; photomicrograph by J. C. Zwaan.
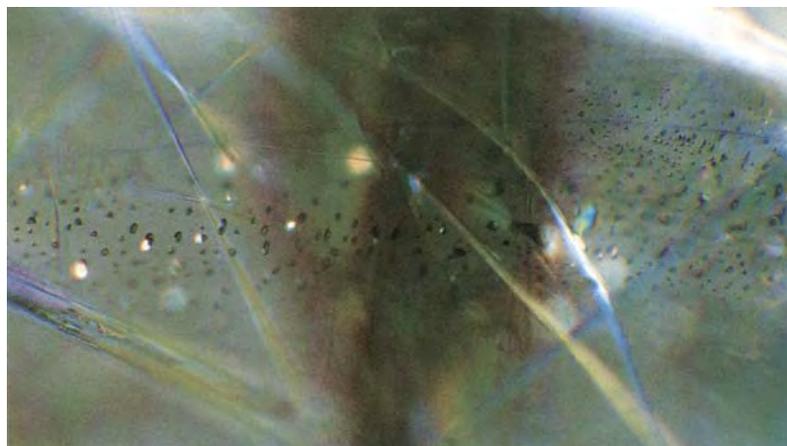
Figure 26. These comma-like, decrepitated, isolated inclusions with whitish carbonate represent the remnants of primary CO_2 inclusions. Transmitted light, magnified 200×; photomicrograph by J. C. Zwaan.
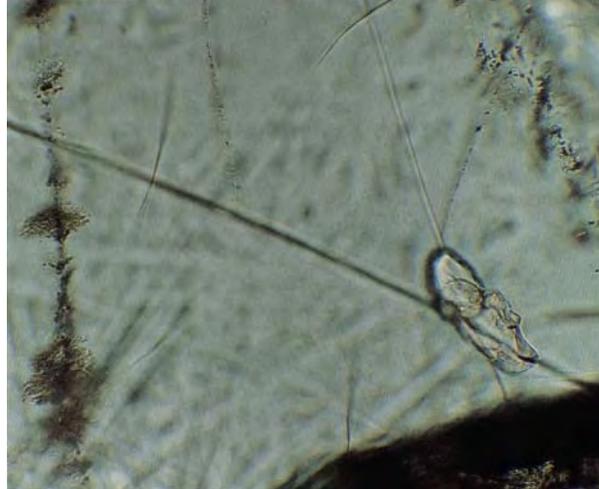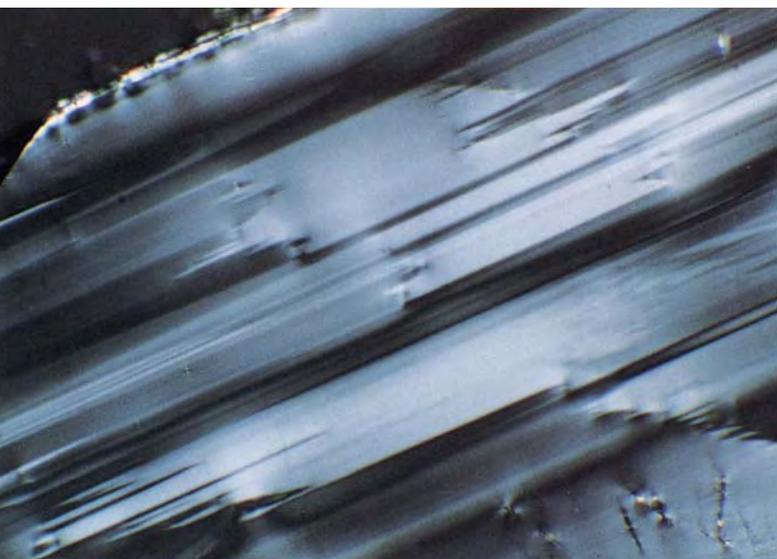

Figure 27. The trail with decrepitated inclusions on the left is a common feature in Sandawana emeralds; it indicates the earlier presence of fluids. Albite crystals are visible on the right. Transmitted light, magnified 125×; photomicrograph by J. C. Zwaan.

Absorption Spectrum. A typical absorption spectrum for Sandawana emeralds is shown in figure 29A. Broad absorption bands around 430 nm and 610 nm (for the ordinary ray), and the sharp peak at 683 nm, are reportedly caused by Cr^{3+}, whereas the broad band around 810 nm is attributed to Fe^{2+} (Wood and Nassau, 1968; Schmetzer et al., 1974). The spectrum is characteristic for a so-called "Cr^{3+}-emerald" (Schmetzer et al., 1974), in which the

Figure 28. Observation of this Sandawana emerald between crossed polarizers revealed complex zoning caused by tapered deformation twins. The anomalous birefringence also indicates crystal growth under considerable directional stress. Transmitted light, magnified 40×; photomicrograph by J. C. Zwaan.

color is solely due to Cr^{3+} ions. The low absorption minimum in the green and the steep slopes of the Cr^{3+} absorption bands produce the vivid green color. Possible chromophores such as V^{3+} and Fe^{3+} are not present in sufficient quantities to contribute to the color (see Chemical Analysis, below). Although present, small amounts of Fe^{2+} do not influence the color, because the peak lies outside the visible-light region, in the near-infrared.

The spectra of emeralds from Sandawana can be distinguished from the spectra of "Cr^{3+}-emeralds" from Colombia by the intensity of the Fe^{2+} absorption band in the former. Only the e-spectrum of Colombian emeralds may show a very weak, broad absorption band around 800 nm, but in most cases an iron spectrum can barely be detected (e.g., Bosshart, 1991; Henn and Bank, 1991). Emeralds from many other localities in which Fe^{3+} contributes to the color show an additional (often low intensity) peak around 370 nm (e.g., Schmetzer et al., 1974; Henn and Bank, 1991). Figure 29 provides examples of spectra caused by various chromophores.

CHEMICAL ANALYSIS

Table 2 gives the average quantitative results that we obtained with the electron microprobe. The Sandawana emeralds are characterized by an extremely high chromium content. Average concentrations varied between 0.6 and 1.3 wt.%, but spot analyses revealed chemical zoning on a small scale within the samples, with concentrations varying from 0.38 to 1.48 wt.%. In one sample from the Zeus mine, the range was even greater, 0.13 to 3.05 wt.%. In those stones where weak color zoning was observed, the slightly darker green zones revealed

more chromium, but often no straightforward correlation between color intensity and chromium content could be found.

From these analyses, it can be seen that the chromium content is partly consistent with the values given by Gübelin (1958), Martin (1962), and Hänni (1982), but it can also be substantially higher.

The Sandawana emeralds also show low Al_2O_3 content but very high MgO and Na_2O contents.

Figure 29. The absorption spectrum recorded in Sandawana emeralds (A) is comparable to that of Colombian emeralds (B), but the former has a strong absorption band in the near-infrared due to Fe^{2+}. The spectrum of one Brazilian emerald (C) shows an additional peak in the violet due to Fe^{3+}. The spectrum of a chrome-free emerald from Salininha, Brazil, which is colored by V^{3+}, is shown in (D). Spectra B and C are from Henn and Bank (1991); spectrum D is from Wood and Nassau (1968). Red line = ordinary ray, blue line = extraordinary ray.
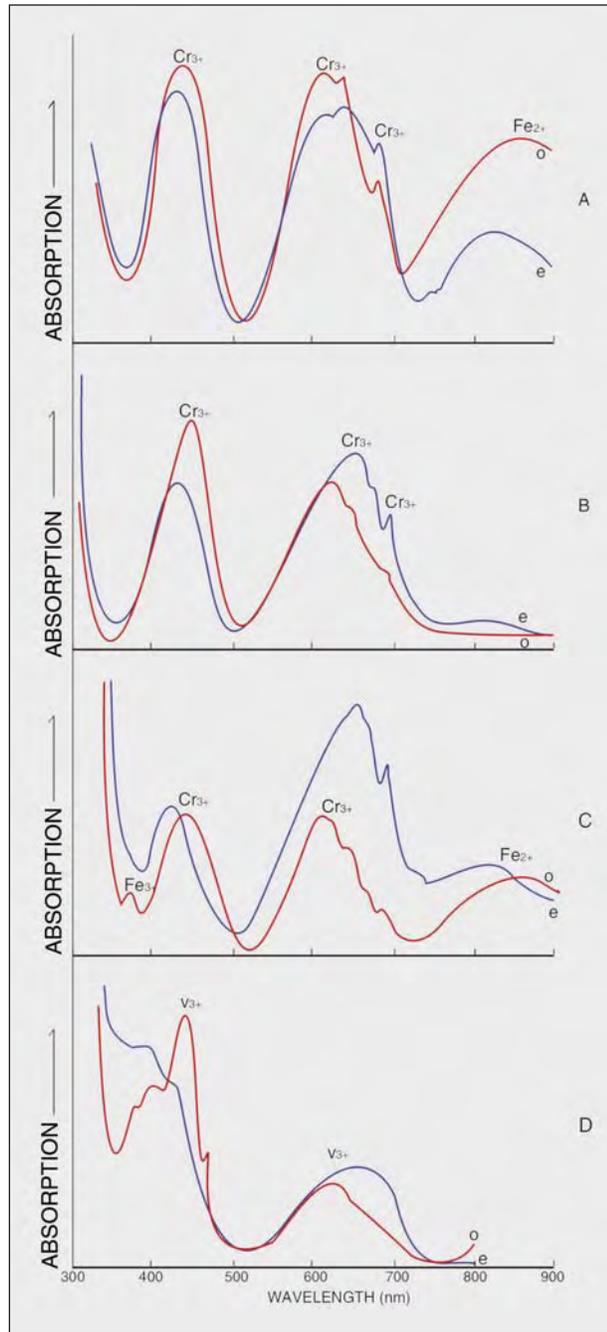
TABLE 2. Microprobe results of analyzed elements in four medium- to dark-green emeralds (range of average results) and one pale green beryl (the average for each element) from Sandawana.[a]

Oxide	Medium- to dark-green emeralds from the Zeus and Orpheus mines (wt.%)		Pale green beryl from the Zeus mine (wt.%)
SiO_2	62.6	–63.2	62.8
Al_2O_3	13.0	–13.7	14.3
Cr_2O_3	0.61	– 1.33	0.16
V_2O_3	0.04	– 0.07	0.04
FeO	0.45	– 0.82	0.71
MgO	2.52	– 2.75	2.38
Na_2O	2.07	– 2.41	2.30
K_2O	0.03	– 0.06	0.06
Cs_2O	0.06	– 0.10	0.09
Rb_2O[b]		≤ 0.04	bdl
CaO[b]		≤ 0.03	bdl
TiO_2[b]		≤ 0.05	bdl

[a] Comments: BeO, Li_2O, and H_2O cannot be analyzed with a microprobe. MnO, Sc_2O_3, F, and Cl were below the detection limits. Total iron is reported as FeO.
[b] Most of the analyses gave values equal to or below the detection limit (bdl).

Using Schwarz's empirical subdivision of low, medium, and high concentrations of elements in emerald (see, e.g., Schwarz, 1990), we would also conclude that the iron content is medium whereas the vanadium content is very low. Notable is the presence of cesium. As observed by Bakakin and Belov (1962), Cs is present typically in Li-rich beryl. Lithium cannot be analyzed by microprobe, but its presence is indicated by Gübelin (1958), Martin (1962), and Böhmke (1982), who reported Li_2O values ranging from 0.10 to 0.15%, respectively.

On the basis of structural refinements, Aurisicchio et al. (1988) proposed three types of beryls: "octahedral," in which substitutions in the Al octahedral site by Fe^{2+} and Mg^{2+} plus Fe^{3+}, Cr^{3+},

V^{3+}, Mn^{2+}, and Ti^{4+} represent the main isomorphous replacement; "tetrahedral," in which the main substitution is Li in the Be tetrahedral site; and "normal," in which the two substitutions occur together, but to a limited extent. In this model, a compositional gap exists between beryls with octahedral and tetrahedral substitutions. According to this model, the analyzed emeralds from Sandawana would fall in the category of "octahedral" beryls.

DISCUSSION

Geology and Occurrence. The magnesium and chromium in Sandawana emeralds come from the greenstones into which the small pegmatites intruded. This is confirmed by the analysis of the pale-green beryl that was found in the pegmatite 1.25 m from the contact with the greenstones (table 2). It contains less Mg and Cr than the emeralds, which were found closer to the contact. Most of the komatiites that comprise the greenstones are Archean in age, and resemble in composition the Archean mantle. In this respect, one could suggest that emeralds from Sandawana owe their magnificent color (caused by chromium accompanied by a relatively low concentration of iron) to the composition of the very old greenstones in which they crystallized. The exact conditions under which the emeralds formed are still under investigation. The fact that most of the fluid inclusions have decrepitated suggests a long crystallization history, but shearing does not seem to be the most important factor. If it were, inclusions would be transposed in a series of secondary healed fractures, which is not commonly the case. Decrepitation of single inclusions is more likely related to episodes of sudden regional decompression (block uplift) after initial formation. However, more evidence is needed before any definite statements can be made on this subject.

Like Sandawana, many other emerald occurrences are located near the margin of cratonic areas, close to mobile belts (a long, relatively narrow crustal region of tectonic activity) or suture zones. For example, the Afghanistan emeralds are located in the Panjsher suture zone, which marks the closure of the Paleotethys Ocean; the Pakistan emeralds occur in the Indus suture zone, which is the collision margin between the Indo-Pakistan subcontinent and Asia; and the occurrence of emeralds in Russia is related to the collision of the European and Asian plates to form the Ural Mountains

(Kazmi and Snee, 1989). However, the Sandawana emerald occurrence is much older than the Asian or Russian deposits. This ancient suture zone may represent a collision between microcontinents, but the extent to which modern concepts of plate tectonics may be applied to this region is still under debate.

Identification. The higher R.I. values of Sandawana emeralds make them very easy to distinguish from their synthetic counterparts. The latter typically have lower refractive indices, roughly between 1.56 and 1.58 (see, e.g., Webster, 1983; Schrader, 1983; Liddicoat, 1989), although some Russian hydrothermal synthetic emeralds have shown R.I.'s up to 1.584 (see, e.g., Koivula et al., 1996).

On the basis of refractive index, birefringence, and specific gravity values (see, e.g., Gübelin, 1989; Schwarz, 1990, 1991; Schwarz and Henn, 1992), emeralds from Sandawana resemble emeralds from the Ural Mountains of Russia, the Habachtal region of Austria, the Santa Terezinha de Goiás deposits of Brazil, certain mines in Pakistan, and the Mananjary region in Madagascar. From table 3, it can be seen that emeralds from most of these other localities show greater variation in properties than the Sandawana stones. Also, most emeralds from the Ural Mountains and from the Mananjary region have lower values than those recorded for the Sandawana stones.

A comparison of inclusions reveals that emeralds from the Swat and Makhad mines in Pakistan do not contain any amphibole fibers and needles but frequently show black chromite and many two-phase (liquid-gas) and three-phase (liquid-gas-solid) inclusions (Gübelin, 1989); thus, they look quite different from Sandawana emeralds. Emeralds from the Charbagh and Khaltaro mines in Pakistan (not mentioned in table 3 because most of the stones examined came from the Swat mines [the largest mines] and Makhad, and can be considered most representative of Pakistan emeralds) may contain brownish green to black actinolite rods, but certainly not thin fibers of amphibole; they also show slightly lower specific gravities and refractive indices (Gübelin, 1989).

Emeralds from the Ural Mountains may contain actinolite rods that closely resemble the long-prismatic actinolite and cummingtonite crystals observed in Sandawana emeralds. However, the thin and often curved fibers seen in Sandawana emeralds have not been reported in Uralian emeralds; in the latter, phlogopite is frequently present

TABLE 3. Physical properties of emeralds from various localities.[a]

Locality	Refractive indices		Birefringence	Specific gravity
	n_ϵ	n_ω		
Sandawana, Zimbabwe	1.584–1.587	1.590–1.594	0.006–0.007	2.74–2.77
Swat Mines, Pakistan	1.578–1.591	1.584–1.600	0.006–0.009	2.70–2.78
Makhad, Pakistan	1.579–1.587	1.586–1.595	0.007–0.008	2.74–2.76
Ural Mountains, Russia	1.575–1.584	1.581–1.591	0.007	2.72–2.75
Habachtal, Austria	1.574–1.590	1.582–1.597	0.005–0.007	2.70–2.77
Santa Terezinha de Goiás, Brazil	1.584–1.593	1.592–1.600	0.006–0.010	2.75–2.77
Mananjary Region, Madagascar	1.580–1.585	1.588–1.591	0.006–0.009	2.68–2.73

[a] *Pakistan data from Gübelin, 1989; Russia data from Schmetzer et al., 1991, and Mumme, 1982; Austria data from Gübelin, 1958, and Schwarz, 1991; Brazil data from Schwarz, 1990, and Lind et al., 1986; Madagascar data from Hänni and Klein, 1982, and Schwarz and Henn, 1992.*

as rounded platelets or as large, elongated tabular crystals (Schmetzer et al., 1991; Gübelin and Koivula, 1992). Although phlogopite has been found in emeralds from Sandawana, it is uncommon. Like the Uralian emeralds, the emeralds from Habachtal contain actinolite rods and phlogopite platelets, but—like the Sandawana emeralds—the Austrian stones also have apatite crystals (Gübelin and Koivula, 1992). However, these emeralds normally show an inhomogeneous—"patchy"—color distribution (Morteani and Grundmann, 1977) that has not been seen in Sandawana emeralds.

Although amphibole has been identified in emeralds from Santa Terezinha, Brazil, these emeralds are characterized by abundant opaque inclusions such as black spinel (as small octahedra and larger irregular grains), hematite, rutile, and pyrite. They also contain various pale-brown to colorless carbonates, which are present as irregular grains, aggregates, and fillings of fractures, but also as rhombohedra (Schwarz, 1990). By contrast, opaque inclusions of distinguishable size are rare in Sandawana emeralds, so separation from these Brazilian emeralds should be relatively easy.

Inclusions in emeralds from Madagascar may look very similar to those found in Sandawana emeralds, because long-prismatic amphibole rods are frequently found (Schwarz and Henn, 1992; Schwarz, 1994) as well as fibrous aggregates of talc (Schwarz, 1994), which may resemble the amphibole fibers present in Sandawana emeralds. Feldspar crystals and carbonates have also been identified, although feldspar is less common in Madagascar stones (Schwarz, 1994). Hänni and Klein (1982) identified apatite, too. However, in many Mananjary emeralds, transparent, somewhat rounded or "pseudo-hexagonal" mica (usually biotite/phlogopite) is the most common inclusion (Hänni and Klein, 1982; Schwarz

and Henn, 1992; Schwarz, 1994). Fluid inclusions were observed in most Mananjary emeralds; the larger inclusions are often somewhat rectangular-shaped negative crystals filled with gas and liquid (Hänni and Klein, 1982; Schwarz, 1994), but three-phase (solid-liquid-gas) inclusions may also occur (Schwarz and Henn, 1992). As mentioned above, neither mica nor fluid inclusions are frequently found in Sandawana emeralds.

The chemistry of emeralds from the mentioned localities provides additional evidence (table 4). The chromium content is distinctly lower for emeralds from the Ural Mountains, Habachtal, and the Mananjary region. For the Uralian emeralds, this was confirmed by Laskovenkov and Zhernakov (1995), who gave typical chromium contents of 0.15–0.25 wt.%, with the content in some stones as high as 0.38 wt.%. In emeralds from Santa Terezinha, the chromium content can be very low, but also very high. However, the sodium content is lower—and, in most cases, the iron content is higher—than in emeralds from Sandawana.

All of the Sandawana emeralds we tested showed high magnesium and sodium contents, with little variation from stone to stone as well as within a stone. The average compositions can thus be compared with compositions of emeralds from other localities with the help of, for instance, Na_2O/MgO and Na_2O/Al_2O_3 variation diagrams (figure 30). In both diagrams, the representative points for Sandawana emeralds show distinctly high contents of both sodium and magnesium. Only some emeralds from Habachtal and the Mananjary region, and emeralds from the Swat and Makhad mines, Pakistan, show comparable contents and ratios. As stated above, this similarity poses no problem for Habachtal and Mananjary emeralds, because these contain less chromium. Emeralds

TABLE 4. Chemistry of emeralds with overlapping physical properties (wt.%).[a]

| Oxide	Sandawana, Zimbabwe		Swat mines, Pakistan		Makhad, Pakistan		Ural Mountains, Russia		Habachtal, Austria		Santa Terezinha, Brazil		Mananjary Region, Madagascar	
SiO_2	62.6	–63.2	62.7	–62.8	62.2	–62.9	64.6	–66.9	64.6	–66.1	63.8	–66.5	63.3	–65.0
Al_2O_3	13.0	–13.7	13.1	–14.2	13.5	–14.2	14.2	–18.3	13.3	–14.5	12.2	–14.3	12.8	–14.6
Cr_2O_3	0.61–	1.33	0.39–	1.17	0.23–	1.26	0.01–	0.50	0.01–	0.44	0.06–	1.54	0.08 –	0.34
V_2O_3	0.04–	0.07	0.01–	0.06	0.04–	0.06		≤ 0.04		≤ 0.04		≤ 0.08		≤ 0.03
FeO	0.45–	0.82	0.52–	0.91	0.44–	0.67	0.10–	1.16	0.61–	1.87	0.77–	1.82	0.91–	1.46
MnO		n.d.[b]		n.d.		n.d.		≤ 0.03		≤ 0.05		≤ 0.02		—
MgO	2.52–	2.75	2.46–	2.50	2.37–	2.68	0.29–	2.23	2.33–	2.92	2.48–	3.09	1.71–	3.00
Na_2O	2.07–	2.41	2.06–	2.11	1.64–	2.05	0.61–	1.72	1.54–	2.24	1.46–	1.73	1.28–	2.16
K_2O	0.03–	0.06		—		≤ 0.02		≤ 0.07	0.01–	0.10		≤ 0.03	0.05–	0.21
Cs_2O	0.06–	0.10		—		—		—		—		—		—
Rb_2O		≤ 0.04		—		—		—		—		—		—
CaO		≤ 0.03		n.d.		n.d.		≤ 0.03	0.02–	0.04		—		—
TiO_2		≤ 0.05		n.d.	0.01–	0.02		≤ 0.05		≤ 0.03		—		n.d.
Sc_2O_3		n.d.		—	0.17–	0.19		—		—		—		—
Mo_2O_3		n.d.		—		—		—		≤ 0.04		—		—

[a] Pakistan data from Hammarstrom, 1989; Russia data from Schwarz, 1991, and Schmetzer, 1991; Austria data from Schwarz, 1991; Brazil data from Schwarz, 1990; Madagascar data from Schwarz and Henn, 1992, and Hänni and Klein, 1982.
[b] n.d. = not detected; — = no data.

from Pakistan may be readily distinguished by their different inclusion scenery. Note that emeralds from the Makhad mine were found to have appreciable scandium (table 4), which was not detected in the Sandawana emeralds.

Because of the relatively constant properties of Sandawana emeralds, these stones can be readily separated from emeralds from other localities on the basis of a combination of physical properties, inclusions, and chemistry.

Figure 30. These variation diagrams of Na₂O versus MgO (left) and Na₂O versus Al₂O₃ (right) in emeralds with comparable physical properties illustrate that the Sandawana emeralds can be distinguished by their high sodium content, with overlapping values for emeralds from Austria and Pakistan. Urals and Habachtal data from Schwarz (1991); Santa Terezinha data from Schwarz (1990); Pakistan data from Hammarstrom (1989); Madagascar data from Hänni and Klein (1982) and Schwarz and Henn (1992).
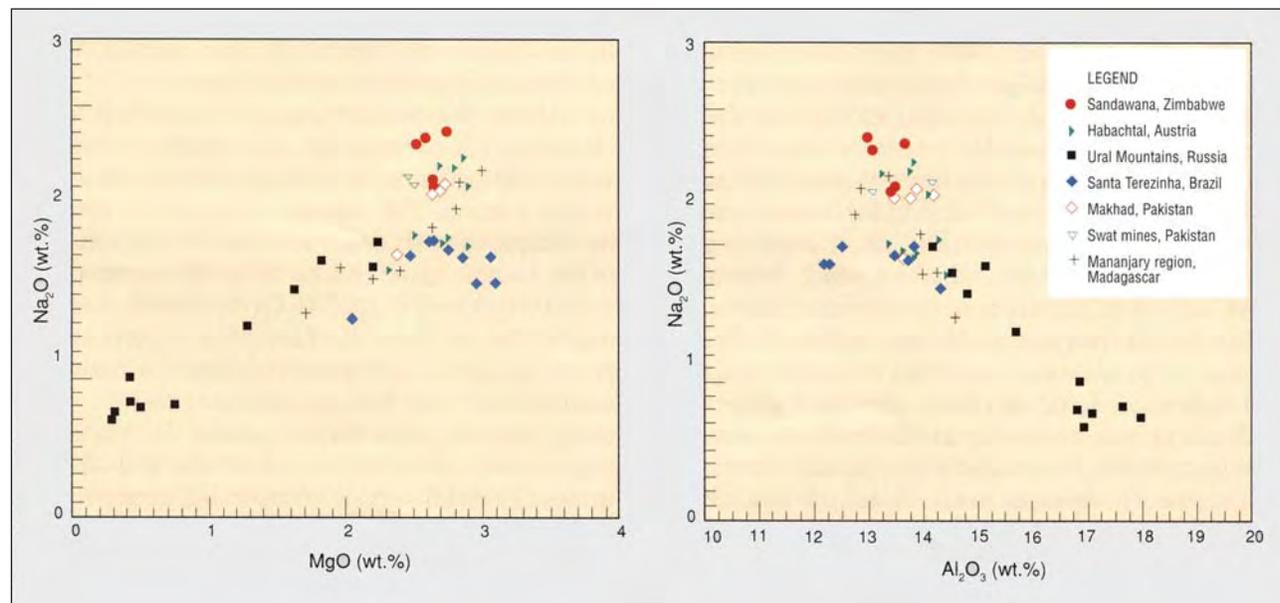
CONCLUSION

First discovered in 1956, Sandawana emeralds have become well known for their splendid vivid green color and the typically small size (0.05–0.25 ct) of the polished stones (figure 31). Since Sandawana Mines Pvt. (Ltd.) assumed management of the mines in 1993, more stones up to 1.50 ct have been produced. Stones above 1.50 ct are still rare.

The emeralds probably formed during a major deformation event around 2.6 billion years ago, when small beryllium- and lithium-bearing pegmatites intruded into chromium- and magnesium-rich greenstones, which incorporated the elements necessary for emerald to crystallize.

Sandawana emeralds show relatively constant physical properties, with high refractive indices and specific gravities compared to emeralds from other localities. Also unlike emeralds from many other localities, they are not characterized by fluid inclusions but rather by laths and fibers of amphibole, both actinolite and cummingtonite (previously reported to have been tremolite). Other common inclusions are albite and apatite. The relative absence of fluid inclusions is due to decrepitation of these inclusions during geologic history. Nevertheless, remnants of fluid-inclusion trails are common features.

The chemistry is characterized by very high contents of chromium, sodium, and magnesium. Chromium contents in some samples were substantially higher than in specimens reported from other deposits.

Although most emeralds from other localities with physical properties that overlap those for Sandawana emeralds also show solid inclusions, including actinolite rods (Russia, Brazil, Austria, Madagascar), it is relatively easy to distinguish emeralds from Sandawana by their internal characteristics. Amphibole fibers, in particular, are seldom seen in stones from other localities, whereas they are abundant in Sandawana stones. Phlogopite and some opaque inclusions, though identified in Sandawana emeralds, are much less common than in emeralds from the other localities. The chem-

Figure 31. Sandawana emeralds are popular in rings because of their saturated color in small sizes. The four emeralds in this anniversary ring weigh a total of 0.32 ct. Courtesy of Suwa & Son, Tokyo, Japan.

istry of emeralds from Pakistan is closest to that recorded for Sandawana stones, but emeralds from the two localities can easily be distinguished by their completely different internal characteristics.

REFERENCES

Anderson S.M. (1976) A note on the occurrence of emerald at Mayfield Farm, Fort Victoria, Rhodesia. *Journal of Gemmology*, Vol. 15, No. 2, pp. 80–82.

Anderson S.M. (1978) Notes on the occurrence and mineralogy of emeralds in Rhodesia. *Journal of Gemmology*, Vol. 16, No. 3, pp. 177–185.

Aurisicchio C., Fioravanti G., Grubessi O., Zanazzi P.F. (1988) Reappraisal of the crystal chemistry of beryl. *American Mineralogist*, Vol. 73, pp. 826–837.

Bakakin V.V., Belov N.V. (1962) Crystal chemistry of beryl. *Geokhimiya*, Vol. 5, pp. 420–433.

Böhmke F.C. (1966) The geology of the Sandawana Mines.

Internal report, Sandawana Mines, Harare, Zimbabwe.

Böhmke F.C. (1982) Emeralds at Sandawana. In *Gemstones, Report of the Sixth Annual Commodity Meeting*, Institution of Mining and Metallurgy (IMM), London, United Kingdom, pp. A110–A122.

Bosshart G. (1991) Emeralds from Colombia (Part 2). *Journal of Gemmology*, Vol. 22, No. 7, pp. 409–425.

Fedo C.M., Eriksson A., Blenkinsop T.G. (1995) Geologic history of the Archean Buhwa greenstone belt and surrounding granite-gneiss terrane, Zimbabwe, with implications for the evolution of the Limpopo belt. *Canadian Journal of Earth Sciences*, Vol. 32, pp. 1977–1990.

Fedo C.M., Eriksson K.A. (1996) Stratigraphic framework of the -3.0 Ga Buhwa Greenstone Belt: A unique stable-shelf succession in the Zimbabwe Archean craton. *Precambrian Research*, Vol. 77, pp. 161–178.

Fleischer J.A., Mandarino J.A. (1995) *Glossary of Mineral Species 1995*. The Mineralogical Record Inc., Tucson, Arizona.

Gübelin E.J. (1958) Emeralds from Sandawana. *Journal of Gemmology*, Vol. 6, No. 8, pp. 340–354.

Gübelin E.J. (1989) Gemological characteristics of Pakistani emeralds. In H. Kazmi and L. W. Snee, Eds., *Emeralds of Pakistan: Geology, Gemology and Genesis*, Van Nostrand Reinhold, New York, pp. 75–92.

Gübelin E.J., Koivula J.I. (1992) *Photoatlas of Inclusions in Gemstones*, 2nd rev. ed. ABC Edition, Zurich, Switzerland.

Hammerstrom J.M. (1989) Mineral chemistry of emeralds and some associated minerals from Pakistan and Afghanistan: An electron microprobe study. In H. Kazmi and L. W. Snee, Eds., *Emeralds of Pakistan: Geology, Gemology and Genesis*, Van Nostrand Reinhold, New York, pp. 125–150.

Hänni H.A. (1982) A contribution to the separability of natural and synthetic emeralds. *Journal of Gemmology*, Vol. 18, No. 2, pp. 138–144.

Hänni H.A., Kiefert L., Chalain J.P. (1997) A Raman microscope in the gemmological laboratory: First experiences of application. *Journal of Gemmology*, Vol. 25, No. 6, pp. 394–406.

Hänni H.A., Klein H.H. (1982) Ein Smaragdvorkommen in Madagaskar. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 31, No.1/2, pp. 71–77.

Henn U., Bank H. (1991) Außergewöhnliche Smaragde aus Nigeria. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 40, No. 4, pp. 181–187.

Kanis J., Arps C.E.S., Zwaan P.C. (1991) 'Machingwe': A new emerald deposit in Zimbabwe. *Journal of Gemmology*, Vol. 22, No. 5, pp. 264–272.

Kazmi A.H., Snee L.W. (1989) Geology of the world emerald deposits: A brief review. In H. Kazmi and L. W. Snee, Eds., *Emeralds of Pakistan: Geology, Gemology and Genesis*, Van Nostrand Reinhold, New York, pp. 165–228.

Koivula J.I., Kammerling R.C., DeGhionno D., Reinitz I., Fritsch E., Johnson M.L. (1996) Gemological investigation of a new type of Russian hydrothermal synthetic emerald. *Gems & Gemology*, Vol. 32, No. 1, pp. 32–39.

Laskovenkov A.F., Zhernakov V.I. (1995) An update on the Ural emerald mines. *Gems & Gemology*, Vol. 31, No. 2, pp. 106–113.

Leake B.E. (1978) Nomenclature of amphiboles. *American Mineralogist*, Vol. 63, pp. 1023–1052.

Liddicoat R.T. (1989) *Handbook of Gem Identification*, 12th ed., 2nd rev. printing. Gemological Institute of America, Santa Monica, CA.

Lind Th., Henn U., Bank H. (1986) Smaragde von Sta. Terezinha de Goias, Brasilien, mit relativ hoher Lichtbrechung. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 35, No. 4, pp. 186–187.

Martin H.J. (1962) Some observations on Southern Rhodesian emeralds and chrysoberyl. *Chamber of Mines Journal*, Vol. 4, No. 10, pp. 34–38.

Mennell F.P. (1906) Somabula diamond field of Rhodesia. *Geological Magazine*, Vol. 3, No. 508, pp. 459–462.

Metson N.A., Taylor A.M. (1977) Observations on some Rhodesian emerald occurrences. *Journal of Gemmology*, Vol. 15, No. 8, pp. 422–434.

Mkweli S., Kamber B., Berger M. (1995) Westward continuation of the craton-Limpopo belt tectonic break in Zimbabwe and new age constraints on the timing of the thrusting. *Journal of the Geological Society*, London, Vol. 152, pp. 77–83.

Morteani G., Grundmann G. (1977) The emerald porphyroblasts in the penninic rocks of the central Tauern Window. *Neues Jahrbuch für Mineralogie Mitteilungen*, Vol. 11, pp. 509–516.

Mumme I. (1982) *The Emerald*. Mumme Publications, Port Hacking, N.S.W., Australia.

Pinet M., Smith D., Lasnier B. (1992). Utilité de la microsonde Raman pour l'identification non destructive des gemmes. In *La Microsonde Raman en Gemmologie—Revue de Gemmologie a.f.g.*, No. outside of series, pp. 11–61.

Robertson I.D.M. (1973) Potash granites of the southern edge of the Rhodesian craton and the northern granulite zone of the Limpopo mobile belt. In Lister L.A., *Symposium on Granites, Gneisses and Related Rocks*, Geological Society of South Africa Special Publication 3, Salisbury, pp. 265–276.

Rollinson H., Blenkinsop T. (1995) The magmatic, metamorphic and tectonic evolution of the Northern Marginal Zone of the Limpopo belt in Zimbabwe. *Journal of the Geological Society*, London, Vol. 152, pp. 65–75.

Schmetzer K., Berdesinski W., Bank H. (1974) Über die Mineralart Beryll, ihre Farben und Absorptionsspektren. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 23, No. 1, pp. 5–39.

Schmetzer K., Bernhardt H., Biehler R. (1991) Emeralds from the Ural Mountains, USSR. *Gems & Gemology*, Vol. 27, No. 2, pp. 86–99.

Schrader H.W. (1983) Contributions to the study of the distinction of natural and synthetic emeralds. *Journal of Gemmology*, Vol. 18, No. 6, pp. 530–543.

Schwarz D. (1990) Die brasilianischen Smaragde und ihre Vorkommen: Santa Terezinha de Goiás/Go. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 39, No. 1, pp. 13–44.

Schwarz D. (1991) Die chemischen Eigenschaften der Smaragde III. Habachtal/Österreich und Uralgebirge/UdSSR. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 40, No. 2/3, pp. 103–143.

Schwarz D. (1994) Emeralds from the Mananjary Region, Madagascar: Internal features. *Gems & Gemology*, Vol. 30, No. 2, pp. 88–101.

Schwarz D., Henn U. (1992) Emeralds from Madagascar. *Journal of Gemmology*, Vol. 23, No. 3, pp. 140–149.

Summers R. (1969) *Ancient Mining in Rhodesia*. Trustees of the National Museum of Rhodesia, Mardon Printers, Salisbury.

Wagner P.A. (1914) *The Diamond Fields of Southern Africa*. Reprinted 1971, Struik (Pty) Ltd., Cape Town, South Africa.

Webster R. (1983) *Gems: Their Sources, Descriptions and Identification*, 4th ed. Rev. by B. W. Anderson, Butterworth-Heinemann, London.

Wood D.L., Nassau K. (1968). The characterization of beryl and emerald by visible and infrared absorption spectroscopy. *American Mineralogist*, Vol. 53, pp. 777–799.

Worst B.G. (1956) *The Geology of the Country between Belingwe and West Nicholson*. Southern Rhodesia Geological Survey, Bulletin No. 43.

MODERN DIAMOND CUTTING AND POLISHING

By Akiva Caspi

This article examines the sophisticated techniques and equipment currently used to fashion a polished gem from a rough diamond. The basic manufacturing techniques—sawing, bruting, blocking, and polishing—are described with regard to the decisions that must be made to obtain the greatest value from a specific piece of rough. Over the last 25 years, the diamond-cutting industry worldwide has been revolutionized by sophisticated instruments for marking, laser sawing machines, laser kerfing machines, automatic bruting machines and laser bruting systems, automatic centering systems, and automatic polishing machines.

*T*o many, a rough diamond looks like any transparent crystal or even a piece of broken glass. When cut as a faceted gemstone, however, it becomes a sparkling, shimmering object that is unique in appearance. Yet most of the people who are involved with gem diamonds—jewelers, gemologists, and the jewelry-buying public—are unfamiliar with many of the details involved in that transformation (figure 1).

The manufacturing of gem-quality diamonds has advanced more since 1980 than in the preceding 100 years. During the past two decades, a quiet revolution has taken place in much of the diamond-manufacturing industry. By adapting computer-imaging techniques, precision measurement systems, lasers, and other modern technological equipment, many manufacturers have improved their ability to cut gem diamonds in ways unimaginable only a few short years before. A significant result of this revolution is a diamond industry that is now better able to operate profitably. In addition, modern manufacturers can handle rough diamonds that would have been difficult, if not impossible, to cut by traditional manufacturing techniques.

This article has two purposes. The first is to describe this technological revolution by discussing the key steps in the manufacturing process and describing the recent technological improvements that have been made at each step. Although this article is based primarily on the author's experience in the Israeli diamond industry over the last 10 years, most of the advanced technology discussed can now be found in major manufacturing centers worldwide. The second purpose is to discuss the critical decisions that a manufacturer must make during the cutting process to obtain the maximum value from the finished stone.

BACKGROUND

The manufacture of a diamond into a faceted gemstone (figure 2) presents some very special challenges, including:

1. As the hardest known substance (10 on the Mohs

Figure 1. The cutting process is critical to the transformation of a diamond from a simple crystal to a brilliant faceted gem in a beautiful piece of jewelry. The faceted diamonds in these contemporary rings range from 1.04 ct for the smallest oval to 1.96 ct for the largest marquise. Courtesy of Hans D. Krieger, Idar-Oberstein, Germany; photo © Harold & Erica Van Pelt.

scale), diamond is also one of the most difficult gem materials to facet.

2. Although diamond is optically isotropic (i.e., it has only one refractive index), its hardness varies with crystallographic orientation, such that it can only be polished in certain crystallographic directions. These directions have traditionally been referred to as the "grain" (see, e.g., Vleeschdrager, 1986, p. 37).

3. The cutting process seeks to take advantage of the critical angle of total light reflection within the faceted diamond to achieve the maximum amount of light return through the crown facets. Diamond has a very high refractive index (2.42), and a mathematical basis for the shape and facet arrangement of the round brilliant cut was established early in this century by M. Tolkowsky (1919). Today, many other cutting styles are also used, including a variety of fancy cuts (see G. Tolkowsky, 1991).

4. The differences between the various color and clarity grades for faceted diamonds can be quite subtle, and very slight variations in cutting style and weight retention can result in significant differences in value.

All of these challenges must be addressed throughout the cutting process. Today, as it has for decades, gem diamond manufacturing involves the following basic steps:

1. Selecting (or sorting) the diamond rough. This includes examining each diamond for its potential color grade, clarity grade, and cutting style.

2. Marking the rough for manufacturing.

3. Cleaving and/or sawing the rough crystal.
4. Bruting the girdle.
5. Polishing the facets.

For large diamonds, some of these steps are repeated a number of times, for example: sawing→table polishing→ bruting→blocking (polishing four or eight facets)→[repolishing the table→ rebruting→ provisional polishing (8 facets)]→final table polishing→final bruting→ final polishing. This comes from a constant effort to improve the final appearance of the stone and the yield from the rough. The conventional means of manufacturing diamonds, and the various cutting styles used, have been described in several texts, including those of Bruton (1981), Watermeyer (1991, 1994), Ludel (1985), Vleeschdrager (1986), and Tillander (1995).

The goal in cutting a rough diamond is to maximize the market value of the faceted stone or stones produced from that piece of rough. This value is based on the well-known 4 Cs: Carat weight, Color, Clarity, and the less easily evaluated Cut. To illustrate, figure 3 shows where diamond manufacturing takes place on what can be thought of as an economic "conveyor belt." In this figure, the assumption is made that the final selling price of a cut diamond in a piece of jewelry is $100. Before the diamond is mined, it has no value ($0). When the original piece of rough is discovered in the mine, extracted from the host rock, and sorted, it has an estimated value of $26. The cut diamond is sold to the jewelry manufacturer for $30, and then to the retail jeweler for $50. Thus, in this example, one sees that the manufacturer's component is only $2, a very small percentage of the total retail value (but about 7% of the price of the loose diamond as it is sold to the trade). Typically, the actual profit would repre-

sent only about 0.5% of the value of the cut stone in a finished piece of jewelry—about 50 cents in this example.

As a second example of this same idea, assume that a 0.50 ct faceted diamond will sell at retail for $4,500 when set in a standard ring, that the rough diamond was sold to the manufacturer for about $1,170, and that after cutting its value was $1,260. The $90 window for the manufacturer must be enough to cover the cost of production, capital investment, risks (some diamonds are damaged during cutting), and profit. To ensure profit, therefore, the manufacturer has to be very efficient when he cuts the diamond. As will be illustrated later in this article, minor errors in diamond manufacturing can cause major losses in value.

In the mid-1980s, the Israel Diamond Institute was one of a few groups in the international diamond industry that made a conscious decision to pursue the use of sophisticated technology in the local manufacturing sector. The Israeli industry at that time was based largely on conventional methods. Earlier attempts to introduce automatic polishing machines had not been totally successful, because the manufacturers lacked not only the knowledge but also any understanding of the available technology.

Recognizing both that the Israeli diamond-manufacturing industry was very conservative and that the sophisticated techniques used in other industries could not readily be applied to the problems of cutting diamonds, the institute's engineer first analyzed the processes and established which areas would benefit most from technological innovations. Gradually, new manufacturing methods were introduced, including computer-aided evaluation of the rough crystals, lasers for precision sawing, automat-

Figure 2. Many decisions are required to turn a rough diamond like the macle on the left into a fine triangular brilliant-cut diamond like the stone on the far right. Courtesy of Kleinhaus, New York; photo © Harold & Erica Van Pelt.

Figure 3. This economic "conveyor belt" illustrates the added value that a diamond attains as it passes through the manufacturing process from the mine to the retail jewelry store. Typically, within this conveyor belt, the diamond manufacturer's component is only a very small portion of the ultimate retail value, about 2%. Within this narrow range, all manufacturing costs must be included as well as some profit for the manufacturer.

ed bruting and polishing equipment, and computer imaging for more accurate measurement of the polished stones. These changes have resulted in significant improvements in the manufacturing process, and have been adopted throughout the Israeli industry and in other cutting centers such as India.

The introduction of new manufacturing technologies is ongoing, with much effort currently under way to educate other diamond manufacturers on how to use these technologies effectively in their own facilities. Since these efforts are still relatively new, few articles describing them have appeared in the trade press (see, e.g., Lawrence, 1996). At present, the best source of information is the proceedings volume published following the October 1991 International Technical Symposium sponsored by the De Beers Central Selling Organisation (CSO) in Tel Aviv, Israel (Cooke and Caspi, 1991). According to Lawrence (1991, p. 1–3) in this proceedings volume, there are many important benefits to using modern technology for diamond manufacturing:

1. Reduced manufacturing costs
2. Improved quality of the finished diamond
3. Increased efficiency, to compensate for the lower labor costs in other manufacturing centers
4. Better decision making regarding the manufacture of a particular piece of rough
5. Increased profits for the manufacturer

THE MANUFACTURING PROCESS

Sorting the Diamonds. Rough gem-quality diamonds are sorted in several ways. The main sorting categories are size, shape, color, and clarity. At the

CSO, rough diamonds are sorted by hand and by machine into more than 5,000 categories (Stewart, 1991, p. 3–2). Most diamond manufacturers have far fewer categories, and they use one or more of a variety of sorting techniques, depending on the quantities they are handling and the typical sizes.

Size. All rough diamonds are sold by weight. However, large parcels of small rough diamonds normally are sorted first by sieving techniques (Bruton, 1981). That is, diamonds are passed through a series of sieve plates, each with holes of a given diameter. Smaller diamonds fall through the holes in the plate, while the larger ones remain trapped in the sieve. Several layers of sieve plates are stacked together, with decreasing hole diameters at each level downward. This enables the sorter to create packages of diamonds of approximately the same size prior to weighing. A scale is usually used to weigh the rough diamonds, although the CSO has some very sophisticated equipment for this purpose.

Shape. Rough diamond crystals occur in nature in different shapes. The diamond manufacturer traditionally describes these shapes using the following three general terms:

1. *Sawable*—rough diamonds, often octahedral or dodecahedral in shape, that will yield more total weight as polished stones if they are sawn or cleaved in two before being polished.
2. *Makeable*—rough diamonds that are polished as a single cut stone without first being sawn or cleaved. They usually require more work than

sawable rough and have a lower yield. Sometimes their grain structure cannot be determined easily. Both macles and "flats" would typically fall within this group.

3. *Cleavage*—irregularly shaped rough that requires special attention, as was the case with the original Cullinan rough diamond.

Sorting by shape enables the manufacturer to decide how best to cut the diamond and which manufacturing process to use.

Color. Color sorting (using a standard color-grading system) is done in natural daylight. In many diamonds, though, color is quite subtle. In addition, colors that result from atomic-level impurities or defects may be evenly or unevenly distributed within the rough crystal. Color can also result from the presence of a colored inclusion(s), or from staining (usually brown) by a foreign material within a surface-reaching fracture. Some diamond crystals have a surface coating or frosting that may be all or partially removed during cutting. Thus, the manufacturer must evaluate all these situations when considering how to cut a particular diamond to obtain the best color possible.

Clarity. Last, rough diamonds are sorted in terms of their potential clarity grade (again, according to a standard system). As with color grades, the better clarity grades are only distinguished by slight differ-

Figure 4. The most critical stage in diamond manufacturing, marking the diamond for sawing or cleaving, requires a complex decision-making process to optimize the value of the finished stones.

ences, such as in the number, visibility, position, and size of internal features (inclusions, fractures, etc.), as these features would appear in the final faceted stone. The uneven surface of the rough diamond often makes internal features difficult to see. The manufacturer must envision the shape and orientation of the stone within the rough crystal, and judge where these internal features may be located and how visible they will be, or whether any or all can be removed by cutting.

Marking the Rough Diamond. The decision as to whether or not to divide the diamond crystal is made by an individual called the *marker*. This is usually the most experienced person in the manufacturing company (very often the owner of the company), a specially trained employee, or even a subcontractor. This step is crucial because it represents *the major* decision on how to manufacture a given piece of diamond rough. As stated by Grochovsky (1991, p. 10–1), "the marking of a stone comes only after considerable evaluation, as any error made at this stage (of the manufacturing process) is irreversible."

To outsiders, marking appears to be a very simple process. The marker examines the rough diamond with a loupe and, frequently, measures the dimensions of the diamond with a gauge. He then marks a black line on the diamond crystal's surface (figure 4). In the next step of the manufacturing process, the crystal will be either sawn or cleaved along this line (Bruton, 1981, p. 235; Watermeyer, 1991, p. 22). In actuality, however, marking is really the most complicated step in diamond cutting (see Grochovsky, 1991, pp. 10–1 to 10–5). This is because the marker must optimize the value of the two finished stones. To understand the marker's decision in marking a particular crystal, we must again review the influence of each of the 4 Cs on the value of the cut diamond.

Carat Weight. When working with sawable rough, the marker must maximize the weight of the two finished diamonds. By examining the rough crystal with a loupe, the marker usually sees several alternatives. However, the marker must keep in mind the value information presented in figure 5 (although the individual prices are fictitious, the relative prices are based on pricing lists over several months in 1996). These two graphs illustrate the relative *price change* for cut diamonds as *carat weight increases* (while the color and clarity grades are kept con-
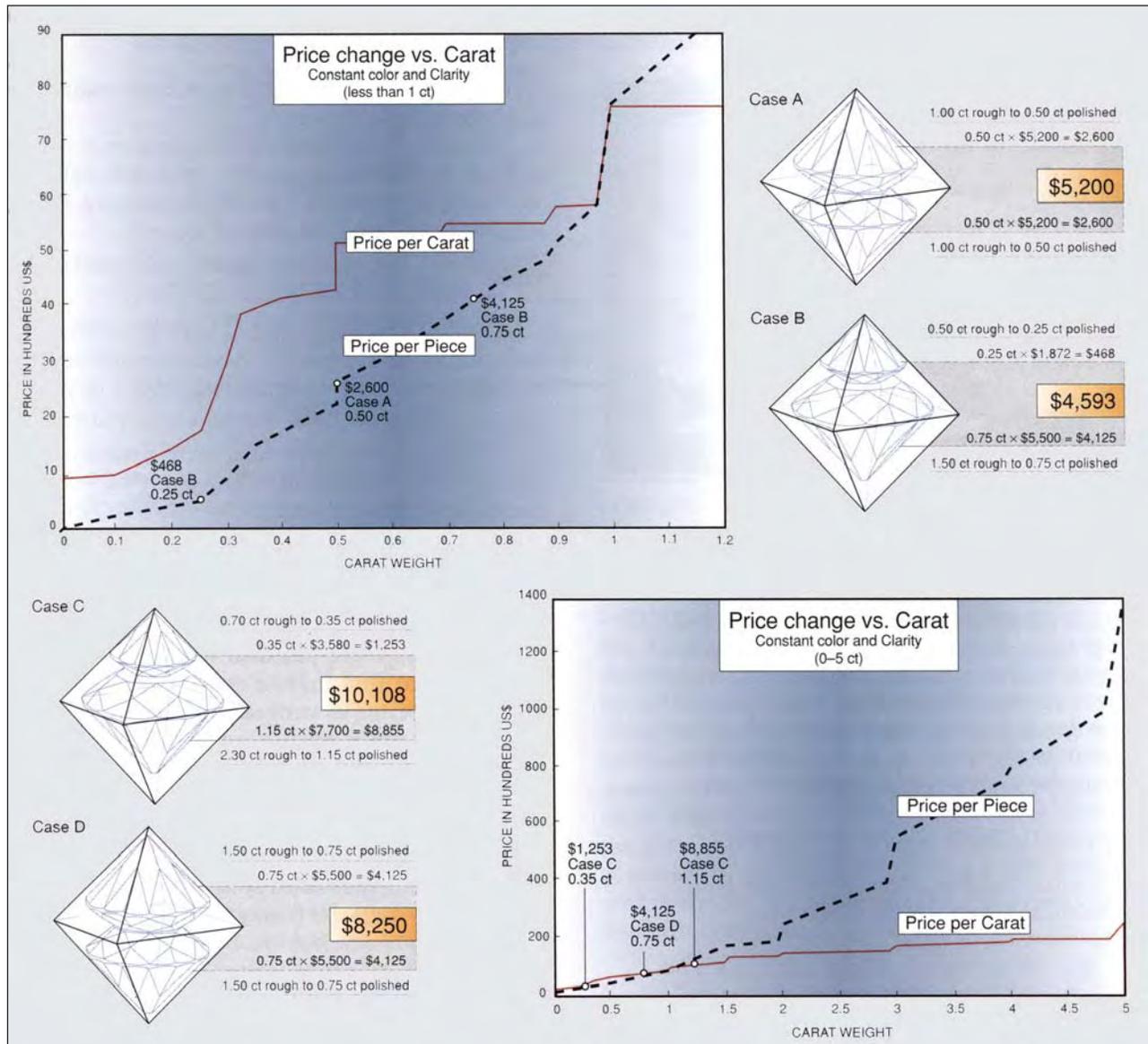
Figure 5. These graphs show the relative prices per carat and per piece for cut diamonds with weights primarily below (top) and above (bottom) approximately 1.00 ct. Note how the price differential increases significantly as carat weight increases (assuming other factors are identical; for the purpose of this illustration, the diamonds are all round brilliants and all have the same color and clarity grades). At certain key points (such as near 1.00, 2.00, and 3.00 ct), price jumps sharply. In the diamond-manufacturing process, the price per piece of the single stone—or total price for the two stones—cut from the original piece of rough is the crucial value to maximize. Even though case B will yield a 0.75 ct stone, case A provides the greater total value for the original piece of rough. However, the added value for the 1.15 ct stone that case C will yield makes it the better choice than the two equal-size stones in case D.

stant). In both graphs, one line represents the *price per carat* and the other represents the *price per piece* (found by multiplying the price per carat by the weight). In figure 5 (bottom), note the significant difference in these two prices as the carat weight increases. In both graphs, also note that the two lines are not smooth; at certain carat weights, the value jumps sharply (nearly vertical line segments). For example, from 0.98 ct to 1.02 ct, where the weight change is only about 4%, the price per piece may change by almost 35%. The marker is mainly interested in maximizing the total value for the two pieces cut from the original piece of rough.

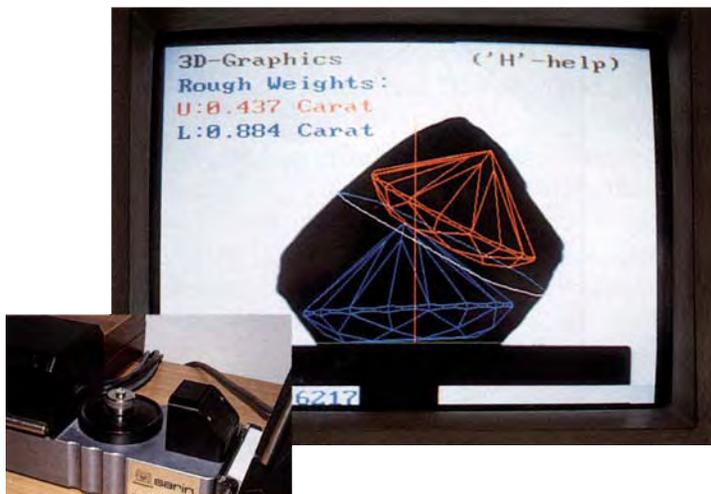To get a better idea of the alternative value

Figure 6. The marker uses the Sarin Dia-Expert system (here, with Dia-Mension hardware) to help identify the best position to mark a rough diamond for sawing or cleaving. The system consists of a sample stage, light source, and camera (inset), as well as a computer system. Within an image of the cross-section of the rough diamond that is depicted on the computer screen, the operator may ask the computer to superimpose computer-generated outlines of possible cut stones that could be manufactured from this particular piece of rough. In the option shown here, the solution is unusual, since the table facets of the two proposed cut stones are not adjacent to the sawing plane, which is the most common arrangement. Photo by James E. Shigley.

choices a marker has when examining a piece of rough, consider the case of a 2.00 ct well-formed octahedral crystal. Furthermore, assume an idealized situation where the two stones fashioned from this crystal will end up having the same color and clarity grades. The marker has many options available, but let us examine two (assuming here a 50% yield—that is, 50% of the original crystal is lost as powder or dust during the manufacturing process, so that the two final cut diamonds total 1.00 ct):

Option 1: To cut the crystal into two identical pieces that will yield two polished diamonds, each weighing 0.50 ct (case A in figure 5)

Option 2: To cut the crystal in such a way that it yields two polished stones of very different weights, 0.75 and 0.25 ct (case B in figure 5)

In this situation, it appears that the two 0.50 ct

stones will yield the maximum total value (see again figure 5).

As another example, if the rough crystal weighs 3.00 ct, the marker again has to decide between similar options (assuming a 50% yield—or a total weight of 1.50 ct for the two cut stones):

Option 1: Two stones weighing 1.15 ct and 0.35 ct (case C)

Option 2: Two identical 0.75 ct stones (case D)

Referring again to figure 5, the first choice—that of manufacturing two diamonds that differ in weight (case C)—will yield the maximum total value.

Of course, real situations are not this simple. The weight, shape, potential color and clarity grades, and current situation in the retail marketplace all influence the very important decision of how to mark a particular rough diamond. The marker must take into consideration all of these factors.

To estimate the polished weight, the marker uses a special tool known as a Moe gauge. This measuring device is calibrated in Moes, units of measurement that are unique to the instrument. The weight of the final cut diamond can be estimated by cross-referencing Moes dimensions for diameter and total depth to a set of tables supplied with the instrument.

A new computer-based system has recently been introduced to help the marker (figure 6). Known as Dia-Expert and manufactured by Sarin, a Ramat-Gan company, this equipment is used as follows:

1. The marker sets the rough diamond on the system's sample stage.
2. He selects the faceting proportions to which he thinks the diamond should be cut.
3. If he chooses, he can define the quality of the cut stone in terms of color and clarity.
4. The system measures the geometric proportions of the rough crystal in a number of orientations, so that a detailed three-dimensional description or model of the crystal is then "known" to the computer.
5. The marker may ask the computer system certain questions, such as what the largest stone and the remainder will be, or what two cut stones will result if the rough diamond is sawn or cleaved along a defined line.
6. For each option, the system will show the potential shapes and sizes of the cut stones

Option	Stone	Weight	Cut quality	Price per carat	Stone's price	Total
A	1	1.12	Very good	$ 9,300	$ 10,416	$ 20,181
A	2	1.05	Very good	9,300	9,765	
B	1	1.82	Very good	10,700	19,474	$ 22,660
B	2	0.54	Very good	5,900	3,186	
C	1	1.67	Very good	10,700	17,869	$ 22,322
C	2	0.73	Very good	6,100	4,453	

[a] For an assumed cutting style and color and clarity grades, the system has made three recommended options (labeled A, B, and C) for manufacturing cut stones from the sawn pieces of this crystal. "Cut quality" is defined by the operator, and "price per carat" is taken from a table in the system. With this information, the system calculates the two weights for each option. Thus, the operator can see the results for each of the three marking options.

superimposed on an image of the rough (again, see figure 6). It also indicates the resulting weight of each cut stone and the total value of each option.

7. When the marker selects a particular option, the system in cooperation with the operator will physically place a black line on the rough crystal, along which the diamond will be sawn or cleaved.

Table 1 presents the type of information that the Dia-Expert system would produce. The system has suggested a particular cutting style and three possible options (here labeled A, B, and C) to manufacture two cut stones from a particular crystal. In each case, the "quality of cut" for the two future stones was selected as "very good," and the prices per carat were determined from another table (not shown, where the marker has made assumptions regarding the clarity and color grades of the two cut diamonds; the basis for the decision as to what qual-

ity of cut to specify is described below). Note that inclusions are *not* taken into consideration in this example, and the system operator might have to change the anticipated clarity grade if inclusions would affect any of the options. The Dia-Expert system gives the estimated weight and orientation of both cut stones within an outline of the rough crystal. Again, the price per piece of each cut stone is derived by multiplying its price per carat by its estimated weight. In this example, the system recommends option B, which gives the maximum value for the original piece of rough. Although use of this system reduces marker uncertainty in evaluating a rough diamond, the Dia-Expert does not replace the marker. At present, the system operator must still consider the presence of inclusions and fractures within the rough crystal that the Dia-Expert equipment cannot resolve.

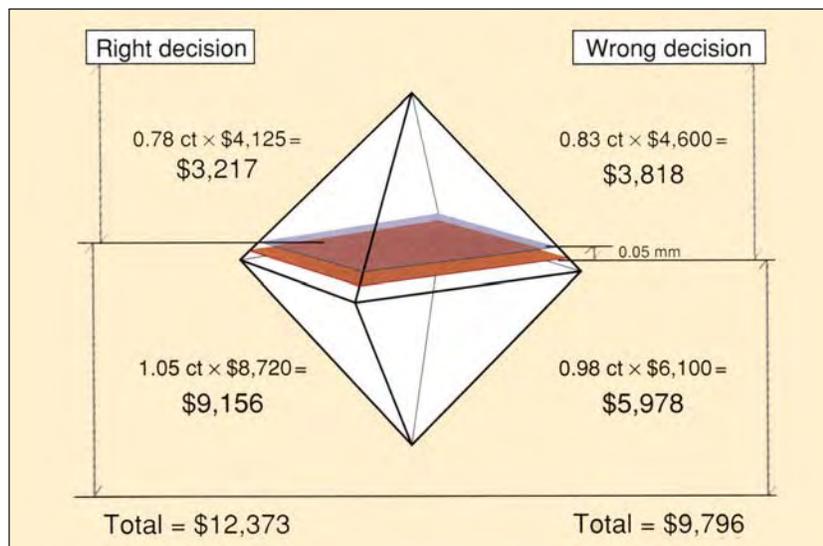Using the same relative prices as are given in figure 5, figure 7 demonstrates how sensitive the

Figure 7. The marker must carefully evaluate where to place the marker line on the rough diamond so as to achieve the maximum yield from that piece of rough. As this illustration shows, even a small, 0.05 mm, change in the placement of this line can result in a major difference in the total price of the two final cut diamonds. To determine the price per piece, the final carat weight of each stone is multiplied by the price per carat (using the same relative prices as are given in figure 5).
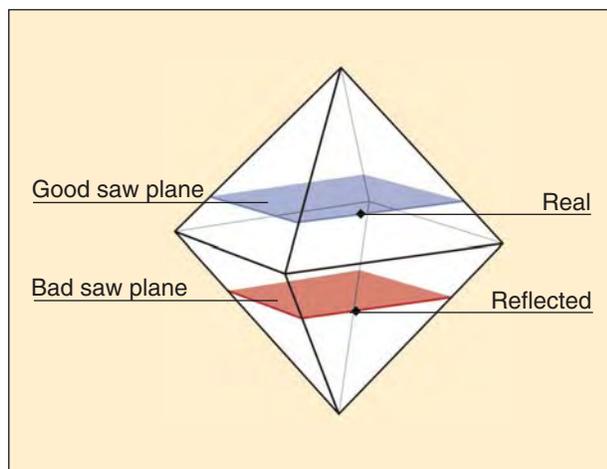
Figure 8. One of the greatest challenges facing the marker is the location of inclusions in the rough diamond and how to avoid or place them in the polished stone. This illustration shows the locations of a real inclusion in a diamond crystal and a reflection of this same inclusion produced by the refraction of light. The diamond could be sawn through either location, depending on where the marker line is placed. If the crystal was sawn through the imaginary "inclusion" (the reflection), the result would be a larger lower-clarity stone and a smaller higher-clarity stone. If the crystal was sawn through the real inclusion, however, it would yield two stones similar in weight to those in the first option, but both would be of higher clarity— and, therefore, would have a higher total value.

marker's decision is. In this representative example, a small inaccuracy of 0.05 mm in positioning the marker line would cause a major loss in value.

As noted earlier, a further challenge associated with marking a rough diamond is the crystal that has a coated or frosted surface, which may greatly limit the marker's ability to see the stone's internal characteristics. With such a stone, it may be necessary to polish one or more flat facets ("windows") for these observations.

Color. Estimation of the final color appearance is very important in the marker's decision whether to polish the diamond to good proportions (high color) or to poorer proportions (lower color grade but higher weight yield). As any of the major diamond price guides will show, the price of a cut diamond drops steadily from one color grade to the next until about "S." At the higher end of the scale ("D"–"G") especially, a drop in color by one grade can change the price by as much as 20%.

Clarity. Clarity is the most difficult feature to assess. The marker must determine not only the existence of an inclusion (which may be very small), but also its exact location within the future cut stone, since he has to decide whether or not to remove it during the cutting process. There often is a trade-off between achieving a smaller, inclusion-free stone and a larger stone that contains an inclusion. If the inclusion is to be left in, every effort must be made to position it within the stone so as to minimize its visibility and optical effect. A small mistake in locating an inclusion or other imperfection—and hence, in placing the marker line—can have disastrous consequences once the rough crystal is cleaved or sawn.

Because of light refraction within a diamond crystal, it is sometimes difficult to decide which inclusions are real and which are reflections (there may be more than one). Figure 8 illustrates such a situation. Let's assume that either option would produce two stones, one weighing 1.10 ct and the other, 0.90 ct. If the marker decides to saw the crystal along the "good" line (i.e., through the real inclusion), he will get two inclusion-free stones. But if he makes the wrong decision, and saws along the "bad" line (i.e., through the imaginary inclusion), the larger, 1.10 ct, stone from the top half will contain the real inclusion; only the 0.90 ct stone from the bottom half will be inclusion-free. Such a misjudgment could result in a significant financial loss, especially if the stone was of good color. Price differences between clarity grades can be substantial, especially for the higher grades (as much as 18% between IF and VVS grades).

Cut. Last, the marker must decide whether to fashion the rough as a round brilliant, into one of the well-known fancy shapes (i.e., marquise, oval, etc.), or into one of the newer cutting styles (see, e.g., Tolkowsky, 1991). The choice of shape will influence the overall appearance (i.e., brilliance, dispersion, etc.), face-up color, and visibility of inclusions (these features would also be influenced by the size of the faceted diamond).

The same faceting shape can be manufactured with different proportions (which define the geometric relationships between different parts of the cut diamond). Achieving better proportions usually results in a lower yield from a given piece of rough. Sometimes going from one set of proportions (an excellent cut) to another set (a fair cut) can increase

the yield by as much as 15%, but the price per carat then decreases.

The main problem for the marker is that the above 4Cs are dependent on one another. Attempts to maximize the value from one factor must often be done at the expense of one or more of the others. If the marker wants to increase clarity, he may have to remove material and thus decrease the size (carat weight). Cutting for better proportions also means tighter tolerances, and thus less weight retention. Consequently, markers must stay constantly in touch with the current market demand for various sizes, shapes, proportions, and color and clarity grades of cut diamonds. This demand can change daily, seasonally, or according to the preferences of the different international markets.

Cost. To these 4Cs, we must add a fifth C: the *cost of production*. This C is used only by manufacturers. For example, depending on the marking, "sawable" stones can be turned into "makeable" ones (with no defined grain orientation), which often require more work to manufacture and thus are more expensive. Also, a fancy cut, as compared to a standard round brilliant, is more expensive to produce. Most manufacturers specialize in certain shapes, which their machines and labor handle most efficiently. A marker working for such a manufacturer will prefer his specialized shape to other alternatives if the difference in value is not significant. Last, laser sawing (see following discussion) is more expensive than mechanical sawing.

The main effect of this fifth C is seen in the geographic locations where diamonds are cut today. Smaller, less-expensive diamonds, where the value added by manufacturing is about 15%, are handled in the Far East—India, Thailand, China, and other countries (known as lower-cost centers, where the cost of a worker is about $30 to $200 per month). Larger, more expensive diamonds are cut in the United States, Antwerp, and Israel, where the added value is low (from 2% to 5%).

Crystal Grain. Before examining the actual manufacturing of the cut diamond, we must first understand how the *crystal grain* affects the cutting process (Bruton, 1981, p. 238; Watermeyer, 1991, p. 18).

Because of crystal grain (in this context, directional variations in hardness relative to crystallographic orientation), a mechanical operation (such as polishing) on a diamond often can take place only in certain directions. In some rough diamonds, these

grain directions can be identified by the shape of the crystal, by certain surface features (such as trigons), or by the internal structure of the crystal. The experienced diamond manufacturer knows the effect of crystal grain on the cutting process. However, problems can arise when: (1) there are no surface or internal features that indicate grain orientation, (2) a crystal changes its orientation (referred to as being in a *twisted form*), and (3) one crystal is embedded in the main crystal (known as a *naat* or knot).

In each of these cases, the manufacturer may not be able to complete some mechanical operations successfully. This happens, for example, in sawing or when a facet is being polished and there is a *naat* present. Then, the diamond has to be polished in two different directions. A detailed description of diamond crystal grain and its features is found in Ludel (1985, Chapter 7).

Sawing the Rough Diamond. *Mechanical Sawing.* Diamonds are sawn today as they have been for many years (for further details, see Bruton, 1981; Ludel, 1985; Vleeschdrager, 1986; Grochovsky, 1991; and Watermeyer, 1991). In mechanical sawing, the rough diamond, held in a dop, is slowly lowered onto a high-speed (~10,000 revolutions per minute) revolving blade (figure 9). The pressure of

Figure 9. In this photo of a mechanical sawing operation, two machines are shown. The sawing machine controls the lowering of the crystal, attached to a dop, onto a thin copper blade that is revolving at a high speed. Photo by James E. Shigley.
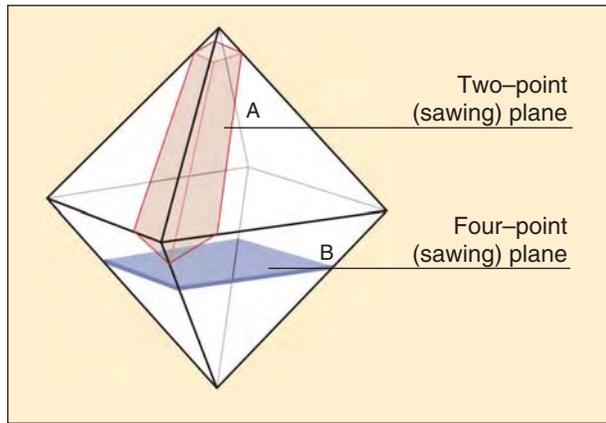
Figure 10. The sawing plane used for an octahedral diamond crystal is indicated by outline B. Mechanical sawing commonly takes place along such planes (ones parallel to cubic faces). This plane is also known as the "four point" plane, because the sawn surface has four equidistant corners. Outline A indicates another sawing plane, a two-point plane; such planes are parallel to dodecahedral crystal faces.

the diamond on the thin (about 0.06 mm) blade is controlled by a manually adjusted screw. The crystal is sawn along the direction indicated by the marker's line.

Sawing must be performed in certain orientations to the grain (figure 10), often called the two-point plane (parallel to a dodecahedral face) and the four-point plane (parallel to a cubic face). Planes can also be labeled by the number of places along the girdle where naturals can occur (see, e.g., Sevdermish and Mashiah, 1996, p. 718).

Recently, mechanical sawing has also benefited from new technology. The mechanical screw that lowers the diamond onto the sawing blade has been replaced by a computer-controlled system, attached to the traditional machine, that is able to sense the pressure of the diamond on the blade (figure 11). When the pressure drops below a predetermined limit, the system lowers the diamond further onto the blade and increases pressure on the stone. This system also prevents the diamond from moving downward beyond a predetermined speed, so that the blade does not penetrate the stone at an undesired plane. An experienced sawer usually can handle 20 to 30 machines at the same time.

Laser Sawing. Laser sawing, in which a laser replaces the metal blade to saw the diamond crystal (figure 12), was first introduced 20 years ago (see Cooper, 1991). The equipment consists of a YAG

(yttrium aluminum garnet) laser with a computer-controlled sample holder and a lens that can focus the laser beam up or down. As figure 13 illustrates, in the special holder or cassette (which may hold several diamonds), the diamond can be moved in a two-dimensional, or X-Y, plane (i.e., side to side or back and forth) under the fixed position of the laser beam. Once the laser beam strikes the diamond, it heats that spot to a very high temperature, "burning" or vaporizing it. As the rough diamond moves beneath the laser beam, a narrow slice through the diamond is created.

Laser sawing has the following important advantages (see also Cooper, 1991; Davis, 1991; Prior, 1991):

Figure 11. Modern sawing machines, like this Dialit AS500, have a pressure controller. After setting the diamond in the machine, the operator sets the required pressure of the diamond on the blade and the maximum velocity in which the diamond will be sawn. The control system continuously checks and adjusts the pressure.
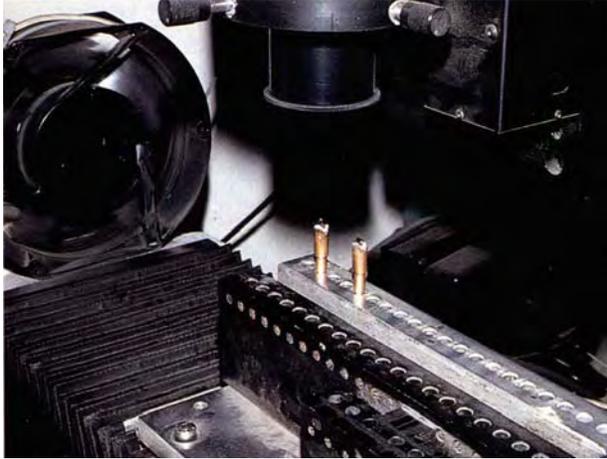
Figure 12. In this laser-sawing operation, a YAG laser is being used to saw two dark yellow diamond crystals. The laser beam is oriented vertically, and it strikes the upper surface of each crystal as the latter is moved back and forth by a motorized cassette. Photo by James E. Shigley.

1. The laser can saw a rough diamond in any crystallographic direction (you are not limited to the directions of cleaving or mechanical sawing). This permits greater accuracy, greater yield, and greater versatility in handling complex crystals that could not be sawn easily by mechanical means.

2. There is no contact of a tool (such as the sawing blade) with the diamond, which eliminates the expense of periodically replacing a worn-out tool.

3. There is the possibility of both greater and constant speed for sawing. For example, a 1.00 ct crystal can be laser sawn in about 20 minutes, as compared to about 120 minutes for mechanical sawing, without hindrance from any grain obstacle (such as a *naat*).

4. The weight loss is similar to that experienced with mechanical sawing.

5. The laser equipment can be operated continuously: As many as 30 rough diamonds can be lined up in a cassette and sawn one after another without any operator involvement after the computer has been programmed with the special parameters of each diamond (i.e., its height and other dimensions). This lowers labor costs.

However, the use of lasers for sawing diamonds also has several drawbacks vis à vis mechanical sawing. These include both (1) the greater expense of purchasing and maintaining laser equipment, and (2) the critical need for safety in operating the laser equipment.

These drawbacks can be overcome by one manufacturer specializing in the use of this technology, and offering it to a number of other manufacturers. However, because of the greater capital costs, currently this equipment is primarily used on those rough diamonds for which mechanical sawing is not possible. It is worth noting, though, that the author knows of one large-volume manufacturer in India who saws all of his diamonds by laser and currently has approximately 30 laser-sawing machines.

Figure 13. In laser sawing, a wide "path" (about 0.2 mm across) is made by moving the diamond back and forth beneath the fixed position of the laser beam. Then, the focal point of the laser beam is lowered and a second, narrower path (about 0.17 mm across) is formed. This process is repeated several more times, with the width of the path decreasing gradually to yield a V-shaped groove by the time the laser beam reaches the bottom edge of the rough diamond.
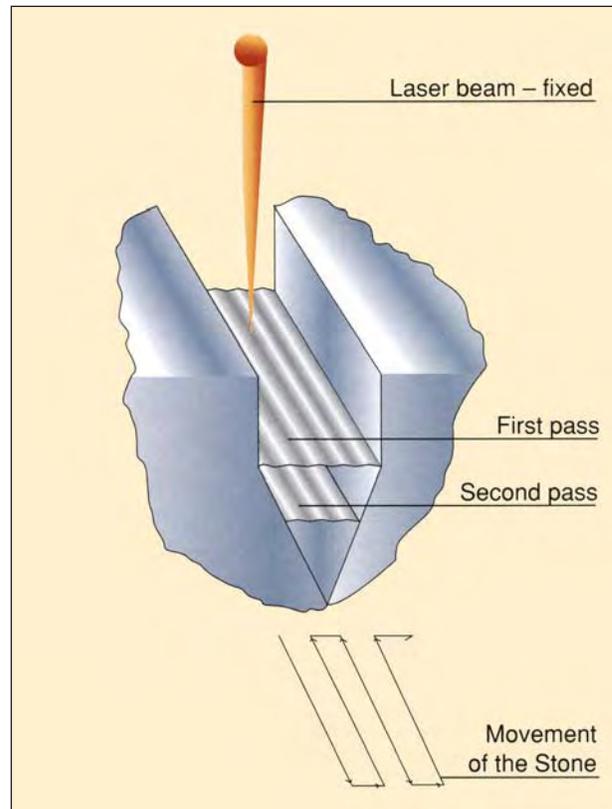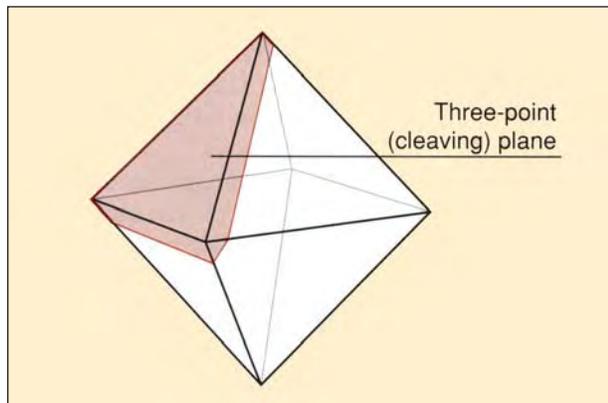
Figure 14. A diamond is cleaved along a different grain orientation than it is sawn. Compare, for example, the cleaving plane marked on this octahedral diamond crystal with the sawing planes marked on the illustration in figure 10. (Note that the cleaving plane is also known as the "three point" plane because of the three corners of the cleaved surface.)

Cleaving the Rough Diamond. Cleaving is the traditional method for dividing a rough diamond into two parts (see Bruton, 1981; Ludel, 1985; Vleeschdrager, 1986; Watermeyer, 1991). Cleaving is performed along a different grain orientation than sawing, as seen in figure 14 (compare with figure 10). The marker's decision to cleave rather than saw a diamond depends on the shape of the rough and the location of inclusions.

The cleaving process has two stages. The first is preparing the *kerf*—a small V-shaped groove carved into the diamond's surface along a specific direction. The laser kerf is the best, as it is a narrow, straight-sided groove that is squared off at the bottom. The second stage is splitting the rough diamond with a special knife. The cleaver taps on the shoulder of the blunt blade with a small hammer, and the diamond is divided instantaneously.

Kerfing. Traditionally, kerfing was a very fatiguing process that was done totally by hand. The cleaver first glued the diamond to a special rod and then used another diamond with a sharp edge to scratch the surface of the first diamond until a groove (the "kerf") was created. Preparing the kerf in this manner was an exacting occupation that required years of study. In addition, the procedure was very time-consuming.

Today, lasers have revolutionized kerfing (see Cukrowicz and Jacobs, 1991; Doshi, 1991). Modern kerfing is performed in the following steps:
1. The rough diamond is installed in a special dop.
2. The *setter* places 20 or more diamonds in a cassette so that the marker line on each is aligned and is at the same height (the same focus position for the laser beam).
3. The cassette is loaded into the laser system.
4. The cassette is moved along the marker's lines in a special pattern so that the laser creates the required kerf in each.

Once the kerf is prepared, the rough diamond is set in a plastic-like material. A thin metal blade is inserted into the kerf, and the shoulder of the blade is struck with a hammer. If the kerf has been positioned correctly, the diamond will split easily.

Laser kerfing has the following advantages over manual kerfing:
1. It can follow the marker line more precisely.
2. The kerf is narrower and shallower, which is all that is needed for cleaving,
3. Because laser kerfing is much faster than the traditional manual method, it is less expensive for manufacturers who handle large quantities of diamonds.
4. Productivity is high: One person using a laser system can kerf more rough diamonds than can 60 individuals using the manual method.

However, there are potential problems with laser safety and damage to the diamond. In addition, the marker still must identify the best cleaving direction by the morphology and surface characteristics of the rough diamond in order to place each kerf correctly.

Bruting. It is with this step that the diamond receives its basic shape (round, marquise, etc.; see Bruton, 1981; Ludel, 1985; Vleeschdrager, 1986; Watermeyer, 1991). Bruting is done by rotating one diamond against another diamond that may also be rotating or may be stationary in the hand of the *bruter* (figures 15 and 16). Thus, the two diamonds are progressively ground away by mutual abrasion. The bruter's task is two-fold: first, to fix the center of the diamond on the dop and, subsequently, to fix the diameter of the cut stone. As with previous steps in the manufacturing process, the bruter must

answer one or more of the following questions to maximize the value of the final cut stone: (1) What should be the shape of the final stone? (2) What should be the faceting proportions? (3) What should be the position of the table facet within the piece of rough being worked? Depending on the shape and the proportions chosen, a wide range of price-per-carat values can be achieved from the same piece of rough.

For round diamonds, the size of the cut stone is determined during this critical stage. Yield is affected by two factors: the diameter to which the diamond is cut, and the center of symmetry around which the diamond is bruted. A minor mistake made in either of these factors because of excessive bruting can produce a significant loss in yield.

Traditional bruting uses a machine with a small motor that rotates at about 3,000 rpm. The diamond to be bruted is cemented onto a dop that is then inserted into a spindle (which will be rotated at high speed). Another diamond is cemented onto a second dop, which in turn is attached to the end of a long rod; this is used as the bruting diamond. The bruter holds this rod by hand and presses the bruting diamond against the spinning diamond so that abrasion takes place (figure 15). During the process, the bruter stops frequently to check the results. If it appears that the stone is not being bruted around the required axis of symmetry, the bruter taps on the spindle to change the axis of the bruted diamond slightly and thus align it properly.

In practice, the traditional mechanical bruting technique was an inexact science. It was based largely on trial and error: bruting, stopping, checking the position of the diamond, changing the center if necessary, and rebruting to achieve the desired

Figure 15. With a manual bruting machine, the diamond is glued to a dop that is set in the machine. In his hand, the bruter holds a stick with another dop to which a diamond has been glued. As the diamond in the machine is rotated, the other diamond is bruting it.

Figure 16. In this photo of an automated bruting machine built by Milano Industries in Israel, two diamonds are mounted for bruting to create a girdle surface on each by mutual abrasion. By viewing the screen, the operator can correctly position each stone and then monitor the progress of the bruting process. Photo courtesy of Milano Industries.
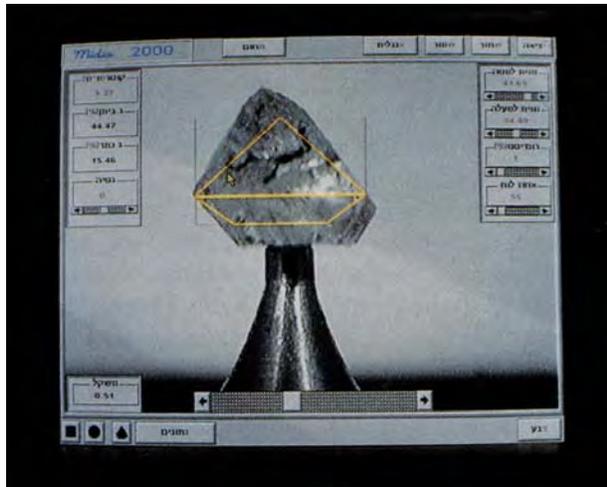
Figure 17. A manual centering system has two video cameras, so that the operator can view the piece of rough from the side and the top. By rotating the image of the rough diamond, the operator can center it on the dop before the glue holding the diamond is hardened. First, an outline of the future cut stone is superimposed on the outline of the crystal. Then, the diamond is centered so that the maximum diameter and maximum yield are achieved. The operator makes sure that the image of the cut stone will fit within the outline of the rough diamond. Photo by James E. Shigley.

shape. To this end, the bruter must also look for signs and marks on the bruted area (such as symmetrical naturals on opposite sides).

Toward the end of the 1980s, a new, fully automated approach to bruting was invented. A number of bruting machines are now in use (see Cooke, 1991a), but they are generally based on the same principle. With these new machines, the two stones are bruted simultaneously (figure 16). Each stone rotates around its own axis of symmetry and, in so doing, each brutes the other.

These new bruting machines operate with little or no supervision. The bruter need only install the diamonds in the machines, center the stones, and stop the bruting when one of the stones reaches its required diameter (in the newest equipment, this last function is performed by the machine). This stone is then replaced by another stone and the process is repeated. One person can operate up to 10 machines simultaneously.

Centering Systems. The introduction of automatic bruting machines has stimulated the use of other modern systems to help the manufacturer increase a diamond's yield. Before the stone is placed in a bruting machine, some manufacturers use a centering system to align the center of the future polished diamond (in the rough) with the center of the bruting machine. These centering systems were developed in two generations: manual and automatic.

A manual centering system has two video cameras for viewing the rough diamond from the side and from the top. A person referred to as the *centerer* glues the sawn or cleaved diamond onto a special dop. On the output screen, the centerer sees both the shape of the rough diamond and a superimposed graticule (image) of the future cut stone that can be adjusted to fit the size of the rough crystal (figure 17). The operator positions the image of the cut stone until it reaches its maximum size, just fitting within the piece of rough. Then, the dop is heated in an oven to harden the glue. After this, the dopped diamond is installed in the bruting machine, for which the axis of rotation has previously been properly centered. At that point, all three axes (i.e., the centering axes of the machine, the dop, and the future cut stone) are aligned.

Use of this manual system offers several advantages over centering while bruting in the machine (see Caspi, 1991):

1. The stone is centered according to the structure of the rough diamond.
2. The proportions of the cut stone can be made to match the manufacturer's requirements more closely than if the stone is not centered before bruting.
3. Most diamonds that have been centered can be bruted without requiring any adjustments to their position on the dop.
4. Both productivity and yield are increased, as a skilled operator can center many more stones in the same amount of time, and the operator of the machine does not waste the time required to center in the machine.

The latest development, the automatic centering system, does all the above procedures automatically (see figures 18 and 19). The system has one or two video cameras and special computer software, which enable it to do all of the following functions without the involvement of the operator:

1. Photograph the rough diamond from many angles and integrate this information into a three-dimensional image of the rough.
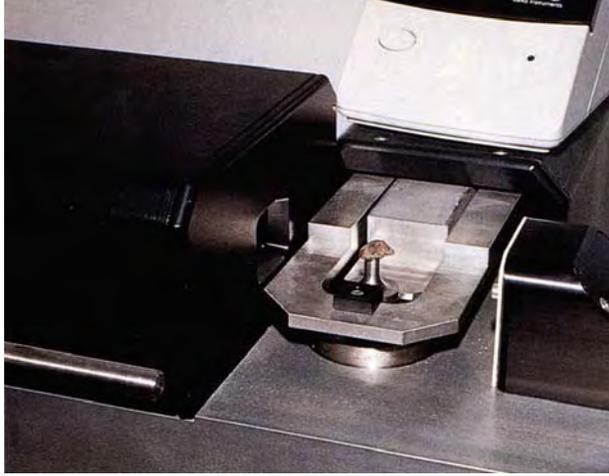
Figure 18. The Sarin automatic centering system (Dia-Center) consists of a sample chamber, light source, camera, computer, and monitor. On the right of the sample chamber (shown above) is the light source, and on the left is the camera. In front of the holder is the mechanical apparatus that moves the holder and centers the diamond. The camera measures the dimensions of the rough diamond, which is glued to a special dop, from a number of orientations. After the computer decides where the optimal center of the future cut stone will be, it moves the upper part of the dop so that the center of the diamond and the center of the bruting machine are co-axial. Photo by James E. Shigley.

2. Identify the largest diamond with the required proportions that can be cut from the particular piece of rough.
3. Move the holder to which the stone is glued so that the center of the optimal cut stone is co-axial with the centers of both the dop and the bruting machine. This process takes about 30 seconds per diamond.

The automatic system provides the best center position and requires no expertise on the part of the operator. Once the diamond is centered, the operator simply sets the holder in the bruting machine, watches the diamonds in the machine, and then stops the bruting procedure when a diamond reaches the diameter specified by the computer.

Laser Bruting. In 1992, a new, laser method of bruting emerged. The main advantage of this method, which is used primarily for fancy cuts, is that the shape is symmetrical and exactly as planned by the bruter or marker. In Israel, most fancy-shaped diamonds with rounded outlines—such as marquises, ovals, and pear shapes—are bruted by this method.

Polishing. This is the final stage in diamond cutting. The *polisher* uses a special tool called a tang (figure 20) to hold the diamond and polish it on a

scaife, a special metal polishing wheel powered by an electric motor at speeds of up to 4000 rpm (for further details, see Bruton, 1981; Vleeschdrager, 1986; Watermeyer, 1991; Curtis, 1991; Schumacher, 1991; *GIA Diamond Dictionary*, 1993).

The Polishing Process. Round brilliant-cut stones are typically polished in the following sequence:

1. The table facet
2. The eight main facets on the pavilion
3. The eight main facets on the crown
4. The eight star facets on the upper crown
5. The 16 upper-girdle (top-half) facets on the crown
6. The 16 lower-girdle (bottom-half) facets on the pavilion

To achieve a good cut (which affects the final carat weight, as well as the color and clarity grades), the following features must be kept in mind (see Schumacher, 1991):

1. The symmetrical arrangement of the facets, facet junctions, and corners (i.e., the quality of the corresponding parts of a stone)
2. The quality of the facet surfaces, that is, their surface texture
3. The overall proportions, such as table size, crown angle, pavilion depth percentage, etc.
4. The girdle size

Figure 19. The automatic centering system also constructs a three-dimensional image of the rough diamond on which it superimposes an image of the future cut stone that gives the best possible fit. Photo by James E. Shigley.
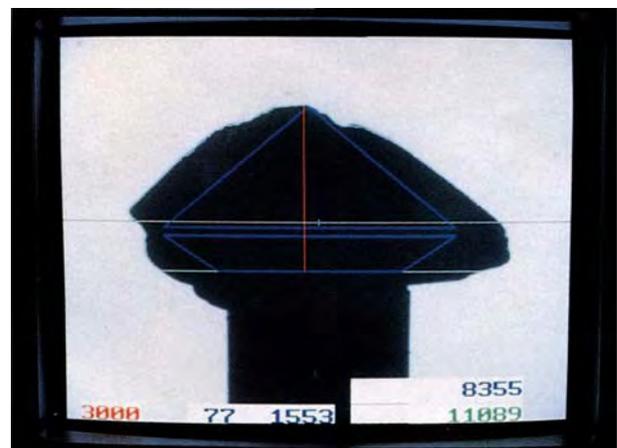
Figure 20. Polishers use a wide variety of tangs (shown here in the foreground and hanging on the central bars), depending on the facets being polished, the shape of the stone, and the like.

An important consideration when planning this process is the polishing direction. As with cleaving and sawing, polishing can only be performed in a certain direction for each facet. This direction is defined as the angle between the linear velocity direction of the polishing wheel and the grain (crystal) orientation of the particular facet. In most other directions, polishing will not occur (Watermeyer, 1991).

An experienced *polisher* identifies the polishing direction for each facet by recognizing certain features on the rough, such as trigons. In some diamonds, however, this direction cannot be determined from surface features, and the polisher has to

Figure 21. The Dialit GS7000 automated polishing machine (left) can polish the crown (excluding the stars) and pavilion facets on a stone. The control panel is on the left. The holder is set in the machine, with a few additional holders in the wooden cassette. The Dialit GSB800 automated blocking machine (right) can block eight facets on the crown or the pavilion. Photos courtesy of Dialit Ltd.
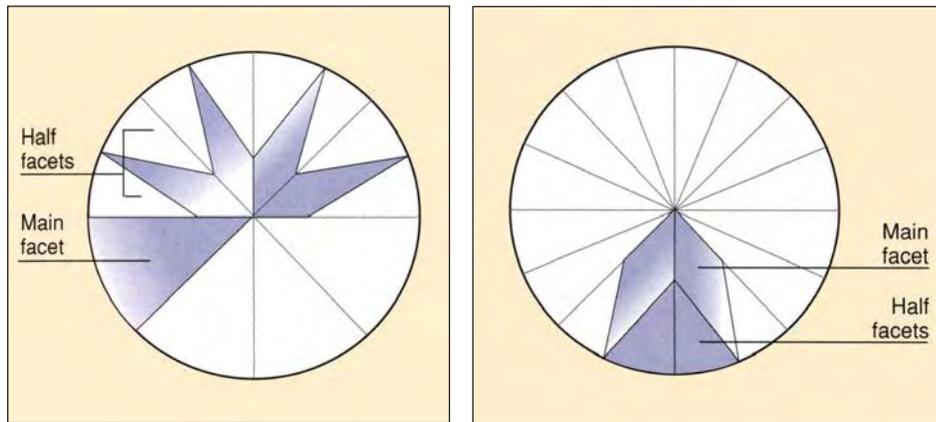
Figure 22. When polishing a diamond by manual methods (left), one first polishes the eight main pavilion facets, and then proceeds to the 16 lower-girdle (half) facets on the pavilion. With automated facet polishing (right), the reverse sequence is followed: the 16 lower-girdle (half) facets of the pavilion are polished first, followed by the eight main pavilion facets.

look for the direction of the grain (for details, see Ludel, 1985, Chapter 7, and Watermeyer, 1991). This requires simple trial-and-error (first attempting to polish the facet and then examining the stone to see if polishing has occurred).

For polishing, the diamond is held by a tang. Used for many years, tangs are still seen today even in the most advanced cutting factories. A wide variety of tangs are used, depending on the facet(s) being polished, the shape of the stone, and the like (again, see figure 20). Modern tangs look basically like the older versions, except for minor changes that help the polisher set the angle of the facets and divide the diamond into exactly eight or 16 sections.

Automatic Polishing Machines. Automatic polishing machines are essentially robots that manufac-

ture round cut diamonds (figure 21). These machines initially appeared in the early 1970s. The first was the Piermatic, which was designed to handle regular four-point sawn goods (Bruton, 1981; Vleeschdrager, 1986; Cooke, 1991b). The basic difference between conventional hand polishing and automatic polishing is the order in which polishing takes place (figure 22). The automatic machine, by a single setting of a holder, can polish two different angles (i.e., eight main pavilion facets and 16 lower-girdle facets). The diamond is set in a special holder, which enables the system to sense when one facet is fully polished and then automatically change to the next facet. Using this equipment, a trained operator can polish 16 diamonds simultaneously.

The holder has two means to halt the further polishing of a facet (see figure 23). When either the

Figure 23. This diagram illustrates how a diamond is set in a holder (left, full holder; right, upper part) for automatic polishing. The angle for polishing the 16 lower-girdle facets is indicated. When the ring comes into physical contact with the scaife, and electrical contact is made, the computer automatically halts the polishing of that particular facet and moves on to the next. When the 16 half-facets are completed, the angle is lowered by approximately 1° and the eight main pavilion facets are polished. For this procedure, an electrical contact is made (and the computer moves to the next facet) when the pot comes into contact with the scaife.
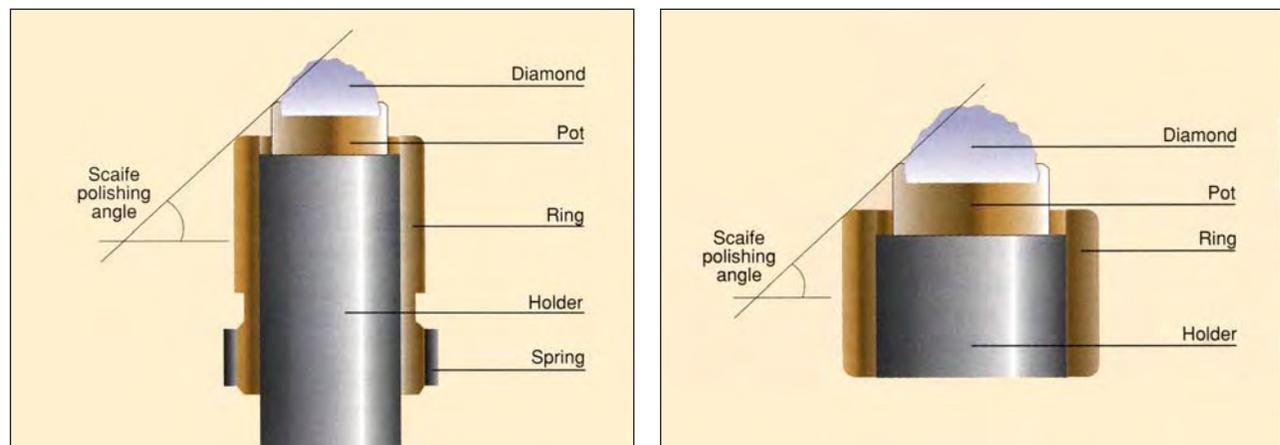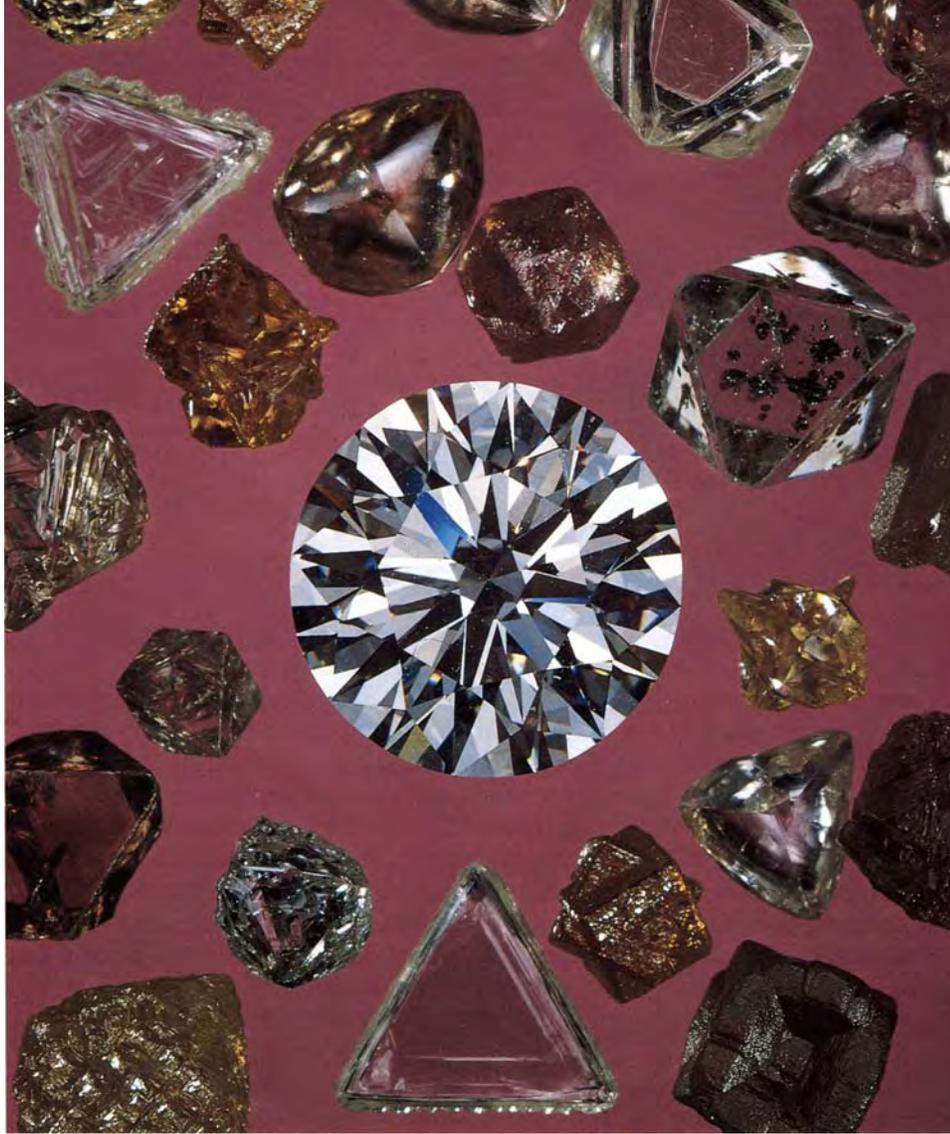
Figure 24. With the new technology and equipment available throughout the diamond-cutting process, modern diamond manufacturers can produce better-quality stones and higher yield from many different types of rough diamonds. Photo © Harold & Erica Van Pelt.

ring or the pot of the holder touches the scaife, an electrical contact is made, which tells the computer to halt the polishing process of a particular facet immediately and move on to the next facet.

To set the polishing angle, the *setter* places the diamond in a setting system. The operator finds the angle that matches the required proportions of the finished stone, and makes sure that it is contained within the rough. Then the ring is adjusted axially to coincide with the selected angle. The holder is set into the machine, and the machine polishes the diamond.

Two methods are used to handle the grain. In regular (four-point) sawn goods, the polishing direction of the 16 lower-girdle facets repeats itself every group of four facets. The machine, after polishing a facet, changes to the next polishing angle (the angles between the velocity vector of the scaife and the grain for the 16 lower-girdle facets are 90°, 150°, 210°, and 270°). The polishing direction of the eight main facets repeats itself every two facets (for these facets, the angles are 120° and 240°).

For diamonds other than four-point sawn goods, a new grain-seeking capability has been introduced into the automatic polishing machines (Cooke, 1991b; Caspi, 1991). The diamond is lowered to make gentle contact with the scaife, and the polishing rate is measured. A special sensor detects if polishing has taken place. If the facet is not oriented in the correct direction, the sensor indicates that the facet did not take the polish, at which point the machine will automatically change the facet orientation and re-measure until it finds the optimum polishing position. This grain-seeking capability enables the modern polishing machines to polish:

1. Makeables
2. *Naated* stones
3. Two- or three-point stones
4. Four-point stones that have been sawn off-grain

CONCLUSION

The revolution in diamond cutting started less than two decades ago, but already it has completely changed the diamond industry in several major cutting centers. With such advances as the decision support system for marking, laser kerfing, mechanical or laser sawing, automatic bruting machines, and automatic polishing machines, diamond manufacturers can obtain better-quality diamonds, with a higher yield per stone, in a more productive operation (figure 24). The main disadvantage of these modern systems is their cost: The capital investment required to start up a modern factory is usually 10 times more than that needed to set up a traditional factory. In most cases, however, the cost of producing an individual diamond with this technology has gone down, because one operator can operate several machines simultaneously and the cost of production is amortized over several diamonds.

Like other revolutions, this one has created some new jobs, but there are also situations where workers who could not adjust to the new technology have had to abandon the industry. It is interesting to note that the new cutting factories have better working conditions, because the machines perform better when operated in a cleaner, air-conditioned environment.

Today, diamond technology is most highly developed in Israel and Belgium, but there are very modern operations in South Africa and Russia. Such technology is rapidly spreading in other centers, such as India and China, as well.

REFERENCES

Bruton E. (1981) *Diamonds*, 2nd ed., M.A.G. Press, London.

Caspi A. (1991) Methods for improving automatic bruting. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 13.

Cooke P. (1991a) Bruting machines currently available. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 14.

Cooke P. (1991b) Automatic polishing machines. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 18.

Cooke P., Caspi A. (1991) *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London.

Cooper M. (1991) Laser technology in the diamond industry. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 6.

Cukrowicz L., Jacobs L. (1991) Laser cleaving: A producer's overview. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 8.

Curtis A. (1991) Scaife technology: Polishing powders and binders. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 19.

Davis S. (1991) Laser sawing. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 7.

Doshi S. (1991) Laser cleaving—India. In Cooke P., CaspiA., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20– 24 October 1991, De Beers CSO Valuation AG, London, Chapter 9.

GIA Diamond Dictionary, 3rd ed.(1993) Gemological Institute of America, Santa Monica, CA.

Grochovsky A. (1991) Sawing review. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 10.

Lawrence J.C. (1991) Technological responses to ris ing costs. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 1.

Lawrence J.C. (1996) Tackling new technology. *Diamond International*, No. 42, pp. 53–57.

Ludel L. (1985) *How to Cut a Diamond*, Nevada.

Prior Y. (1991) Laser processing of diamonds: Design consideration and future trends. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 28.

Schumacher B. (1991) Polishing review. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 17.

Sevdermish M., Mashiah A. (1996) *The Dealer's Book of Gems and Diamonds*, Vol. 2. Mada Avanim Yekarot Ltd., Israel.

Stewart A.D.G. (1991) Research in the C.S.O. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 3.

Tillander H. (1995) *Diamond Cuts in Historic Jewelry*:1381–1910. Art Books International, London.

Tolkowsky M. (1919) *Diamond Design, A Study of The Reflection and Refraction of Light in a Diamond*. E. & F. N. Spon , London.

Tolkowsky G. (1991) Flower cuts. In Cooke P., Caspi A., Eds., *Proceedings of the International Diamond Technical Symposium*, Tel Aviv, 20–24 October 1991, De Beers CSO Valuation AG, London, Chapter 23.

Vleeschdrager E. (1986) *Hardness 10: Diamond*. Gaston Lachurié, Paris.

Watermeyer B. (1991), *Diamond Cutting—A Complete Guide to Diamond Processing*. Basil Watermeyer, Parkhurst, Johannesburg.

Watermeyer B. (1994) *The Art of Diamond Cutting*, 1st ed. Chapman & Hall, New York.

GEM RHODOCHROSITE FROM THE SWEET HOME MINE, COLORADO

By Kimberly Knox and Bryan K. Lees

Massive banded rhodochrosite has long been used for carvings and other ornamental objects. Although intense red transparent rhodochrosite crystals of remarkable size have been known in Colorado since 1895, not until recently were mining techniques developed to recover them economically. These new mining techniques have combined state-of-the-art equipment and technology to detect and extract large, fine-quality rhodochrosite specimens and gem rough. Although rhodochrosite is a soft mineral, faceted rhodochrosite can be set into jewelry provided it receives special handling and consideration with respect to wear. Faceted rhodochrosite can be readily separated from possible imitations on the basis of standard gemological testing.

ABOUT THE AUTHORS

Ms. Knox, a Graduate Gemologist and artist, is the owner of Golden Pacific Arts, 520 Fifth Ave., San Diego, California 92101. Mr. Lees, a geological engineer, is president of Sweet Home Rhodo, Inc., and owner of The Collector's Edge, P.O. Box 1169, Golden, Colorado 80402.

*U*nusual gemstones have increased markedly in popularity over the last several years. This trend has been stimulated not only by the availability of these materials, but also by new cutting techniques and the creative efforts of innovative jewelry designers willing to integrate unusual materials into their works. Critical acknowledgment and distinction for such materials are earned through such venues as the AGTA Cutting Edge and Spectrum Awards. Faceted rhodochrosite, which was recognized at the 1996 Cutting Edge competition, is one of the most exciting new gem materials to appear as cut stones and in jewelry, following years as one of mineral collectors' most sought-after specimen materials (figure 1).

Although rhodochrosite is softer than almost all other gemstones (even opal), it is harder than some, such as pearl. Properly set and cared for, rhodochrosite can be made into outstanding pins, pendants, tie ornaments, and necklaces.

Until recently, rhodochrosite was primarily available as a pink opaque massive material, with the irregular curved or concentric pattern of gray or white banding that is characteristic of its stalactitic or nodular formation; typically, it is fashioned into cabochons, beads, or ornamental carvings (figure 2). With the recent redevelopment of the Sweet Home mine near Alma, Colorado, large (one over 14 cm, but averaging 2.5 cm), fine specimens of transparent-to-translucent rhodochrosite crystals, as well as small amounts of faceted rhodochrosite, have entered the gem and mineral trade. The faceted gems are usually deep, intense pink to red, typically modified by orange, and completely transparent.

Colorado has been known as a source of fine rhodochrosite since the 1800s, and the Sweet Home has been the most significant producer since 1895 (Jones, 1986). According to Sinkankas (1997, p. 408), the mine is "known worldwide for its unmatched crystals of transparent, vivid red rhodochrosite. . . ."

Although there have been and still are other sources of gem rhodochrosite—for example, South Africa's Kalahari Desert and the Pasto Bueno and other districts in Peru—

Figure 1. Long a favorite of mineral collectors worldwide, some rhodochrosite is now being faceted and even set in jewelry. This 5 × 6 cm rhodochrosite crystal on tetrahedrite and the 21.50 ct cushion-cut rhodochrosite are both from the Sweet Home mine, near Alma, Colorado. Courtesy of The Collector's Edge, Golden, Colorado. Photo © Harold & Erica Van Pelt.

their production has been irregular. The Sweet Home remains the single most important source of fine rhodochrosite specimens and faceted stones.

This article describes the history of rhodochrosite and the geology of the Sweet Home mine. Also discussed and illustrated are the novel, contemporary mining techniques developed by Sweet Home Rhodo, Inc. The results of a basic gemological analysis of eight Sweet Home faceted rhodochrosites are presented, along with identification criteria. Last, cutting and setting techniques specific to rhodochrosite are described in detail.

HISTORY

Rhodochrosite was first described in 1813 by J. F. L. Hausmann, using material from Kapnik, Transylvania. Dr. Franz Mansfeld is credited with introducing North America and Europe (around 1934) to "Inca Rose," the massive rhodochrosite found in abundance in Argentina's Catamarca Province (Shaub, 1972). Reportedly the mine was once worked by Incas for silver and copper (Webster,

1975). Dr. Mansfeld hoped to sell large quantities to institutions of applied arts as a carving material. Although his efforts to integrate rhodochrosite into the applied arts were unsuccessful, he did popularize the massive, opaque form of this stone (Shaub, 1972).

Massive rhodochrosite actually occurs in many localities in addition to Argentina. In Europe, it is found in Romania, Yugoslavia, and Germany; in Australia and its environs, it comes from New South Wales, Victoria, South Australia, and Tasmania (Clark, 1980); and in Mexico, it is known from the Cananea and Santa Eulalia mining districts (Jones, 1978).

However, the single-crystal form of this mineral is relatively rare. In 1887, Dr. George F. Kunz of Tiffany & Company reported finding gem-quality rhodochrosite in Colorado, "the first locality to yield crystals of such magnitude and transparency." A specimen of Sweet Home rhodochrosite that was acquired by the second author in 1987 bore a label from the American Museum of Natural History;
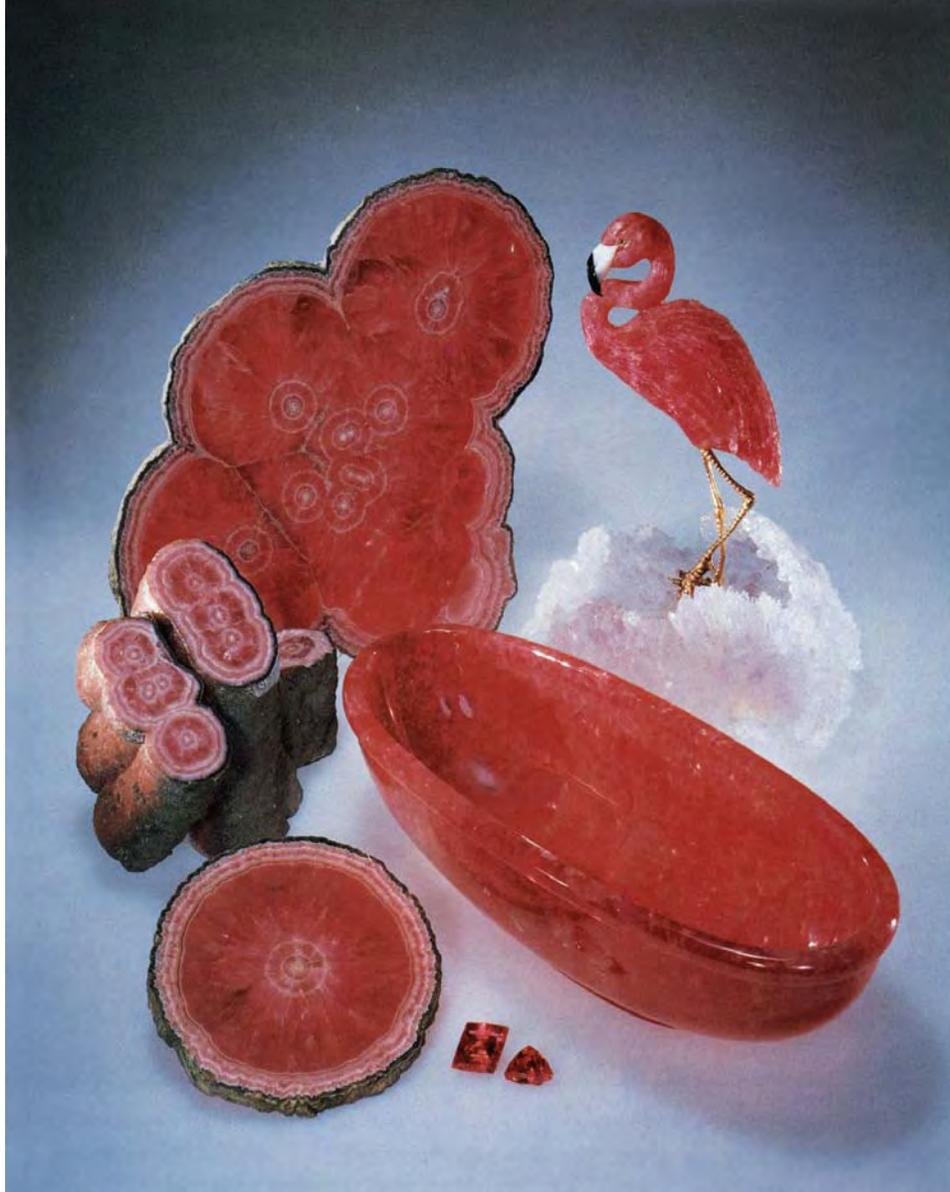
Figure 2. Traditionally, the rhodochrosite seen in the gem trade is the gray- or white-banded massive pink material that has been found in large quantities in Catamarca, Argentina. It is used primarily as beads and cabochons or for carvings. This photo shows some finer examples of this material. The two carvings are accompanied by slices of rhodochrosite taken from large stalactites (similar to the smaller stalactite section shown here). The faceted stones, (5.88 and 17.43 ct), which are from the Hotazel (South Africa) and Sweet Home mines, are included to give some idea of the differences in size between the massive opaque and transparent materials. From the collection of Michael M. Scott; photo © Harold & Erica Van Pelt.

this specimen was traced back to a donation by Tiffany and Company during the 1890s. In addition to the Sweet Home mine, the famous American Tunnel gold mining project of the 1950s in Silverton, the Climax molybdenum and John C. Reed (Alicante) mines (Jones, 1993), and the Moose (Pleasant Valley) and Mickey Breen (Uncompahgre Gorge) mines (Sinkankas, 1997) have also produced rhodochrosite in Colorado.

In 1974, gem-quality rhodochrosite was discovered at the N'Chwaning and Hotazel mines in South Africa's Kalahari manganese fields (Wight, 1985; figure 3). Around the same time, a few superb, large samples of gem-quality rhodochrosite emerged from the Huayllapon mine in the Pasto Bueno district, Pallasca Province, Peru (Clark, 1980; Crowley et al., 1997; figure 4). Since 1985, transparent "deep raspberry-pink to strawberry-red" crystals up to 2.5

cm have been produced from the Uchucchacua mine, in Peru's Oyon Province. However, production from the Kalahari region has been irregular and the crystals are small. Pasto Bueno produced fewer than two dozen "outstanding" rhodochrosite specimens, and the Uchucchacua crystals, like those from Kalahari, are small (Crowley et al., 1997).

An active silver mine since 1872, the Sweet Home (then known as the Home Sweet Home mine) holds one of the earliest U.S. mining patents, No. 106, granted under the General Mining Law of the same year ("Specimen mining," 1994). The mine was operated intermittently almost 90 years, until the 1960s, and extensive tunnels were driven to exploit the mine's silver reserves. During that period, rhodochrosite was regarded as a passing curiosity, and most was discarded on the dumps.

Leonard Beach, owner of the Sweet Home mine

since about 1961, steadfastly maintained that many valuable rhodochrosite specimens were waiting to be retrieved. For over 25 years, through lectures and a circulating mining prospectus, he kept that idea alive. In 1966, following an unproductive silver-exploration effort, contractor John Soules decided to look for rhodochrosite crystals in one of the mine tunnels. A mine map from the 1920s showed a zone where a rich red seam of rhodochrosite had been uncovered but abandoned. This zone was opened and a superb specimen was uncovered (illustrated in Bancroft, 1984, pp. 60–61); it is now in the collection of the Houston Museum of Natural Science.

In 1977, Beach leased the mine to Richard Kosnar and John Saul, owners of the Intercontinental Mining Corporation (Sinkankas, 1997). They uncovered several productive pockets. However, better tools and collecting techniques had to be developed before major pieces could be recovered undamaged.

Most recently, in 1991, the Sweet Home Rhodo, Inc., mining company was founded by a group of investors who were intrigued by Leonard Beach's concept of a stand-alone specimen-mining effort. They spent a quarter of a million dollars to lease and rehabilitate the old mine in order to put it back into production—this time not for silver, but for rhodochrosite specimens. In 1992, the Sweet Home produced the largest specimen known from this locality, the Alma King (figure 5), which contains a rhodochrosite crystal measuring 14.25 cm on a side that sits on a matrix of quartz over 65 cm (more than 2 feet) long. The Alma King is now in the collection of the Denver Museum of Natural History ("Denver fax: Big crystal," 1994).

LOCATION AND ACCESS

The Sweet Home mine lies in the rugged Mosquito Range about 3.8 miles (6 km) northwest of Alma, Colorado, and 80 miles (128 km) southwest of Denver. The Sweet Home lies between two major mining districts: the silver-bearing mines flanking Mount Bross to the north and the gold district to the south (figure 6).

The entrance to the Sweet Home is at 11,600 feet (3,536 m) above sea level. The terrain is steep: Several mountain peaks as high as 14,000 feet (4,267 m) surround the mine. The mine is accessible only two to three months of the year. Mining usually begins in late May, after ice and snow drifts up to 6 m high have been cleared. The only truly snow-free period is between mid-July and mid-August.

Although the mine can be reached by automo-

Figure 3. Another source of fine transparent rhodochrosite crystals is the N'Chwaning mine in northern Cape Province, South Africa. This cluster of red scalenohedral rhodochrosite crystals from N'Chwaning measures 9.5 cm. However, crystals over 3 cm from this region are extremely rare. From the collection of the Houston Museum of Natural Science; photo © Harold & Erica Van Pelt.

bile, the climate and the altitude are harsh. Neither the area nor the nature of the mine—an extensive underground operation with slippery, near-vertical tunnels—is suited for the general public.

GEOLOGY

As noted earlier, gem-quality rhodochrosite has been found in many parts of Colorado (see, e.g., figure 6). Of these, the Climax-Alma area has been the most productive, both in quality and quantity. The region is made up of Precambrian granite and granitic gneiss. About 30 million years ago, this area was intruded by magmas, from which significant amounts of minerals and ore deposits—including the famous Climax porphyry-molybdenum system—formed (Moore et al., 1997).

The Sweet Home deposit sits atop another porphyry-molybdenum system five miles (8 km) east of the Climax system, and the Sweet Home is slightly younger than Climax by one or two million years.

Figure 4. Recovered from Peru's Pasto Bueno district, this rhodochrosite crystal measures 9 cm high. From the Smithsonian Institution collection; photo © Harold & Erica Van Pelt.

Figure 5. The Alma King's largest crystal measures 5-5/8 inches (14.25 cm) on a side. It formed on a matrix of quartz sprinkled with purple fluorite and black sphalerite crystals. From the collection of the Denver Museum of Natural History; photo © Jeff Scovil.

The veins in the Sweet Home mine follow the northeasterly trends that are typical throughout much of the Colorado mineral belt. These veins are polymetallic, principally containing silver, lead, zinc, and copper. The primary ore mineral is silver-bearing tetrahedrite, and rhodochrosite occurs as a gangue (non-ore) mineral inside the ore veins. Other important minerals are galena, chalcopyrite, pyrite, and sphalerite. The ore veins are intersected by north- and east-trending faults.

Rhodochrosite ($MnCO_3$) is deposited from hydrothermal solutions containing metal ions (including manganese), sulfur, carbon, oxygen, and fluorine. These solutions work their way upward from the porphyry-molybdenum system through vertical fissures. When the temperature, pressure, and other conditions are correct, the solutions deposit their minerals along the cavity walls. The sequence of crystallization depends on the relative solubilities of the different mineral species at specific temperatures. For example, at the Sweet Home mine, quartz was the first species to crystallize, followed by tetrahedrite, huebnerite, topaz, and, finally, fluorite and rhodochrosite. As the system cools, for example, quartz will form at about 375°C, whereas rhodochrosite forms at about 300°C. These temperatures were determined by fluid-inclusion analysis of tiny liquid-and-gas inclusions inside crystals of the respective minerals (Moore et al., 1997).

MINING

When, in 1991, Sweet Home Rhodo launched an ambitious effort to uncover and extract fine rhodochrosite specimens, the accumulated debris of almost 100 years was cleaned out, the tunnel walls were widened to accommodate underground loaders, and a new portal (figure 7) was installed together with a high-volume ventilation system. Mine safety and rescue procedures were set up and maintained to code requirements (Lees, 1993, p. 30).

The first major question that needed to be addressed was where to look for the rhodochrosite. On the basis of extensive geologic mapping and target evaluation by Sweet Home Rhodo geologists, a theory was worked out that open spaces capable of containing rhodochrosite typically occurred where the main northeast-trending ore veins were intersected by the fault systems. These potential intersection sites were extrapolated from the mine maps and designated as primary targets. All of these data were assembled via computer-aided drafting to enable two- and three-dimensional analysis (again,
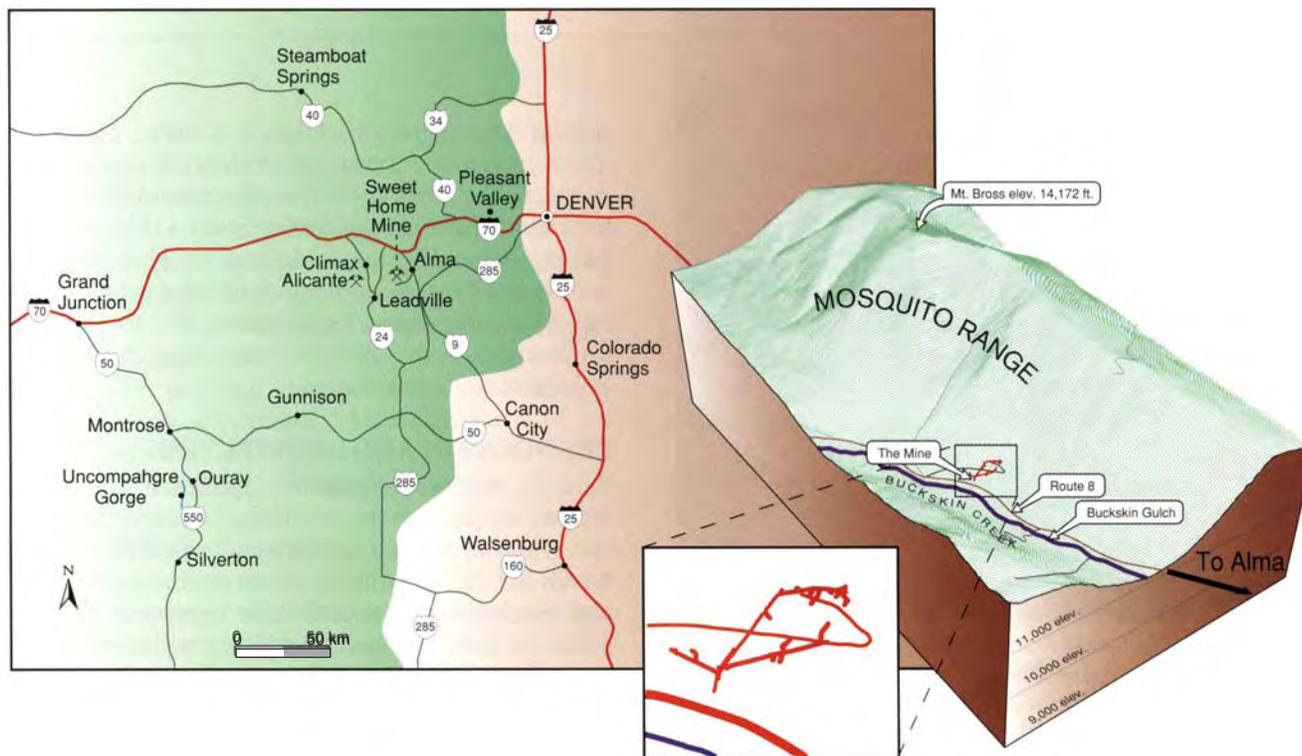
Figure 6. The Sweet Home mine is one of several rhodochrosite-producing localities in Colorado; the cities near which many of these are found are marked on this map of Colorado. The Sweet Home is only a few kilometers from Alma, which is southwest of Denver. In the perspective view looking north-northeast, it can be seen that the mine lies at an altitude above 11,000 feet (3,353 m). Shown in red are the potential intersection sites of the main northeast-trending rhodochrosite-bearing veins and north- or east-trending fault systems, which proved to be the most promising locations for rhodochrosite pockets. Locality map by Jenna MacFarlane. Digitizing and processing of the perspective view by Eugene Kooper; graphics by Bill Tanaka.

see figure 6). During the next few years, these sites turned out to be the primary sources for rhodochrosite pockets.

In addition to geologic mapping, a series of other geologic tools were used to help locate rhodochrosite pockets (Moore et al, 1997). These included:

1. Ground-penetrating radar (GPR) for void detection (see Cook, 1997, for additional information on this technique).

2. Geochemical and microprobe analysis of the host rock to look for trace-element clues that could lead to favorable deposition zones for rhodochrosite.

3. Surface electromagnetic surveys to search for unmapped veins (again, see Cook, 1997).

4. Fluid-inclusion work to identify the best zones for fine quality rhodochrosite and to help build an ore-deposition model.

5. Petrographic evaluation of the ore suite.

After the scientific studies were completed, mining

began and continues to this day. At the Sweet Home, mining involves extensive drilling and blasting along the previously identified ore veins. When the miners near a vein intersection, drilling slows to a careful probing; when contact with a pocket is made, a medical endoscope is used for closer examination. A lens attached to a fiber-optic cable transmits the image of the pocket contents to the observer. To date, a discouraging 90% of the pockets examined have been empty or contained crystals of little value.

Since the veins are nearly vertical in orientation, their intersections with faults are likewise vertical, which has necessitated the development of a series of vertical tunnels called *raises*. These raises ultimately have produced the most value, but they are physically the most difficult to create. The raises progress upward, one blast at a time, from horizontal tunnels excavated into the side of the mountain. After each blast, all of the equipment has to be hauled up ladders to the working face by hand and then taken down again before the next blast. This

Figure 7. The Sweet Home mine is cold, wet, dark, at an extreme altitude, and absolutely inaccessible for all but a few months a year. This new portal leads to an extensive underground mine with slippery, vertical tunnels extending up sometimes 200 feet (61 m) high. Photo © Bryan Lees.

includes drills (approximately 125 pounds [57 kg]), wooden working platforms (several hundred kilograms), hoses, drill steels, and collecting equipment (about 50 kg). Each upward blast advances the face some 1.5 m. Some of the raises reach over 60 m.

When a pocket with top-quality material is identified (figure 8), careful rock removal is critical, as the fragility of rhodochrosite makes its extraction extremely difficult. Two new extraction techniques have shown extraordinary results in specimen recovery. These involve a combination of cutting with a hydraulic diamond chainsaw and hydraulic rock splitting.

First, a chainsaw cut is made along a line around the pocket wall (figure 9). Then, split holes are drilled outside the cut lines, and a hydraulic splitter is inserted into the holes, one at a time, carefully breaking and removing the rock up to the saw cut (figure 10). Once most of the wall rock is removed, the contents of the pocket are carefully removed with the chainsaw. Using this new extraction technique, Sweet Home miners can recover specimens that otherwise would not be viable. Notably, breakage is minimal and few crystals require repair after extraction.

The specimens recovered are indexed, wrapped, and boxed before they are sent to the mine's labora-

tory at The Collector's Edge, in Golden, Colorado. There, each specimen is carefully trimmed and cleaned. The silica that typically coats this material as it emerges from the mine (figure 11) is removed by a combination of acids and air abrasion that avoids any damage to the underlying crystals (figure 12). Most specimens require from five to 10 hours for cleaning; some, like the Alma King, have taken as long as three months.

PRODUCTION AND DISTRIBUTION

Because the Sweet Home is a specimen mine, only broken crystals or those otherwise not suitable for use as mineral specimens are submitted for cutting. Given the current mining methods, easily 100 mineral specimens are successfully recovered for each piece of faceting material. Approximately 100 faceted gems greater than one-half carat have been produced annually since 1992. Over 75% of cut production is represented by stones between 1 and 3 ct. In an average year, fewer than 10 eye-clean stones over 10 ct are produced (P. Cory, pers. comm., 1997). The largest faceted rhodochrosite from North America on record is a 61 ct Sweet Home mine stone (Sinkankas, 1997).

Figure 8. The tiniest evidence of red at the end of the tunnel is the prize at the Sweet Home rhodochrosite mine. Bryan Lees (sitting) and Scott Betz discuss the strategy for extracting the pocket shown here. Photo © Jeff Scovil.
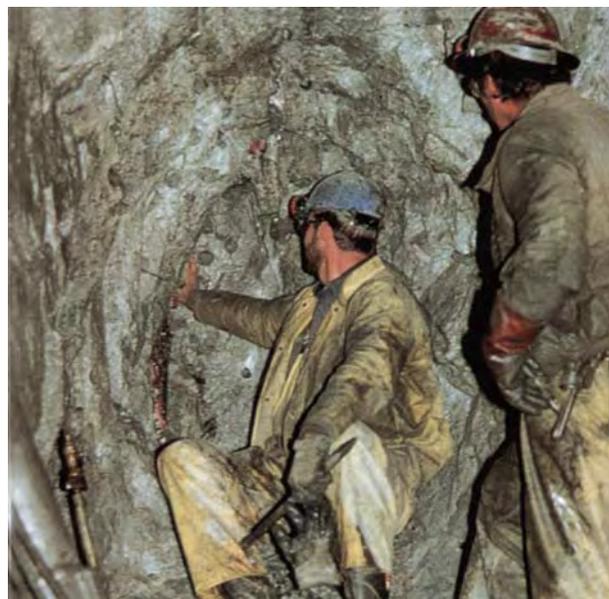
Since 1989, a register of specimens and cut stones from the Sweet Home mine has been maintained by cutter and archivist Paul Cory as a historic record of the rhodochrosites taken from that location. Each crystal specimen and cut stone carries a registration number, the name of the pocket from which it was recovered and approximate date of recovery, the name of the cutter (if appropriate), all pertinent physical characteristics, and, in some cases, specific comments. Although some of the crystals recorded may eventually be faceted, such a record is invaluable to potential collectors.

Approximately 70% of the faceted stones are sold to dealers. The other 30% are sold retail to amateur collectors and retail jewelry buyers. About 80% of those sold to dealers are subsequently purchased by collectors of rare stones or set into jewelry for resale (P. Cory, pers. comm., 1997).

SWEET HOME MINE RHODOCHROSITE

Materials and Methods. Eight faceted rhodochrosites (5.09–26.68 ct) from the Sweet Home mine were examined by Shane McClure of the GIA Gem Trade Laboratory in Carlsbad. A Duplex II refractometer with a near-sodium equivalent light source was used to take the refractive index readings. Specific gravity was determined by the hydrostatic weighing method. On all stones, a desk-model spectroscope was used to examine the absorption spectra. The reaction to ultraviolet radiation was viewed with four-watt long- and short-wave lamps. The internal features in each stone were examined with a standard binocular microscope. The results are given in table 1 and discussed below.

Description of the Material. Rhodochrosite, a trigonal carbonate of manganese, derives its name from the Greek words *rhodon* (rose) and *chrosis* (color; Dana and Ford, 1932). Gem-quality rhodochrosite usually occurs as rhombohedral crystals and occasionally as scalenohedral crystals, with perfect cleavage in three directions. At the Sweet Home mine, the crystals only occur as rhombohedra. These crystals are often accompanied by quartz, fluorite, tetrahedrite, and sphalerite (again, see figures 1, 5, and 12). The translucent-to-opaque banded variety of rhodochrosite is an aggregate, and it is usually found in stalactitic or nodular masses. Massive material has been recovered from veins of the Sweet Home mine, but to date none has been found in any of the pockets.

Figure 9. At Sweet Home, a miner used a hydraulic diamond-impregnated chainsaw to make the initial cut around a pocket. This pocket, recovered in 1994, was named the Corner Pocket, the source of many fine rhodochrosite specimens. Photo © Bryan Lees.

Gemological Characteristics. The eight faceted stones, all of medium quality, ranged from pinkish orange to pink-orange (figure 13). The physical properties of all the samples were remarkably similar: Refractive indices of four stones were 1.600 and over-the-limits of the refractometer, and the other four were 1.599 and over-the-limits. The specific gravity was 3.71 for seven stones and 3.70 for the eighth. Pleochroism was light yellowish orange and orange-pink. The spectrum seen in all eight specimens consisted of a strong narrow band centered at 415 nm and two broader bands from approximately 440 to 470 nm and 540 to 560 nm. There was no fluorescence to either long- or short-wave UV.

Figure 10. Two miners press upward with a splitter, a device similar to the "Jaws of Life," into holes drilled just outside the sawcut made around the Corner Pocket. Photo © Bryan Lees.

Figure 11. When a specimen is first removed from the pocket, it is difficult to know what to expect. While it is clear that a large crystal has been uncovered, its muddy color and the silica coating say little about the gem beneath. Photo © Bryan Lees.

Figure 12. Cleaned of silica and mud by a combination of acids and air abrasion, the specimen in figure 11 emerges as a fine, 16-cm-high, rhodochrosite crystal on snowy white quartz and dark sphalerite crystals. Courtesy of the Collector's Edge; photo © Jeff Scovil.

TABLE 1. Gemological properties of transparent rhodochrosite from the Sweet Home (Colorado) and Hotazel (South Africa) mines.

Characteristic	Sweet Home[a]	Hotazel[b]
Color	Pinkish orange to pink-orange[c]	Pinkish to deep red, with orange, brown, and black secondary colors
Hardness	Not tested	4
Cleavage	Not tested	Easy, perfect rhombohedral
Specific gravity	3.70 – 3.71	3.64
Refractive indices	1.600 – OTL[d] 1.599 – OTL	1.597 – 1.812
Pleochroism	Light yellowish orange and orange-pink	Red and brownish red
UV fluorescence		
Long-wave	Inert	Inert – dull red
Short-wave	Inert	Inert
Absorption spectra	Strong band at 415 nm, two broader bands at 440–470 and 540–560 nm	Band at 535–565 nm, lines at 551 and 410 nm

[a]Information provided by S. F. McClure (pers. comm., 1997) on the basis of eight study stones.
[b]As published in "Rhodochrosite" (1987).
[c]These colors are for the eight stones studied only.
[d]OTL = over the limit of a standard refractometer.

With magnification, it was evident that all stones contained planes of liquid and two-phase (liquid and gas) inclusions; some of the two-phase inclusions were quite large (figure 14). Several stones contained irregular to plate-like transparent dark brown crystals; one had a triangular opaque platelet, and several had straight internal growth striations in two or more directions (again, see figure 14). Note also in figure 14 (right, without a polarizing filter) the strong doubling caused by the high birefringence characteristic of rhodochrosite.

In reviewing the literature for analytical work on rhodochrosite, we examined the results of an informative work published on Hotazel rhodochrosite ("Rhodochrosite," 1987) and compared them to the results for the Sweet Home mine stones (table 1). While there are differences between the Sweet Home and Hotazel rhodochrosites, they are small enough only to indicate (not prove) differences in geographic origin. Because the Catamarcan material is an aggregate—composed also of other distinctly different minerals—and not a crystal, its properties deviate from those of the single-crystal material (see, e.g., Galloni, 1950).

Identification. The identification of single-crystal rhodochrosite from similar-appearing gem materials, such as rhodonite and some Mexican opal, is not difficult because of rhodochrosite's distinctive gemological properties. These include its high birefringence,

Figure 13. Illustrated here are seven of the eight faceted Sweet Home mine rhodochrosites (5.09–26.68 ct) that were tested for this study. Courtesy of the Collector's Edge; photo © Harold & Erica Van Pelt.

characteristic color, and low hardness (for further information, see the *Gem Reference Guide*, 1992).

CUTTING AND SETTING

The Cutting Process. Faceting rhodochrosite requires a great deal of skill and experience. Not only is rhodochrosite very soft, but it also has perfect cleavage in three directions—planes that must be avoided completely during cutting. Following is the technique used by those who cut for the Sweet Home Rhodo mining group.

The material is preformed by hand, slowly and with minimal force, on a 360 grit, continuously wetted grinding wheel. Some of the grinding is accomplished simply by rubbing the stone on a stationary grinding wheel.

The stones are then dopped. The first adhesion of the table to a standard dop is made with ordinary white glue. Once the placement is judged satisfactory, the joint between the dop and the stone is reinforced (surrounded) with a "five-minute" epoxy that

is allowed to cure for one to two hours. Facets are placed first with a 1200 grit flat lap, and then with a tin lap, wax lap, or "Final Lap" (from Diamond Pacific Co.), as the stone requires. Occasionally, as difficulties are encountered, better results are obtained by reversing the rotation of the lap.

Because rhodochrosite is sensitive to heat, the cutter unmounts the stones from the dopstick by immersing the dop and stone together in a bath of methylene chloride (a toxic and flammable substance) at room temperature until the adhesive is completely dissolved and the gem may be removed without any force.

The cutter redops the stone by packing a standard dop with clay, positioning the stone, and surrounding the joined area with five-minute epoxy. The rest of the stone is then faceted, and it is removed from the dop as before (E. Gray, pers. comm., 1997). Occasionally cutters use a wooden dop to reduce the potential for vibrational damage associated with metal dops.

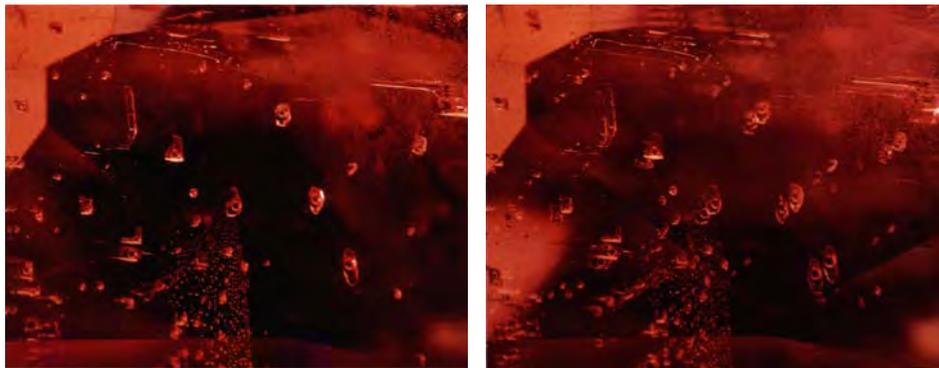It is critical when working with rhodochrosite

Figure 14. Two-phase inclusions were present in all the rhodochrosites examined. Use of a polarizing filter (left) eliminated the strong doubling (right), which results from the high birefringence of the host material. Photomicrographs by Shane F. McClure; magnified 18×.

Figure 15. The Denver Necklace was designed and created to preserve a suite of fine gem rhodochrosites for public display. The center stone is 14.06 ct, with the stones on either side of it about 5.5 ct each, 3 ct each, and 1.5 ct each (moving up the necklace). Designed by Kimberly Knox; created by Knox and Zane A. Gillum of Golden Pacific Arts. Photo © Harold & Erica Van Pelt.

to ensure that the work area is always clean and that all surfaces are soft and nonabrasive. No stone is placed on any surface that has a greater hardness than the gem, and each gem is moved from one pad of clean cotton or felt to another with clean, soft, steady hands; fingers replace metal tweezers.

Setting Techniques. As of March 1997, we knew of at least 35 faceted rhodochrosites from the Sweet Home mine that had been prong-set successfully in gold mountings (P. Cory, pers. comm., 1997).

The setting process for any rhodochrosite first involves a thorough initial cleaning of the entire work area. The stones must be placed safely on a soft cloth when they are not being handled, and any handling should be done only with fingers or soft beeswax. Careful attention must be paid to the angle cut into the prongs, the seat onto which the stone will rest, and to the bearing surface of the upper portion of the prong. Matching these bearing angles exactly to each stone's profile—without any bulges or gaps between the metal and any of the surfaces of the stone—is much more important with rhodochrosite than with gemstones that have greater hardness and toughness profiles. Also uncharacteristic for other faceted gem materials, mountings destined to be set with rhodochrosite must be completely polished and cleaned prior to setting. When fitting the stone into the setting, the jeweler must take care to ensure that the stone barely touches any surface of the setting. A careless bump can cause damage.

The Denver Necklace (cover and figure 15) is an example of the challenges faced when setting rhodochrosite. The necklace was designed and cre-ated by the first author to preserve an unusual suite of gem rhodochrosites for public view. It is now on loan to the Los Angeles County Museum of Natural History. The necklace contains complex and unusually shaped stones, which range from about 1.50 to 14.06 ct, all matched to one another in shape and color. The necklace was designed to mirror the strong shapes and emphasize the rich color of this rare suite of rhodochrosites.

Construction in 20k or 22k gold would have made the setting process possible by more conventional methods, but because of the intricate hinging mechanisms and the additional complication of glass enamel adjacent to every setting junction, we chose the more durable 18k gold. The design called for double-bearing surfaces (i.e., two adjacent surfaces bearing on the stone) at each angle, and even the most painstaking setting methods proved too severe. After several unproductive experiments, and trying also to protect the gems against any possible damage from vibration or thermal shock (as had previously been experienced with specimens), we researched adhesive polymer compounds used by the aerospace industries that (1) maintained long-term elasticity, (2) were good adhesives, (3) had little potential to discolor, and (4) would create a cushion to dampen the effects of both vibration and the differential thermal coefficients of the metal and stone. A polystyrene-based adhesive was selected and chemically modified. Once each stone was fixed in its mounting, we carefully bent the gold over the top.

Care of Rhodochrosite Jewelry. To clean jewelry set with rhodochrosite, soak it in room-temperature soapy water. Rinse the jewelry lightly, rubbing

slightly with your fingers, and then dry it with a very soft cloth. Solvents such as methylene chloride or acetone may also be used. Traditional methods, such as the ultrasonic, steamer, buffing wheel, and mechanical cleaning, must never be employed.

SUMMARY

Although massive rhodochrosite is readily available, transparent gem-quality crystals are relatively rare. Such crystals have been found in few localities: Peru, South Africa, and, most notably, Colorado. In recent years, new exploration and extraction techniques at the Sweet Home mine near Alma, Colorado, have greatly increased the number of fine crystals that are recovered each year.

Because of their rarity and attractiveness, most gem-quality rhodochrosite crystals are preserved as specimens and not submitted to the lapidary. Nevertheless, approximately a hundred 0.5+ ct stones a year are cut from crystals that had been damaged or were otherwise inappropriate for specimen use. Because of its cleavage and softness, faceted rhodochrosite is quite fragile and requires special setting techniques. However, it can be set in jewels such as necklaces and pins that are typically not subjected to direct contact with other surfaces. Extreme care must be taken in cleaning and otherwise handling rhodochrosite jewelry. Because of its distinctive gemological properties, rhodochrosite is readily identified from any similar-appearing materials.

Predicting future potential at the Sweet Home mine is difficult. Because gem-quality rhodochrosite occurs in pockets and not in veins, formulas that are generally used for ore mining are not appropriate. While detection methods continue to improve, nature's code may never be broken: There is still a significant probability of discovering yet another unproductive pocket. Since 1992, the mine has had alternating years of success and disappointment; its continued operation is carefully evaluated annually. Ultimately, the future of the Sweet Home mine depends on advances in the methods used for geophysical exploration.

REFERENCES

Bancroft P. (1984) *Gem & Crystal Treasures*. Western Enterprises, Fallbrook, CA.

Clark B. (1980) Rhodochrosite. *Australian Lapidary Magazine*, Vol. 16, No. 10, pp. 5–6.

Cook F.A. (1997) Applications of geophysics in gemstone exploration. *Gems & Gemology*, Vol. 33, No. 1, pp. 4–23.

Crowley J.A., Currier R. H., Szenics T. (1997) Mines and minerals of Peru. *Mineralogical Record*, Vol. 28, No. 4, pp. 1–98.

Dana E.S., Ford W.E. (1932) *A Textbook of Mineralogy*. John Wiley & Sons, New York.

Denver fax: Big crystal (1994) *Newsweek*, September 1994, p. 6.

Galloni E.E. (1950) The crystal structure of ferroan zincian rhodochrosite. *American Mineralogist*. Vol. 27, pp. 568–569.

Gem Reference Guide (1992) Gemological Institute of America, Santa Monica, CA.

Hausmann J.F.L. (1813) *Handbuch der Mineralogie*. Vandenhöck und Ruprecht, Göttingen.

Jones R. (1978) Mineral in depth: Rhodochrosite. *Rock & Gem*, Vol. 8, No. 7, pp. 28–32, 67–71.

Jones R. (1986) Rhodochrosite: Hot, pink, and pretty. *Rock & Mineral*, Vol. 61, No. 1, pp. 7–8.

Jones R. (1993) Colorado's rhodochrosite. *Rock & Gem*, Vol. 23, No. 2, pp. 42–46.

Kunz G.F. (1887) Rhodochrosite from Colorado. *The American Journal of Science*, Vol. 34, pp. 477–480.

Lees B. (1993) Der Sweet Home Mine, Alma, Colorado. *Lapis*, Vol. 18, No. 2, pp. 30–35.

Moore T., Voynick S., Lees B., Wenrich K., Silberman W., Misantoni D., Reynolds J., Murphy J., Hurlbut J. (in press, 1997) Specimen mining: Article compendium. *Mineralogical Record*.

Rhodochrosite (1987) *Wahroongai News*, Vol. 21, No. 6, p. 18.

Shaub B.M. (1972) Rhodochrosite: The ornamental banded material from Argentina. *Mineral Digest*, Vol. 4, Winter, p. 47.

Sinkankas J. (1997) *Gemstones of North America*, Vol. 3. Geoscience Press, Tucson, AZ, pp. 408, 519.

Specimen mining (1994). *Compressed Air*, Vol. 99, No. 1, pp. 6–13.

Webster R. (1975) *Gems*. Archon Books, Hamden, CT.

Wight W. (1985) Rhodochrosite. *Canadian Gemologist*, Vol. 6, No. 3, pp. 78–81.

Etched CHALCEDONY

In early 1997, a 90.5-mm-long mottled brownish and yellowish orange pierced carving was submitted to the West Coast laboratory for identification. Because the surface was covered with an intricate pattern of swirls, we could not obtain an R.I. reading. Also, the large size precluded specific gravity testing by the hydrostatic method. The carving did have an aggregate optic character, revealed no spectrum when viewed with a handheld spectroscope, and was inert to both long- and short-wave ultraviolet radiation. However, an X-ray powder diffraction pattern (produced from a minute amount of material taken from an inconspicuous spot on the carving) matched that of quartz.

In addition, with magnification and diffused lighting conditions, we saw a raised agate-like banding in many areas of the carving. We also noted that areas within the carved channels appeared to have been dissolved, with most of the ridges between the channels reduced to sharp edges (figure 1). This appearance indicated that the carving had been etched with a caustic solution, such as hydrofluoric acid (which is extremely dangerous). This would also explain the raised nature of the agate-like banding, since acid etching is known to bring out structural irregularities in aggregates. On the basis of this structure and the diffraction pattern, we identified the material as chalcedony. We suspect that this carving was etched to give it an antique appearance.

MLJ, SFM, Dino DeGhionno, and Philip Owens

Figure 1. Details of the surface structure of a chalcedony carving show that the material has been selectively etched, probably by a hydrofluoric acid solution. Note the agate-like bands crossing the etched channels in the carving. Magnified 10×.

Figure 2. A distinctive orange-colored area can be seen under the table and toward the tip of this 1.20 ct heart-shaped Fancy yellow diamond.

DIAMOND

With "Additional" Color

Occasionally we encounter diamonds with overall characteristic color appearances that result from factors other than those that color the diamond itself. For example, inclusions are often responsible for the apparent body color (see, e.g., Fall 1995 Lab Notes, pp. 197–198, and R. C. Kammerling et al., "An Investigation of a Suite of Black Diamond Jewelry," Winter 1990 *Gems & Gemology*, pp. 282–287). In some cases, however, such factors do not affect the overall color, but they do produce an "additional" color. This is well illustrated by a 1.20 ct heart shape recently submitted to the East Coast lab.

Figure 3. Stains in fractures, such as this orange limonitic stain in the stone shown in figure 2, can impart an additional aspect to the color appearance of a diamond. Magnified 32×.

During color grading, we observed a distinct patch of orange that was separate from the yellow body color (figure 2). Closer examination revealed an orange limonitic stain that was confined to a fracture (figure 3). When the stone was viewed in the standard face-up color-grading position, the orange reflections from this stain were seen under the table edge toward the tip of the heart.

In situations such as this where the additional color component does not affect the color grade, a comment is included in the report. We graded this stone Fancy yellow and added the comment: "The orangy color appearance of this diamond is influenced by a stain in a fracture." In our experience, boiling in acid will usually remove such stains.   *John King*

Rough with Contrasting Colors

In recent years, we have been encouraging diamond manufacturers to show us diamonds with a strong green color component when they are still rough or when blocked, because examination of the original crystal surface of such diamonds can be very helpful in determining whether the green component is natural or caused by laboratory treatment. We document the diamond's properties and use these observations along with those of the finished stone when it is submitted for a laboratory grading report. In keeping with this practice, one manufacturer brought us the 2.14 ct piece of green-and-pink rough shown in figure 4.

The slightly distorted octahedron

had the properties of a natural-color pink diamond, especially the pink graining, an absorption at 415 nm visible with a desk-model spectroscope, and blue fluorescence to long-wave UV. The green came from strongly colored green radiation stains that lined several fractures. With magnification, one of these stained fractures showed the spotted appearance typical of natural radiation stains (figure 5). Because these stains were on the surfaces of the fractures and did not penetrate the body of the stone, we predicted that it would be difficult to retain any green color after cutting and polishing—unless one or more of the color-causing fractures were also retained. Ultimately, the rough was cut into a 1.07 ct heart shape that was color graded Fancy Intense purple-pink. All of the fractures were removed during cutting and, as we had predicted, there was no green color in the finished stone.

We have reported radiation stains on colored diamonds before (e.g., in Lab Notes: Summer 1991, p. 110; Fall 1991, pp. 174–175; Winter 1991, p. 249; and Winter 1993, p. 279), but we had not previously seen a stone with such contrasting colors. This example

Figure 4. This 2.14 ct distorted octahedral diamond crystal shows strongly saturated areas of both pink and green.

Figure 5. With 30× magnification, we saw that fractures in the diamond shown in figure 4 have the streaked and spotted appearance typical of natural radiation stains. The green color is largely confined to fracture surfaces.
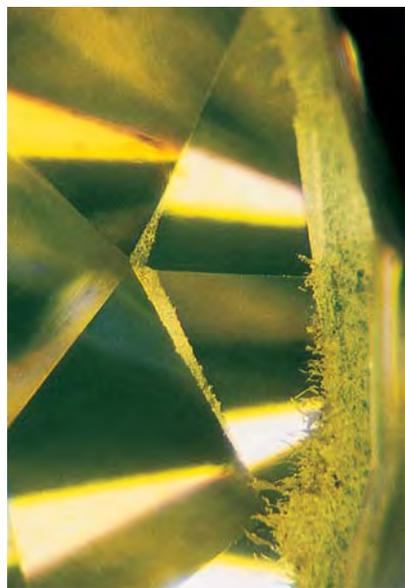
Figure 6. The facet junctions on either side of the upper girdle facets of this 0.59 ct treated green-yellow round brilliant diamond have a frosted, burned appearance that is indicative of heat treatment. Magnified 63×.

is a reminder that any diamond—regardless of its color or inherent properties—may be exposed to natural radiation and thus develop green stains.   *IR*

Treated-Color Yellow Diamonds With Green Graining

Last fall, the East Coast laboratory saw a number of unusual treated-color diamonds. All round brilliants under 1 ct, they displayed highly saturated greenish yellow to yellow-green hues. In the past, diamonds with these colors have been relatively rare, so we were surprised to see several at one time. There were two components to the color in these stones: a saturated yellow body color and a strong green luminescence to visible light. The latter is sometimes referred to as "green transmission." Both the color and the luminescence showed zoned distribution, with brownish yellow graining visible against a pervasive paler yellow body color; only

the graining exhibited green luminescence to a strong visible light source. Prior to examining these particular diamonds, we had believed that green transmission luminescence confined to colored graining was only associated with diamonds of natural color (see, e.g., R. Crowningshield, "Developments and Highlights at GIA's Lab in New York," Spring 1979 *Gems & Gemology*, pp. 153–154). However, other features of these stones proved that this is not always the case.

With magnification, we observed several features that were similar to those observed in diamonds we know to have been burned (see, e.g., Spring 1992 Lab Notes, p. 53). Several of the diamonds showed pitted, frosted surfaces at facet junctions on the crown (figure 6). All of the stones had heavily bearded girdles, and the short fractures in the bearding also had a frosted appearance. Larger fractures, seen in a few of the diamonds, had a similar appearance along their outer edges. At first glance, all the girdles appeared to have been bruted. In reflected light, however, many of them showed remnants of girdle facets, indicating instead that they had been burned. These observations prompted us to look more closely at the other properties relevant to determining the origin of color.

The spectra observed with a desk-model spectroscope showed absorption lines at 415 and 503 nm, with a dark region between 465 and 494 nm, and pairs of absorption and bright emission lines at 513 and 518 nm. (A good example of such a spectrum in a natural-color greenish yellow diamond appears in *Gems & Gemology*, Spring 1961, p. 152.) The fluorescence to long-wave UV radiation was a mixture of greenish yellow and blue, a common response for diamonds with strong green transmission; unlike known natural-color diamonds of this type that we have examined, though, the fluorescence of these stones was strongly chalky.

The spectrophotometer showed us that, in addition to the lines seen with the spectroscope, most of these

diamonds also had a weak peak at 637 nm. We did not see features that we would expect in treated-color yellow or green diamonds, such as the 595 nm line or the GR1 line (741 nm). (The H1b and H1c peaks, which, when present, are seen with mid-infrared FTIR spectroscopy, were also not seen in these stones.) Most significantly, all the diamonds had a peak at 985 nm (in the near-infrared, and thus not visible with a spectroscope), which was weak in some stones and strong in others. This peak at 985 nm is caused by the H2 center (see S. C. Lawton et al., "The 'H2' Optical Transition in Diamond: The Effects of Uniaxial Stress Perturbations, Temperature, and Isotopic Substitution," *Journal of Physics: Condensed Matter*, Vol. 4, 1992, pp. 3439–3452). It has never been observed in a natural-color diamond. However, the H2 peak has been produced by irradiation and heat treatment to extremely high temperatures (greater than 1400°C). Such heat treatment would account for the "burned" surface features we observed in these stones with the microscope.

In general, it is not possible to heat a diamond to these high temperatures for more than a few minutes without a stabilizing factor such as an inert atmosphere or high confining pressure. This suite of diamonds may indicate that a "new" diamond treatment is being used in the trade. Although some factors (such as evidence of burning) may suggest that yellow to yellow-green diamonds have been treated in this fashion, the 985 nm peak is the strongest proof that such treatment has taken place.

IR and TM

EMERALD, An Unusual Assembled Imitation

One of the most elaborate and natural-appearing assembled stones to come to our attention was submitted to the East Coast lab for identification and determination of whether the "emerald" was treated. Weighing just under 1 ct, the stone appeared to be an attractive, moderately included

Figure 7. This 5.95 × 5.92 × 5.23 mm assemblage imitated a fine emerald of 0.98 ct.

Figure 8. Immersed in water, the assembled nature of the stone shown in figure 7 is evident: a faceted gem with a shallow pavilion that has been overlaid with a green material.

emerald (figure 7). The refractive index reading on the table facet was 1.578–1.583, the expected value for natural emerald. A quick microscopic examination through the table revealed the *jardin* typical of natural emerald, as well as a few orange areas in fractures; none of these inclusions extended deep into the pavilion of the stone. As part of the procedure to check for treatment, we exposed the stone to long-wave ultraviolet radiation in a darkened room. (Emerald may fluoresce red or remain inert, whereas some of the materials used to fill fractures in emerald fluoresce yellow.) The fluorescence reaction was definitely not that of emerald, either filled or unfilled: The sample glowed a strong chalky yellow-green! With magnification and UV radiation, we could see that the fluorescence was confined to the pavilion surface.

Because there were no chrome lines in the absorption spectrum, we searched for additional clues to the cause of the strong green color. Immersion of the piece in water revealed a most unusual combination. As seen in figure 8, within the original stone there is the ghost-like outline of another faceted stone, the pavilion of which is considerably shallower than the assemblage as a whole. The dark green color gradually diminishes from the culet upward, ending just below the girdle. Because the refractive index of the pavilion

was 1.50 and the hardness was low on the Mohs scale (as noted with magnification when the needle probe indented a minute area on the surface), we concluded that this portion of the assemblage was a plastic. We were unable to determine if there was even a faint green color in the natural beryl portion of the stone. After careful observation, we determined that the assemblage consisted of a fully faceted natural beryl with a shallow pavilion over which a green plastic had been added to impart the color and add apparent depth. Certainly, if such a stone were mounted, a cursory examination might result in a devastating misidentification. *GRC*

Star FELDSPAR

Asteriated feldspars were once common in the gem trade, but we had not seen one in the GIA Gem Trade Laboratory for several years. In spring 1997, a 64.48 ct dark brown oval double cabochon was submitted to the West Coast lab for identification. It measured about 28.92 × 19.20 × 16.22 mm. In addition to a four-rayed star, it exhibited two parallel bands of chatoyancy (one of which is too faint to be seen in figure 9). The stone had a (spot) refractive index of 1.52 and a specific gravity (measured hydrostatically) of 2.60. It was inert to long-wave UV and fluoresced very weak red to short-wave UV. All these prop-

erties were consistent with a feldspar. An EDXRF spectrum, taken to understand the stone better, detected major amounts of Al, Si, and K, and lesser amounts of Na, Fe, Ga, Sr, Ba, Rb, and Pb. Thus, we determined that it was a potassium feldspar, but we could not establish which feldspar—orthoclase, microcline, or sanidine—without further testing, which was not authorized by the client.

With magnification, we saw platy inclusions—possibly mica—throughout the stone. These appeared to be partially oriented along various planes in the cabochon, one being parallel to the girdle. However, the inclusions were too large and too poorly oriented to account for either of the optical effects. We do not recall seeing another fashioned feldspar gemstone that showed asterism associated with chatoyancy.

MLJ, SFM, Dino DeGhionno, and Philip Owens

JADEITE JADE

Beads of an Unusual Color

An attractive necklace of predominantly brown-and-white (with lesser amounts of green) variegated beads (figure 10), which a client purchased recently in Tucson, was submitted to the East Coast lab for identification. We identified the beads as jadeite on the basis of standard gemological test-

Figure 9. This 64.48 ct feldspar cabochon shows a four-rayed star and two chatoyant bands, one of which is much fainter than the other.

Figure 10. These variegated brown, white, and light green beads (ranging from 8.00 to 10.20 mm) proved to be jadeite.

ing. Although many jadeite boulders have a brown outer layer (or "skin"; see, e.g., figure 6 of Winter 1995 Gem News, p. 278), where the color is due to staining by an iron compound, we do not recall ever having seen beads with this agate-like appearance.

Some years ago, we encountered solid-color brown jadeite cabochons that we believed were the result of such natural staining. More recently we have seen jade of a fairly uniform brown color that appeared to be the result of some type of dyeing process. However, the variegated color of these beads indicates natural color. The fact that a number of the beads in the necklace were banded with grayish green jadeite further supports the conclusion that the color was probably natural and that the beads were cut from near the outside layer of a naturally stained jadeite boulder.

Of the beads that we tested, all exhibited a 437 nm iron line and spot refractive index values within the normal published range for jadeite (about 1.66). For the most part, the beads were inert to both long- and short-wave ultraviolet radiation. The attractive brown-and-white variegated color suggests that these beads had not been subjected to bleaching and impregnation, since the brown veining would most likely be removed during such treatment. Infrared spec-

Figure 11. The green spherules in this polymer-filled cavity in a jadeite bangle make the filler much less conspicuous. Note also the many gas bubbles in the polymer. Magnified 25×.

troscopy on a few of the beads confirmed that they were not polymer impregnated.   *GRC*

**Cavity Impregnated
With a Colored Filler**

Late last year, the West Coast lab was asked to test a bangle bracelet for polymer impregnation. The translucent green bangle, which measured 63.6 mm in diameter and 7.93 mm thick, showed properties typical of jadeite, with blocky grains visible with magnification. Infrared spectra taken on several regions of the bangle demonstrated that it was indeed impregnated with a polymer.

However, bleaching and impregnation was not the only treatment that the bangle had received. A relatively large cavity in the bangle had been filled with a polymer-like substance that fluoresced moderate white to long-wave UV and weak green to short-wave UV. With magnification, this substance was seen to contain numerous tiny green spherules as well as many gas bubbles (figure 11). We suspect that a green coloring agent was added so that the filling material more closely resembled the green jadeite. It certainly made the filled cavity less evident with a cursory examination.

We have previously reported on a polymer-like substance filling the cavities in a bangle (Winter 1994 Lab Notes, pp. 266–267) and used to repair a jadeite carving (Spring 1996 Lab Notes, pp. 46–48). In addition, we have seen a natural stone bead that could have been mistaken for jade with a polymer-filled cavity but in fact was grossular garnet with a softer chlorite-group mineral (Spring 1996 Lab Notes, pp. 45–47).

MLJ and SFM

**Dyed Impregnated Bangle
without a "Dye Band" Spectrum**

As noted in previous entries, significant treatments used on jadeite jade are dyeing, and bleaching followed by impregnation with a polymer or wax. When such treatments are present, the Gem Trade Laboratory notes them explicitly on Identification

Figure 12. Although testing proved that this jadeite bangle had been dyed and polymer impregnated, examination with a handheld spectroscope did not reveal the broad absorption band centered at 640 nm that is typical for dye.

reports. In the case of bleaching and impregnation, infrared spectroscopy is usually needed to identify the treatment conclusively. However, most green dye treatments can be detected by two features revealed during standard gemological examination: (1) color concentrations seen (using magnification) along the boundaries between the jadeite grains, and (2) an absorption "dye band" visible between 630 and 660 nm (as seen, for instance, with a handheld spectroscope).

In spring 1997, a mottled green bangle bracelet measuring 72.6 mm in diameter by 8.21 mm thick (figure 12) was sent to the West Coast laboratory for identification. The bangle had an aggregate optic character, with a refractive index of 1.66. It fluoresced a weak greenish yellow to long-wave ultraviolet radiation, but was inert to short-wave UV. With magnification, the material showed an aggregate structure, with color concentrated along grain boundaries (figure 13) and in some patches. These gemological properties were consistent with jadeite jade that had been dyed green. However, no dye band was visible when the sample was checked with a handheld spectroscope! Nor did we see the three bands (at about 630, 660,

Figure 13. With 20× magnification, dye concentrations between grains could be clearly discerned in the bangle shown in figure 12.

and 690 nm) indicative of chromium in jadeite. Instead, we saw a line at 437 nm (typical for jadeite), a weak band at 600 nm, and a cutoff edge at 650 nm. This spectrum was very unusual, since in our experience jadeite with the depth of color of this bangle should have had either a chromium spectrum, if natural color, or a broad band centered at about 640 nm, if dyed.

We took an infrared spectrum, as we do for all jadeite samples, and found that the bangle had been polymer impregnated. However, because of the lack of a distinctive optical absorption spectrum, we also checked the chemistry using EDXRF spectroscopy. Again, there was no evidence of chromium. We concluded that the bangle was dyed impregnated jadeite jade.

Figure 14. The 8.64 × 6.51 mm doublet in this white metal ring consists of a synthetic spinel crown and a synthetic ruby pavilion.

This is the first instance we can recall where a dyed green jadeite piece did not show the typical dye band in the handheld spectroscope. In light of this development, we strongly advise gemologists to subject *all* green jadeite to careful microscopic examination.

MLJ, SFM, and Dino DeGhionno

RUBY,
Assembled Imitation

Last summer, at the same time that the East Coast lab was testing the synthetic green spinel/natural ruby assemblage (represented as spinel) that was reported in the Winter 1996 Lab Notes (p. 281), the West Coast lab was asked to identify the center red stone in the ring shown in figure 14. The white metal ring was stamped "18K," and the center stone was surrounded by numerous near-colorless round brilliants. Nevertheless, the red oval mixed cut was easily seen to be a doublet consisting of a near-colorless crown cemented to a red pavilion.

The gemological properties of the crown were: R.I.=1.728, singly refractive, medium chalky yellow fluorescence to long-wave UV and strong green fluorescence to short-wave UV. With magnification, we saw small gas bubbles in thread-like arrangements (figure 15). These properties are typical for synthetic spinel, particularly the fluorescence and inclusions. The

Figure 15. Characteristic thready gas bubbles in the synthetic spinel crown and curved striae in the synthetic ruby pavilion are visible in the doublet shown in figure 14 at 40× magnification.

pavilion was doubly refractive, fluoresced moderate red to both long- and short-wave UV radiation, and revealed both curved striae and small gas bubbles with magnification (again, see figure 15). The absorption spectrum, which could only be observed for the doublet as a whole, was typical for ruby. These properties identified the pavilion as synthetic ruby.

A similar doublet was described in the Winter 1984 Lab Notes section (pp. 231–232), but that example was 20 ct. Because of the smaller size of this doublet, and the nature of the mounting, it would more easily be mistaken for a natural ruby. Twelve years after our first encounter with this type of assemblage, we still don't know why such an odd choice of materials was used.

MLJ and SFM

SAPPHIRE,
With Evidence of Heat Treatment

A large proportion of the corundum gems, both ruby and sapphire, seen in the GIA Gem Trade Laboratory have shown evidence of heat treatment. The presence of diagnostic inclusions makes identification of this treatment a straightforward process in many cases. Recently, the East Coast laboratory received a 2.14 ct blue sapphire for identification. The stone contained fine examples of inclusions typical of heat treatment (figure 16). For example, a discoid fracture surrounding a mineral inclusion was prominent under the table; and silk (rutile needles), visible throughout the stone, had been partially resorbed and reduced to strings of "pinpoints." The presence of a small melted cavity with a "fire-skinned" surface, as well as the stone's chalky fluorescence to short-wave UV, provided further evidence of heat treatment.

In addition to these typical features, we saw a very unusual raised area at the culet (figure 17). Careful examination of the culet area with magnification (and with both long- and short-wave UV radiation) strongly

suggested that this raised area was part of the original heat-treated surface of the stone. Such areas are usually removed when a stone is repolished after heat treatment, so that only melted surface areas recessed in cavities may remain. Apparently, the repolishing of this stone after treatment was incomplete.

Additional damage of a quite different appearance was also evident on the pavilion. Rounded spots that had been etched on several pavilion facets (again, see figure 17) had the same appearance as the type of damage sometimes caused by improper jewelry repair. Because corundum is soluble in the heated borax-based fluxes used in jewelry repair, such etched areas can occur on a stone that was not removed from the setting during a repair to the mounting (see, e.g., Summer 1982 Lab Notes, p. 106).

Elizabeth Doyle

SERENDIBITE,
A Rare Gemstone

Last autumn the East Coast laboratory received an identification challenge that turned out to be a truly rare gemstone. The 0.35 ct dark green emerald cut had the following properties: Refractive indices were 1.697 and 1.704. A biaxial optic figure was visible through the pavilion, and the stone showed pleochroic colors of deep blue and pale yellowish green.

Figure 16. A discoid fracture surrounding a mineral inclusion and the partially exsolved rutile needles prove that this 2.14 ct sapphire was heat treated.
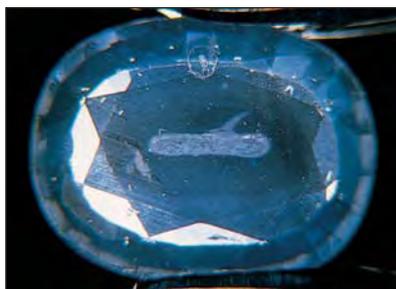
The only features seen with magnification were some transparent to white fingerprint-like inclusions. No fluorescence was observed to either long- or short-wave UV, and a desk-model spectroscope revealed only a weak line at 470 nm. Because of the stone's small size, we used a noncontact measurement device (Sarin's Dia-Mension) to measure the volume of the stone and then computed the specific gravity to be about 3.39.

Although this set of properties ruled out most common gemstones, a careful search of published mineralogical data yielded four minerals that had gemological properties in the observed range: zoisite, dumortierite, serendibite, and sapphirine. The piece was unlikely to be dumortierite, because this material is almost never found in transparent pieces large enough to fashion a 0.35 ct stone. Also, the green zoisite reported to date has different pleochroic colors and absorption spectra (see, e.g., N. R. Barot and E. W. Boehm, "Gem-quality Green Zoisite," *Gems & Gemology*, Spring 1992, pp. 4–15). We next turned to advanced testing techniques to determine whether it was sapphirine, serendibite, or even a possibility that we had not yet considered.

Although the structures of these two minerals differ enough that one could expect their infrared spectra to

Figure 17. The melted surface at the culet of the stone in figure 16 is higher than the surface of the facets, suggesting that the culet was not repolished after treatment. Note also the rounded features that have been etched on some pavilion facets. Magnified 13×.

be distinct, both sapphirine and serendibite are so rare that we did not have reference spectra or even reference stones to which we could compare the spectrum we took. An EDXRF chemical analysis showed silicon, aluminum, magnesium, calcium, iron, and minor amounts of titanium, which is consistent with the chemical formula for serendibite. X-ray diffraction analysis proved conclusively that the gem was serendibite.

Although first described in 1902, serendibite is so rarely seen as a gemstone that it is not found in most gem reference books. We could find no previous mention of it in *Gems & Gemology*, but some of GIA's most senior gemologists recall seeing one specimen in the late 1960s or early 1970s.

The name of this mineral comes from *Serendib*, the old Arabic word for Sri Lanka. This same place name, and a fairy tale about three lucky princes from that island nation, led Horace Walpole to coin the word *serendipity* in the mid-18th century. It was certainly serendipitous that this stone came to our attention.

IR and MLJ

ZIRCON, With "Play-of-Color"

Over the years, we have examined and reported on zircons that displayed a variety of phenomena. These have included aventurescence, chatoyancy, change-of-color, and iridescence. It is not often that we encounter a gem material with a phenomenon that has not been previously reported. It was therefore with great interest that we examined a dark brown zircon cabochon that displayed what appeared to be play-of-color. The gemological properties of this cabochon were typi-

Figure 18. This 12.05 ct brown zircon shows a play-of-color similar to that seen in opal.

cal for zircon: The R.I. was over the limits of the refractometer, the S.G. was 4.15, it was inert to long-wave UV but fluoresced a weak slightly chalky yellow to short-wave UV, and the absorption spectra showed several distinct lines dominated by a pair at 635 nm.

The first thing we noticed on visual inspection were flashes of green and red emanating from several areas of the cabochon (figure 18). We would normally expect such colors in zircon to be iridescence coming from fractures, or perhaps from a finely laminated structure (see *Gems & Gemology*, Spring 1990, p. 108). However, on closer inspection we saw no iridescence in the fractures, and we determined that these flashes of color were coming from three-dimensional regions within the body of the stone. These regions were sharply defined and showed no evidence of a laminated structure (figure
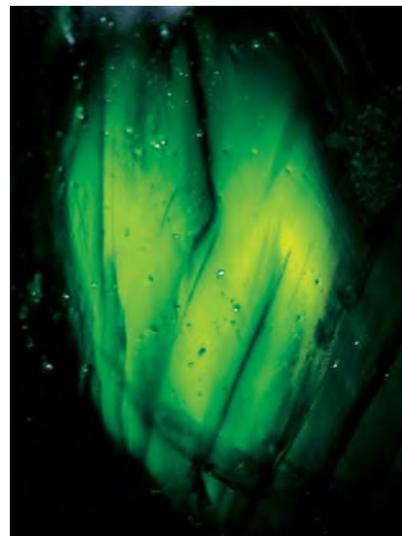

Figure 19. The play-of-color seen in the zircon shown in figure 18 was confined to sharply defined three-dimensional zones, proving that the phenomenon was not due to iridescence from fractures or diffraction from a laminated structure. Magnified 30×.

19). The resemblance of this phenomenon to the play-of-color found in opal was striking and unlike anything we had seen before in zircon. Unfortunately, we could not determine the cause of this phenomenon, because we were not able to perform the necessary structural analysis of the stone in the time that we had available.

SFM

DIAMONDS

Conference on diamond technology. More than 400 scientists—mostly from Europe, the United States, and Japan—attended the DIAMOND 1996 conference in Tours, France, September 8–13, 1996; the attendees specialized in all fields of diamond research, but many were involved with synthetic diamond thin films. The conference was a joint meeting of the 7th European Conference on Diamond, Diamond-Like and Related Materials and the 5th International Conference on the New Diamond Science and Technology (ICNDST-5). Contributing editor Emmanuel Fritsch attended the conference and provided this report.

The conference began with talks about the commercial viability of synthetic diamond thin films. The first goal in achieving commercial viability was to make these thin films as industrial products. Although the consensus was that this goal has been reached, development took longer than expected, and the market for such products is smaller than had been hoped. One reason for the limited market is that synthetic diamond thin films are still expensive. Also, unfamiliar technologies are needed to use these coatings in most customers' applications, so additional education is required. Nevertheless, some applications of synthetic diamond (and diamond-like carbon) thin film technology have already generated over a million dollars in revenue per application. These include hard optical coatings for scanner windows, sunglasses, prescription lenses, and magnetic media; hard coatings for cutting tools and parts subject to heavy industrial wear; laser diode heat sinks; and deposition equipment (reactors) to make thin films. Many other highly specialized "niche" products (such as radiation detectors) have generated smaller, but growing, revenues.

One major field of development for synthetic diamond thin films is electrochemistry—in particular, the use of electrodes coated with conductive thin films (heavily doped with boron). Professor John Angus of Case Western Reserve University, Cleveland, Ohio, described how such electrodes can be used to remove nitrates and other pollutants from water, a process with a potentially enormous market. In another talk, Dr. Pravin Mistry of QQC Inc., Dearborn, Michigan, presented a truly new synthesis technique that uses the combined effects of four "multiplex" lasers to deposit thin films of diamond-like carbon; Dr. Mistry believes that diamond films should be obtainable by the same process.

A number of topics were of gemological interest, if not always directly applicable to gemology. Synthetic diamond thin films now have been successfully deposited on an ever-growing array of materials, including the diamond simulants silicon carbide and strontium titanate, as well as on glasses and various oxide materials usable as gems. In general, a layer with an intermediate composition is first deposited on the substrate material. This guarantees good adhesion (which was lacking in earlier experiments) even when significant shrinkage occurs

Figure 1. The pear-shaped center stone in this ring is a "piggyback" assemblage. The prongs hold a large windowed diamond on top of a smaller pear shape. The assemblage was misrepresented as a 7.78 ct diamond. Photo courtesy of James O'Sullivan.

between the substrate and the thin film during deposition of the film and subsequent cooling. Dr. W. Kalss from the University of Technology, Vienna, Austria, reported the growth of isolated synthetic diamond microcrystals—but not thin films—on precious metals (platinum, palladium, and gold). However, several other teams reported the growth of synthetic diamond film on single-crystal platinum substrates.

Several presentations and posters covered the creation of large, monocrystalline "thick" (about 0.10 mm) films. If such films could be grown thicker, they could be faceted into small mêlée. A method called "tiling" is used to obtain single-crystal films: Adjacent small substrates are crystallographically aligned, like tiles on a wall, and a monocrystalline film is subsequently grown on top of this "multisubstrate." Progress has been made in devising methods for freeing such a newly grown crystal from its substrate. Polycrystalline films are, of course, easier to produce: Large (up to 50 mm in diameter) transparent films up to 1.5 mm thick are now commercially available.

A few posters and talks dealt with high-pressure/high-temperature synthetic diamond monocrystals. Dr. Hisao Kanda from the National Institute for Research in Inorganic Materials (NIRIM), Tsukuba, Japan, reported on some color centers in these monocrystals that were caused by the cobalt used as a solvent during growth. Most of the synthetic diamonds described were yellow to light yellow, types Ib to IaA. The cobalt-related centers did not significantly affect color, but all of Dr. Kanda's samples showed a cobalt-related yellow fluorescence. High-pressure synthetic crystals are being grown in a variety of other solvents. For example, another Japanese team reported on the growth of synthetic diamond crystals in phosphorus that are intended for electronic applications.

A "piggyback" diamond assemblage. Recently, gemologist James O'Sullivan, of Jaylyn, Boca Raton, Florida, told us that he had seen a "piggyback" diamond: an assemblage where two thin diamonds are superimposed to look like a larger stone (see, e.g., Gem Trade Lab Notes, Winter 1985, p. 233.) A customer brought a ring to Mr. O'Sullivan for repair of a loose prong on the center stone, which was supposedly a 7.78 ct pear-shaped diamond of good color (figure 1). On closer examination, the center stone looked shallow and poorly proportioned. With magnification (figure 2), Mr. O'Sullivan saw that it was, in fact, two diamonds—one placed on top of the other. The upper diamond was poorly proportioned and very shallow, with a large window, but the bottom stone was well cut.

Mr. O'Sullivan's client had purchased the ring recently in Florida, with the central assemblage represented as a single stone. Mr. O'Sullivan said that he discovered the misrepresentation because he routinely examines every piece with a microscope before working on it. As with the assemblage in the 1985 Lab Note, the two diamonds were not glued together; the prongs simply held them in place. The platinum filigree mounting hid the bottom stone from view very effectively.

Synthetic diamond thin film jewelry. Jewelry that uses thin films of synthetic diamond (figure 3) was commissioned by Dr. Peter Bachmann of Philips Research Laboratories, Aachen, Germany, a well-known figure in the synthetic diamond thin film research community. Dr. Bachmann told contributing editor Emmanuel Fritsch that he had the parure made for his wife on the occasion of their 25th wedding anniversary. The somewhat drusy plaques in the jewelry were laser cut from a 0.25-mm-thick synthetic diamond plate, 40 mm in diameter, that had weighed 5.5 ct. The larger squares in the jewelry measure 15 mm on edge and weigh 1 ct each; the smaller pieces weigh 0.21 ct each. They were mounted in white and yellow gold by Aachen jeweler Wilhelm Horn.

The plate was grown by microwave plasma chemical vapor deposition (CVD), from a mixture of 2.8% methane in hydrogen gas at about 900°C and at a gas pressure of about 180 mbar. The Raman spectrum of synthetic diamond thin films like those in figure 3 exhibits a single narrow peak at about 1333 cm^{-1}, which indicates that the tiny crystals making up the films are synthetic diamonds of excellent crystallinity (since defects in diamond crystals make this peak wider). The thermal conductivity of the films was measured at slightly over 2200 watts per meter per degree Kelvin, a value comparable to those obtained for natural type II single diamond crystals (see P. K. Bachmann et al., "Thermal Properties of C/H-, C/H/O-, C/H/N-, and C/H/X-Grown Polycrystalline CVD Diamond," *Diamond and Related Materials*, Vol. 4, May 1995, pp. 820–826). Such synthetic diamond films

Figure 2. The true nature of the "stone" shown in figure 1 can be seen when it is viewed from the side: two diamonds in close proximity. Photo courtesy of James O'Sullivan.

Figure 3. This parure, set by Wilhelm Horn, contains pieces of synthetic diamond thin film, the two largest of which weigh about 1 ct. Jewelry courtesy of P. Bachmann; photo by G. Schumacher, Philips Research Laboratories, Aachen, Germany.

are as transparent as glass of similar thickness when polished; the films in this jewelry appear gray because of light scattering from the tiny diamond crystals.

COLORED STONES AND ORGANIC MATERIALS

Color-zoned amethyst from Thunder Bay, Ontario, Canada. We occasionally see slices of ametrine, cut perpendicular to the c-axis, that show yellow and purple

Figure 4. The triangular color zones in this 8.40 ct slice of natural amethyst resemble those seen in ametrine slices. Photo by Maha DeMaggio.
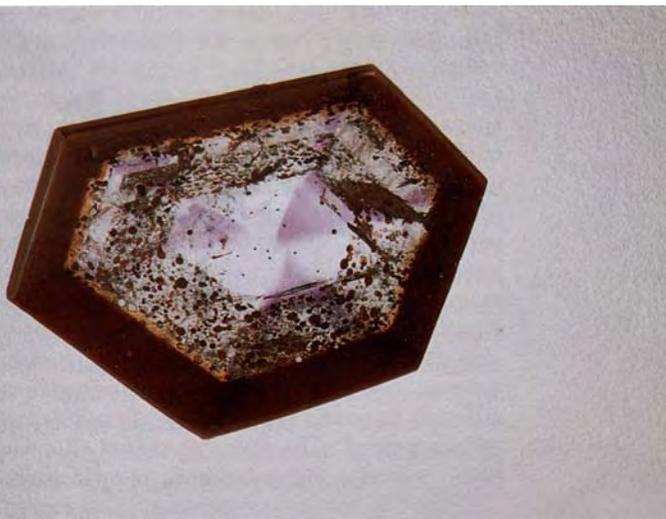
color zones patterned like the universal sign for radiation hazards (see, for example, P. M. Vasconcelos et al., "The Anahí Ametrine Mine, Bolivia," Spring 1994 *Gems & Gemology*, pp. 4–23, especially figures 15 and 20). At a recent Tucson show, contributing editor Shane McClure noticed an 8.40 ct amethyst slice with similar zoning at the booth of Bill Heher, Rare Earth Mining Company, Trumbull, Connecticut. The polished slice (figure 4) still showed the red near-surface phantom layers that are typical of material from Thunder Bay, Ontario, Canada. All of the gemological properties were consistent with natural amethyst. With magnification and polarized light, Brazil Law twinning could be seen in the more intense purple layers. Many natural amethysts are color zoned, so we suspect that others could be cut in this fashion.

Blue- and multicolor-sheen moonstone feldspar from India. We recently had the opportunity to examine three moonstone cabochons that were sent by importer Lance Davidson of Stockton, California. According to Mr. Davidson, these stones come from a site near the town of Patna, in Bihar State, India. Although the deposit was discovered about nine years ago, material has only entered the market in appreciable quantities over the last three years. Some Indian dealers have been marketing it as the "Rainbow" moonstone from southern India; however, those mines no longer produce much high-quality rough.

Mr. Davidson, who markets the stones as "Blue-Rainbow" moonstones, says that most of the material has a "royal" blue sheen, with about 5% having a multi-

Figure 5. These three plagioclase feldspar moonstones are from Bihar State in India; the largest weighs 15.54 ct. Stones courtesy of Lance Davidson; photo by Maha DeMaggio.

color sheen (see examples in figure 5). Large quantities of included material are available, and clean stones up to 1 ct are fairly common. However, clean stones with good color of 5 ct or more are very rare. Smaller pieces and those that are included are faceted into calibrated goods or made into bead necklaces.

We determined the gemological properties of the three cabochons (again, see figure 5): a 7.38 ct round, an 8.34 ct oval (both with predominantly blue labradorescence), and a 15.54 ct oval with "multicolor" labradorescence. All were semitransparent, with a (spot) refractive index of 1.56, a specific gravity of 2.69, and a moderately chalky, even, moderate-blue fluorescence to long-wave ultraviolet radiation. Fluorescence to short-wave UV was

a weakly chalky, evenly distributed, weak pinkish orange. With magnification, all three showed polysynthetic twinning, a feature typical of plagioclase feldspars. Tiny colorless inclusions were visible in the smallest stone. In the Fall 1987 Gem News section (p. 175), Dr. Henry Hänni suggested that "Rainbow" moonstone from India was a labradorite feldspar; the gemological properties of these moonstones are also consistent with labradorite or some other high-calcium plagioclase feldspar (e.g., bytownite). Other moonstone feldspars with blue sheens have been found in Sri Lanka (orthoclase—see P. C. Zwaan, "Sri Lanka: The Gem Island," *Gems & Gemology*, Summer 1982, pp. 62–71), and in New Mexico and other localities (the peristerite variety of albite—see, e.g., Fall 1988 Gem News, pp. 177–178).

"Watermelon" sunstone feldspar carving. Sunstone from Oregon occurs in many hues, including colorless, green, and red-orange. Some stones show all three of these colors. A 32.8 ct tricolor sunstone carving (figure 6), fashioned by Charles Kelly of Tucson, Arizona, shows the concentric color zoning sometimes seen in this material. The carving also shows a playful side of the artisan, in its view of nature in desert regions. In addition to the hummingbird and flower motif, tiny intaglio portraits of a lizard (figure 7), a snake, and a tarantula adorn the carving's base. The piece was shown at the 1997 Tucson shows by the Dust Devil Mining Company, Beaver, Oregon.

Musgravite: A rarity among the rare. For several years now, we have had one particular gem on our research examination "want list." This wanted gem is the mineral musgravite, a very close relative of the rare gemstone taaffeite. Our long search ended recently, when gemologist C. D. (Dee) Parsons of Santa Paula, California, provided the Gem News editors with a transparent, dark

Figure 6. This 32.8 ct tricolor Oregon sunstone was carved by Charles Kelly. Photo by Maha DeMaggio.

Figure 7. In darkfield illumination, some finer details of the carving become apparent, including this dragonfly and lizard. Fine parallel arrays of included copper crystals are also visible. Photomicrograph by Shane F. McClure; magnified 6×.
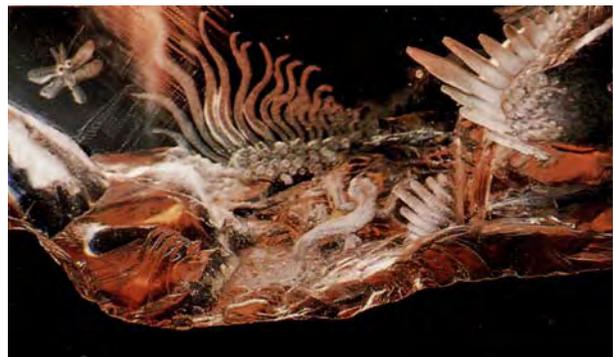
Figure 8. Examination of this 0.60 ct faceted musgravite provided useful identification criteria for this rare gem species. Photo by Maha DeMaggio.

brownish purple, rectangular cushion-shaped step-cut gem that he suspected to be musgravite (figure 8). This stone weighed 0.60 ct and measured approximately 5.53 × 4.77 × 2.86 mm.

The gemological properties of this stone were higher than would be expected for a faceted taaffeite. The refractive indices were n_ω = 1.728 to n_ϵ = 1.721 (uniaxial negative), with a birefringence of 0.007. Specific gravity, obtained in three separate readings by the hydrostatic

method, averaged 3.69. Only a weak absorption spectrum was seen with the Beck prism spectroscope, with no characteristic features that would be useful in identification. Not surprisingly, because iron was a major component, the stone was inert to UV radiation. No inclusions were observed in this stone with a gemological microscope.

Mr. Parsons gave us permission to characterize this stone further by means of energy dispersive X-ray fluorescence (EDXRF) and X-ray powder diffraction analyses, so that we could positively identify the material and obtain much-needed data for our reference files. The EDXRF qualitative chemical analysis, performed by Sam Muhlmeister of GIA Research, showed the presence of aluminum and magnesium, as would be expected from the formula for musgravite, $(Mg,Fe^{+2},Zn)_2Al_6BeO_{12}$ (M. Fleischer and J. A. Mandarino, *Glossary of Mineral Species 1991*, Mineralogical Record Inc., Tucson). Also detected were iron and zinc as major elements, with traces of gallium and manganese. (Beryllium and oxygen are not detectable with our EDXRF system.) Although taaffeite's ideal chemical formula $(Mg_3Al_8BeO_{16})$ does not include iron and zinc as major components, these elements might be present as substitutions. Nor is the presence of iron and zinc, as detected by EDXRF, proof that a taaffeite-like gem is actually musgravite. However, detection of these elements in significant amounts should suggest that additional testing is required before identifying a stone as taaffeite.

X-ray diffraction analysis finally proved that this stone was musgravite. Contributing editor Dino DeGhionno obtained a minute amount of powder from the stone's girdle. From that powder, he obtained an X-ray diffraction pattern that was indicative of musgravite—not taaffeite.

Figure 9. The unusual optical effect in these cultured pearls (largest, 14.5 mm) is caused by faceting. Courtesy of Komatsu Diamond Industry; photo by Maha DeMaggio.

Figure 10. Light reflecting off one facet of this "Komatsu Flower Pearl" shows that the facet is flat, not convex as it appears to the unaided eye. Photomicrograph by Shane F. McClure; magnified 23×.
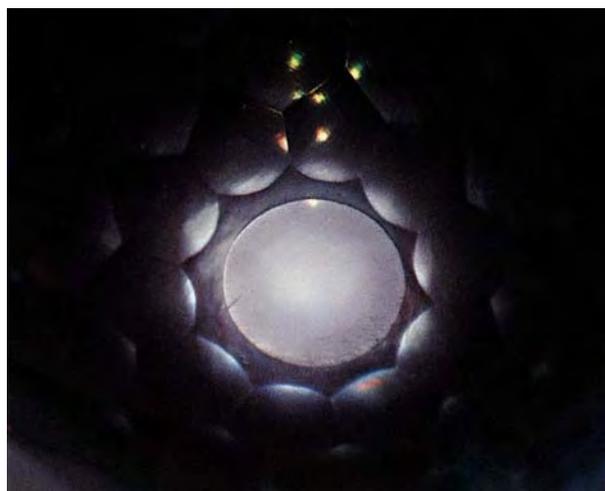
Analysis of this musgravite gave us sufficient reference data to help separate musgravite from taaffeite in the future. Indications of whether a stone is musgravite or taaffeite can be obtained from refractive index and specific gravity determinations, as well as through EDXRF analysis. However, only X-ray diffraction analysis can provide conclusive proof.

Faceted cultured pearls. One of the most interesting discoveries we made at Tucson this year was, in our experience, a unique method of fashioning cultured pearls. Komatsu Diamond Industry of Kofu City, Yamanashi, Japan, is *faceting* Tahitian, South Sea, freshwater, and mabe cultured pearls. The finished products are being marketed as "Komatsu Flower Pearls" (figure 9). According to Komatsu literature, the company is using a faceting technique that was developed in 1992 by Kazuo Komatsu, who was trained as a diamond cutter. Since it would be undesirable to cut through to the shell bead, the cultured pearls selected for this technique must have thick nacre layers. Each fashioned pearl has 108–172 facets and should only require the same care as for more typical cultured pearls, according to Komatsu. However, the manufacturer cautions against polishing mounted "Komatsu Flower Pearls" with a buffer.

We examined 10 of these cultured pearls. The faceting produces a very curious optical effect: All of the facets appear to be distinctly convex. However, closer inspection with a microscope and reflected light showed that the facets were indeed flat (figure 10). The curved effect is apparently produced by the flat facets cutting through the numerous individual curved layers of nacre, bringing deep nacre layers closer to the surface in the middle of the facets. In some cases, remnants of the original surface can be seen between facets.

Inclusions in quartz as design elements. For some time, inclusions in gems have been used to characterize gem materials, and to determine (for instance) their natural or synthetic origins. Many gemologists also appreciate the beauty of inclusions in the microscope. Today, however, more gem cutters and jewelry designers are recognizing the aesthetic appeal of gems with large, prominent inclusions, and they are fashioning gems to display these inclusions to best effect. Examples that we have seen include: quartz with a three-dimensional jasper(?) scene (Lab Notes, Fall 1987, pp. 166–167) and with a magnified plane of three-phase inclusions (Gem News, Summer 1993, pp. 132–133); morganite beryl with an iridescent fracture plane (Gem News, Summer 1996, pp. 132–133); and a faceted tanzanite with a "wagon-wheel" appearance caused by a centered needle inclusion (Gem News, Summer 1994, p. 128).

Last year, Judith Whitehead, a colored-stone dealer from San Francisco, California, showed us a few samples of fashioned rock-crystal quartz that had bold patterns of included rutile and what appeared to be carbonate crys-

Figure 11. An aesthetically pleasing pattern of rutile and carbonate(?) inclusions adds a special design element to this 33.38 ct rock-crystal quartz cabochon. Courtesy of Judith Whitehead; photo by Maha DeMaggio.

tals. One such stone, a 33.38 ct pear-shaped double cabochon, is shown in figure 11. According to Ms. Whitehead, this is one of several pieces from a piece of rough that Roger Trontz, of Jupiter, Florida, found and had cut. The identification of the rutile was obvious. However, the sparse but prominent rhombohedral crystals, with slightly curved light brown surfaces, might have been calcite, magnesite, dolomite, ankerite, siderite, or some other mineral (though probably a rhombohedral carbonate).

Another example is a pendant that was recently sent to the Gem News editors for examination. Created by Kevin Lane Smith of Tucson, Arizona, the pendant was a free-form design that weighed 121.50 ct and measured 54.58 × 40.09 × 7.80 mm (figure 12). It was fashioned from Brazilian rock-crystal quartz. What makes this creation unique is that an intricate system of large fluid inclusions dictated the overall shape of the finished piece.

With magnification, it was evident that portions of the overall fluid inclusion pattern had been drained of fluid, because they were decorated with an epigenetic iron-containing compound in various shades of yellow to brownish yellow. Other portions of the fluid inclusion system remained intact; some even contained minute mobile gas bubbles. The overall effect produced by the presence of the inclusions in this pendant suggests ancient writing in clay or stone.

Figure 12. Fluid inclusions provide the design element in this 121.50 ct rock-crystal quartz pendant. With magnification (inset), it is evident that some areas have been drained of fluid and stained with iron-colored epigenetic matter. Photo by Maha DeMaggio. Inset photomicrograph by John I. Koivula; magnified 5×.

TREATMENTS

A new emerald filler. Arthur Groom–Gematrat, of New York and other cities, has reportedly developed a new filling material for emeralds, which was introduced to the trade at the Las Vegas JC-K show in June. Before the show, the Gem News editors spoke with Fernando Garzón of Arthur Groom–Gematrat, who loaned us an emerald for examination both before and after treatment, together with some samples of this and other emerald filler materials.

The 15.22 ct emerald was first cleaned by a special technique the company developed to remove any evidence of previous filling material (figure 13, left). Then it was refilled using the new, proprietary method (figure 13, right). According to Mr. Garzón, the filler consists of a resin and a catalyst (that is, a hardening agent). It can be removed with warm acetone and isopropyl alcohol; how-

ever, it is durable enough that the emerald can be recut with the filler in place.

Mr. Garzón also showed us glass test tubes of the new filler (resin plus catalyst) and Opticon (resin plus catalyst), which were poured in pairs at six-month intervals, beginning about three years before our examination. These samples were intended to demonstrate that, in comparison with Opticon, the new filler is not yellow when first poured, nor does it turn yellow over time. We hope to present more information about this filler at a later date. Emeralds filled with this new material are being studied by GIA Research and the GIA GTL Identification Department as part of a comprehensive study of emerald treatments.

SYNTHETICS AND SIMULANTS

Update on vanadium-bearing synthetic chrysoberyl. Green vanadium-bearing chrysoberyl (with no change of color) was described in the Fall 1996 Gem News section (pp. 215–216). Natural stones were stated to originate from one of the new deposits in southern Tanzania, and synthetic material of similar appearance was being grown in Russia. As reported in that entry, electron microprobe analysis and EDXRF spectroscopy of one natural and two synthetic samples revealed differences in the amounts of trace elements they contained.

Contributing editor Karl Schmetzer subsequently examined one 1.75 ct "rough" sample of this synthetic material and the two faceted samples (1.00 and 1.12 ct) illustrated in the Fall 1966 entry, all of which were made available to him by the SSEF in Basel, Switzerland. The gemological properties of these synthetic chrysoberyls were within the range of values reported for their natural counterparts. These include: refractive indices of n_α = 1.742–1.743, n_γ = 1.751–1.752; a birefringence of 0.008–0.009; a specific gravity of 3.76; and no reaction (inert) to both long- and short-wave UV radiation. With careful microscopic examination, all three samples revealed a distinct pattern of curved growth striations, which was clearly visible using methylene iodide as the immersion liquid (figures 14 and 15). In addition, the unfashioned sample contained small, slightly elongated bubbles in the outer growth zones of the crystal.

The microscopic properties of the three samples indicated a growth from the melt. In general, however, the growth pattern of these synthetic chrysoberyls differed from the more regular curved growth striations seen previously in Czochralski-pulled synthetic alexandrites. The distributor had mentioned the floating-zone method, but the growth pattern of this material is completely different from previously examined synthetic alexandrites grown by Seiko using the floating-zone technique. However, a brief item in a Fall 1994 Gem News entry about new Russian production of synthetic gems (p. 200) did mention the synthesis of nonphenomenal green chrysoberyl in Novosibirsk by means of the hori-
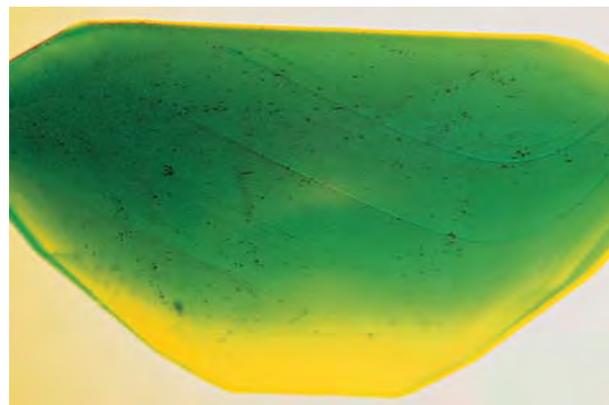
Figure 13. These photos show the appearance of a 15.22 ct emerald before (left) and after (right) it was filled by a new, proprietary method being marketed by Arthur Groom–Gematrat. Photos by Maha DeMaggio.

zontal-growth method. In this modified floating-zone technique, a flat container with nutrient is moved horizontally through a high-temperature melting zone in a specially designed furnace. If this technique is the growth method for the samples described above, then the irregular growth pattern becomes understandable.

"Cat's-eye" synthetic emerald. Usually, a 6 ct rectangular block of transparent synthetic emerald would be fashioned in a way to minimize weight loss. However, we obtained a block that had been sliced on five sides; one large side retained its rough crystal surface with an array of many subparallel growth steps. (The block was grown in Russia by the hydrothermal process.) No inclusions were visible through the rough faces of this highly transparent piece.

We recently examined, photographed, and described

some fashioned natural gem materials with decorative crystal faces incorporated into their design (Gem News, Winter 1996, p. 283). With this in mind, we tried to think of a way to incorporate the rough face with the growth steps into the finished stone, instead of grinding it off to produce a traditional flat facet.

The first idea was to keep the rough surface as a table facet on a rectangular emerald cut. However, because the growth steps appeared to be highly reflective, we decided to create an oval cabochon, with the growth steps remaining on the base of the finished piece, in the hope that some interesting reflections might be projected and magnified through the dome.

The rough block was turned over for cutting to Phil Owens, a gemologist and lapidary in the GIA GTL Gem Identification Department. The result was somewhat surprising: The finished cabochon actually showed a

Figure 14. When immersed in methylene iodide, this Russian synthetic nonphenomenal green chrysoberyl shows strong bands of curved zoning. Photomicrograph by Karl Schmetzer; magnified 30×.

Figure 15. At higher magnification, the irregular nature of these growth bands becomes evident. Photomicrograph by Karl Schmetzer; magnified 60×.
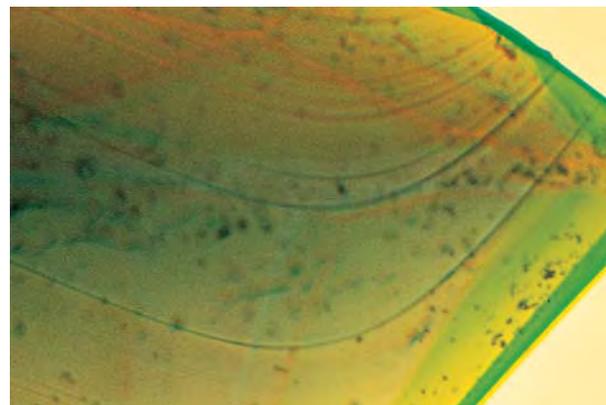
Figure 16. A weak cat's-eye effect can be seen in this 4.77 ct cabochon of Russian hydrothermal synthetic emerald, which retained on its base the original rough surface. Photo by Maha DeMaggio.

Figure 17. The base of the synthetic emerald cabochon in figure 16 is decorated with an array of subparallel growth steps, which cause the cat's-eye effect. Photo by Maha DeMaggio.

weak cat's-eye effect in reflected light (figure 16). This could be attributed to the fact that the growth steps on the base of the cabochon were subparallel and aligned perpendicular to the length of the finished piece (figure 17). Light entering the cabochon is reflected by the growth steps and is concentrated, on its return, across the length of the cabochon's dome.

Emerald rough—buyer beware! Apparently, imitations of Zambian emerald crystals are as common now as they were back in the late 1980s and early '90s.

The Spring 1989 Gem News section (pp. 50–51) contained two reports on quartz imitations of emerald crystals that had been purchased by emerald buyers in southern Africa. In these reports, the emerald "crystals" were actually composed of fragments of quartz crystals that had been glued together with a green epoxy resin. The evidence of assembly was hidden by a glue coating on the surface that was covered by small mica flakes and other bits of fake matrix, which also gave the specimens a more realistic appearance. An almost identical imitation was reported by another contributor in the Summer 1990 section (pp. 167–168). In Spring 1990 (pp. 108–109), we reported on a five-sided (!) glass imitation of an emerald crystal, which had been obtained in Zambia by a group of Zambian emerald dealers. The rough surfaces were enhanced with an orangy brown clay-like "matrix" and flakes of mica.

The most recent imitation brought to our attention, by gemologist John Fuhrbach, has some features not seen in previous imitations. When Mr. Fuhrbach, of Amarillo, Texas, visited Zambia with his wife in the summer of

Figure 18. This "matrix"-decorated, green-coated smoky quartz crystal imitation of emerald was obtained during a visit to Zambia. As shown here, it weighed 473 ct. Photo by Maha DeMaggio.

Figure 19. After removal of the "matrix" and coating from the imitation Zambian emerald, the underlying smoky quartz crystal weighed 407 ct. Photo by Maha DeMaggio.

1996, they were offered several fake emerald crystal specimens by local "gem dealers." Some of these rough "emeralds" were large and gemmy looking, and a real bargain at only US$450 per gram. To a typical tourist with no knowledge of emeralds, these might prove too tempting to resist. However, a trained gemologist could easily detect these fakes, even with a simple 10× loupe. Mr. Fuhrbach eventually obtained one such specimen (figure 18) to examine gemologically, for substantially less than the original asking price.

Unlike previous imitations that we have examined, this specimen was manufactured with a transparent, singly terminated quartz crystal. The crystal was not fractured and glued back together, as we have seen in the past; instead, it was coated with a transparent bluish green, plastic-like material. This colored coating also served as a glue to attach epoxy-laden "matrix" material to the crystal, hiding the quartz termination. With magnification, the "matrix" appeared to be composed of crushed rock, possibly granite, and a micaceous-looking substance. In the coating itself, dust and many small fibers were visible, another obvious piece of evidence. The coating was so thick that junctions between adjacent crystal faces—which should have been sharp—were appreciably rounded.

Mr. Fuhrbach decided to strip off the coating and matrix to see what the original starting material actually looked like. After experimenting with various organic solvents, he found acetone to be the most successful. *[Note that acetone is highly flammable and can cause significant health problems if used improperly.]* Before treatment, the specimen weighed 473 ct (94.6 g); after ultrasonic dissolution in acetone for 24 hours, the remaining light-brown smoky quartz crystal (figure 19) weighed 407 ct.

A bonus to this story is that the smoky quartz crystal was itself host to two tourmaline crystals and a large mica crystal. The largest tourmaline, 12 mm long, was a transparent, singly terminated pink-and-green bicolor. The mica inclusion appeared to be colorless, and it measured about 10 mm on its longest dimension. At least two, and possibly three, large faceted stones—each containing a beautiful inclusion—could be cut from this one quartz crystal.

An especially misleading quench-crackled synthetic ruby. Contributing editor Henry Hänni encountered a tricky identification challenge at the SSEF. A 6.47 ct red octagonal step cut (figure 20) was received from a client who wanted the origin of this "probably Burmese ruby" determined. Staff members at the lab quickly noticed extended fractures in the sample, which showed evidence of a foreign material that contained large, flat bubbles. They assumed that the filling was a glassy substance. Two possibilities were a natural ruby that had been heat treated to an extreme degree, or a synthetic ruby that had been quench-crackled, with the glassy fill-

ing added to mask its synthetic nature.

In the course of further study of the inclusions, the staff members found a series of narrow twin lamellae, meeting at an 86° angle at one corner (figure 21, left). These structural features were best seen when the stone was immersed in methylene iodide and viewed between crossed polarizers. Such twinning is common in natural rubies from various localities (see, e.g., H. A. Hänni and K. Schmetzer, "New Rubies from the Morogoro Area, Tanzania," Fall 1991 *Gems & Gemology*, pp. 156–167), but it is also occasionally seen in synthetic corundums (see, e.g., Winter 1991 Lab Notes, pp. 252–253). The most surprising feature of this synthetic was the very fine Verneuil banding (figure 21, right), well hidden by the treatment features, which provided the conclusive identification of this piece as a quench-crackled synthetic ruby. No individual or swarms of gas bubbles were seen in the body of this synthetic (as opposed to in the fractures), but the extensive fracture system made it hard to detect such small features. This identification experience led Dr. Hänni to wonder whether similar treated synthetics had been reported in the past; he found this to be the case (see, e.g., J. M. Duroc-Danner, "Radioactive Glass Imitation and an Unusual Verneuil Synthetic Ruby," *Journal of Gemmology*, Vol. 23, No. 2, 1992, pp. 80–83).

New information on flux-grown red spinel from Russia. Since the late 1980s, Russian-produced transparent flux-grown red and blue synthetic spinels have become increasingly available in the trade, both as crystals and as fashioned stones. A detailed report on this synthetic

Figure 20. This 6.47 ct Verneuil synthetic ruby (12.23 × 8.28 × 5.54 mm) had been heat treated to induce cracks that were then filled with a glassy material. Photo by H. A. Hänni.
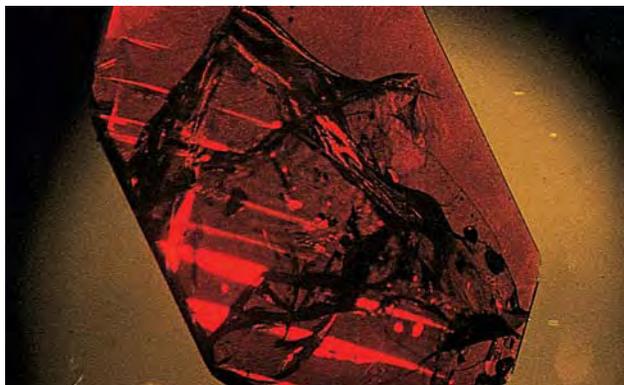
Figure 21. When the sample shown in figure 20 was immersed and viewed between crossed polarizers, two sets of rhombohedral twinning lamellae became visible (seen here on the left side of the photo to the left). Further examination revealed fine Verneuil color banding (seen here in the upper right corner of the photo to the right), which proved that the ruby is synthetic. Photomicrographs by H. A. Hänni.

material (S. Muhlmeister et al., Summer 1993 *Gems & Gemology*, pp. 81–98) noted that one particular type of inclusion was only observed in the blue material. This unusual "dendritic" inclusion forms as distinctly shaped, extremely thin, delicate fans (figure 22).

At the time of the initial report, this type of inclusion was also considered to be diagnostic and quite valuable for separating these synthetic blue spinels from their natural counterparts, particularly from Sri Lankan blue spinels that derive their color from trace amounts of cobalt. It could not be determined why these inclusions were only found in the blue material, and why they were not also seen in the red flux-grown synthetic spinels.

During recent examination of 16 Russian flux-grown synthetic red spinels at the West Coast GIA Gem Trade Laboratory, this inconsistency was put to rest: Three of the stones contained dendritic inclusions iden-tical to those observed in the blue synthetics. These inclusions appear opaque in darkfield illumination. In transmitted light, they may show slight translucency, with a dark reddish brown color (figure 23), but reflected light reveals an obvious metallic luster. Because at this time destructive testing would be needed to determine the nature of the material in these dendritic inclusions, and because of the limited number of included speci-mens that were available, we have not yet identified these inclusions.

Erratum

The tourmaline specimen on the cover of the Spring 1997 issue of Gems & Gemology *is from the Queen mine in the Pala District of California. The incorrect district was listed in that issue.*

Figure 22. Dendritic inclusions such as this one were first thought to be limited to Russian flux-grown blue synthetic spinels. Photomicrograph by John I. Koivula; magnified 20×.

Figure 23. Extremely thin and translucent dendritic inclusions have now been observed in Russian flux-grown red synthetic spinels. Photomicrograph by John I. Koivula; magnified 20×.
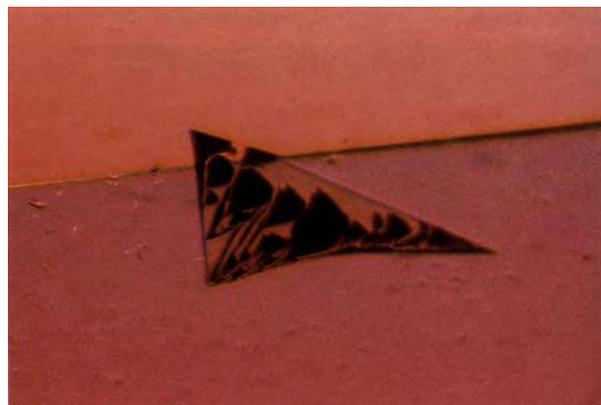
THANK YOU, DONORS

The Treasured Gifts Council, chaired by Jeanne Larson and co-chaired internationally by Martin Harman, has been established to encourage individual and corporate gifts-in-kind of stones, library materials, or other non-cash assets which can be used directly in GIA's educational and research activities. Gifts-in-kind help GIA serve the gem and jewelry industry worldwide while offering donors significant philanthropic and tax benefits. Treasured Gifts Awards are presented to those who have given gifts valued at $10,000 or more. We extend a most sincere thank you to all those listed below who have contributed to the Treasured Gifts Council in 1996.

Treasured Gifts Council Diamond Award
Rio Grande

Treasured Gifts Silver Award
Lelia Larson
Nancy B & Company
Ramsey Gem Imports, Inc.

Treasured Gifts Award
D. Swarovski & Co.
August and Margaret Hansch
Manufacturing Jewelers & Silversmiths of America
Sierra Gems
Robert H. Vanderkay
Vardi Stonehouse, Inc.

Special Recognition Award
The Foredom Electric Co.
Paul H. Gesswein & Co.

Treasured Gifts Donors
A & A Gem Corp.
Susan Adams
Alishan
Ambras Trading Corp.
The Annexton Co.
Antique Cupboard
Argyle Diamonds
Assured Loan Co.
Helen M. Baldwin
Diana Barnhill
Mary E. Barrz
David Barzilay
Bear Essentials
K.C. Bell
Stuart Benjamin
Berthet Jewelers

Marc Bielenberg
Black Mountain Jewelry
Mary Jane Bloomingdale
Mojave Blue
Bluewater Jewelers
Bob Simmons Jeweler
Bremer Jewelry
James Breski
Michael Cabnet
Cabochon Gems & Designs
Edgar Cambere
Capalion Enterprise
Carats Inc.
Cheryl Brooks Designs
Christensen Jewelers
Michael Christie
Donald Clary
Jo Ellen Cole
Colorado Gem & Mineral Company
Bill Conn
James C. Corliss
Michael Couch, Inc.
Arthur Croll
D. Hillhouse
Barry D. Davis
Martin B. de Silva
Dia/Gem Corp.
Lorraine D. Dodds
Diane Dolan
Donald K. Olson & Assocs.
Patricia A. Doolittle
Victoria DuPont
Luella W. Dykhuis
Edrin, Inc.
Epsilon Jewelry
Esslinger & Co.
Ethio-American Development Co.
Exclusive Merchandisers, Incorporated

Jim F. Ferguson
Fersman Mineralogical Museum
Anne W. Findlay
Gloria Fischer
Four Clover Mine
Alan Friedman
Edward J. Gübelin
Arthur H. Gaspar
Gem Cut Co.
Gem-Fare
Gems by Janzen
Gems by Jess
Gemstones
Golay Buchel USA, Ltd.
Gold & Silver Creations
Golden Pacific Arts
The Golden Swann Jewelers & Collectible
Ellen S. Grable
Abby Grunewald
Maggi R. Gunn
Patrick J. Hanratty
Barry Hansen
David Hargett
Harpaz Gem & Pearl, Inc.
Douglas R. Harris
Robert S. Harris
Heyden Stones
Esther Marie Hillman
Peter Hitch
Honeyman's Jewelry
Donald B. Hoover
Alex & Keith Horst
Margaret A. Howard
Peggy Hutchinson
Idelle Hammond-Sass Design
Investment Gems, Inc.
Jan David Design Jewelers
Jewelry Arts, Inc.
Jewels By Angelo, Inc.

Jewels By Nicholas
Robert E. Johnson
Terry Justison
Robert C. Kammerling
Kennecott Exploration Co.
Keyveckay Gems, Inc.
King Plutarco, Inc.
Klaus G. Klement
Bert Krashes
Kyocera Corp.
Bill LaCombe
Lake Valley Minerals, Ltd.
Francine Lambert
Landstroms' Black Hills Gold
Albert M. Lapioli
Lapis Jewelers
Gail B. Levine
Liccini
J.S. Lizzadro, Ltd.
Ronna Lugosch
Conni Mainne
Manning International/ New York
Betsy Ross Marcinkus
James E. Meadows
Nicolai Medvedev
Marion J. Meyer
Jerry Meyeres
David Milanowski
Moses Jewelers
N.G. Inc.
Maria Denise Nelson
New Era Gems
Penny Nisenbaum
Oro America
Pala International, Inc.
Barbara Papp
Carlos D. Parsons
Pasna Gems, Inc.
Paul J. Schmitt, Inc.
Paul Johnson Co.

Pinky Trading Co., Ltd.
Frederick H. Pough
Franz Pulver
Maurice D. Quam
Ralph Mueller & Assocs.
James Rambur
Rapp Jewelers, Inc.
J. Redisi
Ronald H. Ringsrud
Elizabeth M. Roach
Beth Rosengard
Fred W. Rowe
Rox Arcana
Marion A. Rozger
Sather's Jewelers
Jim Schlegel
Shades of the Earth
Pallavi Sheth
John Sinkankas
Mark H. Smith
Spectral
Star Ring, Inc.
Lynda A. Starbird
Gerry Stockton
Margherita Superchi
Suzanne's Source
Jack J. Swain
Edward R. Swoboda
SY Kessler Sales, Inc.
The Ward Warehouse
Tory Jewelry Company
Camilla Van Sickle
Village Goldworks, Ltd.
Fred Ward
John Watkins
Elaine Weisman
Kenneth L. Whipple
Anita R. Wilde
Hank T. Wodynski
Yael Importers, Inc.
Louis Zara

In its efforts to serve the gem and jewelry industry, GIA can use a wide variety of gifts. These include natural untreated, treated, and created stones, media resources for the Richard T. Liddicoat Library and Information Center, and equipment and instruments for ongoing research support. If you are interested in making a donation, and receiving tax deduction information, please call Anna Lisa Johnston, Associate Campaign Director, at ext. 4125 at (800) 421-7250 or from outside the U.S. (760) 603-4125, fax her at (760) 603-4199, or e-mail ajohnsto@gia.edu. Every effort has been made to avoid errors in this listing. If we have accidentally omitted or misprinted your name, please notify us at one of the above numbers.

BOOK

Reviews

SUSAN B. JOHNSON AND
JANA E. MIYAHIRA, EDITORS

CAMEOS IN CONTEXT THE BENJAMIN ZUCKER LECTURES, 1990

Edited by Martin Henig and Michael Vickers, 102 pp., illus., publ. by The Ashmolean Museum, Oxford, England, and Derek J. Content, Inc., Houlton, Maine, 1993, £27.50 (about US$46.00).

This slim volume comprises six lectures that inaugurated the special 1990 exhibition at the Ashmolean Museum featuring the Content collection of cameos, arguably the largest and most important such collection in private hands. The book is a companion volume to the beautiful catalogue of this collection, *The Content Family Collection of Ancient Cameos*, by Martin Henig (Oxford and Houlton, 1990). The lectures chronicle the history of cameo carving from antiquity to the 19th century, incorporating the Content collection into a broader historical framework. Thus, the book includes cameos in glass and hard stone that represent the most significant works of their epochs; and, for this alone, it is an important reference.

Although the book addresses the art historian, the lay reader should not be deterred. The authors, experts in this specialized field, present well-referenced, cogent, and sometimes colorful accounts of some of the most celebrated cameos ever made. They describe how cameos illuminate the historical record and the functions they served in different eras, from their political and propagandist utility, to their ornamental value as a minor art and their artistic importance as the crowning achievement of the luxury arts. A particularly interesting case study is the Cameo of Tiberius, a five-layered sardonyx that depicts more than 20 members of the Roman Imperial family from the first century B.C. to the first century A.D. Produced in the first century to authenticate the legitimacy of the royal line of succession, this is the largest surviving ancient cameo known. Later the gem was mounted into a Byzantine reliquary, from which it subsequently was separated after it was stolen in 1804. In the interim, the gem was seen and painted by Rubens (probably around 1626). The story surrounding the painting, for which considerable documentation survives, fills in some of the gaps in the history of the cameo itself, while it also reflects the fascination of the 17th century culturati with the glyptic arts and antiquity. In a stroke of perfect synchronous timing with the Content exhibition, the Ashmolean acquired the painting in 1990. This is discussed in Christopher White's lecture.

One might like to have Henig's catalogue at hand in order to refer to some of the citations in the text. Also, although the *Lectures* volume stands alone well, an acquaintance with the catalogue would help the reader form a clearer overall picture of this important collection. One might wish for more color plates to do the cameos justice as works of art, but the black-and-white photos illustrate the iconographic elements clearly, and for the serious scholar, this is what is most important. Among the many highlights found in these pages, in addition to the well-known Portland Vase and the Cameo Gonzaga, are Roman cameo glass vessels including the Blue Vase and the Morgan and Getty Cups, hard-stone cameos such as the Gemma Augustea and the Great Content Cameo, and a number of important Post-Antique portraits. Minor art, indeed.

LISBET THORESEN
J. Paul Getty Museum
Malibu, California

GEMSTONES OF NORTH AMERICA, Volume III

By John Sinkankas, 527 pp., illus., publ. by Geoscience Press, Tucson, AZ, 1997. US$65.00*

This is the last of three volumes by this noted author that describe gemstone occurrences on the North American continent. Anyone doing research on the history of a locality should note that this book is intended for use with the previous two volumes. The first volume, *Gemstones of North America*, covers many localities up to 1959, the year it was published. For some localities, such as the famous tourmaline deposits at Mt. Mica, Maine, the histories recounted in this volume date back to the 19th century. The second volume, published in 1976 as *Gemstones of North America in Two Volumes, Volume II*, updates the locality information in the first volume and adds other localities and species. These first two volumes were organized by a stone's perceived importance; consequently, if you were looking for information on one of the lesser-known species, such as iolite, you would probably need to use the index rather than just thumb through the pages.

Now comes the third volume, and, starting with the cover, you can see that this is a high-quality publication. The 15 stones and benitoite necklace depicted (all from the Michael M. Scott collection) are exceptional pieces by any criteria. Inside, the reader is quickly treated to an additional 16 pages of spectacular Van Pelt photographs of significant North America gems. For this volume, the species are presented in alphabetical order and, thus, are easier to locate quickly. Within each species, the localities are laid out in a general north-to-south, east-to-west format, by state (for the U.S. and

This book is available for purchase through the GIA Bookstore, 5345 Armada Drive, Carlsbad, CA 92008. Telephone: (800) 421-7250, ext. 4200; outside the U.S. (760) 603-4200. Fax: (760) 603-4266.

154   Book Reviews   GEMS & GEMOLOGY   Summer 1997

Mexico) and province (for Canada). A short bibliography follows the discussion of each locality. Because this volume is meant to be used with the previous two, Dr. Sinkankas has many entries, such as beryl from Pennsylvania, where he states only "No new developments" and gives the bibliography.

Dr. Sinkankas compiled this information not only from articles and other books, but also from personal communications with people knowledgeable about the localities covered. Note, though, that not every locality is current as of 1996, or even 1995, probably due to the comprehensive nature of the publication. For example, most of the Montana sapphire properties mentioned were consolidated under one company a few years ago. Such omissions are minor, however, given the overwhelming value of this reference work.

When the second volume came out, Van Nostrand Reinhold reprinted the first volume (hence, the long, cumbersome title) in a matching binding. Since this third volume was issued by a different publisher, and the two previous editions are no longer available, the only practical way to complete the three-volume set is to find the first two books in a used-book store or through a dealer in out-of-print books. Even without its predecessors, though, this latest volume has a wealth of information on current localities, as well as the extensive bibliography for each locality that can be used for further research. The book is a necessary addition to any gemological library.

MICHAEL GRAY
Graystone Enterprises/Coast-to-Coast Rare Stones
Missoula, Montana

OTHER BOOKS RECEIVED

Diamond Exploration Techniques Emphasising Indicator Mineral Geochemistry and Canadian Examples, *by C. E. Fipke, J. J. Gurney, and R. O. Moore, 86 pp., illus., Geo-* *logical Survey of Canada Bulletin No. 423, Ottawa, Ontario, Canada, 1995, Can$24.85.* This bulletin is probably the most succinct discussion available on the use of indicator minerals (associated resistant minerals that are more abundant than diamond itself), one of the main techniques in diamond exploration. The three experts have superb credentials: The senior author is credited with finding the Lac de Gras (Northwest Territories, Canada) kimberlite field, and the other two authors have vast experience in diamond exploration in southern Africa and Australia.

The main body of the text addresses the theory and use of indicator minerals both as pathfinders to kimberlite and lamproite, and as a means of evaluating the diamond potential of these primary sources. Proper interpretation of variations in the chemical contents of the indicator minerals is essential, and the methods by which this is accomplished are explained with the aid of many diagrams. The "traditional" indicator mineral approach for kimberlite (using garnet, ilmenite, chromite, and diopside) does not appear to be as reliable for lamproites, for which other indicator minerals (e.g., olivine, tourmaline, zircon) are suggested.

This authoritative bulletin is essential for all those who are seriously interested in diamond exploration.

A. A. LEVINSON
University of Calgary
Calgary, Alberta, Canada

An Overview of Production of Specific U.S. Gemstones, *by Gordon Austin, 41 pp., illus., Special Publication 14-95, U.S. Department of the Interior, U.S. Bureau of Mines, 1995, US$5.50.* The term *gem localities* usually conjures up visions of far-off, exotic lands. However, U.S. sites produced an estimated $84.4 million of natural gemstones in 1992. Statistics such as these, plus historical information and references on several selected gem materials, are the main thrust of the booklet.

For each of the 12 gem materials, the discussion includes a brief description and an overview of the history, market, production, projections, and deposit locations. The booklet is well organized and easy to read. It includes 12 color illustrations, although the quality of the color reproduction is not up to the standards of many other publications.

The strengths of this booklet are the production figures and some of the sections on individual gem materials, especially tourmaline, pearls, and collector or specialty gems. Although it professes to be an "overview," this booklet packs a lot of interesting information into 41 pages, and it leaves the reader wanting to explore the publications listed at the end.

MICHAEL T. EVANS
Gemological Institute of America
Carlsbad, California

Gemmologia Europa V—European Gemmologists on Rubies and Sapphires, *edited by Margherita Superchi, 141 pp., illus, publ. by CISGEM, Milan, Italy, 1996, 35,000 lira (about US$20.00).* This volume is actually the proceedings of the fifth Gemmologia Europa, a biannual event sponsored by the Centro Informazione e Servizi Gemmologici (CISGEM). This, the fifth such conference, was held in Milan, Italy, in October 1994.

The focus of this conference was rubies and sapphires, and the proceedings include transcriptions of talks given by E. A. Jobbins on ruby occurrences, by Kenneth Scarratt on sapphire occurrences, by Dr. Henri-Jean Schubnel on the history and legends of rubies and sapphires, by Michael O'Donoghue on treatments and synthetic and imitation rubies and sapphires, and by Dr. Edward J. Gübelin on inclusions in rubies and sapphires. All of the presentations are well illustrated in color, and all contain much useful and interesting information on gem corundum.

JOHN I. KOIVULA
GIA Gem Trade Laboratory
Carlsbad, California

GEMOLOGICAL ABSTRACTS

C. W. FRYER, EDITOR

COLORED STONES AND ORGANIC MATERIALS

Mammal bones in Dominican amber. R. D. E. MacPhee and D. A. Grimaldi, *Nature*, April 11, 1996, pp. 489–490.

Dominican amber rarely contains small lizards, frogs, or evidence of larger animals (e.g., feathers or animal hairs). In this letter, the authors describe spine and rib bones from a small insectivore—the first mammal bones found in amber—from the La Toca Group of amber mines in the La Cumbre region of northern Dominican Republic. The amber can be no older than late Oligocene or early Miocene (about 26 million years old). *MLJ*

Goodletite—A very rare gemstone. H. Bracewell, *Australian Gold Gem & Treasure*, Vol. 11, July 1996, pp. 36–37.

"Goodletite" is a rock from the South Island of New Zealand that contains dark red opaque-to-translucent rubies (grading into bluish sapphires) in a matrix of chrome tourmaline and green chrome mica. It is also known as "ruby rock." Boulders of this material—possibly transported by glaciers—have been found in the gold-bearing drifts of Rimu Flat (south of Greymouth on the West Coast) and in the Whitcombe Pass area. This ornamental material was supposedly named by a Professor Black of Otago University after his laboratory assistant, W. Goodlett, around 1890; there is reference to it in a 1906 New Zealand Geological Survey bulletin. Because of the different hardnesses of the disparate materials in this rock, it is difficult to cut and polish. *MLJ*

DIAMONDS

California diatreme. *Mining Journal*, London, December 20–27, 1996, p. 496.

Diadem Resources has found that the diamond-bearing breccia it was investigating at Leek Springs, California, is a diatreme (a breccia-filled volcanic pipe, resulting from a

gaseous explosion), with a surface area greater than 316 hectares. Drilling has found diamond-indicator minerals that imply that the pipe is lamproite, not kimberlite. A magnetic survey of the region has found three aligned circular features and several dikes.   *MLJ*

Chinese agreement. *Mining Journal, London,* January 10, 1997, p. 20.

Quantum Resources and Astro Mining have entered into an exclusive agreement with the government of the Xin Jiang Autonomous Region, in western China, to explore for diamonds at Bachu, on the edge of the Tarim Basin, where parts of the Siberian craton occur. At Hetian, within the area, local farmers reportedly found gem diamonds, up to 1.5 ct, in alluvial gravels. Microdiamonds have been identified in material washed from a nearby kimberlite pipe. The exploration program is expected to include bulk testing of known pipes, aeromagnetic surveys to discover more pipes, and sampling of drainages. This is the second such exclusive contract in China. In December 1996, Kensington Resources acquired half-interest in a Shandong Province diamond mine.   *MLJ*

Extensive experience in diamond recovery. *Mining Journal, London,* November 22, 1996, p. 416.

The Debex CDX116VE is a commercially available machine that separates diamonds from alluvial gravels. It uses X-ray luminescence to distinguish diamonds from other gravel materials, and "electro-mechanical ejectors" to separate them. Neither water nor compressed air is necessary. A computer diagnostic system enables users to optimize recovery for specific conditions at their sites. Debex is a member of the De Beers group of companies.

MLJ

Union Pacific says diamond mine trespassing. *International California Mining Journal,* Vol. 66, No. 7, March 1997, pp. 3–4.

Union Pacific Corp. claims that the operators of the Kelsey Lake diamond mine, in Larimer County, Colorado, are trespassing on land for which Union Pacific reserved all mining rights when it conveyed the land to private ownership in 1896. Union Pacific Land Resources filed a lawsuit in U.S. District Court, seeking an inventory of the mine's contents and compensation for the diamonds already sold; they claim that the 1987 mining lease between the land's owners and Diamond Co. (the Colorado subsidiary of Redaurum Inc.) is invalid. Diamond Co. began prospecting in the area a decade ago. The largest diamond recovered to date weighed 28.3 ct.   *MLJ*

Unsettled issues. J. W. Bristow, *Diamond Supplement to Mining Journal, London,* November 22, 1996, pp. 1–3, 6–7, 9, 11.

Diamond supply in the 1990s has been uncertain for many reasons. In 1991–1992, diamonds from Angola flooded the market; in 1991–1994, the Canadian diamond rush threat-

ened (but has not yet produced) many more stones. The breakdown of the agreements between the De Beers Central Selling Organisation (CSO) and both the Russians and the Argyle mine in Australia has created still more uncertainty. All this has both encouraged and dissuaded potential investors in diamond-mining stocks. In 1995, the prices of smaller goods and lower-quality goods decreased by about 14%, while the price of diamonds over 1 ct rose an average of 7%.

In contrast, diamond demand has been remarkably stable. The CSO has imparted consistent, "considerable" value to diamonds by monitoring the market, controlling supply, and stimulating demand. Of course, this makes the discovery of new diamond sources an attractive prospect. The amount of diamond smuggling is hard to measure, but up to 10% of annual mined production may reach the market through smugglers.

In the past 50 years, only seven major kimberlite (or lamproite) discoveries have produced more than 3 million carats (Mct) annually: Argyle in Australia, Orapa and Jwaneng in Botswana, Finsch and Venetia in South Africa, and Mir and Udachnaya in Russia. Before Canadian production begins, mined diamond production is projected to be flat, or even to decline. Argyle and Russian production is declining. In Russia, annual production has fallen from 16 Mct to 10 Mct over the last five years. Lack of capital there makes it unlikely that this source can recover rapidly. Angola continues to suffer from political unrest and a poor infrastructure, but it has large resources. Argyle's open pit will reach the end of its useful life shortly after the turn of the century. The most certain source of new production is Canada, where BHP/Dia Met could be producing over 4 Mct annually from Lac de Gras within the next few years, and the small pipes being explored by Aber/Kennecott could also be developed.

Annual worldwide expenditure for diamond exploration is about US$300 million; most of this has been spent in Canada ($130 million), Australia ($45 million), and South Africa ($40 million). Although diamondiferous kimberlites and lamproites have been found in Proterozoic belts, the only major diamond deposit not found on an Archaean craton is that at Argyle.

This article also contains reports by region, including South Africa, Namibia, Botswana, Angola, Russia, Canada, and Australia. Other countries that now have significant diamond resources—or may develop them in the next decade—include: Sierra Leone, Liberia (both beset by internal conflict), Zimbabwe, the Central African Republic, Tanzania, Brazil, French Guiana, India, Indonesia, the United States, Finland, Sweden, and Greenland. *MLJ*

GEM LOCALITIES

Gem and collection-worth tourmaline from the Pamirs (crystallomorphology, coloring, crystallochemistry) [in Russian]. A. A. Zolotarev, *Proceedings of the Russian Mineralogical Society (Zapiski Vses. Min. Obshch.),* Vol. 125, No. 4, 1996, pp. 32–46.

Crystal morphology, unit-cell parameters, chemical analyses, crystallochemical formulas, and infrared spectra are given for 10 samples of tourmaline from the Eastern Pamirs and magnesian skarns of the Kukhy-lal deposit, Muzeinaya. Also provided are the results of an electron microprobe traverse for Fe and Mn across a color-zoned tourmaline. These tourmalines are mainly elbaite and dravite, with one schorl. *RAH*

O'Briens Creek unmasked. P. O'Brien, *Australian Gold, Gem & Treasure*, Vol. 12, March 1997, pp. 20, 22–24, 26–27.

The best blue topaz in Australia is said to come from O'Briens Creek in North Queensland; the nearest town is Mt. Surprise, about 200 km west of Cairns. The topaz occurs in a large alluvial tin deposit (5,000 hectares); citrine, smoky quartz, and occasional aquamarine are also found. The stones are usually recovered by dry sieving. Pieces of rough topaz as large as 350 ct have been found. Locality names include Elizabeth Creek, Nugent's Gully, and Tourmaline Gully.

A nearby deposit, Blue Hills, is the upstream source of the O'Briens Creek topaz *[Abstracter's note: However, from the description in this paper, it may not be the primary source of the alluvium]*. Rough topaz is found as "sharper" (less rounded) crystals at Blue Hills. One crystal that the author saw, although broken into several fragments, weighed almost 1 kg. In another alluvial working, a lava flow covers topaz-bearing gravels.

Many colorful tales are associated with just about any mining locality. O'Brien's Creek is no exception: One mining lease (now also a rock shop) is called Digger's Rest because its first two lease-holders are buried in the front garden. Note that visitors must obtain a Queensland fossicking license before collecting at O'Brien's Creek. *MLJ*

Praise the 'prase! P. O'Brien, *Australian Gold Gem & Treasure*, Vol. 12, January 1997, pp. 36, 37, 39–41.

Chrysoprase mining in Marlborough, Queensland, is the focus of this article. Chrysoprase, the green variety of chalcedony (colored by nickel), was first discovered at Marlborough in noncommercial quantities in the 1880s. However, a major deposit of "magnificent" green chrysoprase was found in 1963. Local miners banded together to exploit the deposit, forming Capricornia Mineral Development (CMD). At first this material was unsuccessfully promoted as "Queensland Jade," in an attempt to capitalize on a supposedly high worldwide demand for jade. In 1964, CMD was purchased by V.A.M. Ltd., which in turn went into receivership in 1973. Although much of the deposit remained unexploited, it was buried under 30–40 m of overburden, making mining more difficult. Gumigil Pty Ltd. bought the mine in the late 1970s. Today, all of the raw material is sent to Hong Kong, where Gumigil's president operates the largest chrysoprase-cutting factory in the world. The known deposits are suffi-

cient to handle world demand well into the next century.

Mining techniques are similar to those used for opal at Mintabie. The overburden is bulldozed away, while "spotters" behind the bulldozer watch for signs of color. Outcrops of chrysoprase are removed with a small backhoe. Most nodules weigh between 3 and 5 kg, but even the smallest chips are recovered. The largest piece to date was 337 kg. In addition to the commercial mine and a museum, the region has a nearby "fossicking" site, where amateurs can collect chrysoprase from old mine dumps. *MLJ*

Sapphire City. P. O'Brien, *Australian Gold Gem & Treasure*, Vol. 11, April 1996, pp. 20, 22, 24, 26, 30.

Inverell (alias "Sapphire City") is situated on the western side of the New England Ranges in northern New South Wales, Australia. The area produces mainly blue sapphires and, says O'Brien, is famous for its "cornflower variety, which is known far and wide as 'Inverell Blue.'" Within a 60 km radius of the town center (which includes a local mining museum) are amateur collecting sites. One can dig for sapphire, quartz (including smoky quartz, citrine, petrified wood, and agate), rhodonite, "tin crystals" (probably cassiterite), "grass stone," and scarcer gems such as aquamarine and other beryls, topaz, spinel, and tourmaline. The author visited Nullamanna (an alluvial source for sapphires, cassiterite, and rock crystal), Elsmore (cassiterite), Swanbrook Creek (sapphire), the ford at Frazer Creek (sapphire), and Poolbrook sheep station (sapphire)—but with little success, despite seeing sapphires as large as 18 ct found by fellow "fossickers." He concludes that the Inverell area is not "easy pickings" for an amateur with little time.

Sapphires were first noticed in the Inverell region in 1853, and recovery began (as a byproduct of tin mining) in 1870. Sapphire mining took off in 1919, but it was badly hit by the Great Depression in 1929; in the years since mining resumed in 1940, several booms (and busts) have taken place. Today, individual mines, most run on a casual basis, have some success; some large operations—such as Dejons, on Glen Innes Road—have played a major part in stabilizing sapphire prices. *MLJ*

INSTRUMENTS AND TECHNIQUES

Measurement of refractive index by the apparent depth method. D. Bennett, *Australian Gemmologist*, Vol. 19, No. 7, 1996, pp. 292–294.

The author describes experiments with two microscopes to determine the accuracy of the direct-measurement method for calculating the refractive index of faceted gemstones and manufactured materials. The first microscope that was used to determine refractive index by the direct-measurement apparent-depth method was a Siewa binocular microscope with magnifications of 20× and 40×. *[Abstracters' note: Figure 1, however, shows a uniocular*

Siewa microscope.] The second microscope was a monocular Shimadzu with fixed 50× magnification.

Each microscope was fitted with a dial gauge that had a range of 10 mm. It was soon determined that the most accurate focus was obtained with the microscope set at maximum magnification and that several readings would be needed for each measurement, with these results averaged.

The gemstone was mounted on a transparent glass graticule (reticule), table up, with its culet contacting the upper surface of the graticule. The center of the table and the surface of the glass graticule under the culet were marked with a small spot by a permanent marker. The spots were then centered on the microscope stage. When the microscope was focused, the table center, the culet, and the spot on the surface of the graticule were all in the same central optical axis.

For each stone, five successive gauge readings were taken to measure both the position of the table and the apparent position of the culet. Subtraction of these values allowed the apparent depth of the culet to be determined to tenths of a millimeter. Chips on the culet made it very difficult to locate the absolute bottom of the stone with the microscope. With the direct-measurement apparent-depth technique for determining refractive index, it is possible to confirm that the refractive index of a stone that does not register on a standard refractometer is indeed over-the-limits. It is very likely that the refractive index obtained with this method is accurate enough to identify a particular stone. Some disadvantages of this method are the cost of the microscope and the fact that it is time-consuming. *MD*

JEWELRY HISTORY

The Dactyliotheca of the Pope Leo XII. G. Graziani, *Periodico Mineralogica*, Vol. 65, No. 1–2, 1996, pp. 79–204

A study has been made of a 388-item gem and ornamental stone collection that was given by His Holiness Pope Leo XII to the Mineralogical Laboratory of Rome University "La Sapienza" in 1824. From their hallmarks, the period and place of manufacture for a ring and two collets (collars) were established as 1792–1809 in Rome. Most of the specimens appear to consist of small, polished, rounded or octagonal plates of various varieties of silica, but the first section includes 32 jewels, for the most part rings, that are described in detail in an appendix. The gems include topaz, opal, aquamarine, garnet (previously cataloged as zircon or "ruby spinel"), yellow diamond, and yellow sapphire. *RAH*

JEWELRY MANUFACTURING

The song in the stone: Developing the art of telecarving a minimal surface. *Science News*, February 17, 1996, pp. 110–111.

Sculptor Helamun Ferguson carves marble into forms that represent mathematical equations. One series is based on theoretical minimal surfaces (the shapes seen when soap films are stretched across a bent ring), especially one known as the Costa surface. This shape looks vaguely like a top hat twisted through itself.

Mr. Ferguson uses equipment devised by members of the Robot Systems Group of the National Institute of Standards and Technology. This equipment was designed to translate geometric forms drawn on the computer monitor into guidelines for how much material should be carved away from any point on the surface of the rough stone to produce the desired image. Precision to 1 mm can be achieved with this new technology, which combines human versatility with mechanical power and computational precision to provide a method that is more efficient and cost effective than relying on either humans or robots alone.

Mr. Ferguson also reports that marble vibrates ("sings") as it is carved; if it "quits singing," some hidden flaw or incipient fracture is indicated. *MLJ*

JEWELRY RETAILING

Diamonds Hit the Heights. V. Becker, *Retail Jeweller & British Jeweller*, May 15, 1997, pp. 12–13.

Yellow diamonds were the high points of both Sotheby's and Christie's April 1997 jewelry sales in New York. At Christie's, the American Siba Corporation paid $728,500 for a 10.14 ct fancy vivid yellow diamond ring. At Sotheby's, a new world record was set for a yellow diamond sold at auction: A 13.83 ct stone sold for $3,302,500, or $239,000 per carat. It went to an international dealer, as did most top lots at the jewelry sales.

A circa 1935 bracelet with diamonds and Kashmir sapphires brought $585,000, almost triple the high end of its pre-auction estimate. Invisible-set jewelry did well, particularly two ruby flower brooches, one by Van Cleef & Arpels ($255,500) and one by the Aletto Brothers ($299,500). A New York dealer paid $640,500 for a fancy intense blue and intense pink diamond cluster ring, while a private European buyer paid $332,500 for a rectangular-cut sapphire and diamond ring that was made by Van Cleef & Arpels.

Phillips drew crowds with its April 1997 sale of antique and 20th century jewels in London. The prize lot was a Fabergé brooch, set with a central octagonal topaz surrounded by a rose diamond frame with ribbon bow. The piece, complete with original case, went to London specialists Wartski for £26,450, well above estimate. A yellow sapphire and diamond ring sold unexpectedly high at £3,680. A pair of French Belle Epoque diamond tassel earrings doubled expectations at £2,990. Pointing to a revival of interest in Victorian gold jewelry, a pair of typical 1870s gold Victorian earrings in rich bloomed gold, with domed centers, sold for £1,955. A late-Victorian necklace sold for £9,775. Standard modern jewels were difficult to move throughout the sale. *MD*

PRECIOUS METALS

Consumers Trade Up on Gold Spend. J. Boddington, *Retail Jeweller & British Jeweller*, May 15, 1997, p. 1.

In the first three months of 1997, British consumers paid an average 25% more for each piece of gold jewelry purchased compared to the same period two years ago, according to the World Gold Council (WGC). Although these consumers are buying slightly fewer pieces, pieces tend to weigh more and, consequently, are of greater value. British consumers now pay an average £76.20 for each item.

The reduction in sales volume was not considered substantial by the WGC. Even though 310,000 fewer pieces of gold jewelry were sold in the first three months of 1997 than during the same period in 1995, the United Kingdom is still the largest volume market fell in Europe.

Self-purchased plain gold pieces in the UK fell an average of 15% in price, whereas gift purchases rose by 89%, to £175.70. In contrast to the 42% average price increase for plain gold jewelry, gem-set pieces showed a 12% average price decrease. *MD*

Speculation Grows Over Silver Price as Worldwide Demand Rises Again. S. Pearson, *Retail Jeweller & British Jeweller*, May 29, 1997, p. 5.

Worldwide silver demand exceeded supply from mine production and scrap for the seventh consecutive year in 1996, prompting speculation: How long before silver prices rise? Almost all growth in fabrication demand came from the jewelry and silverware industries. Demand there jumped almost 17%, to 263 million ounces. Growth in jewelry fabrication was highest in India—up almost 50%, according to a Silver Institute survey. India is now the largest importer of silver.

In Europe, the UK and Ireland saw some of the strongest growth, with jewelry and silverware rising 12%, to 3.34 million ounces. The past five years have seen demand rise 75%—a 40% increase in the number of articles. Average weight per article climbed from 20 to 25 grams.

Italy continues as Europe's largest silver jewelry and silverware manufacturer, using 40.5 million ounces in 1996. Production of silverware fell 5% last year, but silver jewelry production compensated, rising 13%. Elsewhere, North American fabrication increased a record 12% to almost 28 million ounces, with most of the growth attributed to Mexico.

Despite the increasing gap between demand and mine supply, the survey does not predict an immediate price rise for silver. It does say, however, that silver bullion stocks are being steadily transformed into fabricated products. In fact, if the existing holders of remaining bullion stocks chose to maintain rather than dispose of their holdings, the silver market could only be balanced through a significant price increase. *MD*

SYNTHETICS AND SIMULANTS

Hydrothermal growth of diamond in metal-C-H$_2$O systems. X.-Z. Zhao, R. Roy, K. A. Cherian, and A. Badzian, *Nature*, February 6, 1997, pp. 513–515.

The authors mixed 2 wt.% quarter-micron (0.25 μm) diamond powder "seeds" with 95 wt.% glassy carbon and 3 wt.% powdered nickel into gold tubes; this material was processed at close to 800°C and 1.4 kbar water pressure for 50–100 hours. The black starting mixture turned gray. With a scanning electron microscope, the authors observed larger (several micron) particles and very large (several tens of microns) bonded aggregates. They think that these particles and aggregates resulted from new growth of diamond on the pre-existing seeds, based on three clues:

- X-ray diffraction patterns indicate a larger volume of diamond in reaction products than in the starting materials.
- The diamond Raman peak in the starting material shifted from 1331 cm^{-1} to 1319 cm^{-1} as the laser power increased. However, in the reaction products, the Raman peak stayed at 1331 cm^{-1} at all laser powers. The authors interpreted this to mean that there is enough new growth or new bonding to give good thermal contact among the grains in the aggregate.
- The product had a strong luminescence spectrum that resembled that of CVD "diamond" films (with an indication of peaks at 2085, 3780, 4325, and 4795 cm^{-1}), but the seeds themselves had a very weak luminescence spectrum.

The authors were unsuccessful in growing "hydrothermal diamonds" when diamond seeds were not supplied; however, they have made synthetic diamond overgrowths on pre-existing seeds with nickel, platinum, and iron catalysts. They do not know the mechanism for the hydrothermal growth process. *MLJ*

The negative side of crystal growth. P. Calvert and S. Mann, *Nature*, March 13, 1997, pp. 127, 129.

This short report discusses the growth of apatite from hydrous solutions on electrically charged ferroelectric crystals. Apatite grows on the negative pole but not on the positive pole of the substrate crystal. Although the primary purpose of this article is to explain natural and synthetic bone growth, the authors also suggest that calcium carbonates *[Abstracter's note: e.g., possibly pearls]* may be successfully grown by this approach. *MLJ*

Derivation of gem and lapidary names. H. Bracewell, *Australian Gold Gem & Treasure*, Vol. 11, July 1996, pp. 54–55.

Many terms in gemology and geology have Greek and Latin roots. The author provides examples of various such terms, including *a-* or *an-*, meaning "without"; *allo-*, meaning "other," as in "allochromatic" minerals (those colored by impurities rather than intrinsic causes); *amygd-*, meaning "almond" (for instance, amygdules);

aster-, meaning "star" (asterism); *chrom-*, meaning "color" (achromatic); *crypt-*, meaning "hidden" (cryptocrystalline); *di-*, meaning "twofold," and *tri-*, meaning "threefold" (dichroism and trichroism, respectively); *glypt-*, meaning "carve" or "engrave" (glyptography is the art of engraving gems); *lith-*, meaning "stone" (sodalite, sinhalite, lithosphere, etc.); and *micro-*, meaning "small" (microscope).   *MLJ*

Gemstones 1995. *International California Mining Journal*, Vol. 66, No. 3, November 1996, pp. 54–58.

This report on 1995 gemstone production and consumption in the United States is a summary of the mineral industry survey by the U.S. Geological Survey. Domestic gemstone production from "indigenous sources" (that is, stones not imported for further processing) was at least $75 million. Although gemstones were produced in every state, six states—Tennessee, Alabama, Arkansas, Oregon, North Carolina, and Arizona—accounted for over 90% of production value. Arizona, for instance, produces more than 15 gem varieties, from peridot and garnet to antlerite and shattuckite. New mines are being developed in Montana (sapphires) and Colorado (diamonds), which could have important future production.

At least $25 million of synthetic gems were produced domestically in 1995, and there was at least as much production of gem simulants (some estimates of combined production of synthetics and simulants exceed $100 million). Synthetic gems produced in the U.S. include: alexandrite, coral [sic], diamond *[Abstracter's note: Synthetic diamond intended for gem use is not yet a commercial product, to the best of my knowledge]*, emerald, lapis lazuli [sic], quartz, ruby, sapphire, spinel, and turquoise. Gemstone simulants produced in the U.S. include: imitation coral, cubic zirconia, imitation lapis lazuli, imitation malachite, and imitation turquoise; also, synthetic sapphire and synthetic spinel are used to imitate other gems (e.g., alexandrite). Cubic zirconia is the most significant simulant in terms of production value. Synthetics and simulants are produced in California, New York, Michigan, Arizona, and New Jersey.

The U.S. imported $6.66 billion in gems, synthetics, and imitations in 1995, from 25 countries, and exported (and "re-exported" after processing) $2.53 billion in gems etc., to 75 countries. Most gem consumption was in the form of jewelry, but loose stones, mineral specimens, *objets d'art*, and certain industrial applications are also included; diamonds were responsible for 89% of this consumption. Of the exports, $2.01 billion was in cut diamonds (87% of the total); $207 million in cut colored stones; $47.1 million in shells and coral (mostly shell bead nuclei for cultured pearl production); $42.3 million in rough colored stones; $14.5 million in fashioned synthetics and simulants; $14.3 million in "rough" synthetics and simulants; $5.33 million in cultured pearls; and $2.85 million in natural pearls.

MLJ

Mining Annual Review 1996. Published by *Mining Journal, London*, 248 pp.

This extensive review begins with a description of advances in mining technology, followed by reports on mining progress in various countries, including diamond exploration in Canada's Northwest Territories; in India, where RTZ-CRA is applying for ventures with Associated Cement; in Botswana, where BHP is involved in a venture in the Gope area; offshore from Namibia, where Namibia Minerals Company and BHP are involved in ventures; and in Finland, where Ashton Mining has discovered about 15 diamond-bearing kimberlites. A combination of aeromagnetic, ground magnetic, gravity, drillhole, and physical property data have found 13 anomalies—possible kimberlites—in poorly exposed Precambrian rocks in Minnesota. Magnetic survey data can now be resolved vertically and horizontally, creating three-dimensional models that extend to depths of 500 m. In airborne surveys for diamond sources, magnetic resonance may be more important than induced magnetism, and dikes can obscure the "bulls-eye" signatures of diamond pipes.

Countries, and their gem mining specifics, include:

- Angola has had its diamond mining seriously affected by political troubles; 90% of production from alluvial workings in the Lunda and Lunda Norte provinces are gem quality. De Beers estimated that total diamond production from Angola was worth US$600 million in 1995; only 20% of this was "official" production, through the state diamond corporation Endiama.
- Australia is home of the Argyle mine, which produced 40.6 million carats of diamonds (Mct) in 1995 (down from 43.7 Mct in 1994). These diamonds, including 3.1 Mct considered gem quality, were worth Aus$570 million. The Bow River mine (also in the Kimberley area) has now closed, and no new sources of diamonds have been found so far. Sapphires worth Aus$18 million were exported in 1995, as were Aus$98 million in opals.
- Botswana is the world's top producer of diamonds by value, and the third largest by volume. Total production rose to 16,802,482 carats in 1995 (from 15,547,200 carats in 1994). The Jwaneng mine produced 10.5 Mct in 1995, a 15% increase over 1994. At Orapa, 5.4 Mct were produced from 7.7 million tons (Mtons) of ore. At Letlhakane, damage to the plant from heavy rains lowered production to 906,000 carats. Production of colored stones—mainly carnelians and agates—increased by 72% to 67 tons in 1994.
- Canada is primarily important to the gemstone market as a potential diamond source. Since 1988, $400 million has been spent on diamond exploration—about 20% of the total Canadian exploration budget—not only in the Northwest Territories, but also in Saskatchewan, Quebec, Alberta, Ontario, British Columbia, Manitoba, and Labrador. Five of the pipes at Lac de Gras are economic and are likely to be developed (over the next 25 to 30 years).
- The Central African Republic produces diamonds from

alluvial workings, 530,000 carats in 1995; over half were gem quality. In 1994, total production was valued at $76 million; however, also in 1994, the currency of the C.A.R. was devalued by 50%.

- Colombia, long an emerald source, produced over 6.3 Mct in 1995, down from 7.2 Mct in 1994. Because of improved stone quality and greater demand, however, value was $450 million (up from $431 million in 1994).
- Finland is being scoured for diamonds (over 500 claims were awarded in 1995), but there were no new finds.
- French Guiana contains diamonds and a possible source—a metamorphosed rock, possibly kimberlitic—in the Dachine permit area.
- Ghana produced 631,337 carats of diamonds in 1995; 293,880 carats came from the Akwatia mine, which had decreased production (by 40,260 carats) since 1994. De Beers pulled out of a joint venture to take over this mine, and Ghana is looking for a company interested in it.
- Guyana has diamonds being mined in the Mazarani area by Exall Resources, using an "environmentally acceptable" dredge.
- India is conducting aerial and mineral surveys, and private companies are interested in prospecting for diamonds in Andhra Pradesh. The Raipur district in Madhya Pradesh, near Orissa, is a source of diamonds and alexandrites.
- Israel exported over US$3 billion in fashioned stones in 1995.
- Kenya produces colored stones: 108,603 kg of green garnet, 10.2 kg of rhodolite garnet, 10,010 kg of other red garnet, 1,200 kg of corundum (mainly ruby), and 224 kg of gem tourmaline. Mgama Ridge is one of the major gem-producing areas in the world.
- Liberia has alluvial diamonds along its border with Sierra Leone, in regions along the Lofa river, being mined illicitly.
- Mali is encouraging mineral exploration, and some evidence exists that diamonds may be found there.
- Myanmar, a major source of colored stones, instituted the new Myanmar Gemstone Law, covering everything from designation of gem mining blocks to finished jewelry. Much mining here is by small groups of miners, who sell portions of their output to the free market; this makes production estimates uncertain. Gemstone production declined significantly (from 307,000 carats in 1993–1994 to 55,000 in 1994–1995), although jade production was more stable (304 tons in 1993–1994, 261 tons in 1994–1995).
- Namibia produced 1.382 Mct of diamonds in 1995, up from 1.314 Mct in 1994, although diamond exports were limited by agreement with the CSO. Namdeb produced 1.34 Mct—457,500 carats from off-shore mining and 748,500 carats from onshore deposits. Rose quartz, agate, and high-quality dimension stone are also mined in Namibia.
- Norway had its first diamond find, in the northern county of Finmark, in summer 1995.
- Pakistan produced a new National Mineral Policy, which creates investment boards, grants four types of mineral licenses, and will centralize geologic data. The Azad Kashmir Mineral and Industrial Development Corporation has found a ruby resource of nearly 125 Mct in the Khandligali-Maidanwali area. Pakistan produced 220,000 carats of rubies, 510,000 carats of green tourmalines, 6,625 carats of topaz rough, and 16,500 carats of spessartine garnet in 1995.
- Russia began publishing production figures for many mineral commodities in late 1995; however, very soon thereafter, production figures were declared secret for certain commodities, apparently including diamonds. Ninety-eight percent of Russian diamond production comes from Sakha (Yakutia).
- Sierra Leone's production has been damaged by war. Total production for 1995 is estimated at 60,000 carats—down from 225,000 carats in 1994. Rampant smuggling may have produced far more stones, however.
- South Africa produced 9,682,700 carats of diamonds in 1996. Diamond production from De Beers's South African mines retreated to 9 Mct from 10.2 Mct in 1994: 4.4 Mct were recovered from the Venetia mine; 1.7 Mct from the Finsch mine (2.2 Mct in 1994); 593,630 ct from the Kimberley mines; 123,213 carats from Koffiefontein; 623,985 carats from Namaqualand; and 1.6 Mct from the Premier mine. De Beers limited production as it dealt with market disruptions and the expiration of the trade agreement with Russia.
- Sri Lanka is an important source of colored stones, including sapphire, ruby, chrysoberyl, beryl, garnet, zircon, moonstone, topaz, and tourmaline. In addition, all restrictions have been removed on the import of rough stones to promote the domestic jewelry industry.
- Swaziland continues to produce diamonds from the Dokolwayo mine, but the future of the mine looks bleak.
- Tanzania's production included 16,000 carats of diamonds from the Williamson mine, which resumed production in October after eight months of inactivity, and 97,571 kg of colored stones—mainly tanzanite.
- Ukraine has kimberlite pipes, and diamonds have been found there. The most promising areas for diamond exploration are the Azov, Volyn-Podolya, and central Pobuzh areas.
- Venezuela's large diamond deposits, located in the Guaniamo region, are being worked by several private companies.
- Zaire produced 17.3 Mct of diamonds from 16 local mining centers, with a value of $314 million. A large percentage of diamond production continues to be exported illegally, despite vigorous government intervention.
- Zimbabwe has one producing diamond mine, River Ranch, but 150 exploration prospecting orders have been granted for diamond mining. Total production for the country was 223,628 carats (up from 150,683 carats in 1994). *MLJ*