FIELD GEOLOGY

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With Appendix on Geologic Mapping

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TO

THE MEMORY OF

My Mother

PREFACE

This book treats the subject of geology from the field standpoint. It is intended both for a textbook and for a pocket manual. As a manual the author hopes that it will be of service not only to students of geology, but also to mining engineers, civil engineers, and others whose interests bring them in touch with geologic problems. The book has been written on the assumption that the reader has an elementary knowledge of general geology and also an acquaintance with a few common minerals and rocks.

The first twelve chapters are concerned with the recognition and interpretation of geologic structures and topographic forms as they are observed. Here the aim has been to describe together phenomena which in certain respects resemble one another, but which may be of diverse origins. Where possible the treatment has been empirical rather than genetic. In order to assist the reader in identifying various forms and structures, a number of tables or keys have been prepared. From the very nature of geology they can not be final or complete. They are presented with the hope that they may be of some value at least in showing what features to observe in the field.

In the last six chapters are described methods of geologic surveying, the nature and construction of maps, sections, and block diagrams, the interpretation of topographic and geologic maps, the solution of certain geologic computations, and the preparation of geologic reports.

An appendix containing several tables of practical value, a bibliography to which there are many footnote references throughout the text, and an index which has been made as comprehensive as possible, will be found at the end of the book.

The author wishes to express his sincere gratitude to his wife, to Professors W. M. Davis, W. Lindgren, R. A. Daly, and H. W. Shimer, and to Dr. J. D. Mackenzie, for valuable advice and criticism.

For illustrations the writer is indebted as follows, the specific sources being noted in certain cases in parentheses: to Professor W. Lindgren for Figs. 143 and 218 ("Mineral Deposits"); to Professor R. A. Daly for Figs. 78, 89, and 102 ("Igneous Rocks and Their Origin"); to the Geographical Journal (London) for Fig. 287; to the Harvard Geological Museum for permission to photograph specimens for Figs. 13–17, 69, 201, 205, and 206; to the University of Chicago Press and the Journal of Geology for Figs. 48 and 353; to the Carnegie Institute of Washington for Figs. 248, 262, and 263; to the Geological Society of America for Figs. 4A and B (modified), 141, 142 (modified), 225, and 258; to Dr. W. F. King, Chief Astronomer, Department of the Interior, Ottawa, for Fig. 64 (from R. A. Daly's "Geology of the North American Cordillera at the 49th Parallel"); to Mr. R. W. Sayles for Fig. 32; to the Geological Survey of New Jersey and the U. S. Geological Survey for Fig. 267; to the U. S. Geological Survey for Figs. 5 (An. Rept. 7), 40, 71, 89, 90 (Bull. 404), 149–151 (An. Rept. 13), 199 (Bull. 275), 204 (Bull. 239), 220 (An. Rept. 4), 222 (Folio 15), 239 (Bull. 576), 240, 242–246, 250 (Prof. Paper 82), 259 (An. Rept. 17), 265, 268, 269 and 270 (Prof. Paper 82), 272, 273, 275, 276, 281, 284 (Prof. Paper 64), 286, 289 (Bull. 273), 290, 291, 294 and 295 (Prof. Paper 61), 296 (Prof. Paper 67), 306, 309 (Prof. Paper 61), 310 (Monog. 1), 311–313, 314 (An. Rept. 21), 315, 377 (Bull. 300), 383, and 407; to the Coast and Geodetic Survey for Plate I; to Professor C. K. Leith for Fig. 121; to Professors E. Blackwelder and H. H. Barrows for Fig. 203B; and to Professor W. M. Davis for Figs. 236–238, 279, 307 and 308. Figs. 236 (redrawn by F. H. L.), 237, 238, 279, and 307 were taken from Professor Davis's "Geographical Essays," and Fig. 308 from "Physical Geography" by W. M. Davis and W. H. Snyder, by permission of Ginn and Company, Publishers.

To Professor H. F. Reid the author is grateful for permission to draw from his articles published in Bulletins 20 and 24 of the Geological Society of America.

The late Dr. C. W. Hayes very generously gave the writer entire freedom to borrow from his "Handbook for Field Geologists." Fig. 333 and several mathematical tables were copied from this source.

F. H. L.

BOSTON, MASS.,
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FIELD GEOLOGY

CHAPTER I

INTRODUCTION

General Definitions

1. Processes of Erosion.—On the earth's surface various agents are engaged in the work of rock destruction. Rivers wear their channels; waves undermine the cliffs along shores; wind, when it has free play, scours the rocks over which it blows; and glaciers abrade their beds. These are all processes in which the agent is moving while in operation. There are other kinds of work in which the agents are essentially motionless. For instance, alternate heating and cooling in regions of wide temperature range may cause the separation of grains and chips from the surface of a rock; moisture in the cracks of a rock expands in freezing and may wedge off block after block; certain minerals may be decomposed and carried away in solution; and so on. Whether accomplished by moving or motionless agents, the various processes of rock destruction come under the head of *erosion* (*e*, off, + *rodo*, gnaw). Many of the processes effected by agents which are essentially motionless are included in the term, *weathering*. Weathering accomplished in a chemical way is *decomposition* and that accomplished in a mechanical way is *disintegration*.

2. Products of Erosion.—Through erosion a quantity of débris is formed equivalent to the amount by which the rocks are worn down. Ordinarily it is borne away from its source, part being in solution and part being handled mechanically, and is eventually accumulated as sedimentary materials.[1] Deposits of this sort are called *transported*. If products of erosion remain *in situ* they are known as *residual deposits*. Transported deposits are *chemical* if they were precipitated from solution, and they are *mechanical*, *fragmental*, or *clastic*, if they consist of detached particles and fragments of the parent rock and if their accumulation was brought about by mechanical means. Chemical and mechanical sediments may be *organic* or *inorganic*, depending either upon the nature of the materials or upon the agent of their deposition. All these deposits, including clay, mud, sand, gravel, soil, and the like, are known collectively as *mantle rock*.

3. Bedrock, Outcrop, and Exposure Defined.—Everywhere below the mantle rock, solid rock, or *bedrock*, is known to exist. When the bedrock projects through the overlying mantle of detritus, the protruding portions are called *outcrops*. Outcrops and also sections in the unconsolidated superficial mantle rock may be referred to as *exposures*.

4. Lithosphere Defined.—If erosion should continue long enough in any region and if the products of this erosion should be removed, at last rocks might be exposed which were once at great depth. This is just what has happened over broad areas on the continents and consequently we are able today to see and study rocks some of which have been several miles below the earth's surface. We may say, then, that we are in some degree familiar with the solid part of the earth down to a depth of several—probably well within 25—miles, at least as far as the continents are concerned. Of the ocean basins we know much less; but of this fact we can feel certain, that for some distance beneath the ocean floor, as likewise for some distance beneath the land surface, the earth consists of *rocks* of one kind or another. This outer rocky shell of the earth, of which the continental

[1] *Sediment* and *sedimentary* are used in this book in their widest sense with reference to all rocks which originate upon the earth's surface and which are derived through the destruction of preëxisting rock.

portions have been to a certain extent brought within our observation, is the *lithosphere*.

5. Field Geology Defined.—When rocks and rock materials are investigated in their natural environment and in their natural relations to one another, the study is called field geology. Field geology seeks to describe and explain the surface features and underground structure of the lithosphere. Physiography and structural geology are equally important in the science of field geology.

6. Observation and Inference.—Field geology is necessarily founded upon observation and inference. Only features that are superficial can be observed; all else must be inferred. We may study the surface of an outcrop, of a valley, or of a sand grain, but in attempting to explain the internal structure of the outcrop, or what underlies the valley, or how the sand grain was fashioned, we are forming inferences by interpreting certain visible facts. The ability to infer and to infer correctly is the goal of training in field geology, for one's proficiency as a geologist is measured by one's skill in drawing safe and reasonable conclusions from observed phenomena.

7. Correlation.—No geologic structures and no land forms, such as hills, valleys, and the like (**226**),[1] exist as isolated phenomena. Every geologic feature is in some way dependent upon, or associated with, other geologic features, and this dependency or association the field geologist must discover. This is what is meant by *correlation*. The word signifies the description or explanation of one geologic phenomenon in relation to others. Here is an example to illustrate the case: By definition all outcrops are exposed portions of the bedrock underlying the superficial unconsolidated mantle rock. Accordingly, when the geologist examines a series of outcrops he should bear in mind that they are not single, detached forms, but that they are visible parts of a rock body which is continuous beneath the soil and that the rocks or structures which they

[1] Numbers in parentheses refer to the articles in the text, denominated by the side headings.

exhibit are in some way mutually related. He will be correlating these outcrops when he studies them from this broad point of view and endeavors to explain these mutual relations.

8. Multiple Working Hypotheses.—Geologic interpretation is facilitated by what is termed the method of multiple working hypotheses. Suppose, for instance, that the surface of a rock is marked by parallel grooves. In order to explain the origin of this feature, the geologist should call to mind all possible ways in which such parallel grooves might be produced. These are his working hypotheses. To determine which is the right one, he must examine the rock surface for other phenomena which are associated with the grooves, for each hypothesis postulates a certain group of geologic features which are mutually related.

The same principle may be applied where extensive correlation is necessary. The distribution of outcrops in a small area may be such as to suggest that a certain igneous rock comes into contact with a certain sedimentary rock, but the actual junction line may be concealed beneath the mantle rock. The relation may be explained on the assumption that the two rock bodies meet in an intrusive contact, in a fault, or in a surface of unconformity. These three working hypotheses the geologist would have to keep in mind while looking for further evidence to ascertain which is the true interpretation.

9. The Study of Exposures.—Every geologic surface has features which deserve an explanation. They may be purely superficial or they may be cross sections of structures or forms that extend below the surface. In the latter event they probably belong to the structure of the rock. To discriminate between such superficial and structural characters, break off a fragment of the bedrock, or, in the case of an unconsolidated deposit, scrape off some of the surface material. The freshly exposed surface will settle the question.

If the observed features are superficial, in respect to their origin they may be related to the surface on which they are found in one or another of these four ways: (1) They may still be in process of formation, although perhaps the agent that made them is not acting continuously. (2) They may have been made by some agent no longer working and may not yet have suffered alteration under the new conditions. This often holds for Pleistocene glacial scorings on hard, fine-grained rocks; but smoothed, striated surfaces are soon destroyed on exposed coarse granular rocks, which are much more susceptible to disintegration. (3) The surface features, if on bedrock, may have been preserved for a time under unconsolidated deposits which have recently been removed (**71, 72**). Disintegration in coarse rocks may be prevented by such a cover. On the other hand, a soil mantle may sometimes promote decomposition of the buried rock. (4) A buried surface like that just mentioned may be preserved for a much longer time by a thick cover of consolidated strata (**73**). Erosion of the overlying formation may reëxpose the old surface provided the latter happens to coincide with the new erosion surface; but such instances are very rare and the exposure of the old surface can not be complete.

If the observed features are structural, extending into the bedrock or the mantle rock, as the case may be, they should be examined with this fact constantly in mind. A line is then the cross section of a surface and an area (band or patch) is the cross section of a body that has three dimensions. The trend of the line is often indicative of the form of the surface which it represents, and the shape of the area is suggestive of the form of the body, but there are many exceptions. The geologist should always look over the outcrop or the deposit to see if he can find the structural surface or body exposed on two faces of this outcrop as nearly as possible at right angles to one another.

10. Primary and Secondary Features Defined.—It is sometimes convenient to refer to the features on exposures as *primary* or *secondary* according as their origin was contemporaneous with, or subsequent to, the origin of the material in which they are seen. Examples of primary structures are bedding in sedimentary rocks, ripple marks, flow structure in lava, and the like. Among secondary features may be mentioned surface stains on outcrops, glacial scratches, and fractures in rocks.

11. Dip, Strike, and Attitude Defined.—When one wishes to state the position of an inclined flat surface, two definite quantities are necessary. One must know the *dip*, that is, the maximum angle of slope of the surface, and one must know the *strike*, which is the direction of the intersection of the surface with any horizontal plane (Fig. 1). The dip is an angle in a vertical plane and must always be measured *downward* from the horizontal plane. The direction of dip is perpendicular to the strike. Dip and strike together determine the position or *attitude* of a surface with respect to horizontality and to compass directions. Obviously the attitude of a relatively thin layer of uniform thickness will be that of the layer's upper or lower surface.

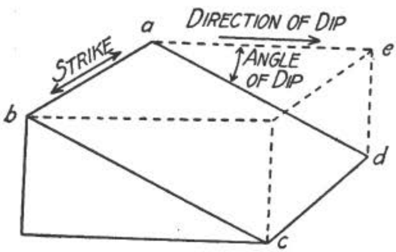


FIG. 1.—Dip and strike. *bae* is a horizontal plane.

12. Discrimination between Transported and Residual Deposits.—Transported and residual deposits have been defined in Art. **1**. They can usually be distinguished in the field by their relations to the underlying bedrock. As a rule, transported materials are quite unlike the rock beneath them, whereas residual deposits commonly grade down into the subjacent rock or at least show some chemical resemblance to the latter (refer to Chapter III and to Arts. **71, 72**).

TABLES FOR THE IDENTIFICATION OF ROCK FEATURES

13. Use of the Tables.—The succeeding tables are intended for use by beginners in field geology. They require very little acquaintance with geologic structures, but they do call for an elementary knowledge of the more common mineral and rock species. They are not to be regarded as absolutely complete. They are suggestive rather than final, indicating by references the places in the text where further information may be found. These references are to the numbered articles. Chapter and page citations are designated as such.

Among the general terms employed, the following may need definition. *Parallel banded or streaked character* refers to any structure or surface marking which may catch the eye on account of its linear appearance. *Massive character* may be regarded as the opposite of banded or streaked character. There is no linear appearance. *Inclosed areas* are superficial patches or spots scattered here and there on the surface of the exposure. *Inclosed bodies* are crystals, pebbles, rock fragments, or any other individual forms, entirely surrounded by a matrix of some kind of material. A contact, in general, is a surface between two contiguous rock masses. In this book the word is used to include igneous contacts (**103**), surfaces of conformity (**70**) and of unconformity (**71**), faults (**164**), and vein contacts (**219**). A *contact line* is the line of intersection of a contact surface with the surface of an exposure or with the surface of bedrock covered by mantle rock; *i.e.*, a contact line may be exposed or concealed. Other terms are either self-explanatory or are defined in the citations.

14. Parallel Banded or Streaked Character.—The exposure has a parallel banded or streaked appearance

A. Due merely to a system of parallel fractures (see Art. **21**)

B. Not due to parallel fractures. The banded or streaked appearance is
   1. Purely superficial (**9**), being due to
      a. Parallel stains which trend down a sloping surface or follow parallel grooves. Such stains may consist of iron rust (yellow, buff, brown), fine soil (brown, gray, black, etc.), moisture, or organic growths (green, yellow, pink, etc.) (refer to Chapter II).
      b. Parallel scratches or grooves (**33**).
   2. Due to a structure which extends into the rock, but is viewed only in cross section, this structure being
      a. A parallel arrangement of constituents which are longer than they are wide. If the rock is composed of constituents of different kinds and
         (1) All the constituents have parallel orientation, the rock is probably a schist; less likely, a gneiss. Mica or hornblende is usually abundant (Chapter IX).

(2) Only one or two kinds of constituents are distinctly orientated,
(a) The constituents with parallel arrangement being larger and more conspicuous than those not so arranged, the parallel constituents may be
(a_1) Flat concretions, with their flatness in the planes of the bedding of clay or mudstone, sand or sandstone.
(b_1) Flattish pebbles in an unmetamorphosed gravel or conglomerate (**86**).
(c_1) Flattened or somewhat spindle-shaped pebbles in a moderately sheared conglomerate. Such pebbles are generally more or less coated with mica.
(d_1) Broken strips (inclusions) of country rock inclosed in an igneous matrix, probably arranged in the direction in which the matrix flowed when it was molten (**125**).
(e_1) Phenocrysts in an igneous rock, probably arranged in the direction in which the matrix flowed when it was molten (**102**).
(f_1) Flakes of clastic mica, usually muscovite in this case, in muds, sands, mudstones, or sandstones (**87**).
(b) The constituents with parallel arrangement being smaller than those not so arranged, the parallel constituents probably belong to the matrix or groundmass of a schist containing metacrysts (**205**).

b. A single layer which may intersect other structures in the adjacent rock (wall rock) and may, or may not, trend parallel to some fracture system in the wall rock (refer to Art. **15**).

c. A layered structure in which the several layers differ in respect to the composition, or size, or some other character, of their constituents. If
(1) The banding is limited to a particular belt or strip of rock and
(a) The banding is parallel to the edges of the strip, this banding may be due to
(a_1) Successive injections of igneous material along the the same course. This feature, when seen, is most common in dikes and sills.
(b_1) Flow structure in a dike or a sill along the trend of its contact (**115**).
(c_1) Vein structure. For the distinction between veins and dikes refer to Art. **225**.
(b) The banding forms an acute angle with the edges of the belt or strip, the structure is probably cross-bedding (**80**).
(2) The banding is not limited to a particular belt or strip of rock. If

(a) The banding is simple, in one set only, and

(a_1) The rock is fine-grained or has no grain, and

(a_2) Any visible constituents are not conspicuously oriented in parallel position, the banding may be

(a_3) Flow structure in lava (rhyolite, etc.) (**102**), especially if amygdales or phenocrysts are scattered through the rock. However, some fine-grained lavas look exceedingly like rocks of (b_1).

(b_3) Lamination, or bedding, in mud, clay, fine sand, etc., and in rocks derived therefrom, provided large grains, if anywhere present, are grouped in layers parallel to the banding. Exceptionally, sand grains or pebbles may be seen scattered indiscriminately in laminated muds and shales (**84**).

(c_3) Lamination or coarser bedding in limestone and chemical precipitates for the recognition of which chemical tests are often necessary.

(b_2) Visible constituents, principally mica, have parallel orientation, the banding is probably schistosity (**205**).

(b_1) The rock is as coarse as a medium-grained sandstone, or coarser, so that the grains can be recognized, and

(a_2) The banding, as a whole, is of fairly regular and continuous character along its trend, although some layers may be lenticular, this banding may be due to

(a_3) Flow structure in an igneous rock along the trend of its contact with its country rock (Cf. *c*, (1), (a), above).

(b_3) Stratification in transported sedimentary materials (**60**).

(c_3) Any parallel structure, answering to the description, in residual materials, such structure having been originally present in the rock from which these materials were derived. Look for the parent rock (**12, 72**).

(d_3) Gneissic structure (**205**), seen in both primary and secondary gneisses. Secondary gneisses are generally associated with mica schists and often have schistose layers and other evidences of metamorphism. For the discrimination between primary and secondary gneisses see Art. **214**. In gneissic structure there is always a certain degree of mineral parallelism.

(e_3) Schistosity, this term always likewise implying parallel mineral arrangement (**205**).

(b_2) The bands (sometimes mere streaks) are present in igneous, usually granite-like, rock. They are generally short, and grade, especially at their ends, into the surrounding rock. They are often darker than the surrounding rock. Such bands or streaks are probably schliers (**102**).

(*b*) The banding is complex and is

(a_1) Due to differences of color or intensity of color, and is often definitely related to two or more intersecting sets of fractures (refer to Art. **16**).

(b_1) Due to differences of texture in adjacent layers, and has no necessary relation to fractures, it is probably a variety of cross-bedding (**80**).

15. Single Strips or Bands.—The exposure exhibits a strip or band which distinctly differs in character from the rock on each side. The band may be associated with others of the same kind, but it is not one of a series of more or less similar parallel bands which together form the entire surface of the exposure. If

A. The band is purely superficial, it is probably a local stain (**9**).

B. The band is the cross section of a structure which extends into the rock, and

1. Consists of angular fragments of the rocks on both sides of it, it may be a fault breccia or a vein breccia (**204**).
2. Consists of silicate minerals such as are common in igneous rocks, or consists of rock glass, or of very dense, compact material showing no grain (felsite), it is probably
   a. A sill or a flow if it is essentially parallel to associated strata (**104, 132**).
   b. A dike if it crosses an igneous rock or the stratification of a sedimentary rock (**104, 225**).
3. Consists of vein minerals, it is probably a vein (**219, 225**).

16. Intersecting Banded Pattern.—The exposure is marked by intersecting bands which trend in various directions. If

A. The bands are merely the result of a color variation in the rock and are always definitely associated with fractures in intersecting sets, they are probably an effect of weathering, the agents having worked inward from the fractures (**29**).

B. The bands differ in texture or composition from the adjacent rock, and
   1. Consist of silicate minerals common in the igneous rocks, they are probably intersecting dikes.
   2. Consist of vein minerals (**221**), they are probably veins which were deposited in intersecting fractures.
   3. Consist of sandstone in shale, or of mudstone or calcareous mudstone in limestone, they may be the lithified fillings of old sun cracks viewed in plan (**56**).

17. Massive Character.—The exposure has a massive appearance, its constituents being neither grouped in layers nor oriented in parallel position. If

A. The rock is of very fine and uniform grain,[1] and is
   1. White, gray, or light-colored, rather soft or medium hard, and reacts for carbonates, it is probably a fine, massive limestone, marble, or dolomite.
   2. White or light-colored, highly siliceous, and very hard, it may be a fine quartzite or a siliceous replacement of massive limestone.
   3. Gray or dark gray, brownish, buff, etc., generally has a clayey odor, and may be soft or hard, it may be a dust deposit (loess), a deposit of unlaminated clay, or the consolidated rocks derived from these materials (**62**).

B. The rock is as coarse as a medium sandstone or coarser, being of relatively uniform grain, and consisting very largely of
   1. Grains of calcite or of dolomite, it is marble (**205**).
   2. Grains of quartz, it is quartzite (**205**).
   3. Grains of the silicate minerals which ordinarily constitute igneous rocks (Appendix II), it is an igneous rock or is the residual disintegration product (often arkose) of an igneous rock (**72**).

C. The rock as a whole is relatively coarse, consisting of large grains or fragments in a finer matrix, reference should be made to the key in Art. **42**.

18. Inclosed Areas or Bodies.—The surface of the exposure exhibits conspicuous bodies or areas (generally cross sections of bodies) surrounded by a relatively fine matrix. If

[1] In all cases under "A" further search may prove that the rock is a thick bed interstratified with other sedimentary rocks.

A. The areas are purely superficial (**9**), they may be color stains (Chapter II), or exfoliation scars (**31, 129**), or erosion remnants such as are described in Art. **137**.

B. The areas are cross sections or faces of inclosed bodies which are

1. Single crystals, in part or entire, they may be

   a. Phenocrysts in igneous rocks, especially if the matrix is massive and is composed of silicate minerals (**102**). If the matrix is banded, the phenocrysts are apt to have parallel orientation.

   b. Metacrysts in a metamorphic rock, especially if the matrix is marble (test for carbonates) or is schistose (**205**). If the matrix is banded or streaked and its constituents have parallel orientation, the metacrysts are apt to have diverse orientation.

2. Mineral aggregates, or are bodies clearly not single crystals, and if these bodies

   a. Have well-marked outlines and

   (1) An angular form with sharp corners as if due to breaking, they are probably fragments in some kind of breccia (refer to **204, 43**).

   (2) A more or less well rounded form, without sharp corners and without projecting knobs, and have

   (*a*) A radial or concentric arrangement of some or all of their constituents, as seen in cross section, and

   (a_1) Form the bulk of the rock, adjacent individuals being in contact, having a flattened oval shape, and usually measuring 1 ft. to 2 or 3 ft. in length, the bodies may be "pillows" in "pillow lava" (**102**).

   (b_1) Do not form the bulk of the rock, adjacent individuals, seldom in contact with one another, being

   (a_2) Inclosed within a very fine dense or glassy matrix, the bodies may be spherulites or lithophysæ in lava (refer to a good textbook of petrology).

   (b_2) Inclosed within a fine-grained matrix which may have flow structure, the bodies may be amygdales, especially if they are oval in cross section, are arranged with their lengths parallel (**102**), and consist of vein minerals (**221**).

   (c_2) Inclosed within a fragmental matrix usually consisting of angular pieces of lava and volcanic dust, as in volcanic agglomerate (**204**), are probably volcanic bombs (**102**).

   (d_2) Inclosed within a massive matrix consisting of silicate minerals characteristic of igneous rocks, are probably segregations or rounded inclusions (**127**).

(*b*) A concentric fracture structure, most pronounced toward the periphery, but no concentric or radial arrangement of constituents, and are contained in a matrix of the same constituents, in an unconsolidated or consolidated state, the bodies are probably bowlders of disintegration still *in situ* (**48**).

(*c*) No radial or concentric structure, and are

(a_1) Inclosed within a fine-grained matrix which may have flow structure, etc. (continue as in (*a*) (b_1) above).

(b_1) Inclosed within a fragmental matrix, etc. (continue as in (*a*) (c_2) above).

(c_1) Inclosed within a massive matrix, etc. (continue as in (*a*) (d_2) above).

(d_1) Inclosed within a matrix of sand or sandstone of uniform texture, the bodies may be

(a_2) Concretions if they are formed of similar sand or sandstone, more compactly cemented (**65**), or

(b_2) Clay galls if they consist of clay (if in sand), or shale (if in sandstone) (**84a**).

(e_1) Inclosed within a matrix of clay or argillite, the bodies may be clay concretions if they consist of similar clay or argillite, more compactly cemented (**65**).

(f_1) Inclosed within a matrix of sand grains and smaller pebbles, as in an ordinary gravel, the bodies are pebbles (**48**).

(3) A more or less well rounded form, often with projecting knobs or excrescences, they may be

(*a*) Concretions (of clay, marcasite, flint, etc.) if they are in a sedimentary matrix (**65**).

(*b*) Corroded inclusions if they are in an igneous matrix (**125**).

(4) An elongate oval, spindle-shaped, rodlike, or lenticular form, the bodies may be

(*a*) Sheared pebbles in a schistose matrix, especially if they are clearly individual bodies (**49**).

(*b*) Lenses in a schistose or gneissic matrix, if they are merely lenticular areas (aggregates) which are relatively poor in mica, between wavy or winding layers relatively rich in mica (**205**).

b. Have indistinct or blended outlines, gradational into the surrounding matrix, and are

(1) Irregular, often wavy streaks or patches in a distinctly igneous rock refer to Art. **14**.

(2) Irregular, often bent and twisted, sand or gravel layers in gravel or till, they may be "nests" (85).
(3) Roughly lenticular bands of sand or gravel (sandstone or conglomerate) in distinctly sedimentary banded materials, the body is a lens (81).
(4) Lenticular areas in schists, refer to (4) above.

19. Contact Lines; Mutual Relations of Contiguous Rock Masses.—An exposure has two (or more) parts which meet in a fairly well defined line (contact line) and differ from one another in color, texture, composition, structure, or surface marking. Neither occurs included or surrounded by the other. If

A. The difference in character is superficial (**9**), and
  1. Is not related to any underlying difference within the rock, it may be due to the fact that
    a. The rock is stained in one place and is not stained, or is stained in a different way, in another place.
    b. The rock is wet in one place and dry in another.
    c. The rock has been affected in a different manner in two places, possibly because it was partly protected from erosion for a time (**9**).
  2. Is related to an underlying difference in the rock, it is probably due to the fact that the two kinds of rock are affected in different ways by the same erosive agents (see B, below).
B. The difference in character is due to a difference in the underlying rock, and
  1. The contact line lies between two bands, both of which are parallel to the line, and
    a. The bands are sections of adjacent laminæ or beds in unmetamorphosed, or metamorphosed sediments (**213**) (refer to Art. **14**), the line may be called a line of conformity (**70**).
    b. The bands consist of igneous or of metamorphic rock, refer to Art. **14** for the banding.
  2. The contact line lies between two bands, or two banded series, which are not parallel both to one another and to the line,[1] and
    a. Both bands or banded series are sections of adjacent laminæ or beds in sedimentary rocks, or in metamorphosed sediments, the

[1] Both banded series may be parallel to one another and not to the line, or one series may be parallel to the line and not the other, or the series may be parallel neither to one another nor to the line.

line may be a line of local unconformity (**77**), or one of regional unconformity (**71**), or a fault line (**164**) (**288**).

b. Both bands or banded series are not sedimentary, the line may be one of unconformity, an igneous contact, or a fault (**288**).

3. The contact line has any other relations, not mentioned above, to banded or massive rocks, determine the nature and classification of the rocks and then refer to Art. **288.**

20. Gradational Changes in Rocks.—A rock exposure displays a gradational change in the texture, composition, or structure, of the materials of which it consists. If

A. The change appears to be directly related to a contact line, and
  1. Is present in a sedimentary rock or in a metamorphosed sediment (**213**), and if
    a. The contact line is a line of conformity or of unconformity (Art. **19**), the variation is probably an effect of slow and uniform change of conditions during sedimentation when the rock was formed (**83, 77**).
    b. The contact line is an igneous contact (Art. **19**), the variation is probably attributable to contact metamorphism which was induced as a result of the eruption (**103, 118–121**).
    c. The contact line is a fault, the variation is a result either of heat or pressure involved in the faulting, or of metamorphism accomplished by solutions or gases which travelled along the fault (**121, 218**).

B. The change does not appear to be directly related to a contact line, it may be an effect of blended unconformity (**72**) or of blended igneous contact (**103**).

21. Cracks or Fractures.—The rock exposure is traversed by one or more cracks. Examination of such a crack shows that

A. The broken ends of structures which trend across the crack have not been separated, or have been only very slightly separated, along the crack. If
  1. The crack is one of a set of closely and rather regularly spaced, parallel fractures, the crack is a cleavage crack and the set is called a cleavage (**203, 205**).
  2. The crack is single, or is one of a set of fractures not very closely spaced, the crack is a joint and the set is a joint set or joint system (**193**).

B. The broken ends of structures which trend across the crack have been separated by displacement along the crack. Such a crack is a fault (**164, 172**).

22. Curvature of Bands or Streaks.—The rock exposure has a banded appearance and the bands are curving. First determine the probable nature of the rock and the banded structure by reference to Art. **14.** If

A. The rock is igneous, the curved form is probably a result of flow when this rock was molten (**102, 115**).

B. The rock is sedimentary, and

  1. Has a finely banded (laminated) character, and the laminæ are in sets which

     a. Are not parallel to the main bedding, and if the laminæ in all sets are curved, those in each set having simple and nearly parallel curvature and being truncated by the adjacent sets, the phenomenon is probably a variety of cross-bedding (**80**).

     b. Are parallel to the main bedding, and if

       (1) The laminæ in some or all sets are curved, those in each set having a wavy curvature in which the arches and troughs are of approximately equal size and shape, and the arches are never bent over the troughs, the phenomenon is probably ripple-mark (**80, H**). The span of the arches and troughs may be different in different sets, and any set may have its arches truncated by the overlying laminæ, whether these be straight or curving.

       (2) The laminæ in some sets are curved and in other sets are straight or are much less curved, those in the curved sets often being of more or less irregular form or of unequal size, with associated breaks in their continuity and with the arches often bent well over the troughs, the phenomenon is probably a variety of folding such as is described in Art. **154.**

  2. Is finely or coarsely bedded, and all the beds or laminæ are more or less similarly curving, sometimes in a very complicated manner, the curves consisting of archlike and troughlike bends, the phenomenon is probably a result of similar folding such as is described in Arts. **150, 143.**

C. The rock is metamorphic, the curvature of the bands may be

  1. An original feature (A and B, 1, above) not yet destroyed because the rock has not suffered much deformation.
  2. Folding such as that described in B, 2, above, but generally of a more complex nature. This is to be expected in the mica schists.

23. Inclination of Banded Structure.—The exposure has a banded appearance and the bands are inclined. First determine the probable nature of the rock and the banded structure by reference to Art. **14.**

A. The rock is igneous, the inclined attitude (**11**) in itself has no particular significance.

B. The rock is sedimentary, being
   1. Mud, clay, argillite, shale, or slate, and has its bedding inclined more steeply than 3° or 4° to the horizontal, this rock has probably been tilted from its original position (Art. **69**).
   2. Sand, sandstone, gravel, conglomerate, volcanic ash, or any other relatively coarse fragmental material, and has its bedding inclined more steeply than 35° to the horizontal, it has probably been tilted from its original position (**69, 227**).

C. The rock is metamorphic, the attitude of its banding is significant according as it was derived from an igneous rock or from a sedimentary rock (refer to A and B, above).

CHAPTER II

FEATURES SEEN ON THE SURFACES OF ROCKS

Colors of Rocks

24. Black, Gray, and Dark Brown.—In igneous rocks primary gray shades are generally due to an intermixture of light and dark minerals. The more black grains (biotite, hornblende, augite, magnetite, etc.) there are, the darker gray is the rock. Gray sandstones also may owe variations in tone to variations in the content of black mineral particles, especially of magnetite. In shales, slates, and limestones, grays are often caused by carbonaceous matter in the rock.

Dark brown and black incrustations of secondary origin are seen on some outcrops in arid regions. They are called *desert varnish.* These coatings consist of iron and manganese oxides believed to have been deposited from evaporating moisture which has risen to the surface by capillary action.

25. Yellow and Brown.—Yellow and brown are nearly always secondary colors. They are caused by the rusting (oxidation and hydration) of such iron-containing minerals as biotite, hornblende, augite, garnet, pyrite, etc. Because iron-bearing minerals break down very readily, this sort of yellow staining may be found even in dry climates. Some bright yellows are due to the growth of minute organisms.

26. Red and Pink.—Conglomerates, sandstones, and mudstones are sometimes red because the pebbles or grains which compose them were derived from an older red rock. The color is primary with the sedimentary rock, although it may have been either primary or secondary in the original parent rock. In this way red feldspar, containing finely disseminated hematite, may color a sedimentary rock. Some pinkish and purplish sands are tinted by garnet grains.

Secondary pink and red hues are usually indicative of the presence of hematite. Orthoclase feldspar is apt to become reddish early in its weathering. (What rocks might owe their reddish or pinkish color to this cause?)

After rocks have been broken up by weathering in warm, humid climates, derived residual soils and clays may become red by superficial dehydration of ferric hydrates. Below the surface they remain yellowish or brown. Rounded quartz sands of which the grains are coated with red iron oxide may be regarded as of desert origin.

In some places bright pinks and reds, like certain yellow tints, are produced by organisms.

27. Lighter Shades and White.—Through weathering original colors may be changed to lighter secondary shades of the same hue, or to white. This may be caused in at least five ways: (1) Feldspar grains in a rock may decompose to dull white powdery kaolin. (2) By the formation of minute solution cavities in more or less transparent soluble minerals, such as calcite, transparency is lost and the grains appear to be white. These two processes are characteristic of moist climates. (3) Organic coloring matter is sometimes "bleached" out of sedimentary rocks. (4) In dry climates, where the rainfall is slight, thin white incrustations of certain carbonates may be formed on the rock surfaces in the same way as the desert varnish, above described. (What effect would a heavy shower have upon these soluble incrustations?) (5) Another phenomenon to be seen in climates where disintegration prevails is the production of minute fractures within the mineral grains, due to the action of frost or of temperature changes. Whitening of this origin, like that mentioned in (2) above, is due to the reflection of light from innumerable minute surfaces.

28. Green and Gray Spots.—Green or grayish spots or bands on red rocks owe their presence to organic matter. Either the green has been produced by a reduction of the red iron oxide in proximity to the organic remains, or the rock has been reddened by oxidation except surrounding this organic matter. In any case the green or gray color is the effect of an organic reducing agent.

29. Relations of Colors to Surfaces of Weakness.[1]—A change of hue is sometimes associated with joints, faults, or even with igneous contacts, which are intersected by the outcrop surface. This is because such surfaces of weakness may afford access to decomposing solutions that bring about discoloration. The rock may appear to be striped or perhaps marked with a pattern of irregularly crossing bands. Since agents of discoloration always work inward, the maximum change is found at the surface of attack.

In a small joint block, a uniform inward gradation of color is not always seen. The water may enter from all sides, dissolve or decompose a little of the rock substance, carry it in, and then deposit it more or less concentric with the surface of the block. Such a joint fragment, if several times subjected to the same process, may display a number of concentric bands when it is split open.

Surface Features Other Than Color

30. Smoothness and Polish.—Smooth rock surfaces, and particularly those which are distinctly polished, have probably been rubbed by some abrasive agent which was furnished with finely divided scouring material, such as dust, rock flour, etc. Coarser particles scratch (**33**). Polish is generally limited to hard rocks, for it is not taken so well by softer varieties. Outcrops may be polished by wind carrying dust or ice crystals, by glacial ice, and by water currents or waves which are transporting sand or silt.

Polish made by wind, waves, and streams, is rather dull, whereas glacier-made polish may be of such perfection that objects are clearly reflected in it. Eolian dust polish is to be

[1] Any fractures or contacts, and even the mutual contact surfaces of the grains, in rocks may be called *surfaces of weakness.*

expected in desert regions and in other places where the prevailing winds are dry. Ice-crystal polish is seen only at high altitudes and latitudes where projecting rocks, unprotected by a snow cover, are frequently subjected to snow storms accompanied by winds of high velocity. Glacial polish is found in districts formerly overridden by ice. Another method by which rocks may be polished is by faulting, but here the smoothed surface can not be seen unless the rocks on one side of the fault are gone. Fault-made polish is associated with slickensides (**33, H**). Polished surfaces are not necessarily flat or broadly rounded. They may be hummocky, grooved, scratched, or pitted.

31. Granularity.—Frost action, repeated temperature changes, and certain other processes of disintegration, cause the dislodgment of the grains of such coarse rocks as granite, diorite, gneiss, coarse marble, etc. The grains separate either in fragments along their mineral cleavages, or individually or in aggregates along their contacts with adjacent grains. Sometimes thin sheets or great slabs of rock may spall off by exfoliation (**43**). The effect of this loosening of mineral grains, singly or in groups, is to roughen the surface of the rock. So rough may the outcrops become in arid climates and at high altitudes that the sharp edges of the grains cut one's fingers Such surfaces, if exposed to wind erosion, become more or less smoothed and polished.

Granularity of surface may be produced under water when one of the rock constituents is peculiarly susceptible to hydration. Accompanying this chemical change there is usually an increase in volume which, when affecting hundreds of grains over a rock surface, brings about strains and stresses that finally cause the dislodgment of particles. This is an example of disintegration performed by decomposition.

32. Great Irregularity.—The original surfaces of some kinds of lava are exceedingly irregular (**108**). This character may be observed on recent flows and also on lava sheets which have been buried and subsequently reëxposed.

If a rock suffers disintegration, not by the removal of small grains or spalls, but by the detachment of joint blocks, the outcrop acquires a secondary surface which is of great irregularity. Sometimes faults, cleavage planes, or other surfaces of weakness, function instead of joints. The process by which the blocks are detached is called *natural quarrying*. It includes the bergschrund action of glaciers, the plucking of moving ice, the ordinary frost action of northern climates, and the maintenance of cliffs undermined by rivers and waves (**231**). In the last case the blocks fall because their support has been eroded away by the undermining, but their loosening is often assisted by frost action or by root growth.

On some irregular secondary rock surfaces corners and edges are sharp (Fig. 2) whereas on others they are more or less rounded. Rounding may be the result of concentric weathering (**48**) or of some sort of abrasion. Evidently, if in a given region rock exposures continue highly irregular with all edges and corners

Fig. 2.—Profile section of an outcrop which is undergoing erosion through the removal of joint blocks. There are two prominent joint sets inclined in opposite directions.

sharp, the dislodgment of blocks must be more rapid than any rounding process. On ordinary surfaces of low inclination concentric weathering or scouring, as the case may be, can generally keep pace with natural quarrying. It follows that sharp edges and corners are found typically on vertical or steeply inclined surfaces. They are present on the roofs of erosion caves (**252**) and overhanging cliffs. They are more common in fine-grained and homogeneous rocks, for disintegration is often too rapid in the coarser varieties.

Rock exposures of the kind just described may subsequently undergo abrasion. If ice is the abrading agent, it is apt to destroy all traces of the original surface; but wind and water merely round off the corners and scour out the hollows. They smooth over the ruggedness of the old exposure and produce a hummocky surface. The lee sides of roches moutonnées may show this kind of rounding performed by the later current action of glacial waters. Rocky coasts which are not very steep display hummocky, wave-worn erosion surfaces (Fig. 3), for, since the joint blocks are wedged out one at a time at long intervals, the waves are able to keep pace with the quarrying.

It is easy to distinguish between those hummocky surfaces which originate by abrasion and those that originate by disintegration. The former are more or less smooth, while the latter are granular and rough.

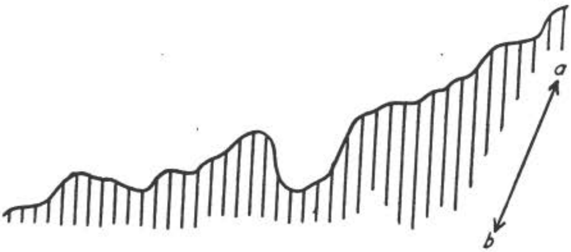


FIG. 3.—Profile section of a rock surface worn by wave erosion. Note the definite relation between the joints, inclined in the general direction *ab*, and the outline of the rock surface.

33. Scratches, Grooves, and Ribs.—Under the head of primary grooves and ribs may be mentioned the ropy structure of pahoehoe lava, and, in sedimentary rocks, ripple marks and rill marks (**53, 55**).

Scratches are always made by abrasion. Some secondary grooves are the product of scouring and others are made by weathering. Scratches on the floor and side of a groove, about parallel to its trend, may be accepted as proof of its origin by scour. Scratches and abrasion grooves may be produced by ice, wind, landslides, mud flows and rock glaciers, by faulting, and by human means. Other secondary grooves may be made by solution and by differential weathering. All abrasion furrows indicate by their trend the general direction in which the agent moved, but whether the motion was in one way, along the line, or in the other, must be demonstrated by other criteria.

Below is a table to assist in the identification of scratches and grooves. The letters in parentheses refer to paragraphs in the succeeding context.

KEY FOR THE IDENTIFICATION OF SCRATCHES AND GROOVES

A. Scratches (always implying abrasion),
  1. If notably parallel,
    a. May be slickensides (**H**) if they are on a rock surface that can be traced into the bedrock and if displacement is visible where this surface passes into the bedrock.
    b. May be landslide scratches (**D**) if they are on a bare rock surface which is on a steep hill slope and is just above a mass of landslide débris, or if they are on a rock surface which is locally covered by landslide débris.
  2. If showing some deviation in trend and if
    a. Present on a rock surface which is locally covered by till or other unsorted rock débris, may be glacial striæ (**A**), or scratches made by mud flow or rock glaciers (**E**).
    b. Present on a rock surface which is locally covered by wind-blown sand, may be furrows made by wind scour (**C**).
B. Grooves with smoothed or polished surfaces and with evidences of abrasion,
  1. The marks of abrasion being in the form of definite scratches which
    a. Have the characters of glacial striæ, are probably grooves made by true glacier, rock glacier, or mud flow (**B, E**; see also **J**).
    b. Have the character of slickensides, are probably grooves made by faulting (**I**).
  2. The marks of abrasion being short furrows and subordinate grooves. may be wind-made grooves (**C**).
C. Grooves, usually with rough granular surfaces, and
  1. Not intimately related to the rock structure, may be solution grooves, especially if they are found on such soluble rocks as limestone (**F**).
  2. Parallel to the rock structure, the grooves being on the weaker layers and the ridges on the stronger layers, may be grooves of differential weathering (**G**).

——**A.** *Glacial scratches or striæ* (sing., stria) are found on rock surfaces that have been smoothed by ice scour in regions of past or present local or continental glaciation (Fig. 4, G). They may be present on horizontal, inclined, or vertical surfaces. On valley walls the striæ are commonly inclined about parallel to the grade of the valley floor. Scratches with the same trend are said to belong to one set. When more than one distinct set marks an outcrop, the different sets are generally the effects of the symmetrical retreat of a single ice lobe (Fig. 5). They are not apt to belong to different ice advances, because the earlier marks would almost surely have been destroyed.

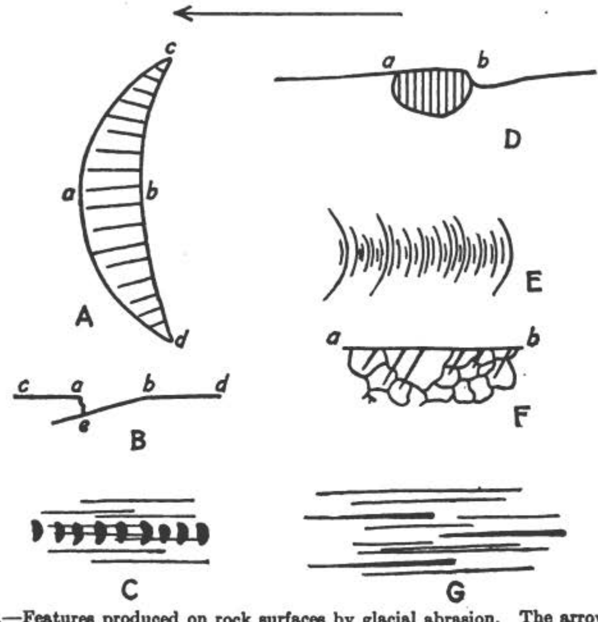


FIG. 4.—Features produced on rock surfaces by glacial abrasion. The arrow points in the direction of ice motion. A, plan of a crescentic gouge. B, section of crescentic gouge, taken through *a* and *b* in Fig. A. *cabd* is the glaciated rock surface. A crack was formed along *be*, and then a chip broke off along *ae*. C, chatter marks associated with glacial striæ. D, section of a pebble which has protected the rock matrix in its lee (*a*), and has caused the ice to gouge out this matrix on the thrust side (*b*). The depression at *b* may occur as a groove on three sides of the pebble, trailing out in the direction of ice motion. E, crescentic fractures in plan. F, microscopic section of quartzite showing six crescentic fractures extending downward from the glaciated surface, *ab*, of the rock (enlarged 14 diameters). G, glacial striæ. Such striæ sometimes begin abruptly and taper out in the direction of ice motion.

——**B.** *Glacial grooves* are in many respects similar to striæ with which they are associated. They range in size from deep scratches to glacial valleys (**250, G**). They may be straight or sinuous, and they may be continuous for many feet. In cross section their profiles not infrequently show an angle or shoulder on each side, which divides the concavity of the groove from the convexity or broader concavity of the adjoining rock surface (Fig. 6).

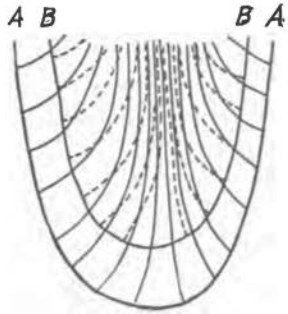


Fig. 5.—Changes in the direction of striæ due to change of glacial motion in the retreat of an ice lobe from *AA* to *BB* (after T. C. Chamberlin).

——**C.** *Wind-made furrows* are not common because their origin necessarily depends upon a very constant direction of wind motion. They have been described as occurring on the crater of Mt. Pelée, where heavy dust-laden steam clouds rolled over the ground down the slopes of the crater and scoured out furrows on the old lava.[1] Grooves of wind origin are short, and they soon narrow and die out to give place to others beside them. Unlike most glacial grooves they round off into the adjacent ridges.

——**D.** The slide of a mass of rock débris, or of snow laden with soil and rocks, may scratch and scour a rock surface to some extent, but abrasion can not be very deep on account of the suddenness and shortness of the action. Landslides are confined to relatively steep slopes and the scars produced are purely local. Landslide scratches trend down the slope. In the same position, high on a valley side, glacial striæ would be likely to trend nearly at right angles to the slope. If scratches

Fig. 6.—Profile section of a grooved glaciated rock surface, drawn transverse to the direction of ice motion.

[1] Bibliog., Hovey, E. O.

are still preserved on a landslide scar, the fallen débris below is probably still recognizable by its hummocky topography (**257**).

——**E.** Mud flows and rock glaciers resemble landslides in that they consist of rock detritus, but their motion is slower and may be continuous for many years. Since they are rare phenomena, surfaces abraded by their agency are seldom seen. By the constant rubbing of the moving mass, bedrock may be scored in great U-shaped grooves sometimes many feet in depth and width. These grooves are broadly sinuous and are marked by smaller parallel furrows and scratches. They are exceedingly like glacial grooves and their discrimination may be difficult. Careful search should be made for the materials—mud flow, rock glacier débris, or true moraine—which did the work.

——**F.** *Solution grooves* are more or less parallel furrows that sometimes develop on inclined and vertical surfaces of soluble and fairly homogeneous rocks like limestone and marble. They always trend down the slope, for they are made through slow corrosion by water as it trickles down over the surface. These furrows can be distinguished from abrasion grooves because they are often very uneven along their course, they are not scratched or striated, and the confluences between them are generally narrow and sharp.

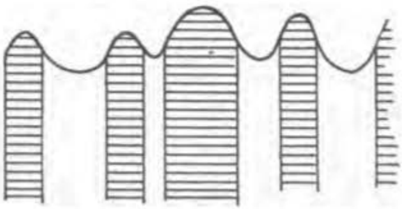


FIG. 7.—Section of a ribbed rock surface. The ribs (horizontally ruled) are of calcareous shale which is here more resistant to erosion than the intervening layers of limestone.

——**G.** In rocks having a parallel structure, for instance, strata and schists, adjacent layers may differ in their susceptibility to decomposition or to disintegration. The layers which are easily affected will be eroded away more rapidly than the others, so that the rock will become ribbed and furrowed (Fig. 7). Since layers which are highly liable to decomposition may be very resistant to disintegration, it follows that the ribmakers in a given rock in a dry, cool climate may be the furrowmakers in a climate that is moist and warm. Grooves of this class coincide with the outcropping edges of the layers. Like the solution grooves in homogeneous rocks, they are uneven along their length and they lack scratches. Their width is dependent upon the thickness of the layers.

——**H.** *Slickensides*, the scratches and grooves produced by faulting (**171**), are sometimes exposed on the earth's surface when one of the fault blocks has been removed by erosion. The fault plane on which they occur may have any position and on this surface the slickensides may lie in any direction. No rule can be laid down for their attitude. Slickensides on a given surface may be straight or they may curve, but they are always notably parallel. They may be interrupted at irregular intervals by steplike breaks (Fig. 8), with the drop always on the same side when well preserved. Fault surfaces are often polished.

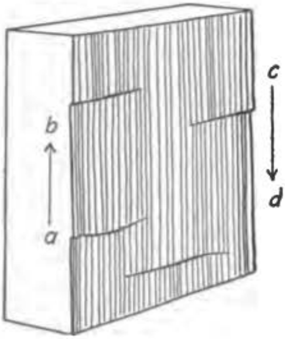


Fig. 8.—Part of a fault surface, showing vertical slickensides. The steplike breaks across the slickensided surface here indicate that the block in the figure moved up (*ab*) with reference to the block which has been removed (*cd*). If the relative motion had been in the opposite direction, these steplike breaks would have been rubbed off.

In regions of glaciation slickensides may be confused with striæ. If followed along their course they will usually be found to pass into the rock where the eroded fault block has not yet been entirely removed. Striæ, if of Pleistocene or later age, are purely superficial on the bedrock. A possibility which must not be overlooked is that of an ancient glaciated surface which has been long concealed under solid rock and has been recently uncovered in part (**9**).

——**I.** By the powerful grinding action of faulting parallel grooves and ribs of considerable size may be chiselled out on the opposing rock faces of the fault.[1] When exposed by erosion these grooves must be distinguished from those of superficial origin. They are more regular than any other type of furrow.

[1] Bibliog., Gregory, H. E.

They are themselves lined with scratches, all parallel. In cross section their profiles usually display no shoulders. They trend nearly straight or in broad curves, and are not markedly serpentine. They are not limited to valley floors nor to any other topographic form. Along their length they may rise and sink, but this they do *as a group*. Individual variations are slight. Exposed fault grooves of large size are seldom seen, and where they do occur they are restricted to outcrops whose surfaces happen to coincide with the fault surface.

——J. Along cart paths and highways, scratches and ruts worn in low protruding rocks by the wheels of passing vehicles are sometimes mistaken for marks of glaciation. If there is doubt, comparison should be made with ledges beyond the reach of wagons, where the real striæ will be discovered if they are present.

34. Pits and Hollows.—Pits and hollows of primary origin include large and small depressions on the surfaces of lava flows, and certain fossil impressions, such as footprints, made on muds and sands while these materials were still unconsolidated. Care should be taken not to confuse with fossil impressions any of the indentations described below.

Secondary pits and hollows in rocks may be the result of abrasion or of weathering. The more common varieties are classified below.

KEY FOR THE IDENTIFICATION OF PITS AND HOLLOWS ON ROCK SURFACES

A. Depressions definitely related to grains, pebbles, fossils, inclusions, or other bodies contained in the rock, are probably due to differential erosion. If these depressions
   1. Have rounded edges and smooth surfaces, and are present on smooth rock surfaces, they may be abrasion pits produced, for the most part, by wind or water (**A**).
   2. Have sharp edges and usually rough surfaces, and are present on rocks with rough surfaces, they may be weather pits due to the solution and removal of grains, pebbles, etc. (**F, I**).
B. Depressions not definitely related to grains, pebbles, etc.,
   1. Comparatively shallow, and

a. **Present on abraded rock surfaces, may be chatter marks, crescentic gouges (B, C), or pits associated with hard obstructions (Fig. 4, D).**
b. **Present on corroded rock surfaces, often of limestone, may be solution pits (G).**

2. **Usually deeper than their lateral dimensions, and**
a. **Present, for the most part, on abraded rock surfaces, may be potholes (D) or cupholes (E).**
b. **Present on weathered or abraded rock surfaces, may be pits due to honeycomb weathering (H) or pits formed by organisms (I, J).**

——**A.** Finely pitted surfaces are characteristic of wind erosion on granular rocks that are composed of minerals of different hardness. When dust or sand is blown against such a rock, the soft grains are worn away faster than the hard ones. At the same time all the edges and corners of the projecting hard grains are rounded. Thus, the surface of the rock becomes smooth to the touch, although closely indented with small rounded pits the dimensions of which depend upon the size of the eroded grains.

——**B.** Chatter marks and crescentic gouges[1] are indentations produced by glacial abrasion. *Chatter marks* are small dents that are found in rows of two or more, sometimes accompanying and running parallel to glacial scratches and grooves. They are produced by a rhythmic vibratory motion due to friction between the bedrock and rock fragments held in the overriding ice. In their origin they resemble the rows of dots made by drawing on a blackboard with a piece of chalk held nearly perpendicular to the board. Chatter marks are often distinctly convex on one side, and the convexity is turned in the direction from which the ice moved (Fig. 4, C).

——**C.** *Crescentic gouges* (Fig. 4, A, B), occasionally met with on the "upstream" or stoss slope of glaciated rocky knobs, measure from a few inches to 5 or 6 ft. from horn to horn and lie with their length perpendicular to the adjacent striæ. Like chatter marks they are found in sets of two to half a dozen or more. Their convex edges usually point in the direction in which the ice moved.

[1] Bibliog., Chamberlin, T. C., 1888, and Gilbert, G. K., 1905.

——**D.** Of much larger size than the depressions already noted are *potholes.* A pothole is formed by the constant swirl of an eddy which carries pebbles or sand round and round in one spot. Gradually a hole is bored downward into the rock. The sand and pebbles that served as the tools may often be found at the bottom of the depression. Whether the vortex be one in a current of wind or water or ice, the action is the same, although the rate of abrasion may vary. Potholes are most commonly of fluviatile origin. Occasionally they may be observed along rocky coasts and in glaciated valleys where the topographic configura-

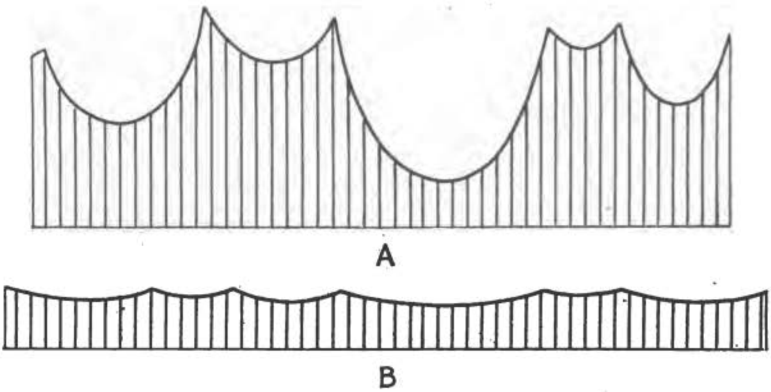


FIG. 9.—Profile section through the surface of a limestone exposure, showing two varieties of solution pit (about ⅔ natural size).

tion localized eddies; but many of the depressions of this nature in glacial valleys are made by water plunging through holes in the ice. These are called "*moulins*" or "mills." Here the concentration of action is due, not necessarily to a constant vortex, but to the maintenance of an opening in stationary ice for a time sufficiently long. Since true potholes open upward, the analogous excavations cut by wind rarely come under the definition, for wind eddies may work in any direction. Yet the process by which the holes are carved is identical.

——**E.** On a small scale abrasion, combined with solution, may wear cup-shaped hollows, called cupholes, on the surfaces of rocks like limestone (Fig. 9, A). In a certain sense they are miniature potholes.

——**F.** Decomposition and solution play an important rôle in modifying rock surfaces. Their action is generally differential. Soluble substances may be leached out from rocks which as a whole do not readily decompose and cavities may then remain, which indicate by their shape the nature of the material removed. Thus, from rocks that contain cubical holes, pyrite may have been carried away. Sometimes fossils are dissolved out and their impressions are left as small cavities on the surface of the rock. Similarly, limestone pebbles in conglomerate may be dissolved out from a shaly or sandy matrix. In moist climates basic segregations (**102**) are apt to decompose more rapidly than the granitic rocks in which they are contained. The hollows formed by their

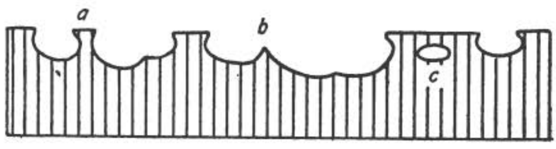


FIG. 10.—Section of a specimen of sandstone exhibiting fretwork weathering. *a*, divide between two depressions; *b*, a similar divide, nearly worn away; *c*, opening into a depression behind the plane of the sketch. The bedding is horizontal. Why is there a projecting rim bordering each cavity?

weathering have granular surfaces. In cases of this kind there are usually some depressions which still have a little of the original substance left in them. These should be sought in order to explain their formation.

——**G.** A very characteristic feature of corrosion surfaces on soluble rocks is the presence of abundant saucer-shaped pits, and this does not of necessity indicate any differential tendency in the chemical wear. Limestones and marbles may be very uniform and yet display this effect, generally on surfaces of low inclination. Where the slope is greater the pits may coalesce and become grooves (**33, F**). Between the hollows are sharp-edged divides (Fig. 9, B). If the divides are rounded, the corroding water probably carried some silt which did a little abrasion.

——**H.** On fine granular rocks such as shale and sandstone, decomposition sometimes produces what is known as *fretwork* or *honeycomb weathering* (Fig. 10). At different spots on the exposure small pits arise through the decomposition of mineral grains. As these cavities grow deeper and larger and as they become more numerous, they unite at the surface while they are still separate below. In the less resistant laminæ enlargement takes place more quickly than in those more resistant.

——**I.** Corrosion of rock surfaces is not restricted to subaerial outcrops. It has been recorded as occurring below water level in lakes. Or, again, it may go on beneath the soil where moisture rich in products derived from vegetable decay may etch a pitted or corrugated surface. Subsequently the soil may be removed by natural or artificial means and so expose the rock.

Corrosion pits are generally a fraction of an inch to a few inches across. Their interiors are often roughened by projecting insoluble grains.

——**J.** Certain molluscs dissolve out cavities in which they dwell. The holes grow larger with the growth of the animal. Their organic origin may be indicated by the presence of the animals themselves, or of the shells, in some of the chambers.

CHAPTER III

ROCK PARTICLES AND FRAGMENTS

General Nature

35. Shape and Surface Markings.—Rocks may be broken into fragments either by forces acting within the lithosphere or by processes at the earth's surface. Sometimes the fragments, as mere products of shattering, suffer no wear, and sometimes they are rubbed or ground or pounded until their original shape is modified. According to their mode of origin, they have distinctive characters of form, surface, or composition. For example, many glaciated pebbles are striated, just as is the glaciated bedrock. They served as the tools by which the ice scratched the rock, and the tools themselves suffered abrasion in the process. It follows that if we examine the constituents of a fragmental deposit or of a consolidated fragmental rock, we may be able to discover how that material was made, for very often the deposit or rock originated under the control of the same agents which were concerned in fashioning the individual constituents. In studying solid rocks there is need to discriminate between destructional fragments of the kind just mentioned and certain other bodies which are of quite a different nature (**41, C**; **50**).

36. Dimensions of Particles and Fragments.[1]—The distinction between sand and gravel has arbitrary limits. In this book the term "sand" will be used for deposits in which the individual grains are not greater than 2.5 mm. nor less than 0.05 mm. in diameter.[2] When the particles are between 2.5 and 0.75 mm. the sand is coarse; when between 0.10 and 0.05 mm., it is fine.

[1] Refer to Appendix III.

[2] Bibliog., Hatch, F. H., and Rastall, R. H., p. 39.

Grains smaller than 0.05 mm. belong to such materials as mud, silt, clay, and loess. Their characters will not be described here since they can not be seen with a hand lens. Particles larger than 2.5 mm. in diameter are of gravel texture and will be discussed below under the term of *rock fragments*. *Pebbles* are rock fragments of small or moderate size which have been more or less rounded and which acquired this form by erosional processes. *Bowlders* are masses larger than pebbles, but of similar shape and origin.

Characters of Rock Particles

37. Composition.—Residual sands formed by disintegration are composed, for the most part, of the minerals present in the parent rock, for they have been subjected neither to attrition nor to decomposition on a large scale. On the other hand, sands that have been transported for a long time consist of minerals that are relatively resistant either chemically or physically or both. (Why?) Quartz is the most common ingredient of such sands, and in regions where micaceous rocks abound, muscovite and bleached biotite may be in considerable quantity. Garnet, magnetite, zircon, and rutile are also counted among the more indestructible minerals, but the last two are seldom abundant. If transportation has been comparatively short and rapid, the sand may contain mineral particles which would have been quite broken up under longer handling.

The composition of sand suggests not only the amount of transportation, but also the climate in the region where the erosion was in progress. A deposit which is rich in decomposable mineral grains is indicative of a very dry climate, and one that is strikingly lacking in such minerals points to decomposition as having been a very efficient erosional process. A high percentage of quartz indicates that the sand is a product of slow erosion in a warm, moist climate, where the more decomposable minerals had ample time to decay and pass away in solution. Feldspar is a decomposable mineral, yet it is not at all uncommon in sands of continental origin, even in moist climates. It is fairly resistant to chemical destruction, although less so than quartz. Consequently, its presence is not to be accepted as unquestionable proof of an arid climate. On the contrary, hornblende, augite, and particularly biotite, all iron-bearing silicates which are extremely liable to decay, are good evidence for aridity, or of erosion by ice.

The nature of the parent rock is likewise indicated by the composition of the derived sand. In this respect sands that have been subjected to little transportation are most valuable. Garnet and magnetite often come from gneisses and schists; quartz and feldspar from gneisses, granites, etc.; and micas from schists and certain igneous rocks.

The significance of clastic mica in muds and mudstones may well be mentioned here. Such mica is typical of continental sediments (**96**). When found in pelites that seem to be of marine origin, it usually means that they were accumulated near the shore.

38. Shape.[1]—Most mineral particles owe their form partly to their manner of breaking and partly to the kind of erosion which has affected them. The grains may be angular, faceted, subangular, or pitted. Their shape is seldom, in itself, a decisive criterion for the origin of the deposit in which they are found, but it is of considerable assistance. One must be careful not to draw conclusions from too brief an examination. Few fragmental deposits consist of grains derived in only one way. Wind-worn particles may be intermingled with those handled by water; and so on. It is the prevailing character of the majority of the particles that must be ascertained.

The key which is given below includes the more common varieties of broken or worn rock particles.

Key for the Identification of Rock Particles

A. Grains sharply angular,
   1. Consisting of volcanic glass or other volcanic material. are probably volcanic sands (**39, B**).

[1] Bibliog., Sherzer, W. H.

2. Consisting of the mineral constituents of rocks especially susceptible to disintegration (usually rocks of relatively coarse texture) are probably disintegration sands (**39, A**).
3. Present in a layer of limited thickness and consisting of fragments of the rocks on both sides of the layer, may be breccia particles (**39, D**).

B. Grains with one or more worn or broken facets which are marked off from the surrounding surface by sharp edges,
1. Generally associated with glaciated pebbles, in till, etc., are probably glacial faceted sand grains (**39, C**).
2. Associated with rounded eolian sands, are probably broken or chipped wind-blown grains.

C. Subangular grains, with edges and corners somewhat rounded may be aqueoglacial sands (**40**) or sands of the next class (D), not fully rounded.

D. Rounded grains which, if broken, show
1. Concentric structure on the fracture surface are probably constructional sands (**41, C**).
2. No concentric structures on the fracture surface, and are
   a. Above 0.75 mm. in diameter, may be eolian, marine, and fluviatile sands (**41, A**).
   b. Below 0.75 mm. in diameter, are probably eolian sands (**41, A**).

39. Angular Particles.—A. Residual disintegration sands have sharp edges and corners (Fig. 11, A) because they have been detached from the bedrock along their contact surfaces with other grains and have suffered no corrosion and no rolling by wind or water. If they break up still further, minerals without cleavage, like quartz, crumble into highly irregular fragments, the micas separate into thin flakes, and most other minerals with cleavages fall into small irregular blocks faced by the cleavage planes.

——**B.** Volcanic sands (Fig. 11, B) are angular because they are largely the product of explosive shattering. They consist of chips and slivers of rock glass with here and there phenocrysts, broken or entire, and occasional pellets of glass rounded in the air by mutual attrition or by twirling, if thrown up as liquid drops.

——**C.** Ice-worn sand grains (Fig. 11, C) have faces which have been ground by glacial abrasion.

——**D.** Solid rocks are sometimes found to have been crushed by movements within the earth (**204**). The finer particles, so made, are angular or subangular.

——**E.** On the whole, angularity of grain signifies disruption in place or disruption followed by brief and rapid transportation. The glaciated particles noted in **C**, above, are an exception.

40. Subangular Particles.—If subjected to corrosion or to attrition for a sufficiently long time, angular grains may become subangular. Their edges become blunted. Aqueoglacial sands (Fig. 11, D), are commonly of this nature, for whatever angularity they may have acquired through fracture or through glacial abrasion has been modified by subsequent wear in running water. The larger grains may still show traces of the facets planed off by glacial scour.

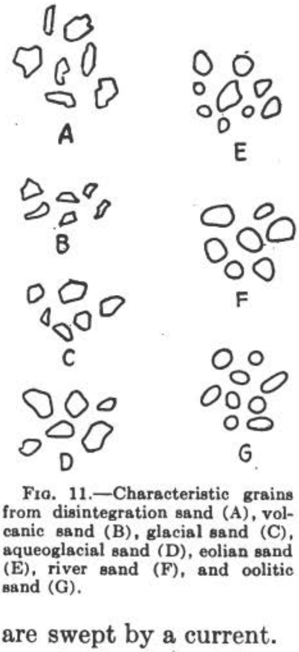


FIG. 11.—Characteristic grains from disintegration sand (A), volcanic sand (B), glacial sand (C), aqueoglacial sand (D), eolian sand (E), river sand (F), and oolitic sand (G).

41. Rounded Particles.—A. Long handling by wind or running water produces rounded grains. This shape is typical of eolian sands (Fig. 11, E). In river and beach sands, too, the grains are usually pretty well rounded Fig. 11, F). Particles having a diameter less than a certain quantity are apt to escape rounding because they are held in suspension as long as they are swept by a current. The size below which the grains remain angular is about 0.75 mm. in running water and about one-fifth this amount in wind. The difference is due to the greater buoyancy of water.[1] Under special conditions marine sands may continue angular or subangular for a long while, even though they are larger than the size just noted. After the fall of the tide, they may be kept moist by capillary action between the grains.

[1]Bibliog., GRABAU, A., pp. 61, 226 and ZIEGLER, V., p. 654.

The moisture serves not only as a cushion to prevent the rubbing of the particles on one another, but also as a check to their transport and handling by wind. However, wind along low open shores soon rounds the dry grains in the upper layer of the beach, and consequently wind-worn grains are often scattered through beach deposits. Typical eolian sands occur only in desert regions. They may contain some particles which were broken or chipped by impact. As a general rule, sands that are well rounded and average considerably less than 0.75 mm. in diameter are probably of eolian origin.

——**B.** The student will probably have very little occasion to distinguish corroded sand grains from those mechanically rounded, since most sands are of mechanical origin. A difference may be mentioned here. Chemical agents tend to excavate small pits on the surface of a grain and the luster of the pits is like that of the whole grain. If there are indentations on abraded particles, these are the remains of the original uneven fracture, or of subsequent hard blows, and they are present merely because the particle has not been worn down enough to erase them. Rolling and repeated slight impact coöperate to fashion an evenly rounded surface, convex on all circumferences. The multitude of minute scars resulting from this sort of abrasion somewhat dull the luster of the particle, so that, in this case, the luster of remaining indentations is different from that of the grain as a whole. These features need a hand lens for their examination.

——**C.** Rounded sands of constructional origin (Fig. 11, G) compose oölites, pisolites, and greensands. Cross sections of these grains show them to have a concentric structure. Further description of their characters may be found in textbooks on petrology.

Characters of Larger Rock Fragments, Pebbles, Etc.

42. Identification.—In Art. **18,** pebbles and other detached rock bodies are listed principally according to their characters when seen in cross section. The following key is based almost wholly upon such features as roughness, smoothness, scratches, dents, etc., which may be observed on the surfaces of the pebbles or bodies. Reference is also made to form.

Key for the Identification of Rock Fragments[1]

A. Angular fragments, bounded by fracture surfaces, may result from various processes of weathering or of brecciation. References are given in the context (**43**).

B. Faceted pebbles which have
   1. The facets smoothed or polished, and sometimes pitted, may be wind-worn (**46**).
   2. The facets scratched or grooved, may belong to classes noted under C below.

C. Scratched and grooved pebbles, if
   1. Of various shapes (round, faceted, blunted, etc.), and with the scratches running in various directions, may be glacial pebbles (**44**).
   2. Of various shapes, and with one or more facets, each facet being local, usually separated from the adjacent surface by sharp edges, and marked by parallel scratches (running in but one direction), are probably slickensided fragments or pebbles (**44**).
   3. Elongate (sometimes spindle-shaped) or flat and sometimes bent, with the scratches or grooves running parallel to the length of the pebble, may be compressed (sheared) pebbles (**49**), especially if they are more or less coated with mica.

D. Pitted or dented pebbles or fragments, if they have
   1. The indentations definitely related to mineral grains, may be wind-worn pebbles (**46**).
   2. The indentations not related to the mineral constituents,
      a. These indentations usually being isolated and saucer-shaped, and generally
         (1) Unaccompanied by fractures, may be pebbles of a soluble rock, like limestone, the indentations having been formed by solution (**45**).
         (2) Accompanied by radiating fractures, may be pebbles of any sort of rock with compression dents (**45**).
      b. These indentations usually being in groups converging at the blunted end of the pebble, are probably glaciated pebbles (**44**).

E. Subangular pebbles are usually fragments which have not yet been fully rounded (see also B) (**47**).

F. Rounded pebbles and bowlders, if with
   1. Smooth surfaces, may be river or beach pebbles (**48**).
   2. Rough surfaces, may be pebbles or bowlders of disintegration (**48**).

[1] The reader's attention is called to Art. **50**.

43. Angular Fragments.—At the earth's surface angular rock fragments may result from exfoliation, plucking, sapping, frost action, disruption by landslide and lightning, and by volcanic explosion. When massive rocks weather by exfoliation, relatively thin, curved, edged pieces split off. These are called *spalls* (Fig. 12). Fragments separated from the bedrock by plucking, sapping, or any of the other processes of disintegration, are bounded by surfaces of weakness (**29**). They are the negatives, as it were, of the outcrop surfaces produced in the same manner (**32**). Such fragments are generally found at the bases of cliffs where they accumulated as slide rock or *talus*.

Fig. 12.—Formation of a bowlder of exfoliation. Part of the original surface of the rock may be seen at the extreme left. The rough edges are the scars of flakes or spalls which have split off. Two such spalls (near the upper part of the figure) are nearly detached.

Landslide detritus is angular if the materials were solid bedrock before the slip. Both landslide débris and talus consist of fragments of all sizes and in both some of the fragments may have bruises or random scratches made in the downfall. The difference between the two kinds of deposit is mainly topographic (**257**).

Shattering of rocks by lightning has been recorded, but is very rarely seen or recognized. In mountainous districts where the work of lightning would be most effective, frost and temperature changes are by far the most active forces of rock destruction.

Other kinds of angular fragments are described elsewhere, as follows: blocks made by volcanic outburst, Arts. **102, 204**; intraformational fragments, Art. **84a**; various kinds of breccia, Art. **204**.

44. Scratched, Faceted Pebbles.—Scratched, faceted pebbles are nearly always the result of glacial abrasion. They have been planed off by rubbing against bedrock while held in moving ice. Such pebbles may shift their position in the ice from time to time and thus receive several facets or "soles." Each

FIG. 13.—A glacially striated pebble found by J. B. Woodworth in Pleistocene till in Gaspé, Quebec. Note the diversity in direction of the scratches.

FIG. 14.—Striated pebble with splintered or snubbed end. (Coll., J. B. Woodworth.)

FIG. 15.—Detached fragment of the striated rock floor over which glacial ice moved. Note the parallel arrangement of the striæ. The figure shows chatter marks in the deepest scratch. (Coll., J. B. Woodworth.)

facet is marked by striæ which run in various directions (Figs. 13, 14). In this respect they differ from detached pieces of the striated bedrock, which are more apt to have a large majority of the scratches on only one face and, on this face, trending in one direction (Fig. 15). Sometimes a pebble which was held in one position for too short a time to become faceted may be round and yet bear striæ.

Occasionally care may be necessary to discriminate between slickensided fragments and glaciated pebbles, especially in deformed rocks having relatively few pebbles in an abundant fine-grained matrix. Where surfaces of internal rock slipping have grazed a pebble, the slickensides probably continue across the pebble into the matrix. Such slickensides, like the striæ on detached fragments of a glaciated rock pavement, lie parallel to one another.[1] In fault breccias the fragments may be slickensided (**171**).

45. Pebbles with Scars or Indentations.—A. Pebbles with concave fracture scars are as typical of ice abrasion as are

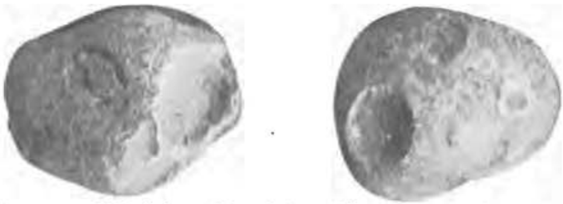


FIG. 16.—Limestone pebbles indented by solution while they were under compression in a conglomerate. The pits mark the spots where adjacent pebbles were in contact.

striated pebbles. They are angular or subangular and may or may not have glacial scratches. The scars are thought to have been made by splintering or wedging of small chips from the pebble while it was pressed with great force by the ice against bedrock, or was jammed between two blocks of rock (Fig. 14). These scars should not be mistaken for the concave indentations next described.

——**B.** Circular or oval concave hollows may be produced, both by solution and by simple pressure unassisted by chemical processes, on the surfaces of the pebbles in a conglomerate.

[1] For further criteria see Bibliog., WOODWORTH, J. B., 1912, a, p. 457.

A solution hollow is formed where, in the compression of the rock, a small pebble is squeezed against a larger pebble. At their mutual contact the larger one is dissolved away and the smaller one is pressed into the hollow. Solution indentations are confined for the most part to pebbles of soluble rocks like limestone (Fig. 16).

——**C.** Concave hollows made by compression without solution are rare. They need special conditions for their origin. The paste of the conglomerate must be relatively weak and compressible, yet it must be strong enough to prevent complete fracturing of the pebbles when the rock is subjected to stress. As in the previous case, the small pebbles indent the larger ones. If the pressure exceeds a certain quantity, variable under different conditions, the impressed pebbles crack.

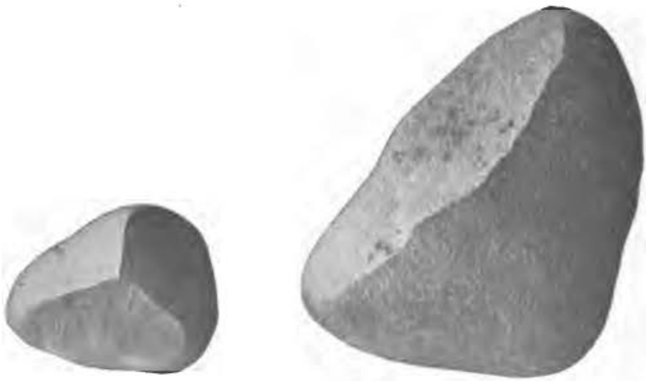


FIG. 17.—Wind-worn pebbles. That on the right is an einkanter; that on the left is a dreikanter.

Both types of indentation (**B** and **C**) interrupt the continuity of the original surface of the pebble, and in both the depth of the hollow is not more than a fraction of the diameter of the smaller pebble.

46. Polished, Faceted Pebbles.—Polished, faceted pebbles are made by wind action. They are called glyptoliths (γλυπτός, carved; λίθος, stone). A pebble too large to be transported is worn by the impact of blown sand and dust. The side toward the prevailing wind direction is planed off and more or less polished, and if the pebble is granular, its surface is pitted. (Why?) Often there are two or three directions from which the wind blows most of the time, so that the exposed surface of the pebble acquires two or three facets which meet in rather sharp, smoothed edges; or, several faces may be worn because the pebble falls into a new position whenever the sand has been blown out from beneath it. If there is one such edge between two distinct faces, the pebble is called an *einkanter* (one-edge); if there are three edges and three faces, it is called a *dreikanter* (three-edge); and so on (Fig. 17).

47. Subangular Pebbles.—Subangular pebbles and bowlders are those which have had their edges and corners somewhat rounded, but which have not yet lost all traces of their original angular character. Glacial faceted pebbles, modified by running water, are typical of eskers and kames (**257**) and of other aqueo-glacial deposits. Talus blocks may lose their angularity through the influence of weathering. Landslide fragments and the fragments in fault breccias sometimes have their edges blunted by rubbing during the movement.

48. Rounded Pebbles and Bowlders.—Rounded pebbles and bowlders are shaped by rolling or by concentric weathering. River pebbles, rolled downstream, and beach pebbles, rolled up and down the beach, are indistinguishable. Both types pass through subangular stages and finally become well rounded with smooth surfaces, free from scratches. Soft and hard grains are planed off alike, although here and there some brittle grains may have been chipped out by hard knocks. The ultimate form depends upon the original nature of the rock fragments. Cubical blocks become spherical, while flat slabs are worn to thin, oval pebbles (Fig. 18).

Concentric weathering is a passive process by which rounded bowlders of disintegration are formed. The agents work inward from the corners, edges, and surfaces of joint blocks. The corners wear away faster than the edges, and the edges faster than the surfaces, so that a rounded internal core at length remains (Figs. 12, 19). From this the grains come off singly or

Fig. 18.—Three building bricks in successive stages of rounding by wave erosion.

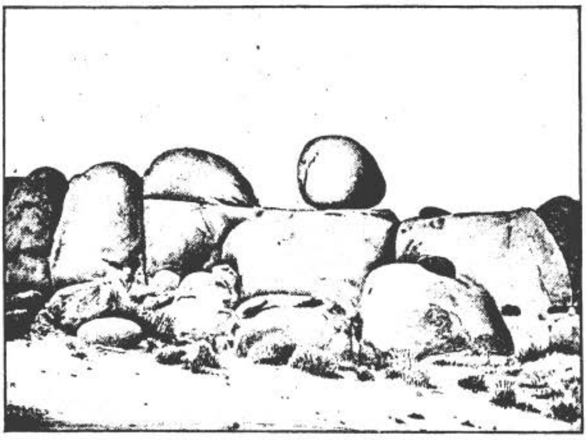


Fig. 19.—Development of bowlders of disintegration. The bowlder in the center of the figure is still in place. It has been formed from a joint block by the gradual removal of the surrounding rock. Other joint blocks appear in less advanced stages of disintegration (Owens Valley Cal.). (Drawn from a photograph by J. H. Blake.)

in shells or spalls. Bowlders of disintegration differ from bowlders of attrition in being much weathered on the outside, and in having rough, granular surfaces (Cf. **31**).

49. Elongated and Flattened Pebbles.—In metamorphic rocks pebbles and other rock fragments may have their original shapes entirely altered. Even equidimensional pebbles may be compressed in such a way that they become long, spindle-shaped rods, or they may be flattened into thin sheets. By rubbing against adjacent pebbles they may be slickensided, fluted, and ribbed (Figs. 20, 21).

Fig. 20.—A pebble of quartzite elongated by compression in dynamic metamorphism. Length about 6 in.

Fig. 21.—A pebble of quartzite elongated, edged, and fluted by severe compression in dynamic metamorphism. Length about 9 in.

50. Pebble-like Bodies.—Sometimes rocks contain pebble-like bodies which are really not pebbles at all. In plutonic rocks rounded or oval masses may be segregations or inclusions (**102, 127**). They differ in composition from the matrix which surrounds them. Other pebble-like or bowlder-like forms include concretions (**65**), some kinds of fossils, volcanic bombs (**102**), and lava "pillows" (**102**).

CHAPTER IV

ORIGINAL SURFACE FEATURES OF SEDIMENTS

CLASSIFICATION

51. Identification of Minor Irregularities of Surface.—During the process of construction of sedimentary deposits, there are sometimes produced certain minor irregularities of surface. These may be of considerable value in determining the origin of consolidated strata in which they may be reëxposed either in cross section or, if the rock surface happens to coincide with the original bedding surface, in their old superficial aspect. These features may be grouped according to their general appearance, as follows:

KEY FOR THE IDENTIFICATION OF MINOR SURFACE FEATURES OF UNCONSOLIDATED SEDIMENTS

A. Ridges, or ridge-like forms, associated or not associated with depressions, if
   1. V-shaped in plan, measuring several feet from one to another, and if found near the upper borders of beaches, may be beach cusps (**52**).
   2. Parallel or subparallel ridges, generally between 2 and 6 or 8 in. apart, may be ripple marks (**53**).
   3. Very low ridges, somewhat irregular in form, generally less than ⅛ in. high, trending along beaches, may be wave marks (**54**).

B. Channel-like or groove-like forms, if
   1. Small channels, branching or not, trending down the slope of the beach or other deposit, may be rill marks (**55**).
   2. Cracks in mud or clay, occurring in a ramifying system, are probably sun cracks (**56**).
   3. Short, shallow, gashlike openings in clay or mud, may be frost marks (**58**).
   4. Resembling footprints, may be fossil trails (**59**).

C. Shallow depressions, if present
   1. As scattered circular or nearly circular, saucer-shaped hollows, may be rain prints (**57**).
   2. In series, may be fossil footprints (**59**).

Description and Explanation

52. Beach Cusps.—Along lake and sea beaches, particularly the latter, triangular ridges or cusps are sometimes found at regular intervals of 10 to 40 ft. or more (Fig. 22). "When most typically developed the beach cusp has the form of an isosceles triangle with its base parallel to the beach, but at its upper edge, and its apex near the water."[1] According to Johnson, beach cusps are formed through "selective erosion by the swash" which constructs "shallow troughs of approximately uniform breadth," beginning with "initial, irregular depressions in the beach."[2] Their ultimate size and spacing are proportional to the size of the waves.

Fig. 22.—Plan of beach cusps. The cusps point down the beach.

53. Ripple Marks.—Ripple marks, confined for the most part to coarse and fine sands, may be formed by water waves or by currents of wind or water. Current-built ripple marks are sometimes called *current marks.*

Wave-made ripple marks are common on beaches. They are symmetrical in cross section, having equal slopes on each side of the crest line. While in process of formation they are practically stationary, and, if they are the product of a uniform swell in relatively quiet water, their crests are apt to be sharp and the intervening troughs are rounded (Fig. 23, A). However, by slight changes in the strength of the waves or by a decrease in the resulting agitation of the water, the crests are soon rounded off (Fig. 23, B). Indeed, the rounding may proceed to such an extent, and the sand which has been removed from the crests may so far fill the troughs, that the system of

[1] Bibliog., Grabau, A., p. 706.

[2] Bibliog., Johnson, D. W., p. 620.

ripples becomes a series of alternating flattened ridges and V-shaped depressions (Fig. 23, C). Rounded crests and troughs are most often found. The larger grains lodge in the troughs and the small ones form the crests. Mica flakes settle in the troughs, or on the front slopes (Cf. **87**).

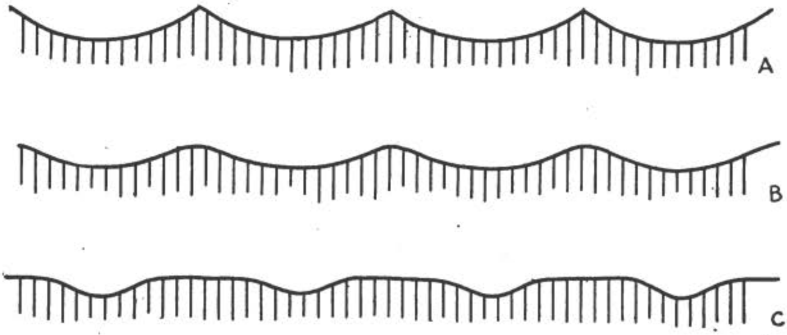


Fig. 23.—Transverse profile sections of wave-made ripple marks.

Current ripple marks, whether made by wind or water, are unsymmetrical in cross section (Fig. 24). One slope is steeper and shorter than the other, and the short slope is always inclined in the directon in which the current is moving. Troughs and crests are both rounded. The sand particles are swept up the long slope and are dumped over the crest down the

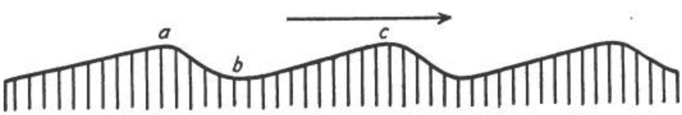


Fig. 24.—Transverse profile section of current-made ripple marks. The current flowed in the direction of the arrow.

steep slope. On account of this migration of particles, the whole system of ripples advances slowly in the same direction as the current. Ripple marks may be made by wind on slopes inclined as steeply as sand will stand (**227**), and their trend may be in any direction on such a slope; but ripples formed by water are seldom observed on surfaces that slope more than

5° or 6°. In eolian ripple marks the coarse grains are on the crests and the finer ones are in the troughs. In water current-made ripples the fine grains are on the crests and the coarse ones are in the troughs and on the short, steep slopes of the ridges (Cf. **87**). The span between adjacent crests of a ripple system is rarely more than a few inches.

54. Wave Marks.—Wave marks are very low, narrow, wavy ridges to be seen on sand beaches. They are seldom over $\frac{1}{16}$ in. high and $\frac{1}{8}$ in. wide. Each is made by the swash of water that runs up the beach after the breaking of a wave. As the tide goes down, every swash more or less destroys the earlier wave

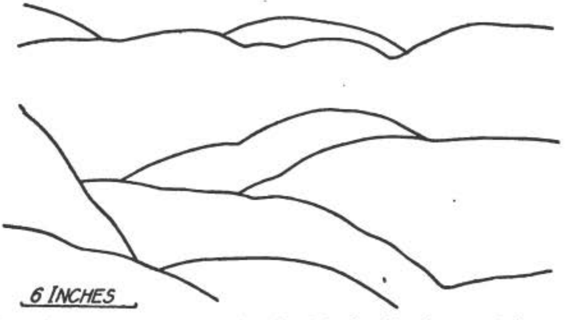


FIG. 25.—Plan of wave marks on a sea beach. The land is above, and the sea below, the figure, as drawn.

marks, and builds one of its own, so that it is common to find wave marks cutting into those next higher on the beach (Fig. 25). This relation may possibly be of some use in showing in which direction the sea lay when sediments, now consolidated, were deposited.

55. Rill Marks.—The word "rill mark" has been applied to three kinds of structure. (1) After the swash of a wave up the beach, the returning water may scour little channels in the sand, which unite in trunk channels, and these again join with others, like a miniature river system. In this case each set of rill channels branches *up* the beach (Fig. 26, A, B). (2) Small streams that debouch on sandy or clayey flats sometimes divide and may branch many times before the water finally runs off or passes into the ground. The channels or rill marks of this type branch *down* the slope (Fig. 26, C). They resemble

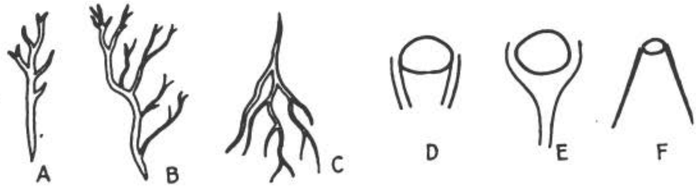


FIG. 26.—Types of rill marks. In each case the water flowed in a direction from top to bottom of the diagram.

the much larger channels made by the distributaries on deltas. (3) Water flowing down a sandy beach scours a small channel on each side of such an obstruction as a half-buried pebble or shell (Fig. 26, D–F) and the two channels generally unite in a short gully just below the obstruction. On the upstream side a low ridge may be built. This third kind of rill mark is evidently an index to the direction in which the current flowed. Of the three varieties the second is most apt to be preserved.

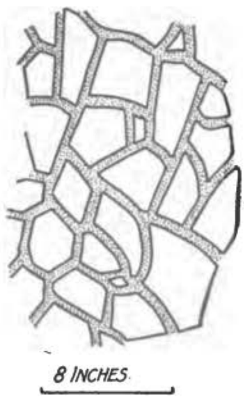


FIG. 27.—Sun-cracked clay as seen in plan. The shrinkage of the clay has exposed an underlying bed of sand (stippled) in the cracks. (Cf. Fig. 28).

56. Sun Cracks.—When dried under the sun's rays for a sufficiently long time, mud and clay shrink and crack in a network of fissures which inclose polygonal areas (Fig. 27). These fissures are called sun cracks, mud cracks, or desiccation fissures. In cross section they may be wedge-shaped, thinning out downward, or they may have parallel walls (Fig. 28). They may be as much as several inches wide at the top and 10 ft. deep,[1] but they are generally smaller. Their best development is found in localities where long exposure and a dry,

[1] Bibliog., GRABAU, A., p. 709.

warm climate are possible conditions. Sun cracks are therefore most characteristic of playas and the flood plains of large rivers in semiarid and arid regions. They may also be found

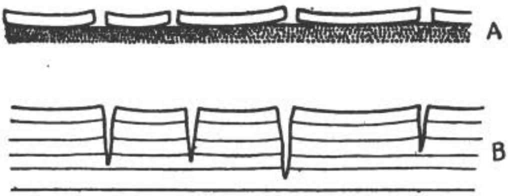


FIG. 28.—Sun cracks in section. A, sun-cracked clay layer above a bed of sand. The sand is exposed in the cracks (Cf. Fig. 27). The clay chips have curled a little at their edges B, sun-cracked clay, the cracks tapering out downward.

on exposed, low, shelving shores of lakes in seasons of low water, and, more rarely, on tidal mud flats. Locally they may be seen in the bed of any drying mud puddle. They are essentially continental in origin and always indicate that the

FIG. 29.—Rain prints in clay. (About ⅔ nat. size.)

water in which the mud or clay accumulated was relatively shallow.[1]

57. Rain Prints.—Clays, muds, and fine sands may preserve the impressions of rain drops. Each imprint is a shallow circular

[1] Bibliog., BARRELL, J., 1906, p. 524.

hollow with a very slight encircling ridge which was raised by the impact of the drop (Fig. 29). If there was no wind during the shower, the rim is of approximately equal height all round each impression; but if the rain fell obliquely, the part of the rim on the lee side of the hollow is higher (Fig. 30). Rain prints are especially characteristic of continental mud deposits.

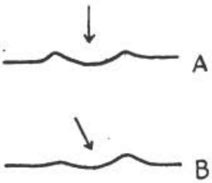


FIG. 30.—Profile sections across rain prints formed during a shower (A) when there was no wind, and (B) when the wind was blowing from left to right.

58. Frost Marks.—Frost as well as rain may leave its vestiges. When moisture in mud or clay freezes, it forms bladed and branching crystals of ice, casts of which remain after the crystals have melted and the water has passed away. Under the conditions for the perservation of mud cracks, rain prints, etc., frost marks may become lithified.

59. Animal Tracks.—Sometimes terrestrial animals leave records of their existence in footprints and trails in fine-grained sediments, particularly in clays of playas and river flood plains. If these impressions are left on marine sand or mud at low tide, they are generally, though not always, washed away by the next incoming tide. Most tracks and burrows preserved on the borders of lakes and seas are those of aquatic organisms. Depressions of various kinds, particularly those due to differential weathering of inclusions, segregations, pebbles, or other such bodies, are not infrequently mistaken for footprints (see Art. 9 for the discrimination between superficial and structural features).

CHAPTER V

STRUCTURES AND STRUCTURAL RELATIONS OF SEDIMENTARY ROCKS

Stratification

60. Bedding in Mechanical Deposits.—Mechanical deposits consist of the fragments of preëxisting rocks. If such fragments are transported prior to their accumulation, the agent that carries them may have the power of separating the lighter ones

Fig. 31.—Bedding consisting of layers of sand and gravel. The thick sand bed in the lower half of the figure was somewhat eroded by the stream that deposited the overlying layer of gravel. (Length about 20 ft.)

from those which are heavier. This process is called *sorting.* It is characteristic of handling by wind and by running water. As long as the transporting current is weak, it moves only light particles and these are somewhere spread out as a fine-grained layer. If the current becomes stronger, it may bear heavier fragments and may distribute them as a coarser layer above the earlier, finer materials. Thus, by variations in the efficiency of the transporting agent, a deposit may come to have a layered structure, known as *bedding* or *stratification* (Fig. 31). The *beds* or *strata* (sing., *stratum*), as the layers are called,[1] may differ from one another either (1) in texture, that is, in the size of their constituent particles or fragments; or (2) in composition, since variation in weight may be due to differences in specific gravity, a property closely related to chemical composition; or (3) in both texture and composition. Evidently, then, bedding in a deposit is a proof of changing conditions during accumulation.

61. Bedding in Chemical and Organic Deposits.—In chemical and organic deposits, likewise, bedding indicates that the conditions of accumulation were not uniform. In superficial chemical deposits (salt, gypsum, sodium carbonate, bog iron ore, etc.), bedding may be produced, during sedimentation, by changes in the chemical substance precipitated or by variations in the quantity of contained chemical or mechanical impurities. These changes may owe their origin to oscillations in weather or climate.

62. Absence of Bedding in Sedimentary Deposits.—Provided we accept the statement that bedding is a result of changing conditions, then absence of bedding, or perfectly uniform character, is what might be expected in deposits accumulated under very uniform conditions. However, there are other explanations for this feature. The several important causes for such absence of bedding in a sedimentary deposit may be summarized as follows: (1) the rate of accumulation may have been too rapid for sorting; (2) the transporting agent, by its nature, may have lacked the power of sorting; (3) the method of accumulation may have been unadapted to sorting; (4) the materials supplied may have been too uniform in character; (5) slumping of the materials after their deposition may have destroyed an original bedded structure.

In the sudden fall and quick heaping up of landslide débris there is no chance for sorting. Talus is practically free from

[1] Very thin beds are usually termed *laminæ* (sing., *lamina*).

bedding, although there is a tendency for the larger blocks to roll to the base of the slope. The slow accumulation of materials by overriding ice (drumlins, etc.), the gradual lowering of englacial and superglacial débris in the melting of a stagnant glacier, and the falling of rock particles and fragments of all sizes from ice walls or from the ice front —— these are all processes which are not accompanied by sorting, provided water has no share in the deposition. Such deposits, of glacial origin, are

FIG. 32.—Section in till. Note entire absence of bedding. The hammer handle is about 15 in. long. (Photo by R. W. Sayles.)

called *till* (Fig. 32). Till may be defined as glacial material which shows no bedding, or, at best, bedding of very obscure and irregular character. Even in water-laid materials sedimentation may be too rapid for sorting. Thus, alluvial cone gravels at the base of a steep mountain range may have very rude bedding and they may even closely resemble till, so poorly defined are the strata. Likewise, the gravels of eskers and kames are rarely well stratified, because their formation is rapid, débris of all sizes falls out from the supporting ice walls, and the beds, such as they are, are obscured or destroyed by slumping after the supporting ice is removed by melting. Absence of bedding in coarse deposits of water-worn materials is sometimes called *pell-mell structure.*

In fine sediments absence of stratification indicates very uniform conditions of deposition, that is to say, there was probably very little action of waves or of currents to modify the process. This massive structure may be found sometimes in dust deposits (loess), in quiet water deposits, and in chemical and organic deposits.

63. Interstratification of Materials of Diverse Origin.—If one carries to an extreme the idea of changing conditions as related

Fig. 33.—Section of a basalt flow resting on alluvial cone gravels, as seen on the wall of a small canyon. The contact runs from left to right near the middle of the figure. The lava is vesicular near its upper surface and less so near its lower surface, and is compact in its middle portion. It is partly covered by later river-laid gravels, not shown. Note the rude hexagonal columnar jointing. (Owens Valley, Cal.)

to stratification, one can easily understand how mechanical and chemical deposits, chemical and organic deposits, and other rock materials which are formed at the earth's surface, may be interstratified. Good examples of this phenomenon are: (1) the interstratification of salt and gypsum with layers of mud and sand in the basins of salt lakes which have suffered considerable variations in depth and salinity; (2) the interstratification of peat with clay or sand; (3) the interstratification of bedded with unbedded deposits, such as aqueoglacial sands and gravels with till (**72**); and (4) the interstratification of lava flows or pyroclastic débris with materials derived by ordinary processes of erosion (Fig. 33).

64. Pseudostratification.—Occasionally till deposits which have been overridden by ice (drumlins, etc.) exhibit a structure concentric with their surfaces and somewhat resembling stratification. This is not true bedding for it is not due to sorting. It is caused in part by the plastering of layer on layer by the ice and in part by shearing of the till by the great pressure of the ice.

The student should guard against confusing cleavage in metamorphosed rocks (**208**) and sheet jointing in some eruptive rocks (**197**) with stratification. Both of these structures are of secondary origin (see also Art. **87**).

Consolidation

65. Consolidation of Mechanical Sediments.—Mud, sand, and gravel are unconsolidated mechanical sediments. Under certain conditions these may become mudstone, sandstone, and conglomerate, respectively. In like manner all fragmentals have their consolidated equivalents. Now, there are several ways in which consolidation may be brought about, and, while it is generally effected at considerable depths within the lithosphere, it may occur at the earth's surface. For instance, the baking of clay under the sun's hot rays is a surface phenomenon, but this kind of consolidation is only partial and the dried clay would hardly be called a rock in the popular sense of the word. Another example is that of the coquina, or shell rock, of Florida. This is a sandstone composed of shell and coral fragments which have been heaped together by the wind. The process of solidification is thought to be going on at present. Rain water, descending through the deposit, dissolves lime carbonate from the particles and redeposits it a little lower down as a binder between the grains. Occasionally the same kind of thing may be seen in the case of ordinary sands or gravels where the fragments contain abundant iron-bearing minerals. The descending waters decompose these minerals and redeposit the iron, in the form of limonite (iron rust), as a cement. Superficial consolidation is generally accomplished by one of these two methods, namely, by drying or by the introduction of a cement.

At greater depths consolidation by cementation is a very common process, for the chemical activity of interstitial water increases with increment of temperature, and temperature increases with depth. The weight of the overlying burden assists, too, for pressure is an aid to consolidation. Without going further into details, we may conclude that the most important difference between consolidated and unconsolidated mechanical sediments lies in the presence of a cement in the former and its absence in the latter. Like all rules, however, this one has its exceptions.

The cement may have been brought in from without or, more often, it has been derived within the deposit. The five most common binding substances are ferrous oxide (FeO), hematite (Fe_2O_3), limonite ($2Fe_2O_3 \cdot 3H_2O$), calcite ($CaCO_3$) and silica (SiO_2). Ferrous oxide has no distinctive color and requires chemical analysis for its identification. Hematite is red. It is the chief binder in many red sandstones. Limonite is yellow, buff, or brown, and is the cement in brown sandstones. Calcite, colorless or white, may be detected by testing with dilute HCl. Silica, best recognized by means of a polarizing microscope, is very hard and is often the cement in extremely hard sedimentary rocks, such as quartzite.

Occasionally evidences are found of cementation which has been concentrated about such objects as fossil shells, leaves, etc., in a sedimentary accumulation. Each fossil thus becomes surrounded by a jacket of cemented sediments, a jacket which thickens as long as cementation continues. If the unconsolidated sedimentary matrix be removed, these coated bodies, or *concretions*, are found to be of various shapes. Some are spherical, some ovoid, some disc-shaped, and some are very irregular if two or more have become attached in their growth. Fossils are not always found in the hearts of concretions. If chemical deposition once begins at any point, the minute portion already crystallized may stimulate further deposition about itself. The matrix is not always unconsolidated; it is merely less firmly consolidated than the concretions. Concretions may originate, also, by the localized deposition of substances which make room for themselves by actually forcing aside the surrounding rock.

By differential weathering concretions may be loosened from their matrix and accumulated as a residual gravel. They should not be mistaken for true pebbles.

66. Consolidation of Chemical Sediments.—Chemical sediments do not undergo the same type of lithification as do fragmental sediments. Many chemical deposits are precipitated in the crystalline condition, and the resulting crystalline aggregate, if pure, is nearly as hard as the mineral composing it. Abundant impurities may weaken the adhesive properties of such a rock. In other cases the chemical sediment accumulates in a colloidal state and subsequently hardens by a gradual loss of moisture, or, sometimes, by ultimate crystallization. Bog iron ore is a rock probably consolidated from a colloidal condition by loss of water.

67. Consolidation of Organic Sediments.—With respect to their consolidation deposits resulting directly or indirectly from organic processes may be regarded as chemical or mechanical. Some of these sediments, like the unbroken central portions of coral reefs, are precipitated in solid form by processes which are as truly chemical as they are organic. Others, such as certain kinds of coal and the coral sand rock above described, are accumulations of plant débris or of the fragments of animal skeletons, and these, therefore, are mechanical. Their consolidation is accomplished by one or more of the methods described in Art. **65**.

68. Compression of Sediments.—If sediments become consolidated under a heavy overburden, they usually undergo compression, and the looser they were in the unconsolidated state, the greater will be the amount of their compression. Except in certain metamorphosed or highly folded rocks (**205**), most of the compression is vertical and it is generally about uniform within moderate distances in a given stratum. Evidence of it may sometimes be seen in finely banded mudstones where the laminæ bend, both above and below, round isolated pebbles (Fig. 34).

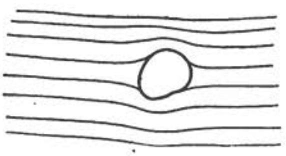


Fig. 34.—Section of laminated slate, showing how the laminæ have been bent against the pebble in the compression of the rock. The presence of an isolated pebble in deep-water sediments like this suggests that it was rafted out and dropped.

Modes of Occurrence

69. Primary Dip.—During accumulation the attitude assumed by strata depends upon the attitude of the constructional surface upon which they are being deposited. Alluvial cone gravels are laid down in rude beds approximately parallel to the surface of the cone (**241**). Sand blown over the crest of a dune falls on the steep lee slope where it is built up layer on layer. If a hole be dug in a beach, the strata will often be seen to dip seaward parallel to the surface of the beach. Scores of other examples might be cited. The vertical angle between such an inclined layer and the horizontal may be called the *primary dip* of the layer.

Primary dip, being immediately dependent upon constructional slopes, can never have angles greater than the maximum angle of repose for unconsolidated materials (**227**). Its values will range for the most part between 30° or 35° and 0°.

Probably a majority of strata of one kind or another are built with a primary dip; but the deeper offshore water deposits of oceans and lakes, the slowly settling dust accumulations of eolian origin, interbedded chemical and mechanical deposits of saline lakes, and a few other types of sediment, are spread out with nearly or quite horizontal attitude.

70. Conformity and Its Significance.—When sediments are being laid down, deposition may be continuous for long periods of time, and yet, because of variations in the strength of the transporting agent or in the nature of the depositing agent, the strata may differ, as we have seen, in texture and composition (**60**). Such beds, formed one above another, in uninterrupted sequence, are usually parallel to one another. Any stratum in the series is *conformable* with the beds above and below it. This relation between the beds is called *conformity*.

While conformity is often the result of uninterrupted deposition, it is not always so. Sedimentation may entirely cease for a few hours or days or even for several months or years, and, provided the part of the deposit already laid down suffers no kind of erosion or deformation, renewed sedimentation will be in conformity with the older beds. Within the formation evidence of a lapse of time of this sort would rarely be discernible. The essential fact to remember is, that *in a conformable series, there has been no interval of erosion to interrupt the accumulation of the strata.*

71. Relations Between Unconsolidated Transported Deposits and Bedrock; Regional Unconformity.—The upper surface of the bedrock beneath any transported deposit is a sharply defined boundary between the rock and the deposit. It is usually an old destructional surface which is now protected to a large extent from further erosion by its cover of sediments. Such a buried surface of erosion is called a *surface of unconformity.* Furthermore, it is termed *regional unconformity* because the surface is of wide extent.

Four types of regional unconformity are possible. In each the rock upon which the surface was worn was consolidated at the time of its erosion.[1] This rock, in any given locality, may be (1) a plutonic rock, such as granite or diorite (Fig. 35, A), (2) a sedimentary formation that has undergone consolidation but no folding (Fig. 35, B), (3) a folded series of consolidated sediments (Fig. 35, C), or (4) a body of regionally metamorphosed rocks (Fig. 35, D). Granite and other plutonic rocks are usually

[1] Regional unconformity between two unconsolidated sedimentary formations is possible, although uncommon. The best example is that of the superposition of the deposits laid down by continental ice sheets in two distinct glacial epochs (**101**).

injected into some older *country rock* at considerable depth, and at the time of intrusion the country rock forms a thick roof over the magma (**102**). Extensive consolidation of sediments rarely occurs except after deep burial. Finally, folding on a large scale and regional metamorphism are processes which are limited to depths of several hundreds or thousands of feet below the earth's surface. As each of these four types of rock requires a thick cover for the origin of its existing characters, this cover in each

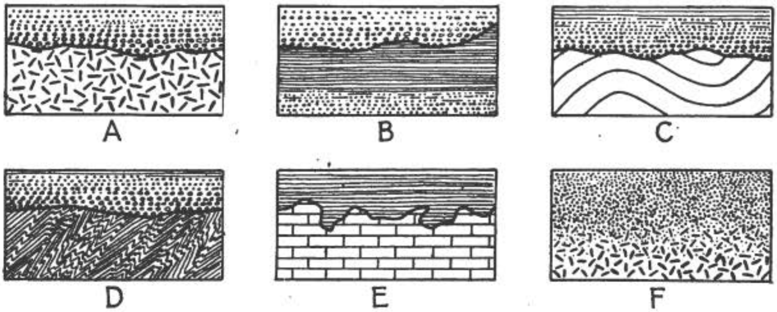


FIG. 35.—Types of unconformity. A, unconformity between granite (below) and sediments (above); B, disconformity; C, D, nonconformity or angular unconformity; in D the underlying rocks are schists; E, unconformity between limestone and the residual product of its decomposition; F, blended unconformity between granite and the residual product of its disintegration.

case must have been removed down to the level of the present surface of unconformity. Erosion of so much material, most of which was probably hard rock, takes a long time. *Regional unconformity therefore represents a long period of erosion.*

Two special cases of regional unconformity are mentioned above as existing between stratified formations. (1) Stratified rock which is essentially horizontal, never having suffered deformation, may be eroded and overlain by sediments with their bedding parallel to the strata beneath them. This relation is called *disconformity* (Fig. 35, B). (2) On the other hand, if the older formation was tilted or folded before its erosion, there will be an angle between the strata of the two series. This relation is *angular unconformity* or *nonconformity* (Fig. 35, C). The angle may vary from place to place.

In the deposit above a regional unconformity are often found pebbles, fragments, or grains of the underlying bedrock. These have usually been transported some distance and they must not be regarded as having been derived necessarily from that part of the bedrock which is just below them. By the nature of the particles and fragments much can be learned of the depositing agent (see Chapter III). If the unconsolidated sediments can be removed, the exposed surface of the bedrock may exhibit features which will indicate the agent of erosion (see Chapter II). Very often by such means deposition of the younger formation and erosion of the older rock will be found to have been performed by the same agent, the erosion necessarily antedating the sedimentation.

As examples of partially developed regional unconformity between unconsolidated deposits and bedrock the following may be cited: (1) river gravels on a rock floor formerly channelled out by the river; (2) eolian sands resting on wind-carved rock surfaces of desert regions; (3) glacial wash and till on glaciated bedrock; (4) beach gravels and sands upon a wave-cut bench (**237**).

72. Relations between Unconsolidated Residual Deposits and Bedrock; Regional Unconformity.—In regions where decomposition prevails the residual deposits sometimes consist of substances which were contained in the bedrock and which can not be removed in solution. Terra rossa, a red clay derived from limestone, is an example. An accumulation of this sort gradually thickens as a layer that covers and conceals the remaining bedrock (Fig. 35, E). The contact surface, or surface of unconformity, between the two is generally pretty sharp and, if artificially exposed, may exhibit superficial features of corrosive origin, for it is chiefly on this buried surface that the rock has been and still is undergoing chemical erosion.

Residual gravels and sands originating through disintegration grade downward into the rock from which they were derived (Fig. 35, F.) If they are later overlain by other sediments and so become the basal portion of a deposit of some thickness, the relations between this sedimentary formation and the underlying bedrock are certainly those of regional unconformity; yet, in this case, there is no distinct *surface* of separation; there is no surface of unconformity. This condition might be called *blended unconformity.*

73. Regional Unconformity in Bedrock.—When sediments become consolidated, all the relations of unconformity are preserved. There are then two rock formations separated by the surface of unconformity. At least four distinct events are represented: (1) the origin of the older, subjacent formation; (2) the erosion of this body of rock down to the level of the surface of unconformity; (3) the origin of the younger, overlying formation; (4) the erosion of this later series to a depth sufficient to lay bare evidence for the unconformity. The old formation, as stated in the preceding articles, may consist of igneous or sedimentary rocks, metamorphosed or not, but the new formation can consist only of rocks which originate on the earth's surface (sedimentary or effusive). If the lower part of this younger formation consists of conglomerate made of pebbles of the older formation, it is called a *basal conglomerate.* If it contains a large percentage of feldspar it is a *basal arkose.*

For the methods of studying regional unconformity, see Art. **97.**

74. Overlap.—The relations of regional unconformity show that a sedimentary formation is generally initiated by the accumulation of materials on an old erosion surface. It is hardly conceivable that the basal sediments of such a formation could have been laid down simultaneously throughout their extent. We must believe that deposition commenced in one or more restricted, but favorable spots and that the sediments, as they grew thicker and thicker, spread laterally and encroached upon the domain of erosion. In so doing, they *overlapped* the edges of the strata already formed.

Two kinds of overlap are recognized: the transgressive and the regressive. Each may be marine or nonmarine. *Transgressive overlap* may best be illustrated by the case in which the sea is

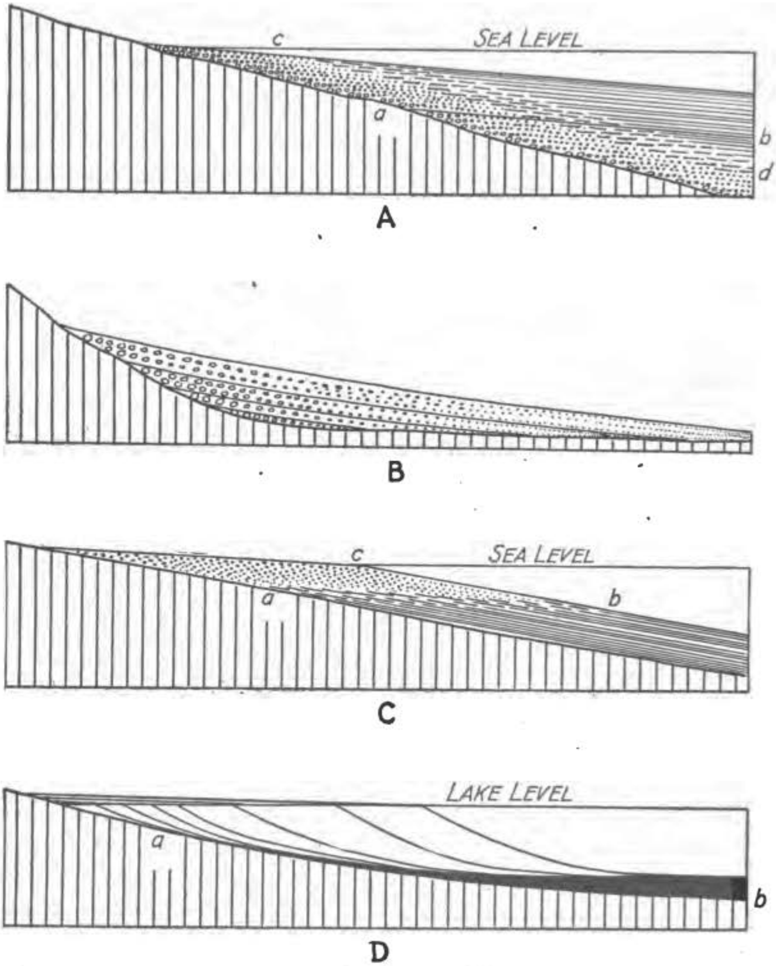


FIG. 36.—A, marine transgressive overlap; lines parallel to the sea floor are called *time lines* (*ab*), for they run through materials deposited contemporaneously; lines essentially parallel to the gravel, sand, and mud deposits are called *formation lines* (*cd*). B, transgressive overlap resulting from the upbuilding of an alluvial cone. C, marine regressive overlap; *ab*, formation line; *cb*, time line. D, lake regressive overlap; the lake floor muds (black) are gradually covered by coarser sediments (cf. Fig. 46).

advancing, or *transgressing*, upon a low shelving land mass (Fig. 36, A). At the shore line sand and pebbles accumulate. Their composition and texture depend upon the nature of the rocks of the invaded land area and upon the kind and degree of weathering to which these rocks may have been exposed. Away from the land, beyond the beach sands, are muds, and again beyond these muds there may be organic oozes on the sea floor.

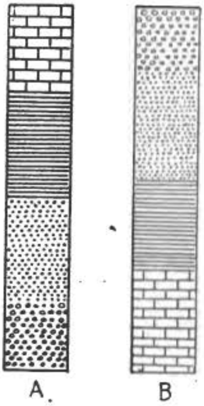


FIG. 37.—Ideal sections to illustrate the sequence of deposits laid down (A) in a transgressing sea, and (B) in a regressing sea.

As the sea encroaches on the land, the relative positions of these three types of deposit remain more or less constant and the beach sands and pebbles are laid down upon the old erosion surface; but the mud comes to overlie the sand deposited at an earlier date, and the ooze overlies an older portion of the mud body. The mud has lapped over the sand and the ooze, similarly, has lapped over the mud. This is *marine transgressive overlap*. A vertical columnar section through the formation displays *finer clastics over coarser clastics*, or *deep-water sediments over shallow-water sediments* (Fig. 37, A).

Another type of transgressive overlap is that resulting from piedmont deposition by rivers. In the growth of an alluvial cone, the sediments are carried farther and farther out on to the plain, so that they overlap the lower edges of the older strata. Here the overlap is away from the source of supply, whereas in the marine type it is toward the source. To a less extent there is also a headward overlap at the upper margin of the cone where the materials are heaped up against the flank of the range (see Fig. 36, B.) (Suggest certain limitations to this upbuilding process.)

Marine regressive overlap (Fig. 36, C) is produced where the sea recedes (regresses) from the land, *i.e.*, when sea level falls. By this process the beach zone migrates out over earlier offshore muds, and at their seaward ends these mud beds overlap the older oozes. In a vertical columnar section, *coarser clastics overlie finer clastics, or shallow-water sediments overlie deep-water sediments* (Fig. 37, B). Actual lowering of sea level is not necessary for the origin of marine regressive overlap, for a similar regressive section may be produced if the sea level is stationary and there is a sufficient supply of sediments, or even if sea level is rising, provided the rate of supply exceeds the rate of subsidence of the land.

Lake regressive overlap is very much like marine regressive overlap. Feeding streams constantly tend to fill a lake, so that the shore sands and pebbles are forced to encroach upon the lake floor muds. A vertical section through a choked lake exhibits *coarser sediments over finer sediments.* This is often called the *normal lake succession* (Fig. 36, D).

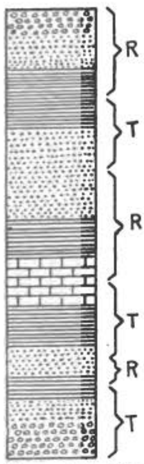


FIG. 38.—Ideal section through a series of marine and littoral strata deposited during alternate transgressive (T) and regressive (R) conditions.

Different types of overlap may be combined in the same stratigraphic section. Thus, the sea may have advanced on the land and then receded, so that regressive overlap relations are found above those of transgression, and this alternation may be repeated several times (Fig. 38). Again, marine overlap may be replaced by nonmarine overlap, or *vice versa.* In fact, the complications are too numerous for consideration in this volume.[1]

75. Clastic Dikes.—The normal method of sedimentary accumulation is such that, in the terms of stratigraphy, any portion of a deposit must be younger than the materials which underlie it and older than the materials which overlie it **(98)**. The age of a stratum is gradational from oldest at the bottom to youngest at the top. Now, it is a curious fact that there are instances known of *clastic dikes,* that is, of layers of clastic material which intersect other rocks and which, unlike true beds,

[1] For further information on this subject, see Bibliog., GRABAU, A., Chapter XVIII.

are of approximately the same age at opposite points in their sides. It is easy to imagine how sand, perhaps, might drift into and finally fill a fissure in bedrock at the surface of the ground or under water (Fig. 39). This mode of origin has been proposed for these dikes in some cases. Another suggestion offered is that detritus has slowly been let down *pari passu* with the opening of spaces by gradual leaching and removal of the original materials in solution (Cf. Fig. 35, E). Generally the dike filling seems to have come up from below. Upturned strata in the wall

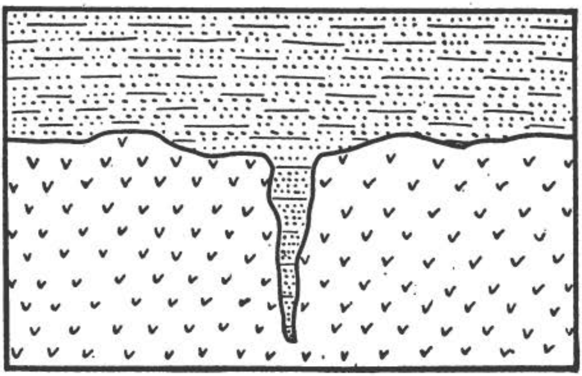


FIG. 39.—Clastic dike formed by the filling of a fissure from above.

rock, upward thinning and termination of the dikes, evidence of flow structure parallel to the walls, inclusions of the wall rock in the dikes, the great size and continuity of some of the dikes,[1] and the similarity of the dike materials with underlying sediments—all these facts point to rapid injection and a source below (see Fig. 40). There are good reasons for believing that the injection was performed under considerable pressure (hydrostatic pressure, or pressure from gas, from the weight of the superjacent rocks, or from combinations of these forces).

[1] Clastic dikes have been found ranging in thickness from mere films up to several hundred yards and in length from a few inches to over 9 miles. See Bibliog., NEWSON, J. F.

Clastic dikes have been recorded as consisting of asphalt, clay, shale, gravel, conglomerate, bituminized and unbituminized sand, hard sandstones, and limestone, and as intersecting granite, sandstone, sand, shale, clay, limestone, and especially coal. The best condition for the origin of these dikes is the presence of unconsolidated sedimentary material overlain by a hardened, cracked stratum. The dikes are thought to be an effect of earthquake shocks and earth stresses which tend to fracture rocks and redistribute mobile substances.

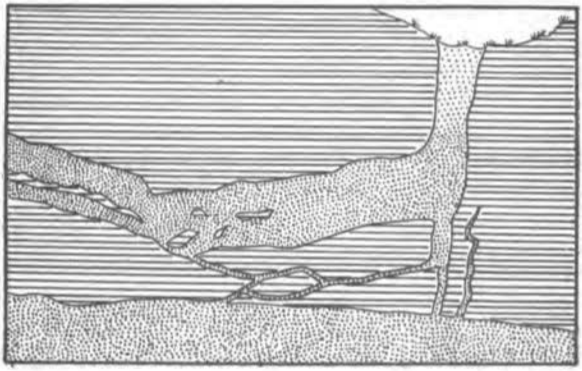


FIG. 40.—Dikes of bituminous sandstone (stippled) in Miocene shale (lined). Section about 50 ft. high. (Taken from folio 163, U. S. G. S.)

76. Clastic Pipes.—Clastic "intrusions," instead of being sheetlike, may have one long and two short dimensions, like a rod. When they have this shape they are termed *pipes*. They are the fillings of irregular tubes and usually have approximately a vertical position. From the fact that the surrounding rock is nearly always limestone and from the structural relations of these pipes, they are believed to have originated either (1) by the filling of sinks (**249**), or (2) by the slow settling of débris into a depression which, contemporaneously, was being made in the bedrock by solution. According to both explanations the materials enter from above.

Structures Depending upon the Mutual Relations of Beds or Laminæ

77. Local Unconformity; Contemporaneous Erosion.—Sometimes deposition is interrupted by a period of erosion. The beds already laid down may be somewhat dissected. After a relatively short time the accumulation of sediments may begin again and the eroded surface will be covered up by the later beds. In a deposit built in this manner the upper younger strata are *unconformable* with the lower older strata, and the buried surface of erosion is a *surface of unconformity;* but this structure differs in several respects from regional unconformity (**71, 72**). In the first place the area of erosion is often of small dimensions compared with the whole formation, so that this may be called *local unconformity*. Second, the erosion is accomplished during a short cessation in the upbuilding of the deposits, and is therefore spoken of as *contemporaneous* erosion. And third, the sediments below the surface of unconformity were not lithified at the time of this erosion (see footnote, page 63).

The most common type of local unconformity is the result of stream action. At time of flood a river may cut into and sweep away part of the mud and sand deposited while its current was less impetuous. By its increase in velocity this stream is enabled to carry coarser sand and gravel. As soon as the speed begins to slacken again, deposition commences. The heavier fragments are dropped first and, while the flood subsides, finer and finer particles are deposited until normal conditions again prevail.

A vertical cross section through beds separated by a local unconformity usually shows a finer stratum overlain by a coarser stratum and the two divided by an irregular line (of unconformity) which cuts across the bedding of the lower stratum (Fig. 41). The major stratification above the line of unconformity is parallel to that below. (How does local unconformity differ from disconformity?)

Contemporaneous erosion may be caused also by the shifting of aggrading streams on flood plains, deltas, and alluvial cones; in marine deposits by changes in the strength or direction of marine currents; in lake deposits by similar changes in currents; and in eolian deposits by variations in the wind. In all these cases the unconformity is local.

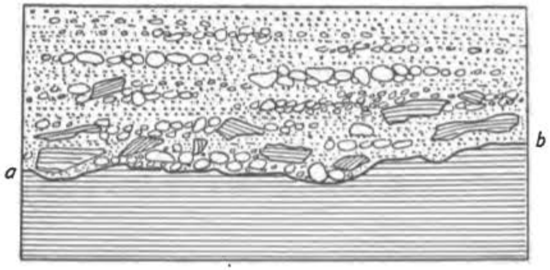


FIG. 41.—Section of a surface of local unconformity (*ab*) between an older slate and a younger stratum of sandy conglomerate. The fragments of slate in the conglomerate are termed intraformational pebbles.

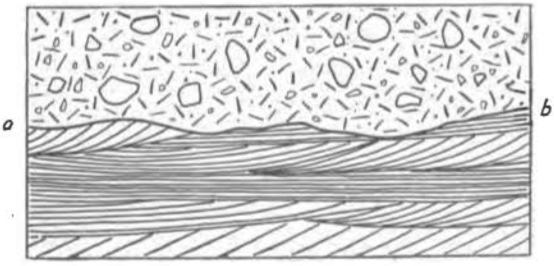


FIG. 42.—Section of a surface of unconformity (*ab*) between older cross-bedded sand and younger till.

There is a somewhat similar relation between older and younger sediments which may be associated with glaciation. In front of an ice sheet or a mountain glacier aqueoglacial deposits accumulate. Beneath the ice till may be deposited. While the ice front is advancing the water-laid sands and gravels may be overridden, more or less eroded, and subsequently overlain by till (Fig. 42). The pebbles in such till are many of them water-worn, having been dislodged from the underlying wash, and those which are striated are characterized by very numerous and very fine scratches produced by rubbing against sand rather than bedrock. On the other hand, in the retreat of the ice front, water derived from melting may flow over and erode somewhat earlier till and lay down aqueoglacial muds, sands, and gravels upon this till (Fig. 43). The latter relation is more common than the former because in most cases advancing ice completely destroys the wash over which it passes. The

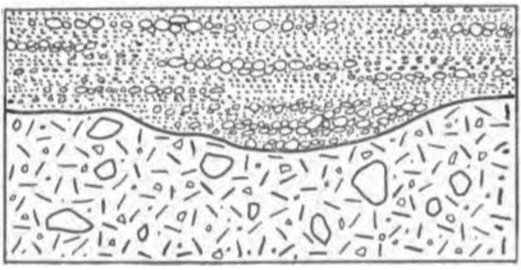


FIG. 43.—Section of a surface of unconformity (*ab*) between older till and younger gravel.

chief differences between local unconformity and the unconformity produced in each of these cases is that these are surfaces of such broad extent that they can hardly be termed *local*, and they are the result of a change in the agent itself. Nevertheless, they are examples of contemporaneous erosion, as the term has been defined (Cf. **71, 101**).

78. Sun Cracks.—Sun-cracked loam and silty clay disintegrate so quickly when moistened that there is little or no opportunity for the preservation of the cracks. Purer clays, if exposed long enough to dry thoroughly, may hold together until the cracks are filled with sand by an invading sheet of water. Sun cracks may be filled also with wind-blown dust or sand. In any case a cross section would show a fine mud or clay deposit overlain (usually) by a somewhat coarser stratum from which small projections, wedge-shaped or rectangular (**56**), would extend downward a few inches (Fig. 44). The contact between the two deposits would be sharp and would represent a time interval during which sedimentation ceased. In this interval erosion might or might not occur. It would not be unnatural to find contemporaneous erosion exhibited somewhere along the line of contact. Alternating sun-cracked clay laminæ and laminæ of sand give the rock the appearance of a conglomerate (or breccia) (Fig. 45).

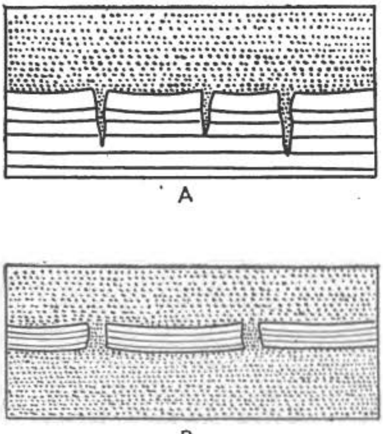


FIG. 44.—Sections of sun-cracked clay which has been buried by sand. In B a thin clay layer rested on sand (cf. Fig. 28).

79. Contemporaneous Deformation.—Sometimes an agent of contemporaneous erosion not only scours away strata which have been laid down recently, but also buckles them up or breaks and faults them. Undisturbed beds are then deposited upon the truncated edges of the dislocated layers. This structure, which may be called *contemporaneous deformation*, is mentioned here merely to call attention to it as being a feature which may be developed in strata prior to their lithification, but its description is reserved for Art. **154**.

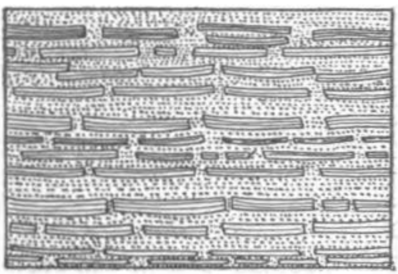


FIG. 45.—"Edgewise conglomerate" produced by interbedding of sand laminæ and sun-cracked clay laminæ.

80. Cross-bedding. A. Cross-bedding Defined.—In some deposits, especially in sands, certain beds may exhibit an original lamination oblique to the main stratification. This structure is called *false bedding* or *cross-bedding.* It is generally caused by current action, either of wind or of water, and in some instances is produced by wave action. It is found in deltas, torrential deposits, sand bars in rivers, marine current deposits, sand reefs, and eolian deposits. Ripple-mark, both of wave and current origin, is a special case

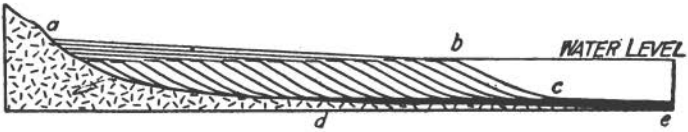


FIG. 46.—Delta structure. *ab*, topsets; *bc*, foresets; *de* bottomsets or prodelta clays. Note relation of water level to the angle between the foresets and the topsets.

of cross-bedding. The principal kinds of cross-bedding are described in the succeeding paragraphs.

——**B. Delta Structure.**—In a delta that has been built under ideal conditions in a standing body of water there are three series of beds, namely, topset, foreset, and bottomset beds (Fig. 46). The *topsets* have a primary dip equal to the angle of slope of the subaerial surface of the delta upon which they were laid down by an aggrading stream. The *foresets* consist of materials dumped over the front of the delta into the lake and hence their primary dip is the angle of repose of the materials under water (20° to 35°). The younger foresets of large deltas have lower primary dips than the older ones.[1] The *bottomsets* are nearly horizontal for they are formed of fine muds or silts that float out and gradually come to rest on the floor of the lake. They are often termed *prodelta clays.*

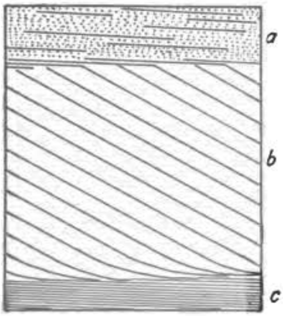


FIG. 47.—Detailed vertical section through the deposits of a delta. *a*, topsets; *b*, foresets; *c*, bottomsets or prodelta clays.

The foreset group meets the topsets in an angle or in an abrupt curve and it merges with the bottomsets in a broader curve (Fig.

[1] Bibliog., GRABAU, A., p. 702.

47). Variations in load, course, or velocity may cause the aggrading stream temporarily to degrade its channel and so produce local unconformity between the topsets and the foresets; but erosion of this kind can never occur between the foresets and bottomsets. (How might contemporaneous erosion occur between the foresets and bottomsets?)

The upper ends of the foresets of deltas formed in large bodies of water are often broadly eroded if the action of tides or waves is strong. Whether or not a subaqueous plain of denudation can be maintained on the growing delta depends upon the comparative efficiency of river and waves. If the river is the stronger,

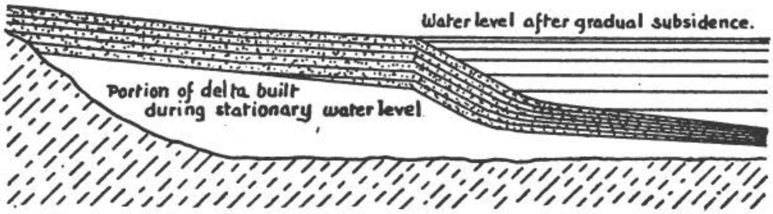


FIG. 48.—Ideal section of a delta built out into quiet water while subsidence just balanced deposition. The shore line remained stationary. (After J. Barrell.)

the delta will encroach upon the water; but if the waves are stronger, they may carry away and spread the delta deposits below water level.

Provided there has been no erosion of the foresets, the junction between any foreset and the immediately overlying topset bed is a little below the water level at the time that foreset bed was deposited (Fig. 46). This is because the stream can maintain its current for a short distance out from shore. (Explain.)

Uplift and depression of the sea floor may have significant effects upon marine deltas. Slow subsidence (normal condition) results in great depth and volume of topsets (Fig. 48), while small uplifts favor great volumes of foresets and tend to shift seaward the zone of terrestrial sedimentation.[1]

[1] Bibliog., BARRELL, J., 1912, pp. 400–401.

—C. **Compound Foreset Bedding in Deltas.**—The so-called normal delta structure is represented in radial vertical sections as in Fig. 46. If a vertical section were cut concentric with the front edge of a delta, *i.e.*, parallel to the strike of the foresets, no cross-bedding would be seen. All other vertical sections would expose foresets with an inclination less than their true dip. In the construction of a lobate delta (**241**), adjacent lobes interfere in such a way as to cause the building of foresets dipping

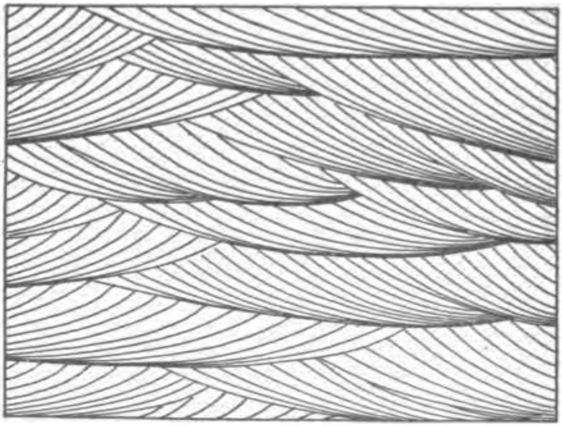


FIG. 49.—Compound foreset bedding. Note that each set of laminæ is truncated by the next overlying set. The section is about 4 ft. long.

now in one direction and now in another.[1] By changes in the stream, such as decrease in load, increase in volume of water, or shift in course, or by fluctuation of the lake or marine water level, foresets recently deposited may have their upper ends truncated and may then be overlain by new beds of similar nature dipping in the same or in a different direction. *Compound foreset bedding* produced in one or another of these ways is abundantly exemplified in glacial sand plains (Fig. 49). A special variety, called backset bedding, has been described by W. M. Davis.[2]

[1] Bibliog., SMITH, A. L., p. 437.
[2] Bibliog., DAVIS, W. M., 1890.

——**D. Torrential Cross-bedding.**—In torrential deposits fine, horizontally laminated strata alternate with uniformly cross-bedded strata composed of coarser materials. The cross-laminæ meet the horizontal beds at an acute angle both above and below (Fig. 50). This type of bedding is believed to originate under desert conditions of concentrated rainfall, abundant wind action, and playa lake deposition. The cross-bedded layers are built forward by temporary streams where they debouch upon

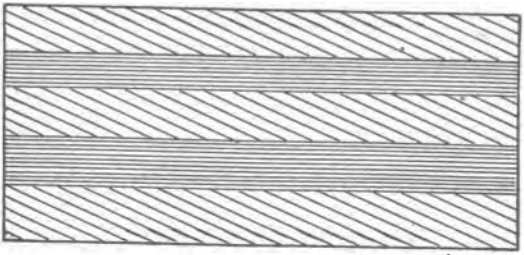


FIG. 50.—Torrential cross-bedding.

the playa lake, and the horizontal layers are materials which settle from suspension from the playa lake waters after the feeding stream has withered away.

——**E. Other Types of Foreset Bedding in Water-laid Deposits.**—Sand lenses, such as those described in Art. **81,** frequently exhibit a uniform cross-bedding of the foreset variety. In the building of a river sand bar, the materials are carried over the bar and are dumped on its front or downstream slope. Filling of hollows and deserted channels may proceed as in the construction of a normal delta, the sand being laid down in successive foreset beds. These may be seen in sections of the deposit.

Spits are built by the action of longshore currents. Sand is dumped over the growing end of the spit and there it slides down and assumes the angle of repose. The resulting bedding is therefore of the foreset type.

Under certain circumstances minor foreset bedding is produced by currents on the floors of lakes and seas, but it is not characteristic of deposits there accumulated. Yet it has been found even in marine limestones. Cross-bedding of this origin is rarely seen in unconsolidated sediments.

——**F. Wave-built Cross-bedding.**—Lake beaches and marine beaches are built largely by the work of waves. Sand or gravel is thrown up layer upon layer and the beach thus grows toward the water. Since the slope and profile of a beach depend chiefly upon the strength of the waves, and since the stratification and surface of a growing beach are parallel, it follows that variations in wave efficiency may produce slight variations in the structure of the deposit. . . . "The beach strata are considerably inclined" and "each layer or group of layers is apt to be intersected by other layers lying at different angles."[1]

This beach structure is not of the same origin as foreset bedding. The angles of inclination of the laiminæ are less than the ordinary angles of repose. Also, the angles between adjacent groups of laminæ are usually only a very few degrees. Wave-built cross-bedding is not often visible in unconsolidated materials. It occurs chiefly on the outer parts of sand reefs. In gravel it is obscure and the arrangement of pebbles may suggest pell-mell structure. In sections of lake beaches it is to be distinguished from the steeper, less regular structure produced by the shove of ice.[2] The portions of sand reefs above the reach of the waves are of eolian origin and the inner margins are built by the dropping of wind-blown sand into the neighboring lagoon (**263**).

——**G. Eolian Cross-bedding.**—Cross-bedding of wind construction is marked by its extreme irregularity (Fig. 51). This is due to the variability of direction of winds and the frequent alternation of scouring and deposition. The cross-laminæ of a growing sand dune are of two sets: (1) the foresets which are built on the lee slope and dip at the angle of repose of dry sand (about 30°), and (2) the topsets which are formed on the windward surface of the dune and have an average dip of 5° or 10° against the wind. (How does this differ from the topsets of

[1] Bibliog., Shaler, N. S., 1895, p. 165.
[2] See Bibliog., Fenneman, N. M., p. 31.

deltas? What happens to the wind-blown materials corresponding to the bottomsets of deltas?) The topsets are rarely permanent and may be very thin or absent if the dune is migrating

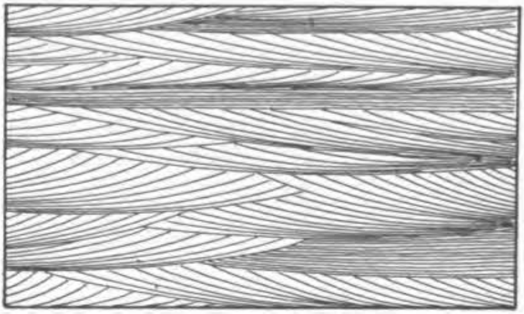


FIG. 51.—Eolian cross-bedding.

rapidly (Figs. 52, 53). The dip of the foresets decreases down the slope so that these layers curve with their concave sides uppermost. As the dune moves forward, a part of the lower por-

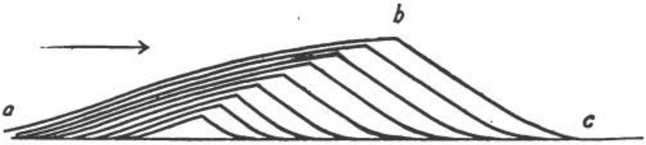


FIG. 52.—Section of a dune, showing topset bedding (*ab*) and foreset bedding (*bc*). The crest (*b*) has advanced a little in the direction of the wind (see arrow), but the dune as a whole has not migrated.

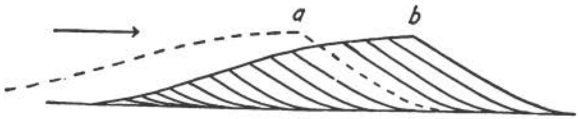


FIG. 53.—Cross section of a dune, showing foreset bedding. The dune has migrated from *a* to *b* by the blowing of sand from the windward side (see arrow) to the lee side. Contrast this figure and Fig. 52 with reference to the quantity of sand supplied.

tion of the foresets may be left behind and upon these truncated foresets a new dune may advance from the same or a new direction. By a repetition of this process the sand deposit comes to

6

have a highly complex structure. Care should be taken to discriminate eolian cross-bedding from compound delta structure and from wave-built cross-bedding.

——**H. Ripple-mark.**[1]—The ripple marks seen in sections of deposits are more commonly of the current-formed species. Since each one of these ripple marks is a miniature dune, we may speak of the laminæ which dip against the current as topsets (Fig. 24, *bc*) and those that dip with the current as foresets

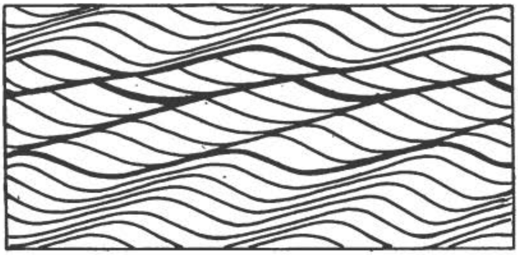


Fig. 54.—Ripple-mark in section. Below *ab* and above *ef* the migration of the ripple systems was not so rapid as to prevent the deposition of topsets. Between *ab* and *cd* the ripple marks moved forward just fast enough to prevent topset deposition, but not fast enough for erosion of the foresets. Between *cd* and *ef* migration of the ripple marks was so rapid that the foresets suffered some erosion of their upper ends.

(Fig. 24, *ab*). Topsets are laid down provided deposition is sufficiently rapid during the process of ripple-making (Fig. 54); but if the strength of the current increases beyond a certain limit, which is variable according to several factors, migration of the ripple system is too rapid, and erosion instead of deposition will occur on the back slope of each ripple (Fig. 54). Change in direction of current may cause the superposition of rippled laminae in which the foresets are inclined in different directions. Variations in the speed of the current may bring about superposition of sets of ripples with different spacings between the crests.

[1] "Ripple mark," in this book, is written unhyphenated to signify a single ridge of that name. The plural is "ripple marks." The hyphenated term, "ripple-mark," is used here for the structure which is seen in a cross section of a group of ripple marks.

——I. **Comparison of Types of Cross-bedding.**—From what has been said, clearly it is not always possible to tell at a glance whether a cross-bedded deposit is of wind or water origin. In most cases its accumulation must have been associated with current action, but sometimes the structure is the work of waves. The foreset type of cross-bedding is the commonest. In deltas it is usually of relatively large dimensions and is associated with topset and bottomset bedding. Torrential stratification is very regular and consists of alternate horizontal and cross-laminated beds. Compound delta structure (foreset and backset) much resembles eolian cross-bedding, but it is more regular, the sand is not wind-worn, and there are often gravel layers interbedded. The form of the unconsolidated deposit as a whole is that of a delta or a sand plain and not of a dune. In beach structure the laminæ are inclined to one another at very low angles and there is not so much irregularity as in dunes and in compound foreset bedding. Ripple-mark is on a smaller scale. Sand reefs are not very permanent. They are ultimately thrown on shore and then become eolian deposits. Beach structure is really true bedding with a rather steep primary dip. Bars may be more or less preserved. If they shift they may show some local unconformity. They are truly cross-bedded. Wind cross-beds are usually on a larger scale than water-made ones. The bedding of sand bars may perhaps resemble that of sand dunes. For the discrimination of eolian and aqueous deposits, it is worth while remembering the characteristic distribution of the coarser and finer sand grains on ripple marks (**53**).

81. Lenses.—Gravel deposits sometimes contain isolated, roughly lenticular beds of sand, which thin out and terminate laterally (Fig. 55). These *lenses* may be the fillings of original hollows or channels in the gravels or they may be buried sand bars. They may exhibit a uniform cross-bedding of the foreset variety. There is often local unconformity between the lens and the overlying gravel. (Why?)

The opposite relation may be seen, in which sand contains gravel lenses, but in this case the local unconformity, if present, is between the lens and the underlying sand (Fig. 56). The gravel occupies a channel scoured out and then filled by a current of water. Other like associations may be found. It should be understood that in order for a channel filling to be of lenticular shape in cross section, the section must be more or less across the trend of the channel.

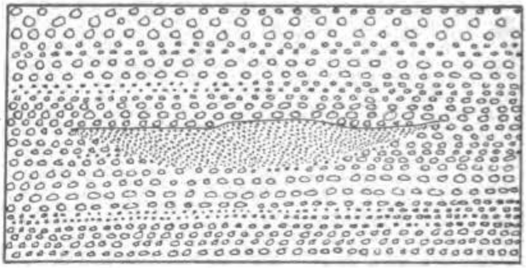


FIG. 55.—Section of a lens of cross-bedded sand in gravel. The sand was deposited by a current flowing from left to right. The upper surface of the sand is a surface of local unconformity.

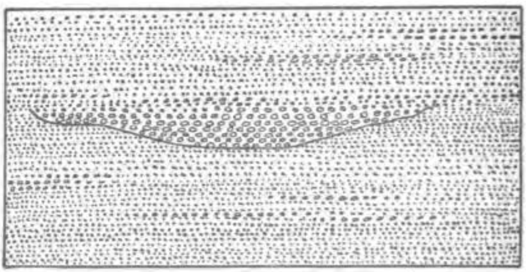


FIG. 56.—Section of a lens of gravel in sand. The lower surface of the gravel is a surface of local unconformity

82. Uniform Lamination.—Very fine and even lamination, free from cross-bedding and ripple-mark is often a sign of deposition under quiet conditions, yet under conditions which permitted sorting. This kind of bedding is especially characteristic of some muds and clays which settle gradually to the bottom of quiet water bodies after having been carried thither by surface currents or by wind.

83. Textural Variation within Single Beds and Laminæ.—It is not uncommon to find that individual beds, which have been transported by wind or by water currents, grade from coarser below to finer above, and that there is a rather sharp transition between the fine part of any bed to the coarse lower portion of the next overlying bed. This is because the velocity (or volume) and therefore the carrying strength of a current generally increase much more rapidly than they decrease. The increase may be so sudden as to cause some local erosion (**77**).

FIG. 57.—Section of fine laminated sandstone, illustrating the gradation in texture in individual laminæ.

The same kinds of variation, from coarse below to fine above, may be seen in thin uniform laminæ of quiet water deposition and likewise in volcanic ash and tuff formations. With reference to laminæ deposited in water, whether wind or water current was the transporting agent, after each accession of dust, mud, or silt, the larger grains dropped down before the smaller ones. The next time the water became turbid, large grains settled upon the finest particles of the layer last deposited (Fig. 57).

PARTICLES AND FRAGMENTS IN CLASTIC DEPOSITS

84. Isolated Pebbles and Bowlders.—The presence of large isolated bowlders in relatively fine gravels or sands of shallow water deposition is not very difficult to explain. Such bowlders are characteristic of some alluvial cone deposits, and they may be found in beach accumulations. They are common in eskers and kames where they have fallen from the adjacent ice walls, now long ago vanished.

In fine-grained sediments deposited in quiet water, the occurrence of isolated pebbles may be explained by flotation (Fig. 34). Pebbles floated out by drifting roots of trees or by ice may drop here and there into the fine bottom sediments. By their weight these pebbles may bend and somewhat compress the soft layers below them where they fall. Subsequently, if they are buried by continued normal deposition, the overlying laminæ will show no bending. After consolidation of the material, the layers above these pebbles may be a little bent, but not as much as those below (**68**).

84a. Intraformational Fragments.—Under certain circumstances, when an unlithified surface deposit is exposed to erosion, it is sufficiently hard and compact to break into slivers or blocks instead of disintegrating into the grains of which it is composed. There are two main causes for such superficial hardening—sun-baking and freezing of interstitial water.

1. When muds, clays, or limy materials are dried by exposure to the atmosphere, sun cracks develop. Under these circumstances polygonal fragments between the fissures may peel and become loosened from the underlying beds, and if deposition begins again they may be incorporated in the sediments immediately above the original sun-cracked surface. These fragments are said to be *intraformational*, and the strata containing them are *intraformational breccias or conglomerates.*[1] Usually they are angular and they may look as if they had been torn. They are commonly seen in association with contemporaneous erosion (Fig. 41).

Sometimes in semiarid regions the dry, curled "clay-shavings" are blown away and buried in sand. Then, in the following wet season, moisture, percolating through the sand, may soften the buried shavings and cause them to flatten out parallel to the bedding. In this form they are called *clay galls*. They are regarded as proof of the subaerial origin of the sand or sandstone in which they are found.

2. In cool climates water-soaked muds, sands, and gravels may become cemented by the freezing of their interstitial moisture and may then be disrupted by glacial erosion. If the broken blocks are deposited in till, they are preserved; but if they are handled by water they quickly fall to pieces. These blocks, also, are intraformational provided their erosion was

[1] Bibliog., Walcott, C. D.; Hyde, J. E.

of such a nature that it may properly be designated contemporaneous (**77**). They are angular, with shapes indicative of fracture (Fig. 58). In till deposits and occasionally in aqueoglacial wash, they are striking features, for when seen they are unconsolidated like the matrix that surrounds them. Similar

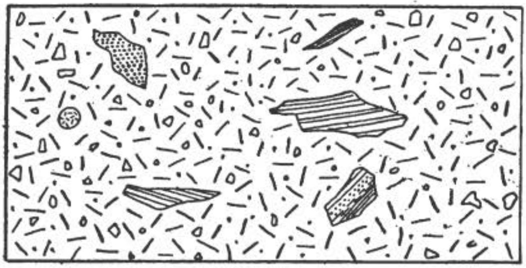


FIG. 58.—Section of till containing angular masses of unconsolidated sand and clay.

ice-formed blocks have been observed in the lithified state (shale, slate, sandstone, etc.) in tillite (Appendix III).

Any intraformational fragments may be warped or bent either by the weight of the superincumbent beds or, as in the second example, by the force of the eroding ice.

85. Isolated Masses of Unconsolidated Material in Surface Deposits.—The ice-made intraformational blocks just described (**84a**) are isolated masses of unconsolidated material as long as the matrix in which they lie remains unconsolidated. Short lenses of sand or gravel in till, contorted or not, are referred to as "nests" (Fig. 59). They are really *in situ*, having been deposited by water in association with the ice that formed the till. While they may closely resemble the intraformational blocks, they seldom have outlines which are suggestive of disruption.

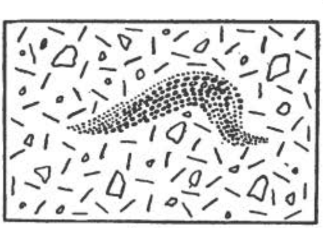


FIG. 59.—Section of till containing a deformed lens of gravel.

Till and wash deposits, and indeed any surface deposits of sufficient age, may contain entirely disintegrated pebbles and bowlders of such rocks as granite, schist, and gneiss. Their sharp outline, their rounded or subangular form, and sometimes the indications of surface markings of erosive origin, prove that these bowlders were fresh and hard when deposited and that they have disintegrated since they were buried. Their composition and usually their shape are sufficient to distinguish them from the incorporated blocks of sand, clay, or gravel.

86. Arrangement of Pebbles.—In bedded deposits pebbles which are not essentially spherical assume a definite position which varies according to several factors. On beaches composed of a great quantity of thin platy pebbles and beaten by a heavy surf, the pebbles often stand nearly vertically, wedged closely together, thus presenting the least resistance possible to the force of the waves (Fig. 60, A). When such pebbles are relatively few, they lie flat on the beach. Pebbles of greater thickness, but still thinner than wide or long, usually lie more or less flat on the beach (Fig. 60, B). In river beds where the pebbles lie closely packed, they may imbricate or overlap upstream, dipping downstream more steeply than the grade of the stream bed, and thus offering the least resistance to the current (Fig. 60, C). If the pebbles are few they lie flat on the bed of the stream. In alluvial cones, aqueoglacial deposits, and wind deposits, the pebbles and bowlders are ordinarily so few that they lie flat on the surface. Summarizing, in gravel accumulations where the pebbles are relatively thin and are abundant they present their edges to the force of waves or current; where they are associated with a large amount of sand or other fine débris they lie flat.

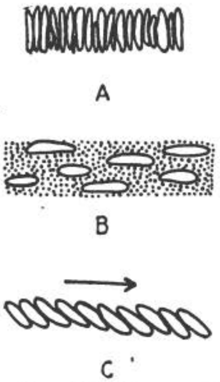


Fig. 60.—Diagram to illustrate the arrangement of pebbles. The arrow in C points with the current.

In unstratified deposits, the rock fragments lie haphazard in all positions.

87. Arrangement of Sand Grains.—The position of sand grains which are not equidimensional is of some geologic importance. Most of the common minerals occurring in sand, namely, quartz, garnet, and magnetite, etc., are such as wear with nearly equal dimensions; but mica (muscovite and, less commonly, biotite) splits along its perfect cleavage into very thin flakes. In sediments which accumulate in very quiet water, mica plates settle

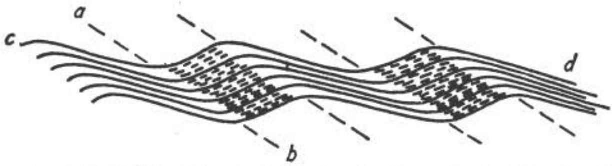


FIG. 61.—Apparent bedding (*ab*) caused by the abundance of mica flakes in the foreset laminæ of the ripple marks. *cd* is the true bedding.

flat with the bedding. They are relatively light and may therefore be separated by sorting so that some laminæ may have more mica and some less. J. B. Woodworth[1] has called attention to the fact that the flakes may settle on the front (or lee) slopes of ripple marks, and that, as a sand deposit is built up, the position of the mica in the laminæ may give rise to a structure resembling true bedding (Fig. 61). In the same manner mica, if present in wind-blown sand, accumulates on the front slopes of dunes, so that the foreset beds contain a much larger proportion of this mineral than do the topset beds.

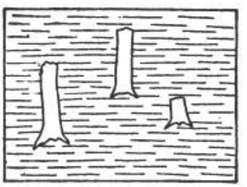


FIG. 62.—Section through strata containing the trunks of ancient trees. The position of the trunks with reference to the bedding shows that they were still standing when buried.

88. Position of Fossils.—The position of a fossil in a stratum depends upon the original mode of existence of the organism and on the method by which it was interred. Plant remains are sometimes exhumed in the attitude in which the plants lived. Ancient trees of the coal period have been found,

[1] Bibliog., WOODWORTH, J. B., 1901.

their roots still buried in the lithified soil and their trunks projecting up through successive layers of the sediments which buried them (Fig. 62). Coal beds sometimes consist of vegetable remains *in situ*. Certain kinds of animal fossils (corals, etc.), also, may occur attached to their ancient rock supports. In such cases it is easy to see that the stratum containing the fossil must be younger than the stratum which served as the foothold for the organism while it lived.

Free-living, unattached organisms fall flat, and their remains are therefore found spread out parallel with the bedding. With

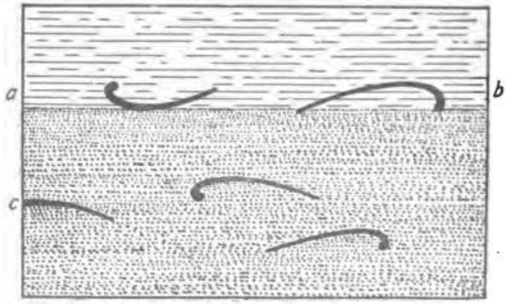


Fig. 63.—Position of concavo-convex shells in accumulating sand.

possible exceptions, this is true for broad leaves, for thin, flat shells and tests, for skeletons of fishes, etc.

The valves of clam shells and other similar concavo-convex shells, while sinking through water, settle with the concave side up and the convex side down (Fig. 63, *a*). If there is any motion in the water, they are soon overturned so that their convex surfaces are now uppermost (Fig. 63, *b*). In this attitude they offer least resistance to currents, and in this attitude they are apt to be buried (Fig. 63, *c*). It is quite common to find shell beds, or clastics containing such shells, with a majority of the valves lying convex side uppermost.

Field Interpretation of Sedimentary Materials

89. Nature of the Parent Rock.—To determine the original character of the rock from which a sedimentary deposit was derived is a task which varies widely in its possibilities. If the sediment is easily recognized as residual and rests upon its parent rock, there is no difficulty. Even if there are no outcrops of the earlier formation, perhaps because it is quite buried or because it has been entirely eroded away, the problem is still easy provided the sediment is a product of disintegration which suffered little transportation, for its constituent particles are then merely the disarranged grains of the older rock. And in the case of a conglomerate or other psephite, the pebbles tell the story.

From sedimentary materials which were laid down after they underwent long transportation and sorting, or considerable decomposition, the facts are harder to ascertain. There is more chance for mistake. For instance, a highly micaceous sandstone may have been formed from a micaceous igneous rock or from a schist or a gneiss. A sandstone containing a large proportion of garnet may have come from a garnetiferous schist or gneiss. Sometimes the geologist is helped by noting the character of associated strata. Thus, mudstones with a high kaolin content interbedded with quartz sands suggest that the parent rock was granite or quartz diorite. (Why?) Further details must be left for the student to work out for himself.

90. Quiet Deposition or Current.—Quiet deposition is indicated by very uniform lamination or by entire absence of bedding in fine rocks of uniform texture. In both cases the rock is usually a mudstone or a fine-grained sandstone. Deposition under the influence of a current is shown by cross-bedding, local unconformity, current ripple marks, wave marks, rill marks, lenses, etc. Wind-laid sandstones and river-laid clastics nearly always bear evidence of current action. Lake and marine deposits may belong to either class.

91. Depth of Water for Lake and Marine Sediments.—Since current action in lakes and seas grows less efficient away from shore, the coarser materials accumulate for the most part in shallow water. In a way, then, texture is indicative of depth of water. Likewise, the evidences for current action, just cited, appertain principally to shallow water deposits. It should be remembered, however, that these structures are sometimes made far from land by deep water currents.

Marine limestone has been said to form only in deep water, but we know now that the most important essentials for its origin are not depth so much as freedom from turbidity. While probably many limestones have been built up at depths greater than the average depth for the deposition of muds, still, some limestones may perfectly well have accumulated in relatively shallow water, provided the land waste was removed by longshore currents.

92. Direction of Current.—Supposing that a rock does contain current-formed structures, we may desire to know in which direction the wind or water was moving, as the case may be. This is shown by cross-bedding, current ripple-mark, wave marks, rill marks, and to some extent by the attitude of included fossils. Seaweeds and other aquatic plants, which are attached at the base, may be trailed out with the current. If they are buried and fossilized in this position, they indicate the direction in which the water flowed.

93. Strength of Current.—Strong currents can handle heavier materials than weak currents. Provided a rock shows evidence of current deposition, its texture is roughly a measure of the efficiency of the agent. In this connection, one should not compare eolian and aqueous clastics. It is unsafe to deduce too definite rules referring to relations between size of grain and strength of current.

94. Climate.—One of the most interesting kinds of information that the geologist is obliged to seek is the nature of the climate at the time of deposition of a given rock formation. Sometimes it is the climate in the area of deposition and sometimes it is the climate in the region where the sediments originated, but whence they were transported before their accumulation. Absence of fossils in marine or lake mudstones may mean that the water was unfavorable to life because of an excessive turbidity, or because of salinity, or because of too low a temperature. Coal is of two kinds, one being formed *in situ*, the fossil roots still passing down into the old soil from which the vegetation absorbed part of its nourishment, and the other formed from vegetable débris which was washed together and buried. Coal of the first type accumulated in marshes. Therefore it indicates a climate which was moist and either warm or cool.

FIG. 64.—Casts of salt crystals in argillite. About ⅓ natural size. (After R. A. Daly.)

Muds containing a large percentage of kaolin show that the land area whence they came was undergoing decomposition in a relatively warm, humid climate. Quartz sands and quartz-pebble conglomerates may be looked for as the coarser clastics associated with such mudstones. On the other hand, mudstones which have a high percentage of soluble mineral components, are evidence against thorough decomposition and therefore against a warm, moist climate. They are generally derived by severe glacial abrasion or by wind scour, so that in the former case they indicate a cool climate and in the latter case an arid or semiarid climate.

A semiarid climate is also suggested in many cases by mud cracks, footprints, clay galls, etc., features which are best preserved where there are long spells of drought interrupted occasionally by showers, or once a year by a rainy season. Desert conditions are indicated by thick eolian sandstones together with playa lake and sheetflood deposits and intercalated beds of salt, gypsum, nitrates, etc. Crystals of salt or their casts (Fig. 64) are considered evidence for aridity during sedimentation. Red color used to be regarded as proof of a desert climate, but it is now known to be characteristic of some widespread decomposition products in warm and temperate humid climates (**26**). Arkose and highly feldspathic sandstone may signify a relatively dry climate, either warm or cold. Glacial deposits betoken a cool or cold climate with an excess of precipitation in the form of snow.

95. Physiographic Conditions at Time of Deposition.—Sedimentary rocks may give us information on the physiography of the ancient regions where they originated. It has been pointed out in the preceding article how they indicate desert conditions. One may even go so far as to suggest that the arid region may have been flanked by a mountain range on the side from which the prevailing winds blew, and that this range caught the bulk of the rainfall on its windward slope.

Peat and coal, when *in situ*, mean that the area of deposition was flat and poorly drained. It was generally near sea level and was subject to occasional marine inundation. Hence the not uncommon interbedding of coal and marine clastics.

Products of long and thorough decomposition, such as decomposition clays, not only point to a moist, temperate or warm climate, but also to the fact that the lands where they originated were probably of low relief. They are suggestive of peneplanation. Thick fluviatile gravels and sands generally belong to piedmont alluvial cone deposits and therefore indicate the proximity of mountainous country.

96. Characters of Marine, Littoral, and Continental Deposits.—Sediments, consolidated or unconsolidated, are divided into three great classes, known as marine, littoral, and continental deposits. The littoral (*littus*, the seashore) zone lies between the average of the monthly highest flood tides and lowest ebb tides. All deposits within this zone are *littoral*. Deposits beyond the seaward margin of the littoral belt are *marine*, and those beyond its landward margin are *continental*, no matter whether the land mass is a true continent or only an island. The student may find it of advantage to have summarized the chief characters of these deposits, in order that their recognition may be facilitated. For the most part the discriminative features must be sought, not in small individual outcrops, but in large structural sections obtained through the correlation of many outcrops (see Appendix V).

Marine deposits lack such structures as mud cracks, rain prints, etc., because they are never exposed to the atmosphere, but they may have ripple marks, and, occasionally, local unconformity. Wave-made ripple marks originate usually at depths of less than 100 fathoms. Marine deposits may attain enormous thickness, but their lithologic variation is less than in continental formations. Their bedding is comparatively uniform. Sand, silt, mud, and ooze, and their consolidated derivatives are the common members of the class. Clastic mica is a rare constituent. Exceptionally, pebbles and bowlders may be floated out by ice and dropped into the finer sediments. Associated conglomerates are probably littoral.

Littoral deposits are not abundant because, being accumulated in a narrow belt, they are never very thick, and because they are especially liable to destruction. They have little variation. They consist chiefly of sand or sandstone with some conglomerate or mudstone associated. Conglomerate beds are seldom more than 100 ft. thick and are generally much less. Being situated between the marine and continental areas, littoral sediments share some of the characters of each of the other two classes. In common with continental deposits, they may contain rill marks, ripple marks, sun cracks, rain prints, imprints and fossils of land organisms, and clastic mica; and, in common with marine deposits, they may have brackish and salt water fossils. Sun cracks, rain prints, footprints, and other phenomena, preserved in mud by virtue of its property of hardening when sun-dried, are less apt to be found in littoral than in continental sediments, because they are destroyed by the advancing tide before they are hard enough for preservation. Wave marks, perhaps, are more characteristic of littoral sands than any other feature, yet even these are sometimes made on lake shores.

Continental deposits constitute the most varied group on account of the many diverse methods in which accumulation may be brought about. Changes from beds laid by one agent to beds laid by another agent are not uncommon. Eolian and glacial sediments are particularly characteristic, although they are not entirely limited to the continental class. The presence of numerous land or fresh-water fossils is a valuable criterion, but their absence is of negative value. Clastic mica in a fragmental rock is usually indicative of continental sedimentation. As regards the different rock types, conglomerates may attain great thickness, sometimes many hundred feet. Finer clastics may bear evidence of ripple-mark, cross-bedding, and local unconformity. Pelites may be variegated in color. They may contain sun cracks, rain prints, footprints of land animals, etc. Indeed sun cracks, formed as they are chiefly on the flats of river flood plains, low lake shores, and playas, are among the most reliable criteria for continental deposition. Coal beds *in situ* are of even greater significance. Limestones are apt to be continental if, like muds, they have been sun-cracked. Such limestones are rare and of restricted distribution. They may contain brackish-water fossils, but not marine ones.

Marine and lake sediments are typically well stratified, the beds being of pretty uniform texture and thickness. Fluviatile and glaciofluviatile deposits are stratified, but poorly so; their strata vary greatly in thickness; there is much textural variation;

and such features as cross-bedding and local unconformity are characteristic. Eolian dust shows little or no bedding, whereas wind-blown sand is remarkable for its varied cross-lamination and excellent sorting. Deposits laid by ice, or resulting from volcanic outbursts, creepage, landslide, or weathering *in situ*, are generally heterogeneous and unstratified.

The principal and most permanent types of continental deposition are the accumulations of large deltas, piedmont slopes, interior basins in pluvial climates, and deserts. The significant characters of these classes of deposit are as follows: (1) *Large deltas:* fluviatile muds or pelites, with mud cracks, etc. (see Appendix V); associated soil beds and swamp deposits; seaward gradation of the continental sediments into littoral and marine materials; intercalated wedges of marine strata, laid when the sea flooded the low delta flats, sometimes penetrating considerable distances landward between the continental beds. (2) *Piedmont slope deposits:* fluviatile sands and gravels with characters such as are listed in Appendix V. (3) *Interior basins in pluvial climates:* the deposits may be largely continental or marine according to (*a*) the depth of the basin, (*b*) the vigor of peripheral stream erosion, (*c*) the breadth and height of surrounding lands, (*d*) the proximity of the sea, and (*e*) the rate of subsidence of the basin floor, assuming subsidence to be in progress; if continental, the sediments may be fluviatile or lacustrine. (4) *Deserts:* lag gravels, eolian sands, disintegration sands and gravels, and interbedded playa muds with associated saline precipitates are the common deposits; the sediments are partly eolian, partly fluviatile, and partly lacustrine; fossils are rare.[1]

97. Conditions of Unconformity.—The field geologist must first of all be able to recognize a regional unconformity and then he must be able to interpret its meaning. The criteria most useful in determining a regional unconformity are: (1) discordances of bedding at a line of contact; (2) evidence of

[1] For further information on this subject refer to Bibliog., BARRELL, J., 1906.

a former weathered or eroded condition of one formation at its contact with another; (3) presence of a basal conglomerate or of a basal arkose at the line of contact; (4) faults in one body of rocks truncated by the beds of another formation (Fig. 65, A); (5) dikes or other igneous intrusive bodies in one rock formation truncated by the other (Fig. 65, A); (6) abundance of intrusive bodies (dikes, sills, etc.) of a particular kind in one group of rocks and an entire absence of the same in an adjacent formation; (7) a distinctly greater amount of folding or of metamorphism in one formation than in an adjacent formation; (8) discordances of areal distribution of rocks or of structures as seen after plotting a geologic map of the region.[1]

Unfortunately there are many chances for error in the recognition of these criteria. (1) Discordances of bedding may be due to contemporaneous erosion, to cross-bedding on a large scale, or to faulting (**288**). Contemporaneous erosion might be confused with disconformity, and cross-bedding with angular unconformity. Nevertheless, both of these structures are usually local and they are not accompanied by the other criteria for regional unconformity. (2) The second criterion mentioned above is difficult to observe. (3) Autoclastic rocks (*e.g.*, fault breccias, crush conglomerates, etc.) may be mistaken for basal conglomerates. Van Hise has pointed out the following differences:[2] (*a*) Autoclastic rocks have derived all their material from the adjacent rocks, often both above and below, whereas in basal conglomerates there are apt to be at least a few fragments from foreign sources and all the materials are derived from the lower formation only. (*b*) In autoclastic rocks the fragments are usually less rounded than in basal conglomerates, but this statement is not intended to imply that the breccia fragments may not be somewhat worn—indeed, sometimes notably rounded—by rock movements, nor that the conglomerate pebbles are always well rounded. (*c*)

[1] See Bibliog., VAN HISE, C. R., 1896, pp. 724–734, for a discussion of these criteria.

[2] See Bibliog., VAN HISE, C. R., 1896, pp. 680, 681, for a discussion of these criteria.

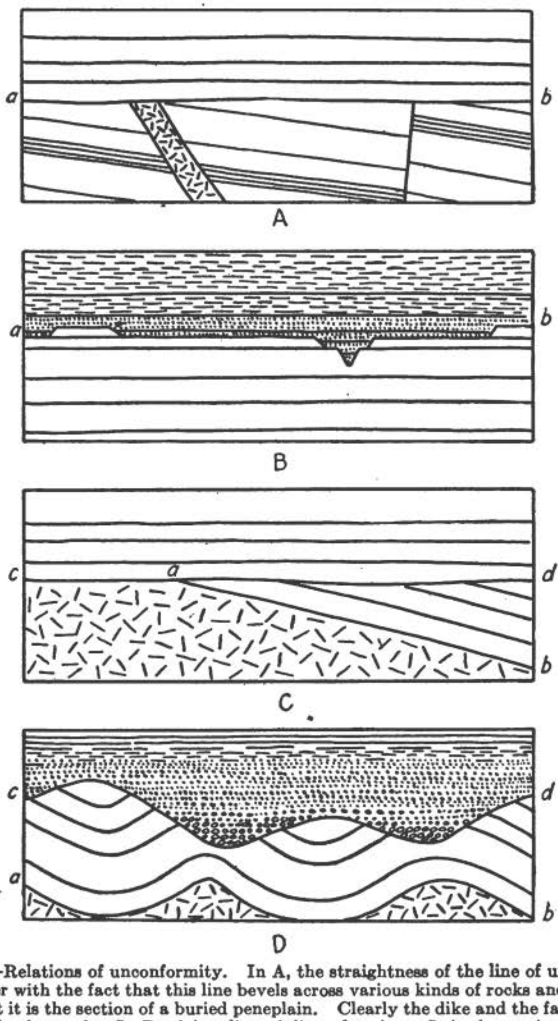


FIG. 65.—Relations of unconformity. In A, the straightness of the line of unconformity (*ab*), together with the fact that this line bevels across various kinds of rocks and structures, suggests that it is the section of a buried peneplain. Clearly the dike and the fault are older than the beds above *ab*. In B, *ab* is a line of disconformity. It is the section of a buried land surface that was characterized by mesas and canyons. A basal sandstone is the lower bed in the younger formation. In C, two lines of unconformity are shown, *ab*, and *cd*. How do we know that *ab* is older than *cd*? What two geologic events occurred in the interval between the deposition of the two sets of strata? In D, *ab* and *cd* are lines of unconformity. *ab* is older than *cd*. *ab* is sinuous because it has been folded together with the beds immediately overlying it. *cd* is sinuous because the land surface of which it is a section was a valley-and-hill topography. What features in the diagram prove the two foregoing statements? A basal conglomerate lies in the valleys above *cd*.

The interstices of the autoclastic are often filled with vein material, while in the basal conglomerates the filling is finer detritus. Finally, (*d*) autoclastic zones may be seen to pass here and there into the unshattered rock, whereas basal conglomerates grade into other finer sediments. Criteria listed under (4) to (8) above should be clear and unmistakable before they are accepted as satisfactory. (6), (7), and (8) might result from extensive faulting instead of unconformity (**288**). In dealing with this problem, do not be contented to base conclusions on one fact. Search for many lines of evidence and, if all point the same way, then the inference is likely to be correct.

As for the interpretation of regional unconformities, the geologist should seek answers to the following questions: (1) What was the agent of the first erosion and what was the nature of this erosion? (2) What was the rate of the first erosion? (3) What was the nature of the old erosion surface? (4) What was the rate of deposition of the basal beds of the younger formation? (5) What was the source of these basal beds? (6) How long a period of time elapsed between the two periods of rock formation? (See "time value," defined below.) (7) What is the range of lost strata (see "hiatus," defined below) as stated in the terminology of the geologic time scale? (8) What thickness of rocks was removed in the first erosion? (9) What events are represented in the section? These questions can be answered only by studying the nature of the surface of unconformity and the characters and mutual relations of the two formations.

Since surfaces of unconformity are surfaces of past erosion, they should bear just such traces of erosion as would be sought on bedrock outcrops of the present day (see Chapter II). The trouble is that the evidences are usually concealed beneath the overlying formation, although sometimes, it is true, recent erosion has exposed portions of the old surface. Ordinarily the surface must be studied in cross section, merely as a line. The greater the length of the exposed part of this line, the safer will be inferences based upon its examination; but even if it is not continuously exposed, the separate scattered outcrops may be levelled up and correlated so that a fair idea of its character may be obtained.

As explained in Art. **72,** a surface (or line) of unconformity does not necessarily accompany unconformable relations. A sharp dividing line between two formations which are unconformable with one another may be due (1) to strong abrasion in the first period of erosion, or (2) to regional decomposition. A blended transition from the older formation to the younger one, with no sharp line of demarcation, points to deep disintegration in the first period of erosion. Here the basal sediments are disintegration products of the underlying rock. Thus, the distinctness of the line of unconformity helps somewhat toward an understanding of the kind and rate of erosion.

Provided the line of unconformity is distinct, its form may indicate the nature of the old erosion surface. If the line is straight or gently undulating for a long distance, the surface was probably a destructional plain, or, less likely, a bench (**237, 242**). Greater irregularity of the line points to a more uneven topography. Several possibilities are depicted in Fig. 65.

For interpreting the past, the basal portion of the upper series is of more value to the geologist than the actual line of unconformity. It should be studied with reference to its composition, texture, and structure, and as regards the shapes and surface features of its constituent fragments, if it is of mechanical origin. Information as to the climate at the time of deposition and as to the agent and rate of this deposition may be obtained in the manner described in Art. **94.** Conglomerate and arkose frequently appear as the lowermost stratum of the upper series. Arkose generally means short and rapid transportation and deposition which have been quickly inaugurated after a period of slow, long-enduring disintegration. A basal conglomerate, always containing abundant pebbles of rocks in the upper part of the lower formation, is significant of encroaching deposition and of effective abrasion during transportation from the source of supply. Sometimes rocks other than conglomerate and arkose are basal. Above an ice-scoured surface, tillite is to be expected; but if a glacial rock basin (**248**) were occupied for a time by a lake, finely stratified shale, originally lake clay, might rest on the grooved and striated surface. Limestone on an old erosion surface means (1) that the initiation of the limestone-forming conditions was so quiet that no mechanical sediments were made, or (2) that such sediments were carried away to be laid down elsewhere as fast as they were formed. Basal sediments, then, need not be deposited by the same agents that eroded the subjacent surface of unconformity. There is no better aid to the interpretation of former conditions than a broad knowledge of present conditions.

Wrong impressions are sometimes formed regarding the source of the basal materials and the direction of their transport. For instance, if a basal conglomerate composed of granite pebbles were observed overlying, let us say, a quartzite, and half a mile away the granite of the pebbles were found as bedrock below the surface of unconformity, one might assume that the pebbles were derived and carried from the locality of the granite to the site of the conglomerate. It is to be remembered, however, that these features are seen only in a single plane, intersecting the unconformity in a line. The pebbles may have been shaped from this granite, but the granite mass may be of very great extent and the pebbles may have been borne, perhaps many miles, from another part of the same plutonic body, not necessarily exposed in the geologic section. Provided the rock was a transported deposit, there is no necessary relation between the trend of the section and the direction in which the materials were carried. Their true source can only be approximated, and even then only after extensive investigation.

From the standpoint of stratigraphy it is desirable to know what interval of geologic time is represented by the unconformity and how many geologic formations are missing at the unconformity. The former is called the *time value* of the unconformity and the latter is the *hiatus*. Hiatus can easily be determined if it is possible to ascertain the geologic age of the old and the young formations at the surface of unconformity (**99**). Time value need not be equivalent to hiatus, for there is no reason for assuming that erosion was continuous throughout the period of time represented by the unconformity. Thus, if the two formations are Upper Cambrian and Triassic, the Ordovician, Silurian, Devonian, Missisippian, and Pennsylvanian, but not the Permian, may have been deposited and then eroded before Triassic deposition commenced, or perhaps only the Ordovician was laid down and was worn away during the remaining time from Silurian to Triassic. In the first case the time value is represented by erosion during the interval from the end of the Pennsylvanian to the initiation of the Triassic; whereas, in the second case, the time value is represented by the interval between the end of the Ordovician and the beginning of the Triassic; yet, in both instances, the hiatus is the same. Time value is a difficult factor to determine.[1]

98. Stratigraphic Sequence.—Since strata are accumulated by a process of upbuilding of layer on layer, any bed in unconsolidated sediments is younger than those below it and older than those above it. This original succession from older below to younger above is referred to as *stratigraphic sequence.* Although in most cases it remains *normal* after the consolidation of sediments, it may be *reversed* by overturning of the beds in severe crustal deformation (**151**).

99. Age Relations of Sedimentary Materials.—The age of a sedimentary deposit or rock, as indeed of any other geologic form or structure, may be regarded from three points of view: (1) If the deposit (or rock) is correlated with its immediate surroundings, it will be found to be younger than some geologic features and older than others. Stated in these terms of comparison, its age is called *relative.* The relative age of any bed within a given formation is obtained by determining the stratigraphic sequence. (2) Geologists have agreed upon a *time scale,* that is, a definite succession of formations for the whole

[1] For further information on this subject, see Bibliog., Blackwelder, E.

world, and the divisions in this scale have received names (Appendix I). Each division is characterized by a certain suite of fossils, which, though showing a good deal of variation in its species and even in its genera, is still sufficiently distinctive to be of use in settling the place of a fossiliferous deposit in the succession. The age of a body of sediments when referred to this time scale is its *geologic age*. If fossils are absent or scarce in the deposit, its geologic age can be obtained only by correlating it with other bodies of which the geologic age is already known. The geologic ages of all structures and of all rocks other than sediments must be found in this indirect way. (3) The *actual age* of a deposit, expressed in years or centuries, can seldom be ascertained. Even attempts to compute approximate values are likely to be far off.

Of these three methods of stating the age of sediments, the first and second are commonly followed. The second is the more definite of the two and is the more difficult to establish because fossil species must be identified. The third method, being rarely essayed, will receive no further comment in this book.

100. Relative Age of Clastic Dikes and Pipes.—Clastic dikes and pipes are clearly younger than their inclosing rock (country rock). If they have originated by filling from above, they are probably associated with some overlying stratum which bears unconformable relations with the country rock, wherefore they may be very much younger than this country rock; but if they were injected from below, the difference between their age and the age of the country rock may be relatively slight.

101. Discrimination between Separate Glacial Epochs.[1]—In regions of Pleistocene and later glaciation evidences have been found which prove that the ice advanced more than once, that the periods between successive advances were often of considerable length, and that during these interglacial epochs the ice front retreated long distances. Some of the more important

[1] For a more detailed discussion of this subject see Bibliog., SALISBURY, R. D., 1893. The writer has drawn freely from this source.

criteria for discriminating between the deposits of successive ice advances are briefly outlined below.

1. If beds of terrestrial origin, containing either plant or animal remains, are found between deposits of glacial drift, and if the organic remains are of species known to have existed in a temperate or warm climate, the evidence is strongly in favor of a long period between the laying down of the lower drift sheet and that of the upper. The mere presence of fossils is not always sufficient evidence, because sometimes life, especially plant life, flourishes near or even upon the ice. But this is more particularly true of local mountain glaciers and piedmont glaciers than of the larger ice sheets.

2. If between two sheets of drift there are found local beds of bog iron ore, or marine or lacustrine strata containing the remains of plants or animals that lived in temperate or warm water, a long interglacial period is indicated.

3. A weathered glacial deposit overlain by fresh drift with a sharp boundary between the two is another criterion for two separate glacial epochs. A red or reddish color in the weathered drift points to a warm, moist climate (**26**). The thickness of the zone of this decay roughly indicates the length of time of exposure to atmospheric influence.

4. When bowlders of certain varieties of rock exhibit a distinctly greater degree of weathering in a given moraine or sheet of drift as compared with the degree of weathering in bowlders of *the same rocks* in an adjacent moraine or in an overlying drift sheet, respectively, the presumption is that the deposits were separated by an interglacial epoch of some duration. In both (3) and (4) care must be taken not to confuse superglacial materials of the older glaciation, which decayed while on the surface of the ice, with that part of the drift which may have weathered after its deposition.

5. During the retreat of a glacier, streams from the ice are usually aggrading (why?); but after the ice front has retreated many miles, aggradation may cease and both aqueoglacial and till deposits may suffer erosion. Upon a readvance of the ice,

channels cut into the older drift and even into bedrock beneath this drift, may be filled up with a new glacial accumulation. Buried valleys of this origin are much larger than the gullies cut by contemporaneous erosion.

6. If, after the disappearance of the ice, a later drift sheet does not entirely cover an earlier one, the topography of the exposed part of the older deposit will show a more advanced stage of dissection than that of the younger. This is as true of the moraines of valley glaciers as it is of the deposits laid by continental ice sheets.

Other criteria, either of less value or more difficult of interpretation, are discussed by Salisbury in the article cited.

With reference to all the criteria mentioned above, the farther north the evidence is found in the case of continental glaciation, or the higher the altitude at which it is found in the case of mountain glaciation, the more reliable will be the deduction for two distinct glacial epochs. To base judgment on any one of these criteria alone is unsafe. Two or more should be sought in the field before drawing final conclusions. On the other hand, if these lines of evidence are wanting, their absence must not be regarded as absolute proof against two glacial epochs.

CHAPTER VI

IGNEOUS ROCKS

Terminology and Classification

102. General Definitions.—While comparatively few people have actually witnessed a volcano in action, yet most of us know that a common phenomenon of volcanic eruption is the outpouring of lava; and we know further that this lava eventually cools and hardens into solid rock. Such lava, in all cases, has come up from within the lithosphere, and there are reasons for thinking that it may have come up a long way, perhaps many miles. Geology teaches us that molten rock does not always rise far enough to reach the earth's surface. Checked in its ascent, it may consolidate between walls of older, cooler rocks. Any rock which thus forms by consolidation from a molten condition is called an *igneous* rock (*ignis*, fire). Those rocks which become solid after ejection upon the earth's surface, either on land or below water, are *extrusive*, and those which harden from molten material injected below the earth's surface are *intrusive*. Molten rock is usually called *magma* when it is well below the earth's surface, and *lava* when it is just below or upon the earth's surface; but "lava" may also be applied to the *consolidated* extrusive rock. "Lava" is not correctly used except with reference to volcanic extrusion.

All igneous rocks, or certainly a large majority of them, are *eruptive* in the sense that each has probably been derived from a magma that had moved or "broken out" from the place where it originated *as magma*, but the word does not necessarily imply "breaking out" at the earth's surface, *i.e.*, it is not synonymous with "extrusive."

Country rock is a purely relative term used for the older rock into which magma has been intruded. It has no significance as to the composition or structure of this older rock. Blocks of country rock entirely surrounded by igneous material in such a way as to indicate that they were immersed in the magma and were then frozen into it, are *inclusions* or *xenoliths*. "Inclusion" must not be confused with "intrusion." The original

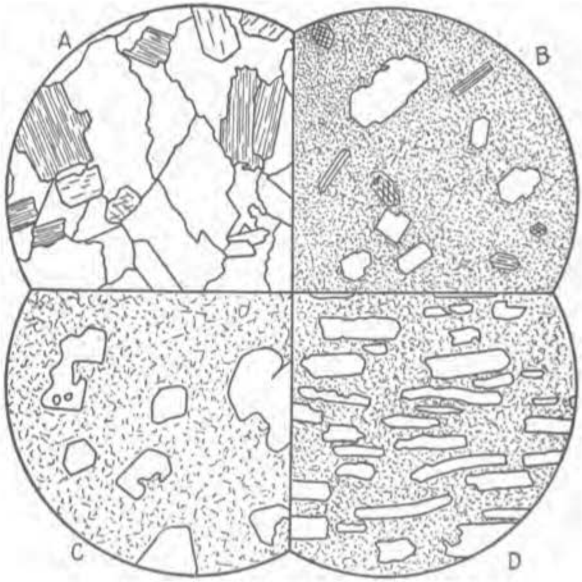


FIG. 66.—Textures of igneous rocks. A, even-granular texture; B, C, D, porphyrític texture. In B the phenocrysts are sharply angular with definite crystal boundaries. In C the phenocrysts have rounded corners and embayments of the groundmass, both features being due to resorption. The parallel arrangement of the phenocrysts in D indicates the direction of flow of the original magma.

bounding surfaces of an igneous body, both before and after consolidation, are its *contacts*. Although this term is also applied to unconformities, faults, etc. (**13**), in the present chapter it will be strictly limited to the walls of igneous bodies. A lava flow has a lower contact that separates it from the bed-rock and mantle rock of the old land surface over which it spread, and an upper contact which may subsequently become the basal surface of younger sediments or of flows superposed upon it without intervening denudation. The contacts of an intrusive rock are the surfaces at which it touches its country rock.

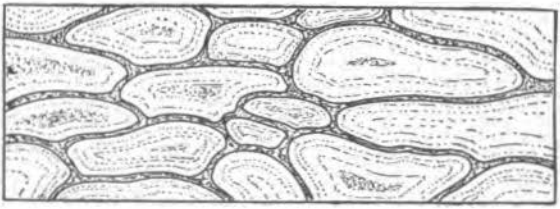
Terms which refer to the grain of igneous rocks, *i.e.*, to its size or to its presence or absence, come under the head of *texture*. Some igneous rocks are distinctly *granular;* others, so fine that no individual grains are visible, are said to be *dense;* and some are *glassy* or *amorphous*. The granular varieties are *even-granular* (Fig. 66, A) if the grains are of approximately uniform size, and *porphyritic* (Fig. 66, B and D) if one (or possibly two)

FIG. 67.—Flow structure in lava (⅓ natural size).

of the minerals is conspicuously larger than the others so that the rock looks spotted. Such a rock is a *porphyry*.[1] The conspicuous grains in it are *phenocrysts* and the finer matrix in which they are scattered is the *groundmass*. The groundmass may be granular, dense, or glassy. If the variation in size of the grains of an igneous rock is so irregular that no distinction can be drawn between phenocrysts and a groundmass, and many of the grains are exceptionally large, or if all the grains are very large, the texture is *pegmatitic* and the rock is *pegmatite*.

[1] A spotted appearance due merely to differences of color is not porphyritic texture.

some pegmatites crystals have been found measuring several t in length.



ɪɢ. 68.—Pillow structure in lava (½5 natural size). The concentric rows of dots repre- layers of vesicles. Observe that the lower sides of the "pillows" are shaped against upper surfaces of the underlying "pillows."

Fɪɢ. 69.—Basic segregations in a granitic rock.

Features depending upon the arrangement of the constituents within a rock are *lithologic structures.* In lavas and sometimes along the contacts of intrusive bodies there may be a parallel streaking which was caused by movement of the molten material before it quite consolidated. This is *flow structure* (Fig. 67). The same term is given to the parallel orientation of elongate or tabular crystals in an igneous rock and to the parallel position of flattened vesicles (see below). A similar local streakiness in rocks of granitic texture, probably likewise due to movement within the viscous magma, is called *schlieren.* The streaks are *schliers. Pillow structure* is formed in mobile lavas under special conditions of viscosity, temperature, and pressure. It makes the surface of a lava flow hummocky. In cross section it is seen to consist of roundish bunches, or "pillows" of the lava, piled irregularly upon one another (Fig. 68), with the spaces between the pillows filled with volcanic ash, clastic sediments, limestone, vein deposits, or other materials.[1]

In the crystallization of molten rock certain minerals sometimes grow in groups, or *segregations*, in the magma (Fig. 69). When these segregations are exposed they appear as roundish spots and patches, commonly darker than the inclosing rock, and often with concentric structure. Lavas, when fresh, may be

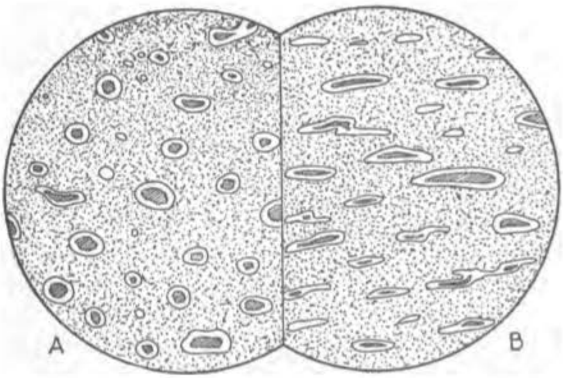


FIG. 70.—Amygdaloidal structure in lava. Quartz (white) was deposited on the walls of the original vesicles, and subsequently epidote (lined) filled the remaining open spaces. The vesicles in which the amygdales of B were deposited were flattened and drawn out by the flowing of the lava. (Natural size.)

full of small pores or *vesicles*. They are then said to be *vesicular*. While the lava was still liquid, these pores were bubbles that contained gas or water vapor. If vesicles are subsequently filled with minerals that are deposited from solution in water or gas, the fillings are called *amygdales* and the structure is *amygdaloidal* (Fig. 70).

There is another group of rocks which should be mentioned here because, while they are like normal clastic rocks in their manner of consolidation (by pressure, cementation, etc.), they

[1] For an excellent paper on this subject see Bibliog., LEWIS, J. V.

are igneous in their ultimate origin. These are the so-called *pyroclastics* ("fire-broken"). When unconsolidated, they consist of volcanic dust, volcanic ash, lapilli, bombs, and broken pieces, large and small, of older rocks that were shattered by the force of eruption. These materials are also called *ejectamenta*. Dust, ash, lapilli, and bombs are generally particles or lumps of lava which were thrown up into the air in a molten condition, but which partly or completely hardened before they fell. Consolidated masses of dust, ash, and lapilli are known as *tuff*, and coarser pyroclastic débris, if consolidated, is *agglomerate* (**204**). Agglomerate has a tufaceous matrix just as conglomerate has a sandy matrix.

103. Contacts and Contact Zones.—By virtue of their great heat and other properties, magma and lava may induce changes in the characters of the older rocks in contact with them, and conversely, these older rocks may directly influence the molten material while it cools. Effects of the first kind come under the head of *exomorphism* (*ἔξω*, outside, +*μορφή*, form), and those of the second kind come under the head of *endomorphism* (*ἔνδον*, within, + *μορφή*, form). Exomorphism and endomorphism are embraced in the term, *contact metamorphism* (*μετά*, beyond, over, + *μορφή*, form). These changes are usually most marked at the contact and die out away from it. The zone in which they are conspicuous may be termed the *contact metamorphic zone*, or briefly the *contact zone*, for each rock. If, as sometimes happens, the igneous rock blends into the country rock by a gradual change in character (**109**), there is no true surface of contact; there is, rather, a *mutual contact zone*. Except for purposes of discrimination, this may still be called a contact.

104. Classification of Eruptive Bodies.—Geologists speak of the *mode of occurrence* of an igneous rock, meaning by that the general form and size of the eruptive body and its relations to adjacent rocks. Extensive investigations the world over have shown that intrusive masses are of two main varieties. Many were erupted *between* rock walls so that, at the time of their emplacement, they had older rock above and below them, and those which were vertical had side walls that corresponded to such upper and lower contacts; that is, the chambers occupied by these bodies seem to have had relatively small openings by which the magma gained admission. On the other hand, there are certain intrusive forms (batholiths, stocks, bosses) which, as far as observations demonstrate, enlarge downward and have no bottom contacts. No one has ever discovered a base for such bodies; only their upper or roof contacts and their side walls have been found. Accordingly, Daly[1] has proposed a division of intrusive forms into *injected*, those of the first type, and *subjacent*, those which enlarge downward and have no demonstrable basal contact. Igneous bodies which were intruded into sedimentary country rocks are *concordant* if the magma was

FIG. 71.—Sills of porphyry (black) in the Carboniferous formation of the Tenmile District, Colorado. (Tenmile District Special Folio, No. 48, U. S. G. S., 1898.)

injected along the bedding planes, and *discordant* (or *transgressive*) if the magma was intruded across the bedding planes.

A *sill* is a layer of igneous material which has been injected between and along the beds of a sedimentary series (Figs. 71, 73, 74). It is relatively thin as compared with its lateral extent. Theoretically it tapers out at the edges, but this feature is seldom visible in a given sill. An *interformational sheet* is identical with a sill except that it has been intruded along a surface of unconformity. It is always essentially parallel to the younger, overlying formation. A *laccolith* is like a sill except that the ratio between its thickness and its width is much greater than in the sill. Its roof is distinctly arched (Fig. 72). When a laccolith has been intruded along an unconformity it is said

[1] Bibliog., DALY, R. A., Chapter V.

to be *interformational* (Fig. 72). Sills, sheets, and laccoliths, although they are always concordant in their major relations, may break across the bedding locally (Fig. 73).

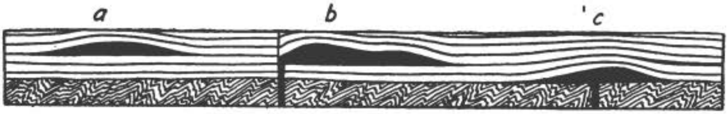


FIG. 72.—Section showing three laccoliths. The feeder of *a* is not in the section. The magma followed a fault in rising to *b*. *c* is an interformational laccolith. Note that the strata are arched upward above each of the laccoliths.

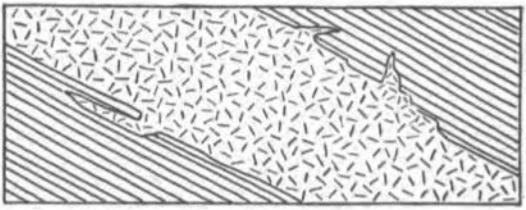


FIG. 73.—Section of a sill from which short apophyses extend into the country rock both above and below.

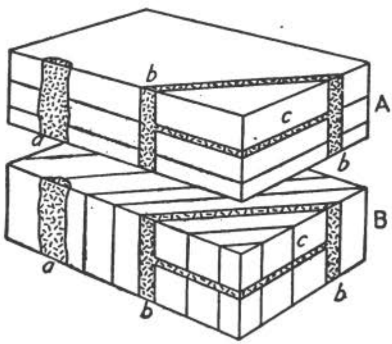


FIG. 74.—Intrusive bodies in stratified rocks. *a* is a neck in both A and B. *b* is a dike in A and a sill in B. *c* is a sill in A and a dike in B.

The term *dike* is used in this book for any sheet of igneous material not concordant with bedding (Fig. 74). Its contacts need not be exactly parallel, *i.e.*, a dike may thin out or it may alternately pinch and swell along its length (**130**). An *apophysis* is a dike which extends out from a larger magmatic body and obviously tapers to a point (as seen in section) (Figs. 73, 77).

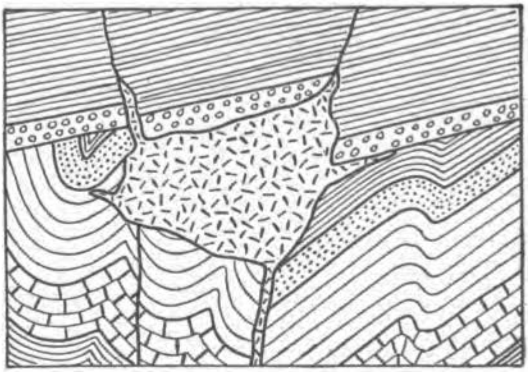


FIG. 75.—Section of a chonolith which was injected *pari passu* with faulting of the country rock. Intrusion was essentially passive.

A *neck* is a roughly cylindrical intrusive mass with one long and two short dimensions. Its axis is usually vertical or steeply

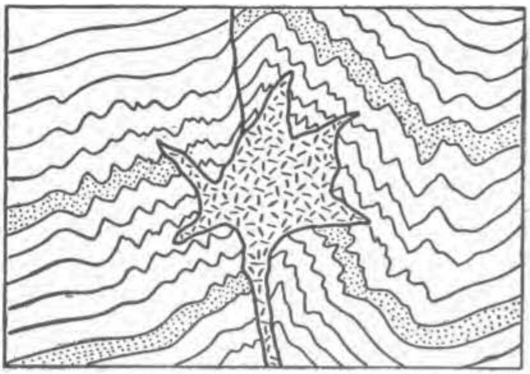


FIG. 76.—Section of a chonolith which was intruded along a fault and which, in its injection, squeezed and contorted the country rock by the hydrostatic pressure of the magma.

inclined (Fig. 74). A *chonolith* is an injection irregular in that its characters are not those of a true dike, sill, sheet, laccolith, or neck, but, unlike the subjacent bodies, it has a floor (Figs. 75, 76).

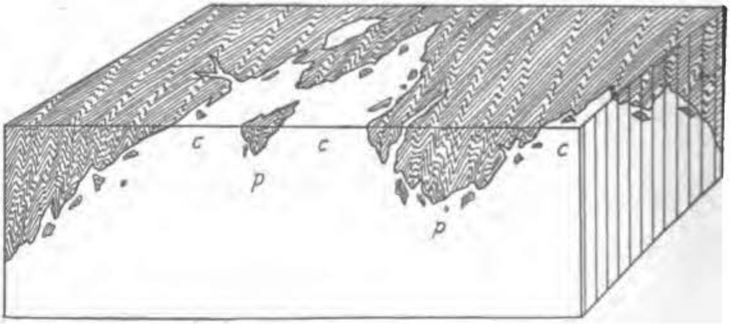


Fig. 77.—Block diagram of part of a batholith (white) and its schistose country rock. *c*, cupolas; *p*, roof pendants. Several inclusions of the country rock have been frozen in near the contact.

A *batholith* is a large, irregular intrusive mass of igneous material which shows no evidence of having a base (Fig. 77). It is discordant in its relations to invaded strata. While its

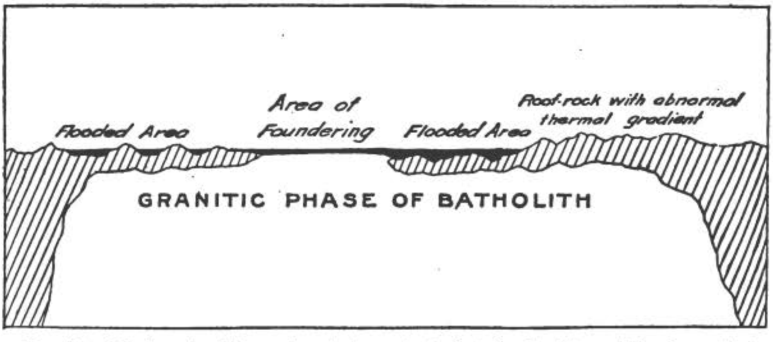


Fig. 78.—Ideal section illustrating the hypothesis that the rhyolite and the thermal phenomena of the Yellowstone Park are directly related to the foundering of part of the roof of a late-Tertiary batholith. (After R. A. Daly.)

roof is roughly dome-shaped, there are often downward projections of the superjacent country rock which are called *roof pendants* (Fig. 77, *p*). Upward projections of the batholith are known as *cupolas* (Fig. 77, *c*). The side walls of batholiths appear to be steeply and outwardly inclined. A *stock* is a small batholith. A *boss* is a stock with a nearly circular ground plan. Stocks and bosses are sometimes cupolas of concealed batholiths.

As regards extrusion, it has been suggested that, perhaps sometimes in the past, magma may have reached the earth's surface by the foundering of part of the roof of a batholith (Fig. 78). This Daly calls *extrusion by de-roofing*.[1] The two commonest methods, however, are by outflow from fissures and from tubular openings or pipes. These are known as *fissure eruptions* and

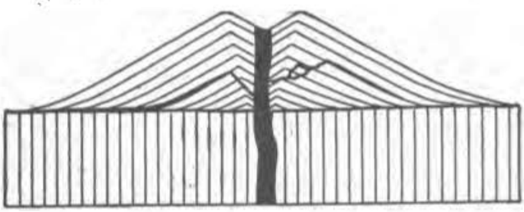


FIG. 79.—Ideal section of a volcanic cone that has been built up on older rock (vertical ruling). The cone consists of pyroclastic material intersected by dikes of lava (black) which branch from the central neck. Along the course of each dike the lava rose until it broke out on the side of the cone, down which it flowed. The dike on the left is older than that on the right. (Why?) Bedding in the fragmental material has the characteristic angle of repose.

central eruptions, respectively. When extrusion has ceased and the lava has become clogged in the conduit, the fissure type of filling is a dike or a sill, according to its relations, and the pipe filling is a *volcanic neck*. A *flow* is a sheet of lava. A *volcanic cone* is a conical, often symmetrical hill of volcanic material, either entirely ash or cinders, entirely lava, or partly lava and partly pyroclastic débris (Fig. 79). In any case it is apt to be intersected by dikes of lava.

The several modes of occurrence above defined may be classified as follows:[2]

[1] Bibliog., DALY, R. A., p. 121.
[2] After DALY, with some omissions and modifications.

A. Intrusive modes
  1. Injected masses
    a. Concordant injections (intruded along bedding planes; occur only in stratified rocks). Sills, interformational sheets, laccoliths.
    b. Discordant injections (intruded across the bedding planes if in stratified rocks). Dikes, apophyses, necks, chonoliths.
  2. Subjacent masses
    a. Batholiths, stocks, bosses.
B. Extrusive modes
  1. Fissure eruptions
  2. Extrusion by de-roofing
  3. Central eruptions.
    Attendant phenomena: necks, flows, cones, etc

105. Size of Eruptive Bodies.—Sills and interformational sheets may range in thickness from a fraction of a millimeter to over 1000 ft., and in lateral extent from a few millimeters to many miles. Laccoliths vary in thickness from a fraction of an inch to several miles; they are commonly thicker than sills. They may be over 100 miles in length and nearly as wide, although they are usually smaller. Dikes may be from less than 1 mm. to over a mile in thickness, and they may be traced a few millimeters or as much as 25, 50, or even 100 miles. Chonoliths have dimensions similar to those of laccoliths. With regard to area of outcrop, stocks and bosses are arbitrarily taken as less, and batholiths as more, than 40 sq. miles. A batholith may be exposed over thousands of square miles. Individual flows are generally several feet thick and they may be over 100 ft. thick. If successive flows have been poured out one upon another, the total thickness may amount to many hundreds of feet. Volcanic necks may be from 10 ft. to a mile in diameter, but are seldom as much as 1000 ft.

Nature and Consolidation of Molten Rock

106. Nature of Molten Rock.—Magma may be regarded as a sort of hot solution of certain volatile and nonvolatile substances. The nonvolatile ones include silica (SiO_2) and the oxides of Al, Fe, Mg, Ca, Na, and K, which, separate or in combination, compose the principal constituents of igneous rocks. There is a wide variation in the proportions of these ingredients in different magmas, and correspondingly igneous rocks vary much in chemical composition (Appendix II). The volatile substances ("mineralizers"), such as water vapor, CO_2, HCl, etc., probably enter only in small part into the composition of the minerals. Most of them escape either into the wall rocks (**121**), or, in the case of lava, into the atmosphere. The explosiveness of some kinds of volcanic eruption is occasioned chiefly by the escape of gases and vapors under diminished pressure.

107. Consolidation of Molten Rock.—By the process of eruption magma is brought up into regions of lower pressure and lower temperature. For subjacent eruption the change in both conditions is probably not large, but for injected and extruded bodies it may be very great. Reduction of pressure may have a number of effects of which, perhaps, the more important are the expansion of the magma itself, the expansion of its gases, the increased activity of these gases, and possibly the combination of some of the gases.

Reduction in temperature induces cooling which may be very gradual or rapid. When magma is cooling a temperature will at length be reached at which some of the nonvolatile constituents will begin to separate from the hot solution as crystals. Now, crystallization always implies that the molecules of which the crystals are being formed must have enough freedom in the liquid to move and orient themselves, and this freedom depends upon the fluidity or mobility of the magma. If the cooling is very slow, so that the magma does not soon become viscous, relatively few crystals will originate and these will grow by the addition of molecules until the mass has become a coarse crystalline rock. But if cooling is very rapid the magma may become so sticky that the molecules are unable to move about and combine. The liquid becomes stiffer and harder, without crystallization, until it is a glass. If cooling is a little less sudden, yet not so slow as in the first example, there may be some opportunity for the molecules to move before the liquid becomes too viscous.

Crystals may then originate at a great many points so near together that they will soon interfere and the resulting rock will be fine-grained. Evidently, then, *rate of cooling* is an important factor influencing the texture of an igneous rock.

The volatile constituents, or mineralizers, may be conceived of as lubricating the magma, as making it less viscous. By virtue of this property, not only do they increase the mobility of the molten material as a whole, but also they facilitate molecular movements within it, *i.e.*, they assist crystallization. In fact, the crystallization of some minerals, such as quartz, orthoclase, and albite (soda plagioclase), seems to be difficult or impossible without the aid of these volatile substances. Since ease of molecular migration in a cooling solution is conducive to the formation of relatively few, large crystals, an abundance of gases and vapors in a magma may function in the same way as a slow rate of cooling. Pegmatitic texture, which is thought to be due to the agency of an excess of mineralizers and particularly of water vapor, is often characteristic of the last portion of a magma to crystallize, because the volatile substances, being for the most part excluded from the composition of the minerals which they help to crystallize, are left in increasing proportion in the residual liquid.

There is still another factor which influences the fluidity of a magma, namely, the proportion of the nonvolatile components. Those magmas (*basic*) which have a relatively high content of lime, iron, and magnesium, and are low in silica, are thinner and more mobile than those (*acidic*) which are high in silica and the alkalies. Basic lavas flow quite freely and sometimes for long distances when they are poured out on the earth's surface, and the magmatic gases are readily given off from them; but acidic lavas are so viscous that the gases escape with much difficulty and generally with explosive violence. It might seem, therefore, that the basic, mobile magmas would consolidate with coarser texture than the acidic kinds, and undoubtedly this is sometimes true; but rate of cooling and volatile content are so much more effective, at least as far as visible results are concerned, that the degree of control by nonvolatile composition is usually indeterminate. Thus, an acidic intrusive may be of coarser grain than a basic igneous rock into which it was injected.

In brief, then, the viscosity and crystallization of magmas and the texture of igneous rocks are controlled by various factors of which temperature change and content of volatile substances are generally the most important. The beginner is advised to disregard pressure change and nonvolatile composition since the parts played by these are more difficult to gauge. Furthermore, he is warned not to make comparisons between the textures of different classes of rock and to draw conclusions accordingly. Because a granite happens to be coarse and a diorite is finer, the granite magma did not necessarily cool more slowly or have a larger proportion of volatile constituents than the diorite magma; but if the granite shows variations of texture within its own mass, these may be ascribed in most cases to the control of one or the other, or possibly both, of the factors named; and the same may be said of variations within the diorite.

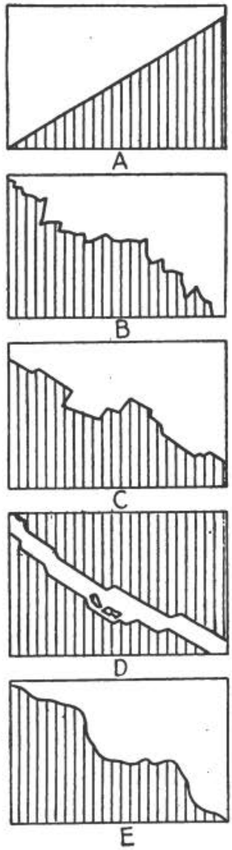


Fig. 80.—Types of igneous contacts, as seen in cross section. The intrusive rock is blank and the country rock is lined. The contact is straight in A, jagged in B, blocky in C, blocky and matched in D, and sinuous in E.

Contacts

108. Shape of Contacts.—Intrusive contacts may be straight jagged, blocky, sinuous, or lobate. These are shown in Fig. 80. Straight, jagged, and blocky contacts point to the invasion of fissures by the magma. They signify that the country rock was in its zone of fracture (**140**), and that probably it was relatively cool as compared with the molten material. In the case of thin injected bodies, such as dikes and sills, the two edges are sometimes *matched*, *i.e.*, indentations on one wall may be seen to correspond to projections of like shape on the other wall (Fig. 80, D); but more commonly small blocks have been broken off and carried away by the magma so that the walls do not match. Sinuous and lobate contacts often indicate that the country rock was within its zone of flowage (**140**). The difference between the temperature of the country rock and that of the intrusive mass may not have been very great.

The upper and lower surfaces of a lava flow are generally very irregular. Below, the sheet is often cavernous, and above,

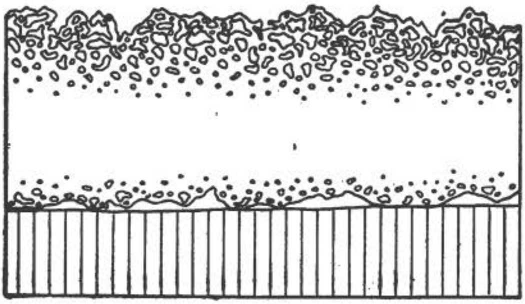


FIG. 81.—Section of a lava flow resting on older material (vertical ruling). The flow is highly vesicular above, less so below. and is compact in its central portion. Its upper surface is scoriaceous (cf. Fig. 33).

it may be relatively smooth and ribbed (ropy lava, pahoehoe), or hummocky (pillow lava), or exceedingly rough and jagged (block lava, aa) (Fig. 81). Block lava owes its roughness to the coalescence and increase of size of vesicles at its upper surface and to the breaking of crusts which formed before its flow had ceased.

109. Sharpness of Contacts.—Some contacts are very definite, so sharp, in fact, that one can put the point of a pencil on the exact line (Fig. 82). In other instances there appears to be more or less blending between the country rock and the intrusive (Fig. 83). Sharp contacts may mean either (1) that intrusion was rapid and the magma was soon chilled against the country rock, or (2) that there was not a strong tendency for the magma gradually to alter or dissolve the country rock (**116**), or (3) that,

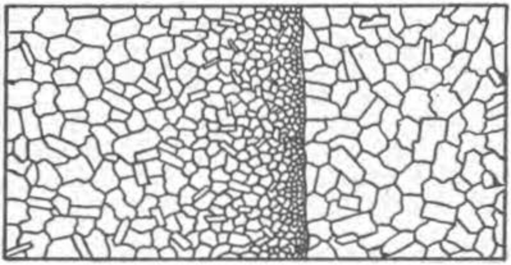


FIG. 82.—Section of a sharp igneous contact between two igneous rocks. The rock on the left is the younger. This is determined by the fact that its texture becomes finer toward the contact, showing that its magma was chilled against the rock on the right, and that here, therefore, its crystallization was impeded. This is an example of a chilled contact zone.

if the magma invaded the country rock by some mode of chemical or mechanical replacement, it did so without filtering into the latter and it removed the products as fast as they were formed.

Blended contacts suggest (1) that the magma may have

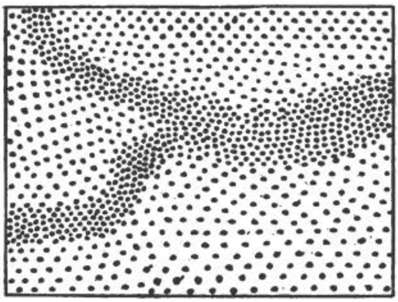


FIG. 83.—Section of a branching dike and its country rock. The contacts are blended, that is, there is nowhere a sharp division line between the two rocks.

worked its way into the country rock and there crystallized in thin stringers or in isolated grains between the constituents of the older rock, or (2) that the magma had the property of gradually breaking down and altering the composition of the country rock. Each of these alternatives points to long-continued magmatic conditions; there could have been no sudden chilling. In other words, the country rock must have been relatively warm.

Contact Zone in the Eruptive Rock

110. Principal Phenomena of the Contact Zone.—The contact zone in an eruptive rock (endomorphic zone) may exhibit the following characters which are more or less dependent upon the influence of the country rock, or, in the case of lavas, of the atmosphere: (1) textural variation; (2) tension jointing (**195**); (3) vesicular and amygdaloidal structures; (4) flow structure; (5) chemical and mineralogical divergence from the normal or average composition of the eruptive as a whole; (6) schliers and segregations; and (7) inclusions (see page 132).

111. Marginal Texture.—Many igneous bodies are of coarser grain centrally than they are near their surfaces. This is explained by the fact that the molten rock after its eruption was chilled by its cooler surroundings, so that its crystallization was hindered (**107**). For the same reason lavas may be glassy above and more or less crystalline inside. These fine-grained marginal zones are spoken of as *chilled contacts* (Fig. 82).

It is worth while noting in this place that rock is a poor conductor of heat. Hence, in large intrusive bodies the chilled contact zone may not be very thick because, when once the country rock has been heated at the contact to a temperature near that of the magma, further loss of heat is exceedingly gradual, so that crystallization may proceed slowly in the unchilled portion of the magma. Lava flows, although rapidly frozen on the surface, may remain red hot and even liquid for a long time beneath a thin crust because this crust is a poor conductor.

Occasionally intruded masses are even-grained up to their contacts or they may actually be coarser near the margins. Even grain indicates that the conditions of the country rock were so near those of the intrusive that the inner and outer parts of the latter were affected almost alike. For example, the country rock may have been so warm, either because of its depth or because the magma flowed by it for a long time, that it did not chill the magma. A coarser marginal phase may often be attributed to the local activity, near the contacts, of volatile constituents derived either from the magma itself or from the country rock.

112. Vesicular and Amygdaloidal Structures.—Vesicular structure is characteristic of extrusive sheets, but it may sometimes be found in rocks which were injected under little pressure. The pores may be marginal or central or they may pervade the mass. In sheets of lava (Fig. 81) they are commonly near the upper surface toward which they may become more and more numerous until the rock is scoriaceous or pumiceous. Vesicles near the lower contact of a flow in many cases originated on the upper surface or at the front of the moving lava and were then rolled under (**204**).

Since amygdales are merely the fillings of vesicles, their forms and relations are the same as those of vesicles.

113. Discrimination Between Vesicular Structure and Weather Pits.—Little cavities left by the removal of the grains of a soluble mineral (**34**) may give to a rock the appearance of a vesicular lava. To discriminate between these weather pits and vesicles, break off a piece of the rock. A short distance in from the surface of the outcrop the weather pits will be seen to have the angular shape of the crystals which were leached out, and, farther in, the original crystals may still be present. Vesicles, on the other hand, will be rounded and empty.

An exception to this statement is the case in which vesicles have been filled with amygdales and the amygdales have been dissolved out by weathering near the outcrop surface. The broken fracture of the rock may show the remaining amygdales. It will then be necessary to apply the rules for distinguishing between amygdales and crystals (Art. **114**).

114. Discrimination Between Amygdaloidal and Porphyritic Structures.—Well-developed amygdales and phenocrysts should be easily distinguished, for amygdales are typically rounded mineral aggregates with concentric structure and phenocrysts are generally single grains with crystal edges and angles (Cf. Figs. 66, B, and 70). Sometimes, it is true, phenocrysts have had their corners and edges rounded by resorption (magmatic solution)(Fig. 66, C), so that some of them look more like amygdales, but the other criteria just mentioned should be sufficient for their discrimination.

115. Flow Structure.—Flow structure is apt to be very irregular and tortuous in lava, where it is best developed (Fig. 67), and it may be present throughout the entire thickness of the sheet. It may also be found in injected bodies, but here it is confined principally to the marginal zones, except in thin dikes and sills, and it is often parallel to the walls by which the movement of the magma was constrained (Fig. 84).

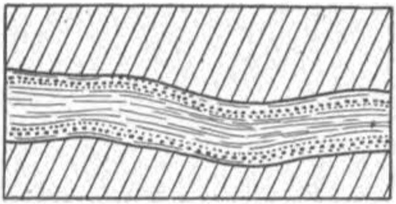


Fig. 84.—Section of part of a dike and its country rock, showing the relation between the contacts and the flow structure of the dike.

116. Marginal Variations in Composition.—Many eruptive bodies have a gradual change in composition toward their contacts in a way to suggest that the variation must owe its origin to some outside control. We can imagine two general methods by which a magma might be so affected, namely, either by solution and incorporation of some of the country rock, or by some internal process whereby certain mineral components might become separated from others and then segregated near the contacts or away from the contacts, as the case might be. The first and direct mode is *marginal assimilation;* the second, indirect way comes under the head of *differentiation.* Conceivably both might go on simultaneously. The products of assimilation are called *syntectics*, and those of differentiation are *differentiates.* Both processes, requiring high fluidity for their successful operation, might be expected to yield their most marked results in those intrusive bodies that consolidate least rapidly. Accordingly, we find that the best-developed contact zones of chemical or mineralogical variation are in the larger intrusive masses.

There has been much controversy about the relative efficiency of marginal assimilation and differentiation, and the problem is not yet solved.[1] Without entering into the discussion, we may briefly point out a few criteria for distinguishing between the results of the two processes. Theoretically, if marginal assimilation had occurred to any measurable extent, (1) contacts would have rounded, lobate embayments into the country rock, and other marks of corrosion; (2) there would be some correspondence between the composition of the igneous rock and that of the adjacent country rock; and, (3) the zone of chemical modification would have an increasing chemical similarity to the country rock toward the contact. For the case of magmatic differentiation, (1) there need be no evidences of corrosion at contacts; (2) the modified zone would have no special relation to the distribution of various types of country rock, and therefore, while maintaining its own general characters, it might have a much greater extent than the area of the contact surface of any one of the invaded types of country rock; and, (3) the modified zone and the adjacent country rock need have no chemical likeness.[2]

In geologic field work it is important to ascertain, first, whether there are marginal zones of chemical variation, and second, if such zones do exist, just what the nature of the variation is, whether it is in any way related to the country rock, and how it is related to the contact.

117. Schliers and Segregations.—Schliers and segregations are sometimes particularly numerous within a few score feet of the contact of large intrusive bodies. They are especially characteristic of the subjacent masses. Schliers are probably examples of

[1] Recently, N. L. Bowen (see Bibliog.) has published the results of definite laboratory experiments which lead to the conclusion that differentiation by the gravitative settling of crystals as they are formed is the most efficient method by which a magma may undergo local change in composition prior to its complete consolidation.

[2] For further details see Bibliog., Barrell, J., 1907; Daly, R. A., Chapters XI and XII.

interrupted differentiation, for in composition they are often similar to some of the main differentiated portions of the frozen magma. Segregations are apparently due to the separation of certain constituents from the magma and their crystallization about isolated objects, such as inclusions.

Contact Zone in the Country Rock

118. Contact Metamorphism.—Physical and chemical changes induced in rock material by the influence of magma or of lava may be accomplished by heating, by the infiltration of volatile and nonvolatile constituents of the magma, or, occasionally, by the pressure of intrusion. By chemical processes, discolora-

Fig. 85.—Section of an igneous contact between an intrusive rock (blank) and its stratified country rock (lined). The latter has been metamorphosed (stippling) in a wider zone on the left where the bedding is transverse to the contact.

tion, baking, and alteration in composition may be effected. Physical changes include tension jointing (195) and peripheral cleavage. The contact metamorphic zone (exomorphic zone) in which these features may be observed varies in thickness from a fraction of an inch to many hundred yards. It is usually thin adjacent to small intrusives and beneath flows. Its thickness and the extent of the alteration are roughly proportional to the size and temperature of the intrusive body, the duration of flow of the magma between the walls of a conduit, and the structure and composition of the country rock. For example, the roof above a batholith may be altered a long distance, sometimes a mile or more, from the main contact, because batholiths are large and they lose their heat slowly. Likewise the contact zone about a volcanic neck may be disproportionately thick if the outflow of lava continued for a long time. Conduction of heat and infiltration of escaped magmatic substances are more easy along, than across, parallel structures, and therefore the thickest portion of the altered zone in rocks having cleavage, bedding, etc., is apt to be where these structures are perpendicular to the contact (Fig. 85). Finally, when magma is intruded into a rock having a composition very different from its own, the metamorphism is likely to be more intense and of greater extent than when the compositions of intrusive and country rock are similar. That is why a sedimentary country rock may be more severely altered than one that is igneous.

The physical and chemical features named above are described in Arts. **119-122.**

119. Baking.—*Baking* refers to the hardening or toughening of rock material through the influence of magma or lava. Sometimes loose clays and sands are cemented just below a lava flow. Shale may become a very hard, flintlike rock, called hornstone, and quartz sandstone may become quartzite. Baking seems to be a process of cementation rather than compression. It may be due partly to the rearrangement and crystallization of substances already in the country rock, and partly to the infiltration and crystallization of some of the magmatic silica, etc. At exposed contacts in thinly and evenly banded shales, the banding may become obscure or fade away in the baked zone. Similarly, the cleavage of slates may gradually pass over into the irregular fracture of hornstone. Being comparatively resistant to erosion, these hardened contact zones may form ridges where the same rock, not baked, is a valley-maker.

120. Discoloration.—Discoloration may be caused by a change in mineralogical or chemical composition. Greenish, grayish, or yellowish rocks may be reddened by magma through the dehydration of limonite ($2Fe_2O_3\,3H_2O$), or the decarbonation and oxidation of ferrous carbonate ($FeCO_3$), and the formation of hematite (Fe_2O_3).

121. Mineralogical and Chemical Alterations.—Alterations more striking than baking or discoloration are common in the

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contact zones of invaded rocks. The changes are brought about largely through the agency of water vapor and gases, most of which have filtered in from the magma, but some of which may have been in the country rock prior to intrusion. Many of these changes come under the head of pneumatolysis. Even silica and other nonvolatile substances are believed to escape in solution from the magma, assisting in chemical reactions, cementing the rock particles, and forming veins in the open spaces (**218**). New minerals are formed by the crystallization of substances

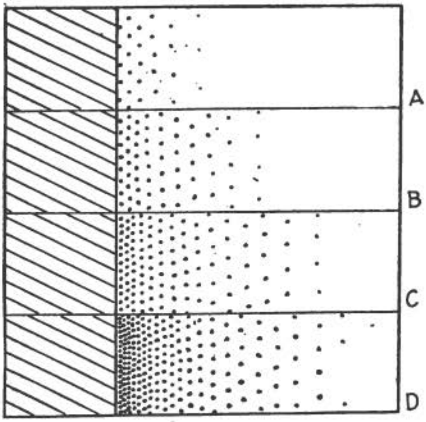


Fig. 86.—Degrees of contact metamorphism. The intrusive rock is diagonally ruled. A, B, C, and D represent successive stages of increasing contact metamorphism (stippling) in the country rock. The more intense metamorphism is indicated by the closer stippling.

derived from the magma, by the breaking down and recrystallization of the original minerals, and by the combining of new and old constituents. Quartz, mica, garnet, andalusite, staurolite, vesuvianite, and tourmaline, are a few of the common species that may be developed in this way. Clay rocks sometimes become spotted in the early stages of metamorphism, the spots or "knots" often being small aggregates of carbonaceous matter. Ordinarily the variety of the new minerals is greater if the original rock was impure, for then there are just so many more substances from which different combinations may be made.

It is important to note, with reference to contact zones showing chemical or mineralogical alteration, that greater changes are produced at high than at low temperatures and that, at different temperatures, the same chemical constituents may unite in different associations to make different minerals. From this it follows (1) that the country rock near the contact will pass through successive stages of increasing metamorphism as long as it is being heated and otherwise affected by the magmatic agents; (2) that ultimately a given type of country rock will be most altered near the contact and less and less so away from it; and, (3) that, other things being equal, the higher degrees of metamorphism existing close to the contact in broad altered zones will be wanting in narrow zones and that consequently a given degree of alteration may be expected nearer the igneous body in the narrower zones (see Fig. 86). As a rule the effects of heat and of the infiltration of the magmatic juices proper are found to have been distinctly antecedent to the effects produced through the invasion of the volatile constituents (pneumatolysis).

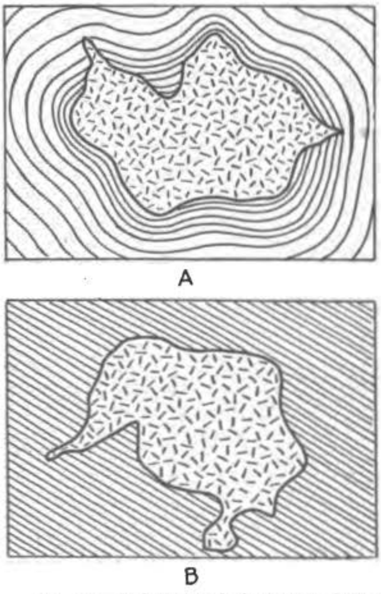


FIG. 87.—Relations of cleavage to intrusive contacts. The dash pattern represents the intrusive rock. In A the cleavage is essentially peripheral, probably because it was produced by the hydrostatic pressure of the magma. In B the cleavage was formed prior to the intrusion of the magma.

122. Cleavage.—As a result of eruption, cleavage is not common. It is generally a product of dynamic metamorphism, with no relation to intrusion, a fact which is demonstrated in numberless exposures where the cleavage is *cut across* by the intrusive bodies (Fig. 87). Where it is a consequence of the force of intrusion, it dies out away from the contact and its attitude is directly related to the igneous mass. It is then roughly parallel to the contact, thus showing that, by the hydrostatic pressure of the magma, the country rock was merely squeezed and not sheared. Cases of intersection of this peripheral cleavage by the contact are local and insignificant.

Inclusions

123. Cognate and Foreign Inclusions.—Inclusions have been defined as blocks of rock which were detached from the walls

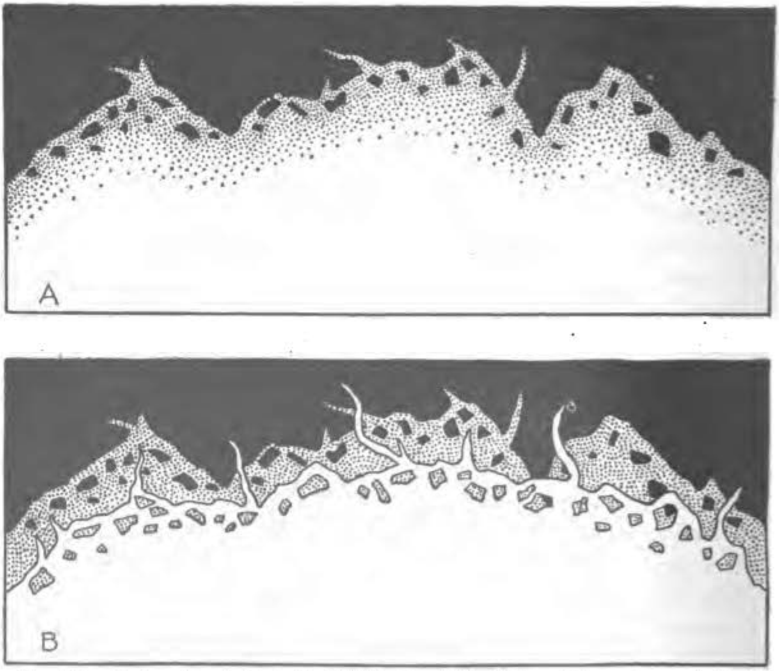


Fig. 88.—Section of part of a batholith (blank and stippled) and its country rock (black) in successive stages of consolidation of the former. In A the stippling represents the portion which, having already crystallized, formed an outer envelope surrounding the still molten interior (blank). By further movements the magma was injected into this envelope (B). Black inclusions are foreign; stippled inclusions are cognate.

of a magma chamber and were eventually frozen into the resulting igneous rock. It is necessary to point out that not all inclusions are of the rock originally invaded by a magma. While a large body of molten material is undergoing differentiation, its marginal parts are crystallizing, so that at length a stage is reached in which the body consists of an outer hardened shell covering a still molten residuum of different composition. Very

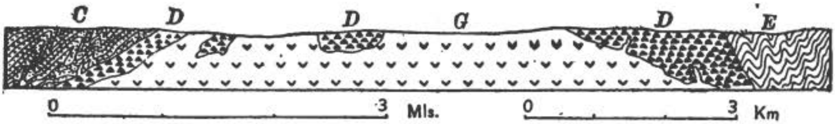


FIG. 89.—Section of part of a batholith and its country rock (*C* and *E*). The batholith consists of granite (*G*) with a basic border phase of diorite and gabbro (*D*). The diorite and gabbro appear to be older chilled phases of the batholith in which the granite later differentiated and into which the granite was intruded. (Penobscot Bay Folio, No. 149, U. S. G. S., 1907.) (Taken from R. A. Daly's "Igneous Rocks and Their Origin.")

often the outer, earlier differentiates are more basic than the inner ones. Now, if the residual magma for any cause is again disturbed and forced to intrude, it will have to invade its own external shell. Relatively acidic, light-colored dikes will penetrate this darker shell and blocks of the latter may be detached and immersed in the magma (Figs. 88, 89). Such blocks, having the same ultimate origin as the magma surrounding them, are called *cognate inclusions.* Inclusions of the country rock proper may be spoken of as *foreign.* Cognate inclusions are sometimes carried up in dikes, sills, etc., and foreign inclusions may be seen in all kinds of intrusive bodies, and even in flows; but both cognate and foreign xenoliths are most extensively developed in batholiths and large injected masses.

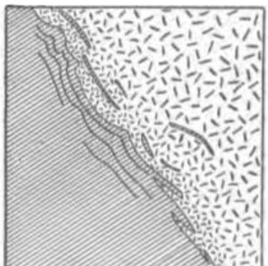


FIG. 90.—Section of a contact between granite (dash pattern) and slate (lined). Fragments of the slate, detached by contact exfoliation, were frozen into the granite as inclusions. (After T. N. Dale.)

124. Overhead Stoping and Intrusive Breccias.—With reference to the large intrusive bodies, the passive rifting of blocks from the walls of the chamber Daly terms *overhead stoping.* He ascribes it to a sort of exfoliation consequent upon the heating and expansion of the wall rock (Fig. 90), assisted by the invasion of dikes (Fig. 91) and sometimes by the movement of the magma. In general the detached blocks sink as long as the magma remains sufficiently fluid. As the viscosity increases this settling is impeded and finally checked, so that the inclusions which are rifted off just prior to consolidation can not move far from their sources. The consequence is that the big intrusive bodies may have an outer shell of *intrusive breccia,* in which inclusions, both cognate and foreign, are very abundant (Fig. 88), and this may pass into an adjacent surrounding cover of country rock ramified by numerous apophyses. If differentiation occurred and the magma was injected at intervals into its hardened portions, the contact zone of intrusive breccia might be very complicated in its nature.

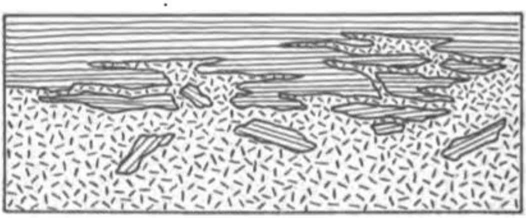


FIG. 91.—Section showing details of a contact between schist and an intruded igneous rock (dash pattern). The separation of inclusions is here due principally to the invasion of dikes. Observe the relation between the shapes of the inclusions and their schistosity. In which direction do the dikes appear to have penetrated with greatest facility?

125. Characters of Inclusions.—Seen in cross section on the surfaces of outcrops, inclusions appear as more or less irregular patches which may be sharply angular, subangular, well-rounded, lobate with embayments, or shredded (Figs. 92, 93). They may vary in size from a fraction of an inch to enormous blocks measuring several hundred feet in their visible dimensions. Their contacts may be clearly defined or blended for the same reasons that were mentioned in Art. **109**. Where sharp contacts and angular forms are common, marginal assimilation has probably played an insignificant part. Sometimes there is a complete and uniform transition from the surrounding igneous rock to the central, unaltered portion of the xenolith, as if the latter had been in process of absorption when freezing stopped further encroachment by the magma. Foreign inclusions may, of course, exhibit the same features, original or metamorphic, as the country rock. In them bedding, cleavage, etc., may still be preserved or, on the other hand, they may be baked, discolored, or mineral-

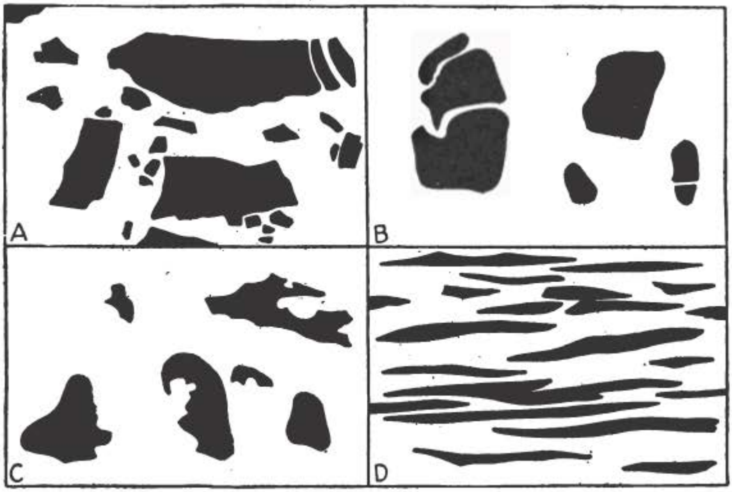


FIG. 92.—Shapes and distribution of inclusions (black) in an inclosing igneous matrix (white). A, angular inclusions. Some of the fragments may be seen to have fitted together. B, inclusions with rounded corners, suggestive of magmatic solution. The small inclusion at the extreme right was evidently broken so late that the corners of the fracture suffered no rounding. C, scalloped inclusions, the embayments of the eruptive rock being places where the magma dissolved its way into the inclusions. D, sliver-like inclusions in parallel position. The form is the result of an original well-defined parallel structure in the country rock. The orientation may be indicative of the direction of flow of the magma.

ized. Their contact zones are concentrically arranged, the more extreme changes being in the outer parts. Since small inclusions are apt to be more thoroughly altered than large ones, original structures should be looked for in the latter.

126. Source of Inclusions.—When inclusions in an eruptive are situated near country rock of the same kind, as seen on an outcrop surface (Fig. 94), their source is fairly obvious, although probably they were not carried directly across from the part of the contact (*b* in Fig. 94) at present exposed. They may have come up from some point on the wall (*bc*) that is now within the rock

FIG. 93.—A rock surface showing basic cognate inclusions in a more acidic matrix. Most of the contacts are irregular, suggesting that the magma was able to dissolve its way into the country rock; but the nearly straight matched contacts of the broad light dike on the left are clearly the result of fracture. They are of somewhat later origin than the irregular contacts (Cf. Fig. 92, B). (About ⅛ natural size.)

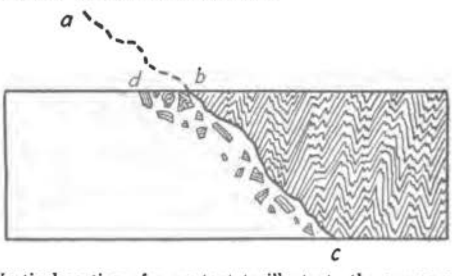


FIG. 94.—Vertical section of a contact to illustrate the source of inclusions.

mass, or they may have come down from a portion of the wall (*ab*) which has been eroded away, or they may have moved along the trend of the contact line. For the geologist they are of particular interest when no country rock remains in the vicinity or when the wall rock that does outcrop is of an entirely different nature. Under these circumstances it is likely, but not absolutely certain, that inclusions in dikes have risen and that those in batholiths, chonoliths, and laccoliths have sunk; in other words, that the parent rock in the first case is below the land surface and that, in the second, it has been removed through denudation. Xenoliths in a batholith which has been broadly uncovered may thus give one a notion of the character of the eroded roof.

127. Discrimination Between Inclusions and Segregations.—The distinction between inclusions and segregations is not always easy or possible. The following characters are generally typical of segregations: (1) relatively small size, often only a few inches across; (2) rather uniform size on outcrops a few square yards or rods in area; (3) oval or circular cross section; (4) concentric arrangement of the constituent minerals; (5) one or more minerals in common with the inclosing igneous rock. On the contrary, inclusions are more frequently of irregular shape and variable size. As pointed out in the preceding paragraph, the larger ones often retain original features. Hence, the true nature of small xenoliths that look like segregations may be determined by comparing their composition and structure with the composition and structure of the outer zones of the larger blocks whose derivation is certain. As for cognate inclusions, there is every gradation between them and segregations, for both are more or less directly related to differentiation.

128. Discrimination Between Large Inclusions and Roof Pendants.—In effecting the uncovering of a batholith, denudation isolates the roof pendants, if there were any such (Fig. 95). On a map they look like islands of country rock encircled by the intrusive rock, exactly the same relations, in fact, as are exhibited by xenoliths in ground plan. Outcrops of country rock in an area which is certainly inclosed by the eruptive rock may belong, then, either to a large inclusion or to a truncated roof pendant. There are some geologists who assert that it is impossible to tell the difference between the two. However, if several of these isolated exposures of country rock are found, and in all of them structures like bedding, cleavage, etc., have a parallel or otherwise orderly arrangement of strikes, they are probably roof pendants. In the case of xenoliths, even when they are very near one another, such structures are apt to have diverse directions and no apparent relations, for blocks of country rock that have been detached from the walls of a magma chamber are free to change their positions.

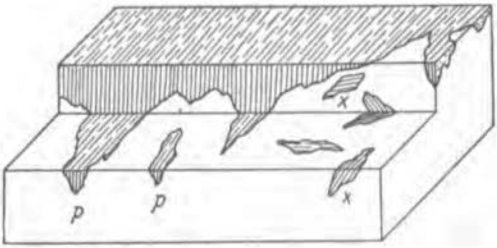


FIG. 95.—Block diagram of a batholith (white) and its country rock (lined) in successive stages of erosion. At the lower level (front of block) one of the roof pendants (*p*) has been isolated and so looks like a xenolith. Compare the orientation of roof pendants and xenoliths (*x*).

129. Discrimination Between Inclusions and Erosion Patches.—Small patches of rock left on a contact that has been laid bare by erosion are sometimes mistaken for true inclusions. These are described in Art. **137.**

Another erosion phenomenon which beginners too often confuse with inclusions is an effect of unequal weathering of igneous rocks. Exfoliation, it will be remembered, is a process by which the outer surface of an outcrop spalls or peels off in thin plates. If these spalls come off unequally, first in one place and then in another, the rock acquires a patchy look for each slab that peels off leaves a scar that has a color somewhat different from the older surrounding surface. It is these scars that are sometimes taken for inclusions. They are especially common in glaciated regions which have been abandoned by the ice long enough for exfoliation to start on the smooth and polished surfaces. They may be distinguished by these characters: (1) often there are all gradations between the color of the latest scar and that of the original surface, for the spalls come off at different times, and with age the scars fade and so grow more and more like the old surface; (2) search may reveal some chips that have nearly come off and others which have separated so recently that they still lie loose on their own scars; (3) if it is possible to break the rock at the edge of a scar, the fresh fracture will be of uniform color both under the scar and under the old surrounding surface. Familiarity with rocks and minerals under various conditions of weathering is the best guide.

Field Interpretation and Classification of Eruptive Bodies

130. Shape of Eruptive Bodies.—Both extrusive and intrusive modes of occurrence may be discussed in this connection. Volcanic ash cones owe their slopes to the angle of repose of the pyroclastic débris of which they are composed (**227**). It may reach 40°. The form of a mass of lava depends in part upon the topography and in part upon the viscosity of the molten rock. Mobile flows spread far and are relatively thin as contrasted with those which are viscous. A cone built of lava poured from a central vent may have an inclination of less than 10°. From this extreme there are all gradations to the type of ejection known as a "spine," a column of lava so rigid that it does not flow at all.

As regards intrusive bodies, their shapes are governed (1) by the viscosity of the magma, (2) by the structure of the country rock, (3) by the weight of the overburden, and (4) by the manner of intrusion. Thinness, coupled with relatively great extent in the other two dimensions (*e.g.*, many dikes, sills, etc.), implies rapid injection and a highly mobile magma, especially if the country rock appears to have been cool (**108, 109**) when it was invaded. A sticky magma would move sluggishly, and slow intrusion would soon be brought to a stop by chilling. Where the country rock was nearly as warm as the magma, thin sheets do not necessarily prove rapid injection. That the country rock was warm and plastic enough to be deformed by the force of intrusion is suggested by the pinch-and-swell form of many pegmatite dikes in schists (Fig. 96), by the local bending of the schist folia against such pegmatite dikes (Fig. 97), and by other phenomena.

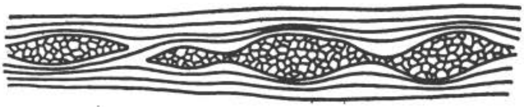


FIG. 96.—Pinch-and-swell form of a pegmatite dike in schist.

The effect of greater viscosity on concordant injection is exemplified in the typical laccolith (Fig. 72), the domical roof of which indicates that the magma, being too sticky to slip in rapidly and far between the beds, heaved them up and arched them by the force of its hydrostatic pressure. Many observed laccoliths are not quite typical, for minor irregularities in the roof and the presence of some inclusions in the igneous rock prove that the act of intrusion was not wholly a process of lifting and wedging, but was assisted by the disruption of blocks from the walls of the chamber. In batholiths this disruptive process (overhead stoping) seems to have predominated as is indicated by the marked irregularity of the contact as a whole, frequently by the abundance of xenoliths, and by the usual total lack of correspondence between the attitude of the contact and the attitude of bedding in the roof rock. Nevertheless, while the shape of the batholith must unquestionably be ascribed in large part to the separation of inclusions, it does not preclude the possiblity that the roof was to some extent uplifted.

FIG. 97.—Section of a pegmatite dike cutting the foliation of a schistose rock.

131. General Summary with Reference to the Interpretation of Contact Phenomena.—For ease of reference we may classify here the principal facts presented in the foregoing paragraphs. *Place of intrusion* within the lithosphere, *i.e.*, whether in the zone of fracture or in the zone of flowage, is indicated by shape of contact, sharpness of contact, marginal textures, tension jointing, and shape of the intrusive body. *Manner of eruption* is indicated by shape and sharpness of contacts, presence of inclusions characters of inclusions, and shape of the eruptive body. Evidences for *kind and amount of assimilation* may be found in shape and sharpness of contacts, marginal variations in the composition of the intrusive rock, shape of intrusive body, and characters of inclusions. Evidences for *differentiation* appear in schliers, segregations, and cognate inclusions, and in marginal variations in composition of the intrusive body. *Rate of injection, rate of flow,* and *viscosity of magma and lava* are indicated by the shape of the eruptive masses. *Conditions of the country rock at the time of intrusion* are suggested by shape and sharpness of contacts, marginal textures of the intrusive, characters of inclusions, kind and degree of contact metamorphism, and shape of the intrusive body.

132. Field Recognition of Eruptive Bodies.—The recognition of modes of occurrence of igneous rocks in the field depends upon a thorough understanding of the definitions given in Art. **104.** It is well also to have a notion of the sizes which are characteristic of eruptive bodies (**105**). Bear in mind that sills are essentially parallel to the bedding of their country rocks; that chonoliths and laccoliths, as distinguished from batholiths, have basal contacts; and that the difference between a sill and a laccolith is principally one of the relations between thickness and lateral extent. There can be no such thing as a sill in a country rock which is not stratiform. For chonoliths, laccoliths, and batholiths, extensive field correlation is necessary because of the great size of these bodies.

Probably the most troublesome problem is the distinction between a sill and a flow which has been buried under later strata, now consolidated. (1) A flow is often vesicular or scoriaceous in its upper portion and may have pores and brecciated structure near its base. On the contrary, a sill is usually free from visible pores; but there are sometimes numerous short apophyses extending into the superjacent strata, and these, when viewed in cross section, may make the upper surface of the sill look as if it were a scoriaceous lava. If longer apophyses can be found, they are among the safest criteria for intrusion. (2) The cavities and depressions of a buried lava flow are generally filled with sediments that have their bedding

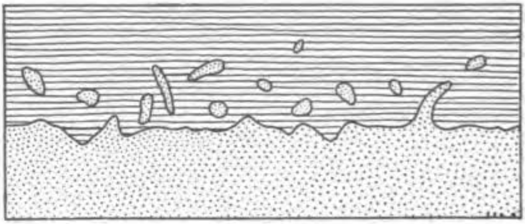


FIG. 98.—Section of the upper contact between a sill (stippled) and its country rock of slate (lined), showing short roof apophyses which are pipe-like in form. The roundish patches of the sill rock in the slate are sections of these "pipes." (Section about 3 feet long.)

lamination parallel to the main stratification above. If a sill has many short roof apophyses, the intervening downward projections of the country rock are apt to show more or less contortion. (3) A flow may rest upon beds of volcanic ash or other volcanic débris; yet it is not to be forgotten that sills, too, may be injected into pyroclastic materials. (4) Flows are not uncommonly overlain by sediments that contain angular blocks or water-worn pebbles of the lava. Eroded fragments of a sill can not be present in the superjacent beds which were invaded by the sill. These overlying beds may seem to contain pieces of the sill rock if the magma was injected upward as a network of ramifying pipes (Fig. 98). Careful study of this case would show that the seeming fragments of sill rock have chilled margins and that the inclosing rock has a metamorphic aureole round each "fragment." (5) Inclusions of the superjacent beds may be found in sills, but never in flows. (6) The effects of contact metamorphism may be present in the roof strata of a sill, but not in the beds above a flow, provided there is no other outside influence by which such alteration might have been induced.

Eruptive Bodies in Relation to their Time of Origin

133. Relative Age.—The age of an igneous rock is dated from the time when it was intruded, or extruded, and was brought into fixed relations with the adjacent older rocks. Thus, every intrusive body is younger than its country rock and every lava flow is younger than the underlying rocks and, if buried, older

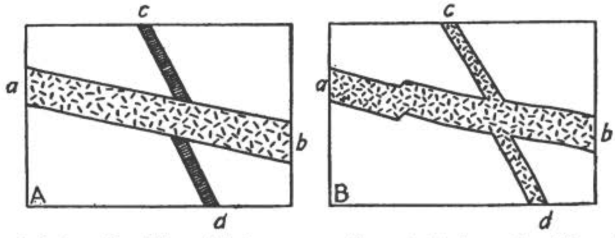


Fig. 99.—A, intersecting dikes, *ab* being younger than *cd*. B, branching dikes, *ab* and *cd* being of the same age. How is the apparent displacement in A to be explained?

than the superjacent materials. In field work an important duty of the geologist is to determine the relative ages of the igneous rocks. This may be done in several ways. If, for instance, there are two kinds of dikes, outcrops should be searched until a place is found where one of these dikes cuts across the other (Fig. 99, A). Sometimes two or three periods of injection by the same type of rock may be demonstrated. Branching dikes must not be confused with intersecting dikes (Fig. 99, B). Where but one contact between two igneous rocks is exposed, the younger rock is apt to be progressively finer toward the contact (**111**). Even if the boundary line is concealed, the relations may occasionally be ascertained by discovering inclusions of one rock in the other, for inclusions are always older than the inclosing matrix.

As regards batholiths and other large intrusive masses, there is probably a long time interval between the consolidation of the outer portions and the freezing of the final residuum. Consequently, in point of crystallization, not only are cognate xenoliths distinctly older than the surrounding rock, but also certain cognate inclusions may be older or younger than others in the same body. Within a given intrusive mass cognate inclusions are younger than foreign inclusions.

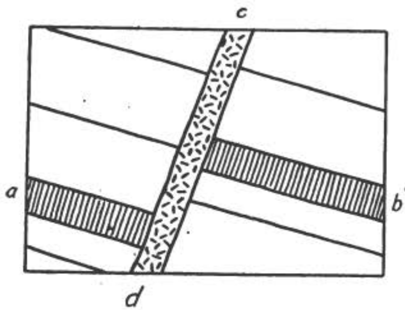


FIG. 100.—Section of a dike, *cd*, which has entered a fault. The fault intersects a series of strata containing a sill (*ab*).

The age of an igneous body with reference to joints, faults, folds, and other structures, should likewise be noted. Straight and blocky contacts, particularly if they correspond to existing joints in the country rock, imply a fracture system antedating intrusion. Tension joints, due to contact effects (**195**), are clearly subsequent to the eruptive body that led to their origin.

A fault which intersects and displaces an igneous mass is younger than the latter (Fig. 100). A fault that is essentially coincident with a contact may be older or younger than the intrusive. Thus, a region may be dislocated and then invaded by magma along the faults (Fig. 100); or slipping may take place along the contact surface of an eruptive body. In the former case the contact and the fault would be one and the same surface, except perhaps where apophyses had branched into the fault blocks; whereas, if dislocation followed intrusion, places could surely be found where the fault and the contact were not coincident, and any apophyses would be intersected by the fault. On the earth's surface, lava flows and ash cones are sometimes aligned in such a way as to suggest that the magma ascended along a fault. The case may be proved by finding topographic evidences of displacement along the general trend of the volcanic vents (see Chapter VIII).

There are many reasons for believing that intrusion of large magmatic bodies and deformation of their country rocks are more or less synchronous. By definition, the updoming of the roof of a laccolith is accomplished by the invading magma. Batholithic intrusion seems often to have closely followed, or even accompanied, large scale deformation. These phenomena are regarded as parallel effects of the same cause.

134. Geologic Age.—Since igneous rocks do not hold fossils their geologic ages must be fixed by correlating them with sedimentary rocks whose age is known. Flows and pyroclastics

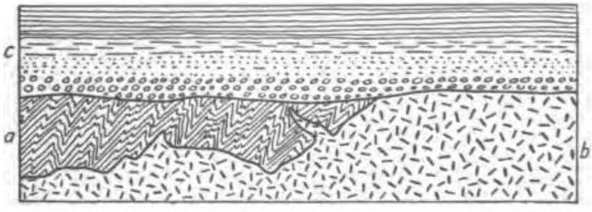


FIG. 101.—Section of part of a batholith, *b*, and its country rock, *a*, both of which were eroded and overlain by later strata, *c*.

are of the same geologic age as the sedimentary rocks with which they are interstratified. For intrusives, the following example may suffice to illustrate the method of correlation. In Fig. 101, *b* is intrusive into *a* and pebbles of *a* and *b* are found in *c*. Fossils show that *a* is Cambro-Ordovician and *c* is Devonian. Hence the age of *b* is between Ordovician and Devonian.

ERUPTIVE BODIES IN RELATION TO THE LAND SURFACE

135. Significance of the Exposure of Intrusive Rocks.—The presence of intrusive rocks upon the earth's surface is evidence of the work accomplished by erosion. Sometimes a thick covering has been removed and sometimes a thin one, for magma, in its eruption, reaches various levels within the lithosphere.

10

Most striking is the case of batholiths. In these bodies the magma probably does not rise to within several hundred or even several thousand feet of the surface except, perhaps, in rare instances (**104**), so that where subjacent masses are exposed, a thick cover of country rock has, little by little, been worn away and the débris has been laid down elsewhere in some area of deposition.

136. Topographic Expression of Igneous Bodies.—Exposed intrusive bodies are so often more resistant than the inclosing country rocks that usually they have a more pronounced relief.

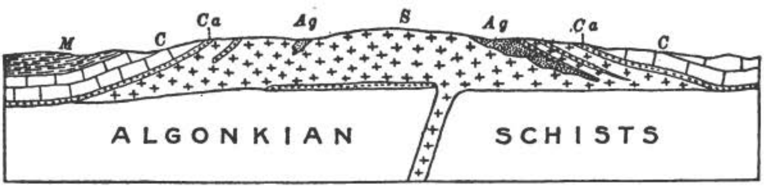


Fig. 102.—Section of an interformational laccolith, Bear Lodge Mts., Wyoming. *S*, syenite porphyry; *M*, Lower Mesozoic; *C*, Carboniferous; *Ca*, Cambrian; *Ag*, "Algonkian?" granite. Scale, 1:105000. (Sundance Folio, No. 127, U. S. G. S., 1905.)

The higher central parts of many mountain ranges consist of batholithic rocks. Unroofed laccoliths may form groups of hills that rise above the surrounding country (Fig. 102). The smaller injected bodies, such as necks, dikes, and sills, are generally more resistant or less resistant than the country rock, and, correspondingly, they may have positive or negative topographic relief (**226**) (Fig. 103). Horizontal or gently inclined sills and flows are sometimes the protective layers surmounting mesas and cuestas (**258**).

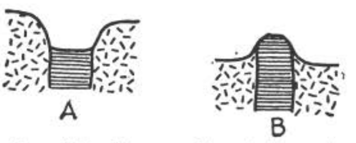


Fig. 103.—Topographic relations of a dike and its country rock. *A*, dike less resistant than country rock. B, dike more resistant than country rock.

137. Relations of Contacts to Erosion.[1]—The student who has arrived at the stage at which he undertakes his own geologic

[1] See also Art. **298**.

surveying will be disappointed to find how often important contacts—usually those he most wishes to map—are quite hidden beneath the soil. The reason is obvious. The agents of erosion, obtaining more easy access along these surfaces, wear the rocks down more rapidly, and the depressions then become floored over with débris. In this way a valley may have its position fixed along a single contact (**250, B**). In other cases, where a weak rock lies between resistant materials, the former may be worn away, and the valley (or gulley) will have its walls situated somewhere near the contacts (Fig. 103, A).

If the rock on one side of a contact is much less resistant to erosion than that on the other side, the weaker rock, whether

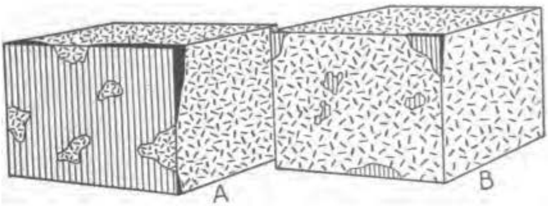


Fig. 104.—The diagram shows an uneven contact between an igneous rock (dash pattern) and its country rock (lined on front face; black on top and side faces). The front face of each block is assumed to be a surface produced by erosion. In A the remaining layer of the country rock has been perforated, and in B, a somewhat later stage, only a few patches of the country rock are left.

intrusive or country rock, may be worn away to such an extent that the outcrop surface practically coincides with the contact. At a certain stage in the erosion, when this coincidence has been all but accomplished, the more resistant rock will be exposed only in small areas where a thin remaining cover of the weaker material has been perforated (Fig. 104, A). A little later the weak rock will be removed except for a few scattered patches (Figs. 104, B; 105). The perforated spots in the earlier stage and the patches in the later stage are very easily mistaken for inclusions.

To determine whether patches on the surface of an igneous rock are truly inclusions or not, look over the whole outcrop and see whether they are distributed on all sides. Erosion patches are limited to those rock surfaces that correspond to contacts. In the earlier stage, above mentioned, the perforation spots can often be enlarged by splitting off some of the layer of weaker rock, and in the later stage the patches themselves can be broken off with a hammer. This weaker rock may be found in place in

FIG. 105.—Patches of a trap dike (dark gray) still attached to its country rock. Here the dike was the weaker rock. (Cf. Fig. 104.) The largest patch is about 15 inches long.

greater amount just beneath the soil at the foot of the outcrop or along the strike of the contact surface on other ledges in the vicinity.

On a much larger scale, the exposure of intrusive bodies presents some interesting problems. Consider, for instance, a batholith with an irregular roof. At first all the bedrock in the region is the normal country rock (Fig. 106, A). As denudation proceeds, the land surface at length reaches what we may call

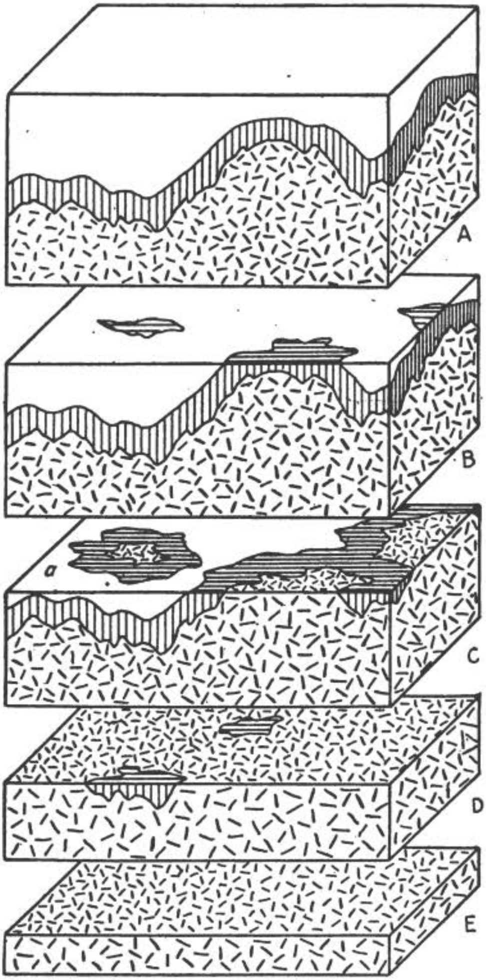


Fig. 106.—Successive stages in the exposure of a batholith through erosion. Batholith, dash pattern; country rock, blank where unmetamorphosed, ruled where metamorphosed. *a* is a stock (cupola) surrounded by the metamorphosed country rock.

stage 2. In this stage, although the bedrock is still entirely the roof rock of the batholith, there are a few closed areas in which evidences of contact metamorphism may be recognized. These are the places where cupolas will soon be uncovered (Fig. 106, B). In the third stage several cupolas (stocks) are exposed, each being rimmed by a collar of the metamorphosed country rock (Fig. 106, C, *a*). There may be closed tracts of metamorphosed country rock which cap the shorter cupolas. The outcrop areas of the cupolas grow larger and coalesce, as erosion goes on, so that, in the fourth stage, the bedrock of the region consists principally of the intrusive, with here and there isolated tracts of country rock which are, in reality, truncated roof pendants (Fig. 106, D). In the fifth and last stage the land surface is entirely on the batholithic igneous rock (Fig. 106, E).

FIG. 107.—Section of part of a batholith (dash pattern) and its country rock (black). Much of the country rock has been stripped off by erosion, so that the land surface in many places essentially coincides with the roof contact. The valleys have been incised below the contact well into the batholithic mass. (The section is about 8 miles long.)

Possibly there are some regions where the roof contact of a batholith or of a flat-lying intrusive mass (sill, laccolith, etc.) has become the land surface over several square miles. The weaker superjacent country rock has been stripped off except for a few scattered remnants, and the resistant eruptive rock has been only locally incised by streams (Fig. 107). The evidences for this broad scale coincidence of erosion surface and contact include, (1) extensive distribution of like contact phenomena on the outcrops of the eruptive; (2) marked decrease in the variety and intensity of contact phenomena downward in those valleys which cut well into the intrusive body; (3) the isolated remnants of country rock, just referred to, especially if these are clearly sessile upon the eruptive; (4) accumulations of débris of the country rock on the summits of hills and ridges now consisting entirely of the intrusive rock; (5) similarity in shape and other characters between the general configuration of the topography and visible contacts beneath the remnants of the country rock.

138. Relations of Contact Zones to Topography.—The breadth of an exposed contact zone is seldom equal to the thickness of

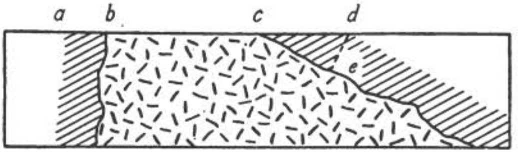


FIG. 108.—Section of an intrusive body and its country rock. The thickness of the contact metamorphosed zone (shaded) of the country rock is the same on both sides of the intrusive mass (*ab* and *de*). The breadth of exposure of this zone is greater the lower the inclination of the contact (*ab* and *cd*).

the zone, because the land surface is usually inclined to contacts at an angle less than 90° (see Fig. 108). Instances of this

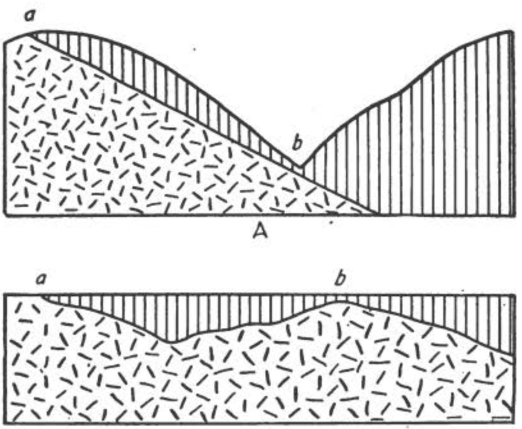


FIG. 109.—Relations of the land surface to the degree of contact metamorphism. Intrusive rock, dash pattern; country rock, ruled. In each case, A and B, the degree of contact metamorphism grows less in going from *a* toward *b*, and then increases again, reaching a maximum at *b*. The explanation is obvious.

kind should not be confused with cases like that illustrated in Fig. 85. Fig. 109 shows two explanations for an observed increase in the degree of contact metamorphism without apparent cause.

139. Effects of Topography on the Shapes of Outcropping Dikes, Sills, and Contacts.—The influence of topography upon the form of outcrop surfaces and layers is most conveniently treated with reference to stratified rocks. Consequently the subject is reserved for Art. **159.** The student has only to remember that, when dikes and sills are of comparatively uniform thickness, their exposed edges are related to the land surface in exactly the same manner as are the exposed edges of strata, and that the same comparison may be made concerning regular igneous contacts and surfaces of conformity in sediments.

CHAPTER VII

FOLDS

DEFORMATION OF ROCKS

140. Fracture and Flowage.—Since the time of their origin many rocks have been more or less disturbed by forces acting within the lithosphere. On a broad scale, the movements which bring about slow changes of sea level (**266**) demonstrate the operation of these forces; but more striking evidence is furnished by the joints, cleavage, and folds that are so often seen in consolidated rocks. The deformation represented by these and other allied structures may be brought about through fracture or flowage. By flowage is meant a gradual change in the form and internal structure of a rock mass accomplished by chemical readjustment and by microscopic fracture while the rock remains essentially rigid. There is no igneous fusion during the process. The rock does not become molten. Under very great pressure and temperature, such as exist deep below the earth's surface, all rocks yield to stress by flowage rather than by fracture. High temperature and pressure, the presence of moisture, and the nature of the rock itself, are factors influencing this flowage. Nearer the surface rocks are more apt to break; but some rocks may flow even at depths of only a few hundred feet. For any rock subjected to differential pressure we have, then, a *zone of flowage* below and an enveloping shell or *zone of fracture* above. The maximum depth of the zone of fracture for rocks least capable of flowage is placed at about 11 miles.[1] Below that depth all rocks flow if deformed. However, when we speak in terms of all rocks, the outer 11-mile shell of the lithosphere becomes almost entirely a *zone of combined flowage and fracture*,

[1] Bibliog., ADAMS, F. D.

because different rocks vary so much in their susceptibility to flowage when under stress.

Structures produced in the zone of fracture are joints, faults, brecciation, autoclastic structures, fracture cleavage, etc. (see Chapter VIII). In the zone of flowage originate flow cleavage, schistosity, gneissic structure, etc. (see Chapter IX). Folds may result from either fracture or flowage, and very often they are the product of both processes combined.

Terminology and Classification

141. Principal Kinds of Folds.—All folds are variations of three principal types, the syncline, the anticline, and the monocline.

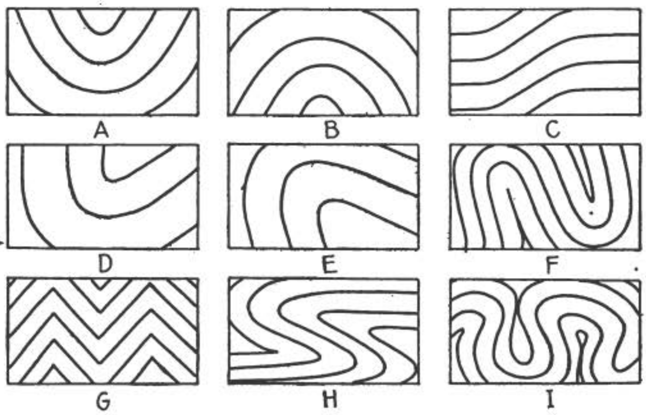


Fig. 110.—Types of folds. A, symmetrical syncline; B, symmetrical anticline; C, monocline; D, asymmetrical syncline; E, asymmetrical anticline; F, isoclinal anticline and syncline; G, chevron folds, H, recumbent folds; I, fan folds.

As seen in cross section the *syncline* is a downfold opening upward (Fig. 110, A), the *anticline* is an upfold, opening downward (Fig. 110, B), and the *monocline* is merely a simple flexure in otherwise horizontal or gently inclined beds (Fig. 110, C).

142. Terms of General Application.—Folds are bodies of three dimensions, that is, they have height, breadth, and length, a fact which is too easily forgotten because they are usually represented

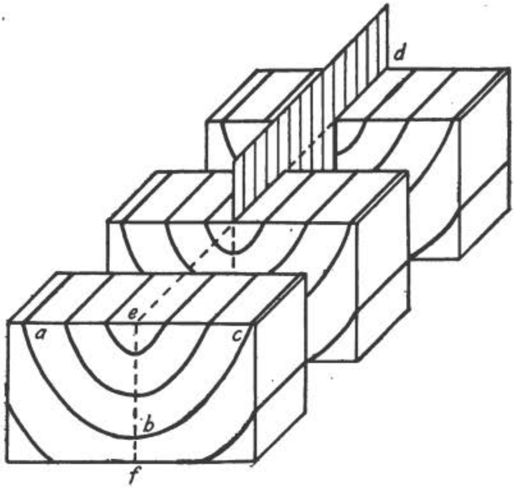


FIG. 111.—Symmetrical syncline shown in three blocks. *ab* and *cb*, limbs; *de*, axis; *def*, axial plane.

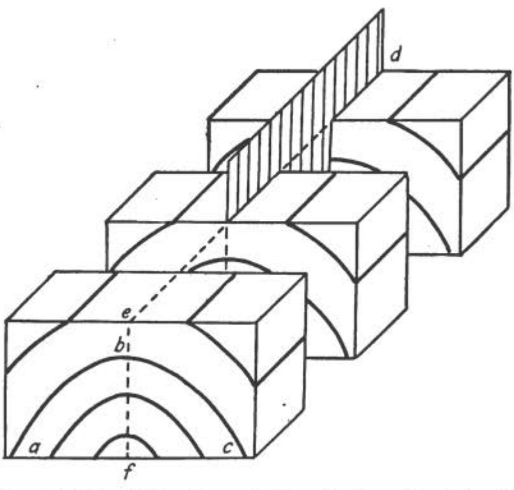


FIG. 112.—Symmetrical anticline shown in three blocks. *ab* and *bc*, limbs; *de*, axis; *def*, axial plane.

in plane cross sections. Figs. 111 and 112 show the directions of the three dimensions of the folds of which only the height and breadth are indicated in A and B, Fig. 110. The crest line of an anticline and the trough line of a syncline are called the *axes* of these folds, respectively (Figs. 111 and 112, *ed*). The plane which passes through a fold axis and roughly bisects the fold is the *axial plane* (Figs. 111 and 112, *def*). On either side of it are the "sides" or *limbs* of the fold (Figs. 111 and 112, *ab* and *cb*). In complicated structure the folds may be so bent that their axial planes are warped.

143. Varieties of Folds.—Anticlines and synclines may be simple, composite, or complex. A fold is *simple* when its curve

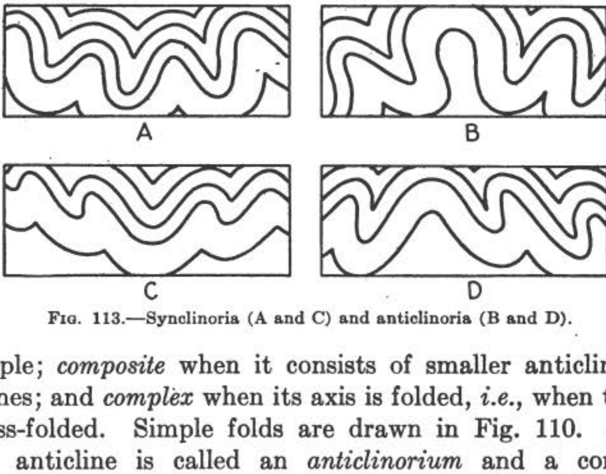


FIG. 113.—Synclinoria (A and C) and anticlinoria (B and D).

is simple; *composite* when it consists of smaller anticlines and synclines; and *complex* when its axis is folded, *i.e.*, when the fold is cross-folded. Simple folds are drawn in Fig. 110. A composite anticline is called an *anticlinorium* and a composite syncline, a *synclinorium* (plurals, anticlinoria, synclinoria) (Fig. 113). Whenever a set of small folds is superposed upon a group of larger folds, the former are called *minor* and the latter *major*. All major folds are composite. If the axial planes of the minor folds converge downward in an anticlinorium or upward in a synclinorium, the major fold is called *normal* (Fig. 113, A and B); if the opposite is true, the anticlinorium and the synclinorium are *abnormal* (Fig. 113, C and D).[1]

[1] Bibliog., VAN HISE, C. R., 1896, pp. 608–612.

Types of complex folds are the dome fold and the basin fold. A *dome fold* is anticlinal in two vertical sections at right angles

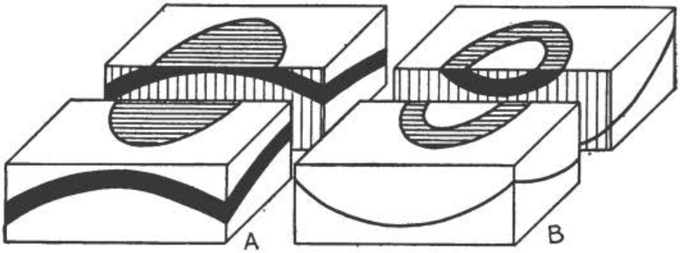


Fig. 114.—A, dome fold; B, basin fold.

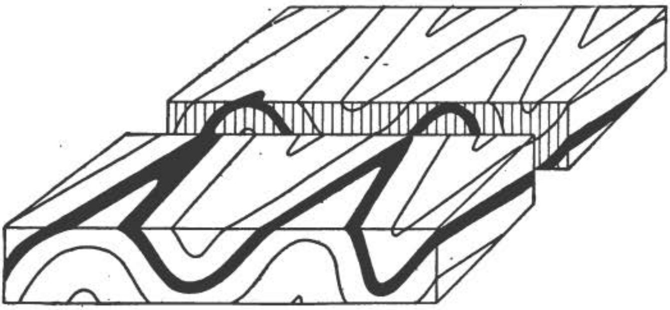


Fig. 115.—Anticlinal and synclinal canoe folds, represented in part. The axes of the folds are inclined downward (pitch) toward the background.

Fig. 116.—A complex fold which is synclinal in one section and anticlinal in the perpendicular section.

to one another, and a *basin fold* is similarly synclinal (Fig. 114). If the folding is much closer, *i.e.*, if the compression has been much more intense in one direction than at right angles to this direction, the basin fold becomes a *canoe fold* and the dome fold becomes what may be called an *inverted canoe fold*, or a *ridge fold*

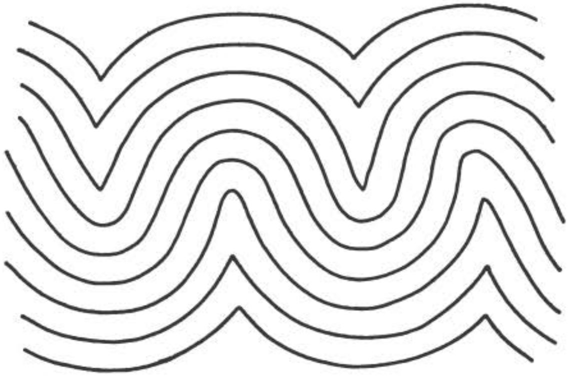


Fig. 117.—Parallel folding.

(Fig. 115). Sometimes a fold which is anticlinal in one section may be synclinal in the perpendicular section (Fig. 116).

Folding may be parallel or similar. In *parallel folds* each bed is of approximately uniform thickness throughout its course in

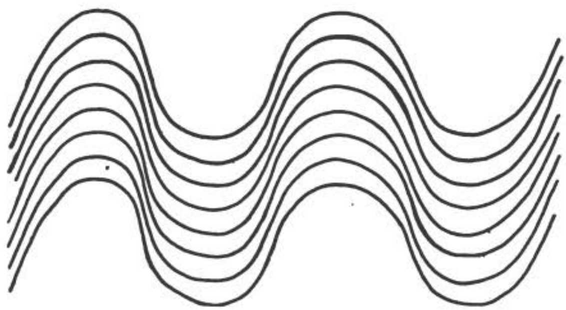


Fig. 118.—Similar folding.

both anticlines and synclines (Fig. 117). The effect of this relation is that the bedding surfaces are not of the same shape. Both upward and downward folds die out. On the other hand, in *similar folds* the bedding surfaces are of similar shape and the beds vary in thickness (Fig. 118). Their limbs are thinned and their axial regions are thickened. Such folds may be persistent upward and downward through a thickness of rock which is very great as compared with the amplitude of the contortions of any one bed. Deformation in parallel folding is accomplished by adjustment between the beds, and in similar folding, by adjustment within the beds. In both cases the movement is differential. In parallel folding this movement is such that a given bed slides upward against the next underlying bed toward anticlinal axes (Fig. 119). Adjustment within beds is effected principally by rock flowage. It requires more energy than the shearing of strata one upon another. Hence we find

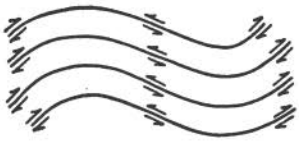


FIG. 119.—Diagram illustrating the differential movement between adjacent beds in parallel folding.

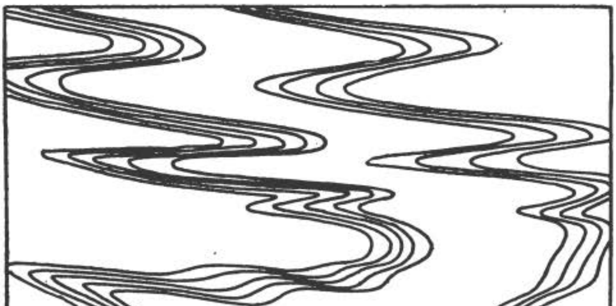


FIG. 120.—Sketch of contorted laminæ in a specimen of mica schist. (Length of figure about one foot.)

that similar folds are characteristic of the zone of flowage, whereas parallel folds are characteristic of the zone of fracture. Similar folding is common in metamorphic rocks having flow cleavage (Fig. 120). The field classification of folds may be aided by the facts enumerated in Arts. **344** and **345.**

144. Size of Folds.—Folds range in breadth from very minute contortions, seen only by the aid of a microscope, to great arches and troughs many miles from axis to axis. Diminutive folds, naturally limited to fine-grained rocks, are always subordinate in that they are superposed upon larger folds. They may form low, subparallel ribs and furrows on the cleavage surface of a rock, and they are then termed *crenulations*.

145. Competent or Controlling Beds.—The unequal susceptibility of different rocks to deformation by flowage seems to indicate that if a sufficient force were applied laterally (parallel to the beds) to a formation consisting of layers of varying resistance, the individual beds would be affected in different ways; and, as a matter of fact, this is actually the case. In a series of this kind a strong stratum, if arched up, may tend to support the overlying beds and thus lessen the vertical pressure on the rocks below it. "Willis' experiments on the mechanics of Appalachian structure[1] showed that the thicker, more competent wax layers rise in simple outline under given conditions of pressure and load until they are unable to lift the load farther. Then they crumple and, in crumpling, thicken, enabling them to lift the load higher. Thus composite folds are really indications of incompetence. Simple folds are more characteristic of the zone fracture; the bed is able to lift itself without interior adjustment, and without crumpling; it is competent."[2] As Leith and others have pointed out, this term, "competence," is one of relative value only. One rock may be competent with respect to a second and incompetent with respect to a third.

When a series of strata is subjected to lateral pressure, there is at first a tendency for the formation of parallel folds. This, as we have seen, means slipping between the beds. If the strata are of different degrees of resistance and the conditions are such that the strong layers are in their zone of fracture while the weak beds are in their zone of flowage, the readjustment by slipping may be concentrated in the weaker, incompetent layers.

[1] Bibliog., Willis, B., pp. 241–253.

[2] Bibliog., Leith, C. K., 1913, pp. 111–112.

The series will then be folded after the parallel pattern, being

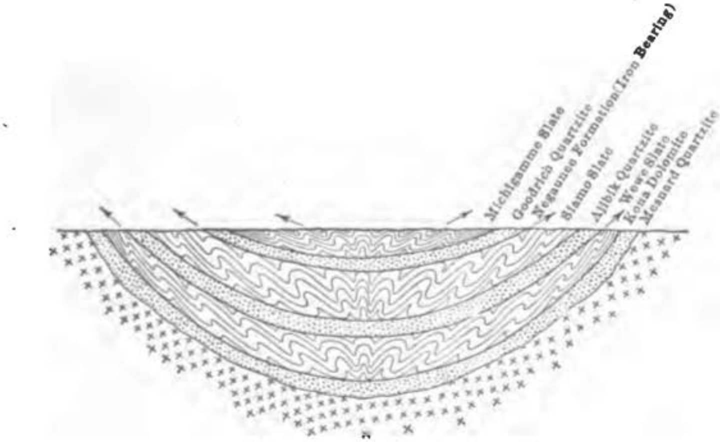


Fig. 121.—Diagrammatic section showing differential movement between competent beds on the limbs of a fold with the development of minor drag folds between them. (After C. K. Leith.)

controlled as a whole by the competent strata; but the incompetent beds will bear evidence of flowage either in flow cleavage or in minor folds of the similar type. Minor folds of this origin are primarily the result of the differential movement or "drag" between the competent strata, and they have therefore received the name of *drag folds* (**150**). Since, in the differential movement between strata, a given bed slips over the subjacent layer in a direction toward the nearest anticlinal axis, the drag folds are overturned in this direction and their axial planes generally converge downward

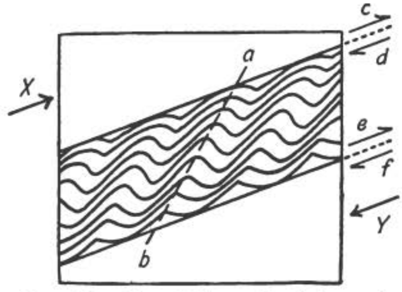


Fig. 122.—Drag folds produced in an incompetent bed between two competent strata (Cf. Fig. 121). The differential motion at the bedding contacts is indicated by the arrows *c*, *d*, *e*, and *f*. *X* and *Y* show the relative differential movement of the two competent beds. *ab* is a section of the axial plane of one of the drag folds. An anticline is to the right of the figure and a syncline is to the left.

in the major synclines and upward in the major anticlines (Fig. 121). Perhaps a more convenient way of stating the same fact is this: the axial planes of the drag folds are inclined with the direction of differential movement (Fig. 122).

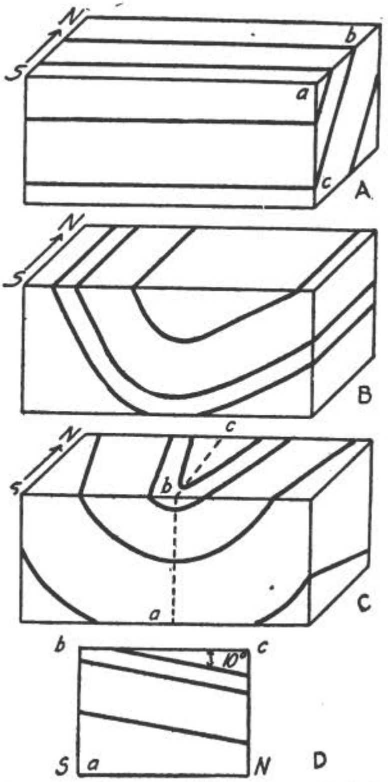


Fig. 123.—Diagrams of dip, strike, and pitch.

146. Strike, Dip, and Pitch.—The definitions given in Art. **11** for strike, dip, and attitude hold for folded strata. In Fig. 123, A, the strike is east-west and the dip is 45° S. In Fig. 123, B, the strike is north-south and the dip is W. on the east side of the block and E. on the west side. The axis of the syncline shown in this diagram is horizontal, but in Fig. 123, C, the axis is inclined northward, and a section through *a*, *b*, and *c* shows the angle of this inclination in its relation to the horizontal (Fig. 123, D). This angle is a special case of dip and is known as the *pitch* of the fold. Here, then, we have a syncline pitching 10° N. It is obvious from the diagrams that the strikes of the limbs of such a fold, the axis of which lies in a north-south vertical plane, are not parallel as in Fig. 123, B. They diverge in the direction of the pitch.

Interpretation of Tilted and Folded Strata

147. Discrimination Between Primary and Secondary Dip.—The inclination of layers, when not over 30° or 40°, may be original (**69, 227**). Sometimes it is hard to discriminate between primary dip and the secondary kind of dip induced by deformation. Ordinarily, laminæ which have a primary dip as high as 25° or 30° are cross-beds in the main stratification, and therefore they are of limited length. When the geologist is doubtful whether he is dealing with primary or secondary dip, he should examine other outcrops in the vicinity, and particularly large outcrops, since on these the major structure may be apparent. Cross-lamination is to be expected in eolian and fluviatile sandstones.

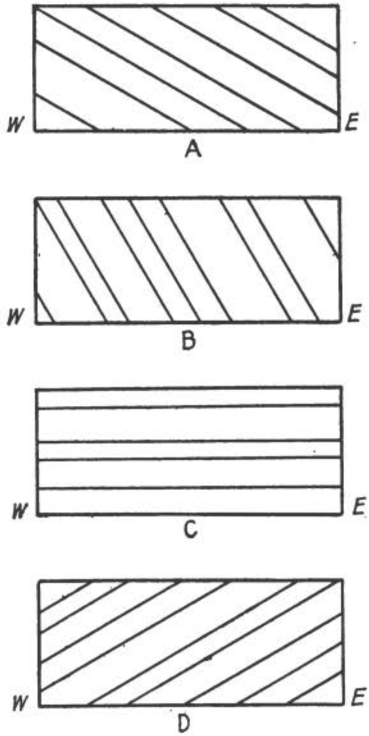


FIG. 124.—Sections of strata illustrating the relations of primary dip to deformation. A, cross-bedding in its original position, with a primary dip of 30° E. B, the same cross-bedding after it has been tilted eastward through an angle of 30°; it now has a dip of 60° E. C, the same cross-bedding as that in A after it has been tilted 30° westward; it is now horizontal, in spite of the fact that the strata have been tilted. D, the same cross-bedding as that in A after it has been tilted 60° westward; it now has a dip of 30° W.

Primary dips of lower angle are distinguished with less facility. In general, where cross-bedding is absent, the main stratification of coarse fragmental materials (sand or gravel) may be expected to have an original inclination of 2° to 5° or even 8°. This remark applies to piedmont alluvial deposits, topset beds of small deltas and sand plains, beach deposits, etc. If the rocks of a region belong unquestionably to these types, and if they have dips of these low angles, their inclination is not sufficient reason for assuming that they have been tilted since their accumulation. On the other hand, strata laid down with approximately horizontal attitude, now inclined at a low angle, have probably suffered slight deformation.

To understand how to solve this problem, one must have a knowledge of the manner in which different kinds of sedimentary material are deposited and one must correlate dips and strikes in many outcrops, sometimes over wide areas. Note that a single outcrop with a low dip, or a small group of exposures with low dips, may be situated in the axial region of a broad fold.

148. Amount of Tilting.—Provided beds were accumulated in a horizontal position, their dip is a measure of the angle through which they have been tilted, in any given locality; but if they were laid down with a primary inclination, the amount of their rotation is not correctly expressed by their present dip. Fig. 124 illustrates three cases (B–D) where the axis of tilting was coincident with the original strike of the strata when deposited.

149. Direction of Forces.—While it is impossible here to enter into a discussion of the dynamics of folding, a word or two may be said concerning the direction in which forces are supposed to have acted in the formation of folds. A monocline is often the product of a vertical or nearly vertical displacement consequent upon crustal tension; or it may be an effect of local adjustment in the vertical bodily uplift of huge blocks of the lithosphere. Anticlines and synclines are generally produced by compressional forces which are thought to act in directions approximately tangent to the earth's surface. In some cases basin folds may be made by vertical downsagging of the area deformed, and dome folds may be due to upthrust or to peripheral settling. For any anticlinal or synclinal fold, compression may be regarded as at a maximum normal to the axis and at a minimum parallel to the axis. That there is compression along the axis is often indicated by pitch. No folds are continuous with horizontal axes for long distances; all die out sooner or later.

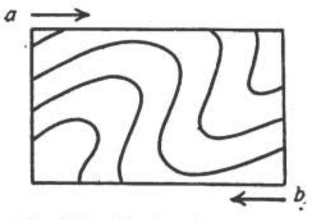


FIG. 125.—Section of an asymmetrical fold which was formed by forces acting probably in the general direction of the arrows.

An asymmetrical fold suggests an overthrust force acting from the direction toward which the axial plane dips, *i.e.*, from the side of the less steeply inclined limb (Fig. 125). This force may have been a differential pressure applied through the mass of the folded zone or it may have been a drag consequent upon the overriding of a more rigid superjacent body of strata (Fig. 122); for there is no reason for assuming that the drag folds must necessarily be small because they are subordinate in a composite fold. The asymmetrical form of a fold might also be attained by an underthrust from the direction of the steeper limb (Fig. 125), but overthrusting is the more common interpretation. The condition of asymmetry depends upon a multiplicity of factors, such as initial surface features of the folded tract, original inclination of the strata, relations of force and resistance, and the like.

150. Significance of Minor Folds in Relation to Major Folds.—Reference is made here only to folds produced by earth stresses. In contorted schists and gneisses, rocks which have undergone severe dynamic metamorphism, the folding is very irregular and all the layers have shared about equally in the deformation. The plications approach the similar type, although not uncommonly one fold may be seen to narrow and die out while beside it another broadens correspondingly. These are actually corrugations on larger folds and the larger ones may be superposed upon still larger ones, and so on. Originating in the same period and under the influence of the same forces, these sets of folds are apt to possess like characters. Their difference lies principally in their dimensions. Naturally we should expect to find that the minor folds pitch if the major fold pitches, and probably in the same general direction. Careful study of these small folds may therefore suggest the nature of the larger structure of a region and serve to guide the geologist in the methods to be adopted in his field investigation (Art. **299**).

Drag folds produced in the manner described in Art. **145** may help to unravel the major structure. Since their axial planes are inclined with the direction of differential movement, they suggest the position of the major folds (see Fig. 126).

In a vertical or steeply dipping series this method also shows which is the top and which the bottom of the beds, for the younger and upper layers are toward the synclinal axes.

151. Top and Bottom of Steeply Inclined, Vertical, and Overturned Beds.—It is customary to assume that any layer in a series of strata is older than the overlying beds and younger than the underlying beds When strata are vertical, their relative age can not be determined by superposition. When they are steeply inclined this method of reasoning is unsafe, too, for they may have been turned beyond the vertical and thus be overturned. Indeed, in very severe folding, beds may be turned quite upside down (Fig. 110, H), but rocks thus affected would presumably show signs of considerable metamorphism. In the investigation of steeply dipping beds and metamorphosed strata of lower inclination, the geologist must therefore seek criteria other than superposition to demonstrate the true relative order of stratification, or, as it is termed, the stratigraphic sequence (**98**).

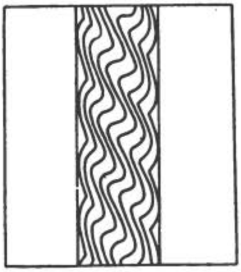


FIG. 126.—Drag folds in an incompetent bed between two competent beds. According to the rule, the competent layer on the left moved up with respect to that on the right. Consequently, these beds must be in the limb between an anticline on the right and a syncline on the left, and the beds on the left must be stratigraphically above those on the right.

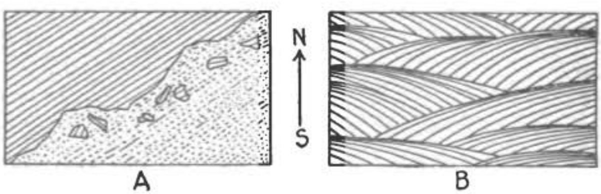


FIG. 127.—Sections of steeply dipping strata as seen on a horizontal or nearly horizontal surface. The younger (upper) beds in both A and B are toward the south. Explain this fact.

Geologic structures of assistance for this purpose are: (1) regional unconformity, with an associated basal conglomerate (**73**); (2) local unconformity (**77**) (Fig. 127, A); (3) curved cross-bedding, concave upward in the bedding and with the upper ends of each set of laminæ truncated above by the next overlying set (**80**) (Fig. 127, B); (4) gradational texture from coarse below to fine above in individual beds or laminæ (**83**); (5) ripple marks, but not in all instances (**80,** H); (6) the attitude of fossils (**88**); (7) the attitude of drag folds (**150**), of cleavage (**209, 210**), and of joints (**209**)

Folds in Relation to their Time of Origin

152. Age of Folds.—In a folded series of strata the deposition of the beds antedated their deformation. The folds are younger than the strata. Generally, joints and faults in such a formation are younger than, or contemporary with, the folding. They should not be regarded as older than the latter unless there is definite proof of the fact.

The geologic age of folding is determined by correlation with strata of which the geologic age is known. In the district sectioned in Fig. 101, the folding was post-Ordovician and pre-Devonian, for the strata (*a*) are deformed, whereas the overlying series (*c*) is not so. Both folding and erosion, as well as the intrusion of *b*, must have occurred between the two periods of sedimentation.

153. Two or More Periods of Folding.—To demonstrate that rocks have been subjected to two or more periods of folding is difficult if the evidences are sought in a conformable series of beds. Both complex folding and the superposition of small plications upon larger folds are phenomena commonly of contemporaneous origin. Moreover, variations in the intensity of folding, parallel or normal to the main axis, are perfectly characteristic of crustal blocks deformed in one diastrophic period. The only safe criterion for two distinct epochs of folding is found in undoubted cases of angular unconformity in which the younger beds have been folded (Fig. 128). Here the older strata must

Fig. 128.—Section of a surface of unconformity between two series of folded strata. The strata below the unconformity have been through two periods of deformation.

have suffered from deformation twice, once to account for the angle between the two series, and again, when the overlying beds were folded. The determination of successive periods of folding requires widespread geologic investigation and careful correlation of the observed facts.

154. Folds That Originate in Unconsolidated Sediments.—There are several ways in which folds may be produced in beds prior to consolidation. Some such plications fall under the head of contemporaneous deformation (**79**); others do not. Like cross-bedding and other primary structures, they may be preserved during the lithification of the strata in which

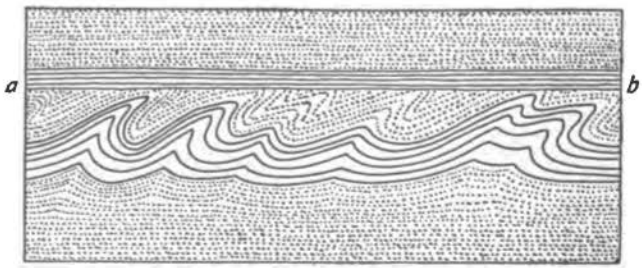


Fig. 129.—Section of contorted fine sand and laminated clay overlain by like sediments which are not deformed. *ab*, line of local unconformity. The shape of the folds indicates that the deforming agent moved from left to right. What is the significance of the fact that the folds die out downward? (Length of section about two feet.)

they are formed, so that their occurrence is not limited to unconsolidated materials. In any case they are of peculiar interest in denoting certain conditions under which the sediments were deposited. Ten varieties are described below and an attempt is made to point out criteria which may be of service in their interpretation.

1. A block of ice floating in a lake or in the sea may scrape over the bottom and rumple up the muds and fine sands which are in process of accumulation (Fig. 129). Folds and faults thus produced are examples of contemporaneous deformation. When formed, they are confined to a relatively thin upper zone and they die out downward. Upward the folds are sharply

truncated by the surface of erosion made by the berg, and they are overturned in the direction of its motion. Since deposition of the mud or sand continues after the passage of the ice, the erosion surface is soon buried and so becomes a local unconformity.

A series of beds exhibiting this kind of contortion is usually characterized by fine texture, by thin, uniform lamination, and by general regularity except in the crumpled zones of the type just described. These zones may be few or many, according to the size and number of the bergs which made them. They are not apt to be of great extent in the plane of the main bedding. In formations that exhibit these features, search should be made for isolated bowlders (**84**) and other evidences of the association of ice in the work of deposition.

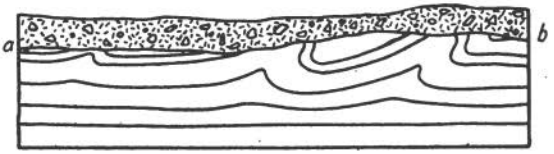


FIG. 130.—Till overlying folded aqueoglacial strata. *ab* is a line of unconformity. The folding and the erosion (*ab*) were performed by ice moving from left to right. (Length of section about 200 feet.)

2. In the forward motion of glacier ice on land the ice may not only erode, but also dislocate, aqueoglacial sediments which have been laid down in front of the advancing ice margin. A thickness of several feet of strata may be affected; the sediments are not limited to uniformly laminated fine sands and clays; and, till often rests upon the eroded surface that truncates the deformed beds (Fig. 130). Many examples have been cited, in the literature, of glacial clays, esker and kame gravels, and other bedded deposits, which have thus been scoured and deformed. Overridden clay beds sometimes reveal grooves and scratches on the surface of unconformity, if this has been exposed. Overturned folds and reverse faults show by their attitude the direction from which the ice thrust came. This structure may also be classified as contemporaneous deformation.

3. A structure very similar to "2" is that of outwash beds which were spread out before a *retreating* glacier and were subsequently overridden and deformed by a new advance of the ice. The time elapsed between the deposition of the strata and their erosion may have been scores, hundreds, or even thousands of years, so that this can hardly be called an example of contemporaneous deformation. The discrimination between the folding and erosion effected by ice moving over its own frontal outwash and the folding and erosion performed by ice moving over the retreatal deposits of an antecedent advance requires careful search for the criteria listed in Art. **101.**

4. During the winter season in northern climates, the expansion of the ice covering of ponds and lakes is relieved by crowding of the ice up the beach. This process, for which evidences may be seen in the bowlder piles of "walled lakes," may be accompanied by slight erosion and by deformation that may be called contemporaneous, provided the disturbed sediments constitute the beach. In most cases the ice probably rubs up over the beach materials, but it may carry along some sand and gravel which have been frozen into it, or it may push up a ridge in front of it. The overridden layers are apt to be crumpled and dragged forward, so that small folds are overturned landward. They may be truncated above by an erosion surface (local unconformity); downward they grade into the uncontorted beds. At most this folded zone can be but a few feet in thickness, and between winters it is likely to be reworked and spread out by wave action. Normally only a narrow strip of sediments along the beach can be handled in this way; but if water level rises or falls during a succession of years, the effects may be distributed over a much wider belt. Stationary water level would result in excessive disturbance of the same materials; falling water level would result in the exposure of the contorted beds to erosion by rainwash, etc.; and rising water level would bring the deformed zone of each winter beneath the water surface where it might be preserved by subsequent lacustrine deposition.

5. When ice crowding occurs in swamps, muds and organic materials may be contorted on a broad scale.

6. By alternate freezing and thawing, sediments that are ordinarily soaked with moisture suffer repeated expansion and contraction which may occasion local deformation in them. Properly speaking this would not be *contemporaneous* unless the time interval between the deposition of the sediments and their deformation were comparatively short.

Contemporaneous deformation originating on lake shores, in marshes, and in water-soaked sediments, is not necessarily associated with a capping surface of unconformity produced by the slight shove of the ice. It is much more probable that the folds will die out both downward and upward. They will grade upward into a zone in which any original bedding was destroyed by the upheaveal and settling of the loose grains and pebbles.

7. Mud flow is a possible cause of folding in unconsolidated beds. The coefficient of friction is so low in moist clays and muds, especially under water, that slipping may be induced even on slopes of only 2° or 3°. The "flow" may be distributed in the form of contortion through the thickness of one or more beds. As might be expected, the folds are overturned toward the direction of motion. Sometimes this distributed crumpling develops into an actual sliding of the overlying mud or clay along a surface that truncates the tops of the little folds and lies approximately parallel to the bedding. The resulting structure, though closely resembling the contemporaneous deformation due to grounding ice blocks, is likely to be of wider extent in the plane of stratification. Isolated bowlders and other evidences for the former presence of ice might serve as a means of discrimination were it not for the fact that there is nothing to prevent mud flow in bodies of water in which icebergs are floating.

8. Valley strata of various kinds, generally fluviatile, may be torn up, folded, and eroded by the sudden deployment of an avalanche. A vertical section would show the heterogeneous avalanche material resting unconformably upon the distorted beds.

9. Removal of mineral matter in solution from a rock which is undergoing decomposition may lead to irregular settling and contortion of overlying strata. Increase of volume induced by decomposition may crowd and fold rocks near the surface. Plications formed in these ways are not overturned in any particular direction.

10. Monoclinal folds, and sometimes more involved folding, may be produced in unconsolidated beds as an effect of faulting in the subjacent rocks.

In neither "9" nor "10" is local unconformity genetically associated with the deformation, and in neither instance is this deformation contemporaneous, as the term has been defined.

155. Discrimination Between Folds Originating Before and After Consolidation.—In folded shales, clay slates, and sandstones, and occasionally in other clastics, some difficulty may be experienced in deciding whether minor folds were produced through superficial agencies or through earth stresses, in other words, whether they are to be interpreted as evidences for conditions of sedimentation or for conditions of diastrophic deformation. Unfortunately, there seems to be no constant and striking character peculiar to either class of deformation. Yet certain features may be noted, which are suggestive of one origin or of the other.

In the first place, superficial folds, having an origin unrelated to stresses and strains within the earth's crust, have no direct structural relation to the major deformation in the neighborhood. Herein they differ from minor diastrophic folds, but the fact is not always easy to ascertain. Second, superficial folds are often much more disorderly and involved than diastrophic plications, because there is less opportunity for readjustment under the pressure and confinement of relatively great depths. Again, superficial folds are usually localized in beds which are overlain and underlain by uncontorted strata. Very often the crests of the anticlines are bevelled off by a surface of contemporaneous erosion (iceberg, glacial ice, shore ice, landslide) or by a shear plane (mud flow, etc.), and more rarely the troughs of the synclines at the base of the folded zone are truncated by a shear plane; whereas small diastrophic folds commonly die out gradually upward and downward into the less deformed strata. However, there are exceptions in which, both upward and downward stratigraphically, superficial folds pass into uncontorted beds, and, on the other hand, diastrophic plications may be found in layers that are truncated above and below where there has been shearing of the undeformed beds over the crumpled zone, and of the crumpled zone over the subjacent undeformed beds. Truncation, then, is not a safe criterion.

The discrimination of these two kinds of folds is not a question that is likely to arise in the case of metamorphic rocks, flat-lying lithified sediments, or unconsolidated strata. In schists and gneisses any original plications that may once have existed have probably been masked beyond recognition. Minor contortion in metamorphic rocks is generally diastrophic and is usually of the similar pattern (Fig. 120). Highly crumpled layers or zones in flat-lying, unmetamorphosed strata, otherwise unfolded or only broadly warped, are pretty surely of primary origin. One important exception to this statement must be made: faults in the lithosphere may cause slips and accompanying local crumpling in the superjacent mantle rock.

Folds in Relation to the Land Surface

156. Topographic Expression of Folds.—Provided folds are large enough and provided they are in strata of different degrees of resistance to erosion, they may exercise a marked control upon the form and distribution of hills and valleys. The harder beds stand up as ridges, and the weaker ones underlie longitudinal valleys. After long erosion the ridges may be carved into ranges of hills with intervening transverse valleys. If the axes of the folds are parallel to the general surface of the ground, the ridges and longitudinal valleys will have a parallel trend; but if the axes pitch, the ridges will zigzag back and forth, always pointing up the pitch in synclines and down the pitch in anticlines (Cf. Fig. 115). In denuded dome folds and basin folds, the ridges and valleys are closed concentric curves (Cf. Fig. 114). In gently dipping beds that have been truncated by erosion, no matter what the shape of the fold may be, the hard layers stand out as cuestas, and in steeply inclined beds these hard layers form hogbacks (**258**).

157. Breadth of Outcrop Defined.—The breadth of outcrop of an exposed bed may be defined as the distance between the

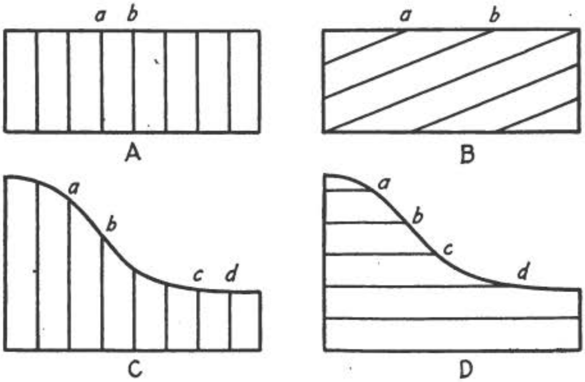


FIG. 131.—Sections illustrating variations in breadth of outcrop (*ab* and *cd*) of strata. The thickness of the beds in all four diagrams is the same.

stratigraphic top and bottom edges of the bed measured on the surface of the ground perpendicular to the strike (Fig. 131, *ab*, *cd*).

158. Effects of Topography on Breadth of Outcrop.—Fig. 131, A–D, will explain more clearly than words how the breadth of outcrop of a stratum may be modified by topographic variations. The essential points to notice are, (1) that breadth of outcrop is least when the surface of the ground is perpendicular to the beds, and (2) that the more obliquely the surface bevels across the beds, the greater is the breadth of outcrop for a stratum of given thickness. (What would be the dip of a bed whose thickness is half its breadth of outcrop on a horizontal surface?)

159. Effects of Topography on the Distribution of Outcrops.—When strata are exposed on an uneven land surface, the trend of their outcropping edges varies according to their attitude.

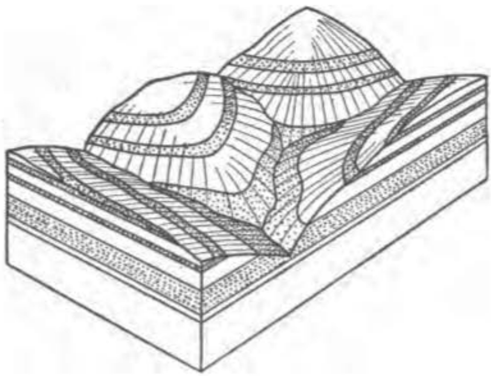


FIG. 132.—Effects of topography on the outcropping edges of horizontal strata.

The edge of a horizontal bed bends out round the spurs and in up the valleys (Fig. 132). If it is followed upstream on one side of

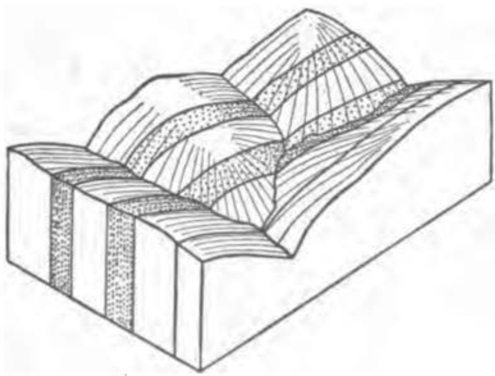


FIG. 133.—Effects of topography on the outcropping edges of vertical strata.

the valley, it is found to approach and finally cross the stream and then turn back on the other side. Isolated hills in the region may be mesa-like, with the same beds exposed all round

(258). Vertical strata outcrop in regular bands which trend straight across hills and valleys with no relation to the topography (Fig. 133). If beds are inclined, they outcrop in parallel

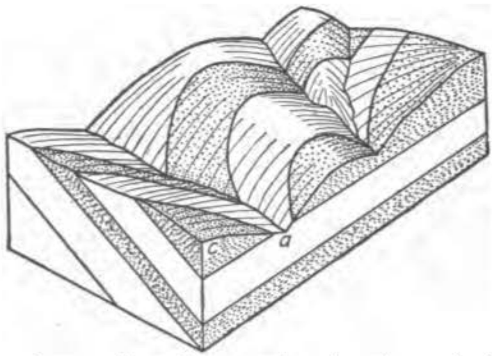


Fig. 134.—Effects of topography on the outcropping edges of strata dipping downstream.

zigzag belts with elbow-like bends which are situated in the valleys and on the spurs (Fig. 134, 135). In the valleys these

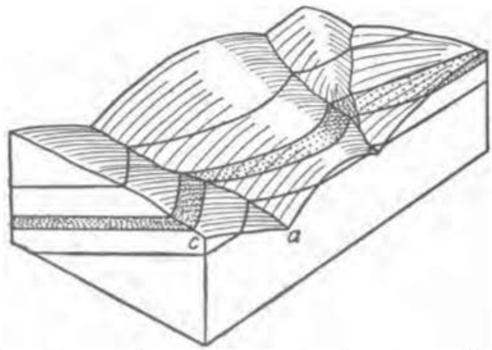


Fig. 135.—Effects of topography on the outcropping edges of strata dipping upstream.

bends point down the inclination[1] of the strata, as measured in the general direction of the valley, unless the angle of this in-

[1] If the strata strike perpendicular to the trend of the valley, this "inclination" is approximately the true dip; otherwise it is a component of the dip, taken along the valley trend.

clination is less than the gradient of the stream. In the latter case, which is very rare, the bends point up the inclination. (What will be the effect if the inclination of the beds and the valley gradient are equal?)

It is to be observed that the foregoing rules, although referring to strata which are theoretically of uniform thickness, are equally applicable to either the top or bottom surface of any given bed, and to any relatively even surface of unconformity. The distance between the outcrop lines of any two parallel bedding surfaces, *i.e.*, the breadth of outcrop, varies according to the slope of the ground as described in the preceding article.

160. Traverses Across and Along the Strike.—Unless the underground structure of a district on sedimentary rocks is exceptionally complex and irregular, a brief study of two or three outcrops should suffice to show in which direction one should walk in order to follow along, or to cross, the strike. In a flat country eroded upon folded strata, and in a hilly country where the strata are vertical, the geologist would keep on the same bed were he to travel parallel to the strike; but if the topography were rugged and the beds dipped less than 90°, he would come on to younger strata in climbing the hills (*a–c*, Figs. 134, 135) and on to older strata in descending into the valleys (*c–a*, Figs. 134, 135), provided, again, that he travelled along the trend of the strike. The object of a traverse along the strike is to assist in determining (1) the distribution of the strata; (2) whether the strike curves and so indicates pitching structure (**143, 146**); (3) whether the strata are continuous or have been faulted (**175**); and, (4) the constancy of the dip of a given stratum.

In traverses across the strike in regions of folded sediments, whether the topography be flat or rugged, successive strata are met. The object of this kind of traverse is to ascertain (1) the breadth of outcrop; (2) the nature of the folding; (3) the position of anticlines and synclines; and, (4) variations in the dip.

161. Sequence of Strata in a Cross-strike Traverse.—As may be noted in Fig. 136, in synclines relatively younger strata (*a*) lie between the older, subjacent beds (*b*); and in anticlines older strata (*c*) lie between younger superjacent strata (*b*). In all cases except where the surface of the ground is parallel to the beds or where it slopes in the same direction as, and more steeply than, the dip of a series of inclined beds, successively younger strata are traversed in walking across the strike in the direction of the dip.

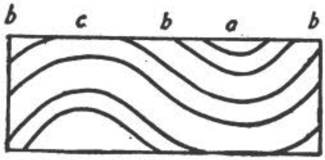


Fig. 136.—Section illustrating the position of strata in eroded folds. *a*, youngest bed in section; *b*, beds of intermediate age; *c*, oldest exposed bed.

162. Correlation of Strata.—A folded stratum, which has been truncated by erosion, may be exposed in places far apart, on the different limbs of a fold or on the limbs of different folds. The fact that these widely separated outcrops belong to the same bed may not be apparent at once. It has to be determined by various methods of correlation. For instance, if the sandstone outcrops at *a*, *b*, and *c*, in Fig. 137, contain the same suite of fossils, they are of the same geologic age and probably belong to the same stratum. The lithologic

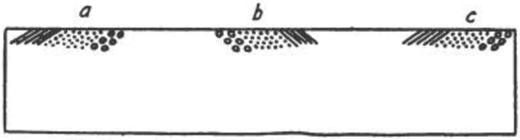


Fig. 137.—Section to illustrate the methods of correlation of strata observed in different outcrops (*a*, *b*, *c*).

resemblance, namely, the sandstone character, at the three localities corroborates this view. If, further, this sandstone is found in each place to overlie and underlie certain types of rock which are constant in their characters at the three localities, there can remain no doubt as to the identity of the sandstone at the different exposures. Of these three methods of correlation, *i.e.*, by fossil content, by lithologic character, and by stratigraphic sequence, the first is by far the most important. Where sedimentary rocks lack fossils, an effort should always be made to correlate them with the nearest rocks which do hold fossils.

CHAPTER VIII

FRACTURES AND FRACTURE STRUCTURES

FRACTURES IN ROCKS

163. Relations of Fractures to Zones of the Lithosphere.—When a mass of rock is not strong enough to resist forces that are tending either to compress it or to stretch it, the rock suffers deformation. The change of form is brought about by flowage in the deeper parts of the lithosphere and by fracture in the upper parts. As pointed out in the foregoing chapter, the zone of fracture for any particular rock seldom coincides with that for another, because rocks differ in their capacity to "flow" under stress. However, since every rock which has been naturally exposed through erosion is within its zone of fracture, outcrops on the earth's surface are invariably and conspicuously traversed by cracks. A large majority of these fissures belong to the class called joints. Other types of rock fracture are faults, fracture cleavage, and breccia structure. Besides these there are certain kinds of fracture which are principally the effects of surface agencies. Such are crescentic fractures of glacial origin, exfoliation cracks along which spalls separate from a disintegrating rock, etc.

FAULTS

TERMINOLOGY AND CLASSIFICATION[1]

164. General Nature of Faults.—A *fault* may be defined as a fracture along which there has been slipping of the contiguous

[1] The author has drawn freely from Bibliog., REID, H. F., 1913. In a few cases he has slightly modified the definitions as given therein, but the fact is noted.

masses against one another. Points formerly in contact have been dislocated or displaced along the fracture. Solid rocks or unconsolidated sands, gravels, etc., may be dislocated in this way. Faulting may result from compression, tension, or torsion. Some faults in loose or weakly consolidated clays, sands, and gravels are produced by the removal of a support (**183**).

In many cases, especially near the earth's surface, the process of dislocation is probably intermittent, although the stresses may be applied continuously and uniformly. This is because the rock does not break until its resistance is overcome. Then it gives way suddenly, and the relief is followed by another period of quiet during which the stresses again accumulate until they occasion another movement, generally on the old fractures. Thus faulting may be accomplished, a little at a time, until the tension or the compression, as the case may be, ceases to be operative. When the release is abrupt, the lithosphere is jarred and we say that there has been an earthquake.[1] Other things being equal, the greater a single movement is, the more violent is the shock and the farther do the perceptible earthquake vibrations travel from their place of origin. The displacement responsible for an earthquake is seldom more than a few inches, although occasionally it amounts to several feet; yet the sum total of all the slipping that has occurred along a fault may be many hundreds or even thousands of feet.

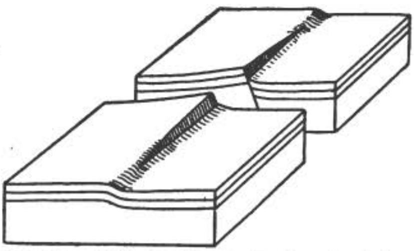


FIG. 138.—A fault dying out and passing into a monoclinal fold at its two ends.

If traced far enough a fault is found normally to die out at its two ends (Fig. 138). Consequently its displacement is apt to be at a maximum near the middle of its length, diminishing toward its extremities. Measured displacements vary from

[1] Not all earthquakes are so caused. Some are due to volcanic disturbances.

microscopic to many miles, and in length faults range also from microscopic to hundreds of miles.

165. Terms of General Application.—The characters of a fault are generally different in different places. An illustration of this statement is the varying amount of displacement shown in the fault in Fig. 138. Consequently most of the terms in use refer only to the part of the fault to which they are applied and not necessarily to the fracture as a whole. This must be kept in mind in connection with the definitions given below.

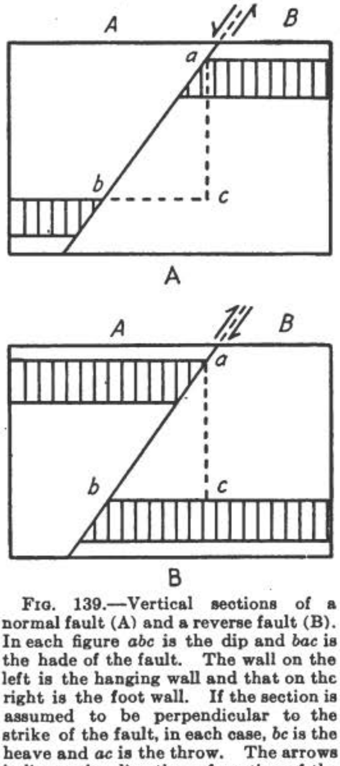


FIG. 139.—Vertical sections of a normal fault (A) and a reverse fault (B). In each figure *abc* is the dip and *bac* is the hade of the fault. The wall on the left is the hanging wall and that on the right is the foot wall. If the section is assumed to be perpendicular to the strike of the fault, in each case, *bc* is the heave and *ac* is the throw. The arrows indicate the direction of motion of the blocks.

The surfaces of a fault are called its *walls*. The upper wall of an inclined or horizontal fault is the *hanging wall*, and the lower one is the *foot wall* (Fig. 139).[1] While ordinarily the walls are irregular in their minor details (**171; 33, H**), when looked at from a large point of view, they may be flat or undulating. Their minor irregularities sometimes give rise to open spaces in which vein minerals may subsequently be deposited. The fracture is not always clean-cut and definite, for there may be more or less crushing of the wall rocks during the act of slipping. Finely pulverized rock flour of this origin is *gouge*. Coarser material,

[1] The reader is reminded that the accompanying illustrations are diagrammatic. In the field fault zones may be found instead of the fault planes herein figured, and they may have much less regularity in direction and shape.

consisting of fragments of various sizes, usually associated with a more finely crushed matrix, is *fault breccia* (Fig. 140, C). The layer of gouge or breccia is termed the *fault zone* or the *shear zone.* If such a shear zone is present, the walls are separated by the width of the zone. Fault zones may have vein minerals deposited between the fragments (**204**). The displaced masses on either side of a fault may be called *fault blocks.* A *horse* (Fig. 140, A) is a large fragment of rock broken from one block and caught between the walls of the fault.

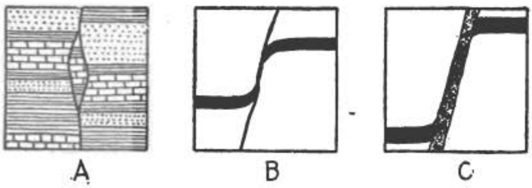


FIG. 140.—Sections of faults showing, in A, a "horse;" in B, drag produced by bending; and in C, drag produced by brecciation.

Sometimes bedding, or some other parallel structure in the fault blocks, has been turned up or dragged against the fault walls during the differential movement. Minor folding of this kind is called *drag* (Fig. 140, B). It is frequently well exemplified in faulted unconsolidated beds. It may produce sharp changes of dip and strike (*drag dips* and *drag strikes*) in the vicinity of a fault. The term is also applied by miners to the stringing out of fragments of a disrupted dike, ore body, etc., along the fault (Fig. 140, C). In the actual slipping the blocks may scratch, groove, and polish one another. The scratches are known as *slickensides.*

Fault line and *fault outcrop* are used synonymously for the intersection of the surface of the ground with a fault.

The words *attitude*, *strike*, and *dip* are used for faults in the same way as for strata (**11**), and they may be applied to a sharp fracture or to a fault zone (Fig. 139). The *hade* of a fault, or of a fault zone, is the complement of the dip, *i.e.*, it is the vertical angle between the plane of the fault and a vertical plane containing the strike of the fault (Fig. 139, *cab*).

166. Kinds of Displacement.—*Displacement* and *dislocation* are words used only with a general meaning in this book. When

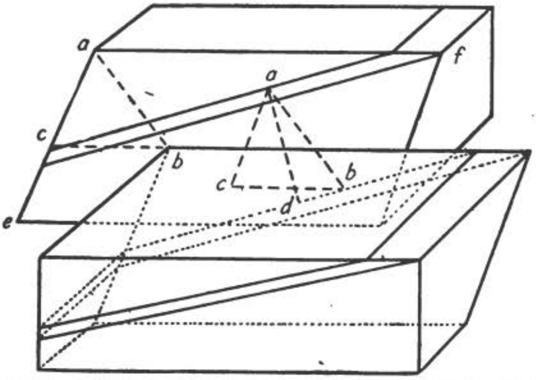


FIG. 141.—Displacements of a fault. The upper and lower surfaces of the block are horizontal. The triangles *abc* and *adb* are in the fault plane, *eaf*. *ab*, slip; *ac*, dip slip; *cb*, strike slip; *ad*, perpendicular slip. (After H. F. Reid, with modification.)

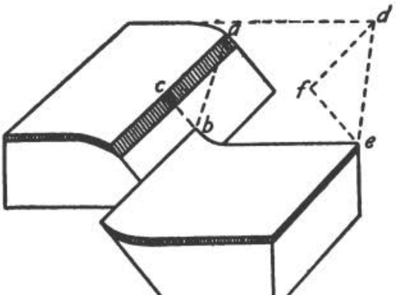


FIG. 142.—Slip and shift of a fault. The curvature of the beds is drag. *ab*, slip; *bc*, dip slip; *ac*, strike slip; *de*, shift; *fe*, dip shift; *df*, strike shift. The words "dip" and "strike" are used for the components of slip and shift which are parallel to the dip and strike respectively of the fault. (After H. F. Reid, with modification.)

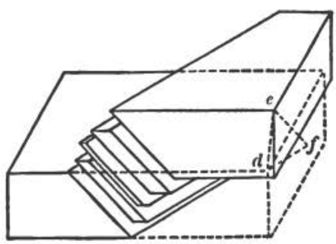


FIG. 143.—Shift produced by a multiple fault. *de*, shift; *ef*, dip shift; *df*, strike shift. (After W. Lindgren.)

more accuracy is desirable, *slip*, *shift*, and *separation* may be employed, with or without qualification. *Slip*, or *net slip*, is "the relative displacement of *formerly adjacent points* on opposite sides of the fault, *measured in the fault surface*"[1] (Fig. 141). If there is drag or other distortion along the fault, the slip is not equal to the displacement that affects points situated outside the immediate zone of dislocation. This is illustrated in Fig. 142, where *ab* is the slip and *de* is the displacement of the point, *e*, in moving from its former position, *d*. This distance, *de*, is called the *shift*. It is distinctly greater here than the slip.

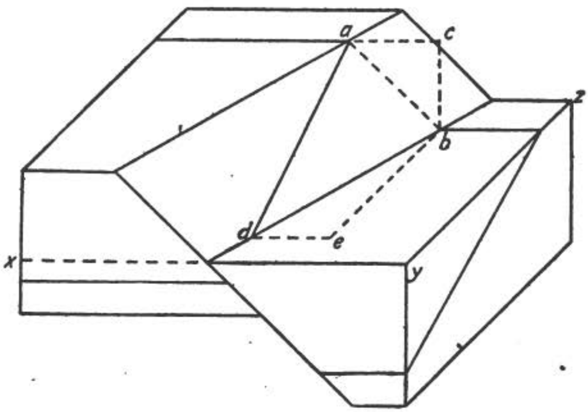


Fig. 144.—Displacements of a diagonal fault. *ab*, slip; *bc*, vertical separation; *ac* = *de*, horizontal separation along the strike of the bedding (gap); *ad*, trace of bedding on fault surface; *be*, offset.

Fig. 143 shows another example of shift. "The shift is of greater importance in the larger problems of geology than the slip." "The *separation* of a bed (Figs. 144, 145, 146), vein, or of any recognizable surface, is the distance between the *corresponding surface* of the two parts of the disrupted bed, etc., measured in any indicated direction. The distance must be measured between the *corresponding surfaces* on the two sides of the fault—for instance, between the upper surfaces of the two parts of the disrupted bed or between their lower surfaces—but not between the upper surface of one part and the lower surface of the other. Moreover, the surfaces considered must be parallel

[1] The quotations in this article are taken from Bibliog., Reid, H. F., 1913.

with the general extension of the bed, vein, etc., such as the upper or lower surface of a bed or the walls of a dike.

"The *vertical separation* is the separation measured along a vertical line (Figs. 144, 145).

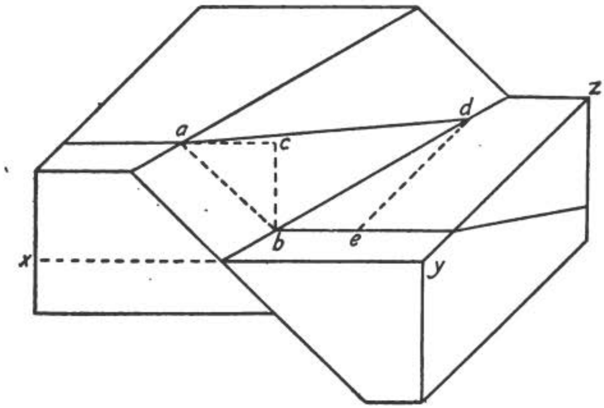


FIG. 145.—Displacements of a diagonal fault. *ab*, slip; *bc*, vertical separation; *ac* = *be*, horizontal separation along strike of bedding (overlap); *ad*, trace of bedding on fault surface; *de*, offset.

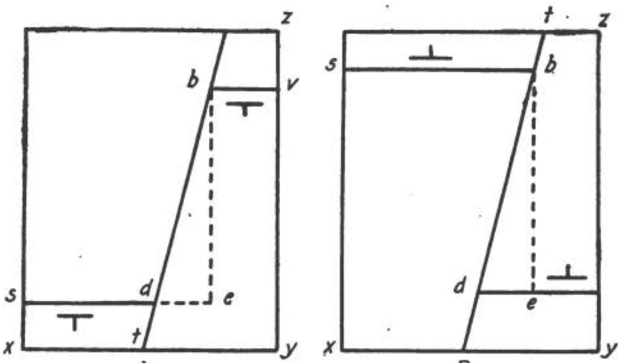


FIG. 146.—Offset, gap, and overlap. A is a plan of the structures which would be seen in the plane *xyz* of Fig. 144; B has a like relation to Fig. 145. *be*, offset; *de* gap in A, and overlap in B. Observe the symbols for dip and strike of the bedding.

"The *horizontal separation* is the separation measured in any indicated horizontal direction.

"The *normal horizontal separation* of a bed or other surface is its horizontal separation measured at right angles to the strike of the bed, etc. It is frequently determined from the outcrops of the bed at the surface of the ground; it is then usually called the *offset* of the bed." If A and B, in Fig. 146, represent the ground plans of oblique faults on a level surface, *be*, and not *bd*, would be the offset of the bed. *bd* would be the horizontal separation along the fault strike. *de*, in the same figures, would be called the *gap* and *overlap* of the bed, respectively; they are measured parallel with the strike of the bed.

"The *perpendicular separation* is the distance between the planes of the two parts of a dislocated bed or other surface measured at right angles to these planes."

"The measures which will be most commonly made are the offset at the surface, and the vertical and horizontal separations in shafts and drifts, respectively." . . . . .

"It is extremely important clearly to distinguish between the slip and shift and the separation. The first two refer to the actual relative displacement of the two sides of the fault, the last to the relative displacement of the surfaces of the two branches of a dislocated bed, etc.

"Movements of one side or of both sides of the fault parallel with the plane of a bed would not alter the separation of the bed, but would materially alter the slip and shift."

By *throw* is meant "the vertical distance between corresponding lines in the two *fracture surfaces* of a disrupted stratum, etc., measured in a vertical plane at right angles to the fault strike. The *heave* is the horizontal distance between corresponding lines in the two *fracture surfaces* of a disrupted stratum, etc., measured at right angles to the fault strike." (Fig. 139.) A vertical fault can have no heave and a horizontal fault can have no throw.

167. Classification of Faults.—Faults are classified according to (1) their distribution, (2) the nature of their displacement, and (3) their relations to disrupted bedding or other parallel structures.

1. An *auxiliary* or *branch fault* is a minor fault ending against the main fault. It may be the boundary of a wedge (Fig. 147, A). Faults that cross one another are *intersecting faults* (Fig. 147, B). When several parallel faults are close together and the intervening fault slabs or slices are not distorted, the group may be termed a *multiple fault*. A multiple fault in which the downthrow is on the same side of each component fault is a *distributive fault* (Fig. 143). A *fault complex* is an intricate system of intersecting faults of the same age or of different ages.

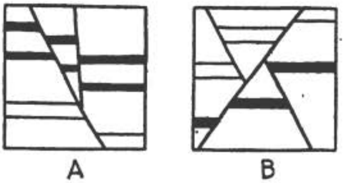


Fig. 147.—A, branching fault; B, intersecting faults. Which fault is the older one in B?

2. A *normal fault* is one in which the hanging wall has apparently slipped down with respect to the foot wall (Fig. 139, A), and a *reverse* (not "reversed") *fault* is one in which the hanging wall has apparently moved up with respect to the foot wall (Fig. 139, B). We say "apparently" because sometimes a normal fault may result from relative uplift of the hanging wall, and a reverse fault may be produced by relative depression of the

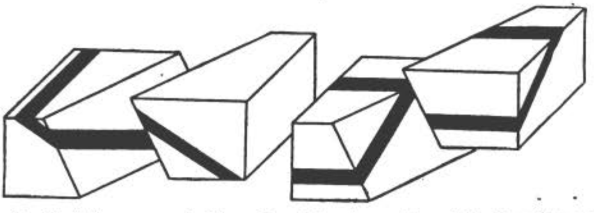


Fig. 148.—On the left, reverse fault produced by depression of the hanging wall; on the right, normal fault produced by uplift of the hanging wall.

hanging wall (Fig. 148). It is not always true, then, that there is extension of area by normal faulting, as if tensile stresses had operated, nor that there is contraction of area in reverse faulting, as if due to compression. "Normal" and "reverse" should "be used purely for purposes of description and not for the purpose of indicating extension or contraction, tension or compression, vertical or horizontal forces."[1] *Thrust* may be reserved for faults which are demonstrably due to compression. Three varieties are noted by Willis: (*a*) *break thrusts*, where the

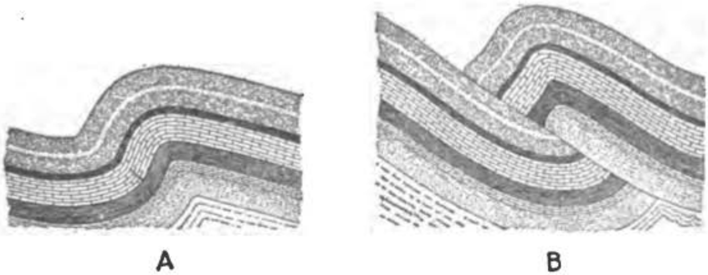


FIG. 149.—Sections illustrating the origin of a break thrust. The position of the overthrust fault shown in B was determined by the fracture represented in the massive limestone bed in A. (After B. Willis.) Observe that in this kind of faulting, and also in the varieties shown in Figs. 150 and 151, older rocks come to lie above younger rocks.

fault follows a previously formed tension fracture (Fig. 149); (*b*) *shear* or *stretch thrusts*, when the break follows the sheared and stretched underlimb of an overturned fold (Fig. 150); and (*c*) *erosion thrusts*, where the competent layer carrying the thrust is

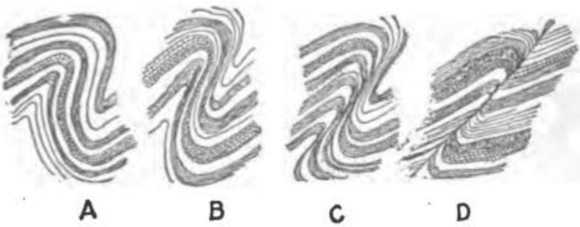


FIG. 150.—Development of a stretch thrust from an overturned fold. (After B. Willis.)

first weakened by erosion at or near the crest of the anticline (Fig. 151).[2] An *overthrust* is any thrust fault having a low dip (large hade) (Figs. 149–151). Faults on which the blocks rotate

[1] Bibliog., REID, H. F., 1913, p. 178.
[2] Bibliog., WILLIS, B., pp. 222–223; LEITH, C. K., 1913, pp. 46–48.

during dislocation are *hinge faults*, *pivotal faults*, or *rotational faults* (Fig. 152).

3. In strata, a *strike fault* (Fig. 153, A) has its strike parallel to

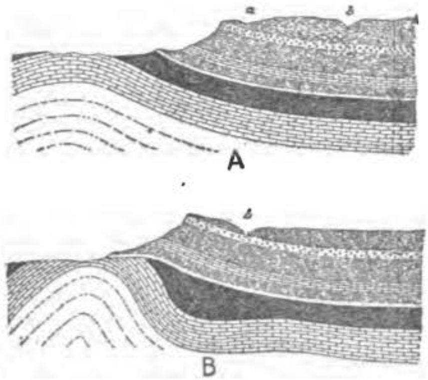


FIG. 151.—Sections illustrating the origin of an erosion thrust. The position of the overthrust shown in B was determined by the land surface condition represented in A, where a weak rock (dark shading) outcrops at the base of a scarp. The force acted from right to left. Erosion is supposed to have continued during the faulting. (After B. Willis.)

the strike of the beds; a *dip fault* (Fig. 153, B) strikes at right angles to the strike of the beds; a *diagonal fault* is one whose strike is oblique to the strike of the beds (Figs. 144–146); a *dip-*

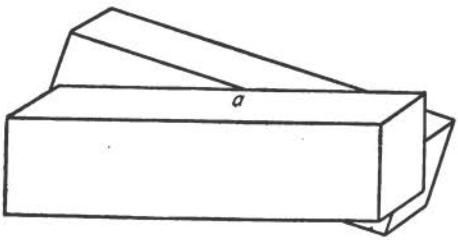


FIG. 152.—Rotational fault.

slip fault has its net slip essentially in the line of the fault dip (Fig. 153, A); a *strike-slip fault* has its net slip along the fault strike (Fig. 153, B); and an *oblique-slip fault* has its net slip anywhere between the dip line and the strike of the fault (Figs. 141, 142); a *bedding fault* is parallel to the stratification (Fig. 154); a *longitudinal fault* strikes parallel to the general structure (fold axes, schistosity, etc.) of a region, and a *transverse fault* strikes across such structure. Other definitions may be found in the article already referred to, and in textbooks on structural geology.

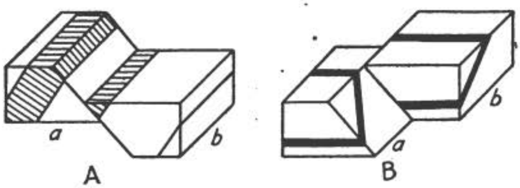


FIG. 153.—A, a dip-slip strike fault. B, a strike-slip dip fault.

168. Terms for Fault Blocks.—A wedge-shaped block between two faults is a *fault wedge* (Figs. 147, A; 155). Wedges are sometimes indicative of considerable lateral motion (Fig. 156). An upthrown block between two downthrown blocks is a *horst* (Fig. 157, A). A downthrown block between two upthrown blocks is a *graben* or *trough fault* (Fig. 157, B). A block which has

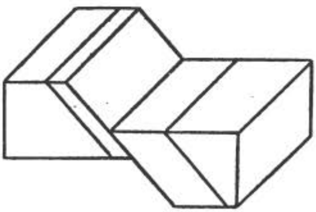


FIG. 154.—A bedding fault.

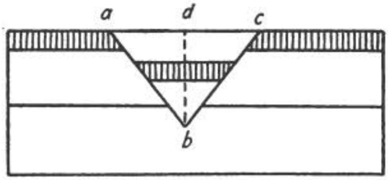


FIG. 155.—Section of a fault wedge (*abcd*).

been lowered on all sides by faulting or by downwarping or by both processes is called a *basin* (Fig. 158). These terms are structural in their significance and they are used irrespective of the topographic form of the block (**186**).

When a fault is approximately parallel to the strike of the strata, the block on the side of the fault toward which the dip of the beds is measured may be termed the *down-dip block*, and the other one is the *up-dip block* (Fig. 153, A). Note that the word, dip, in these two terms refers to the inclination of the beds.

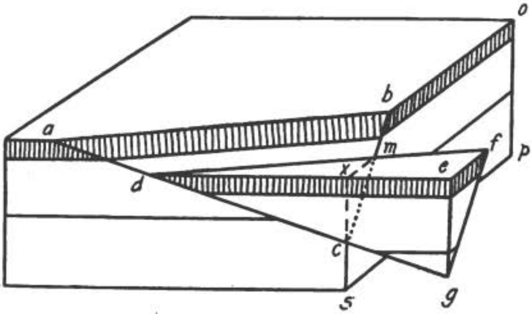


FIG. 156.—Block diagram showing a possible explanation for the dislocation of such a wedge as that drawn in Fig. 155. *efg* corresponds to *dcb* in Fig. 155. *d* has slipped from *a*, and *f* from *b*.

FIG. 157.—Sections of a horst (A) and a graben (B).

FIG. 158.—Block diagram of a structural basin. The dash pattern represents a hard crystalline rock formation upon which a series of strata (lined) rests unconformably. The strata occupy the basin. The little basin on the extreme left is an *outlier* of the main basin, and the mass of crystalline rocks within the basin, bounded on the right by fault *b*, is an *inlier*. Outline the geologic history of the basin.

On the down-dip side of any given stratum, the strike of a diagonal fault makes an acute angle with the strike of the beds (angle *sdt*, Fig. 146, A) on one side of the fault, and an obtuse angle with the strike of the beds on the other side (angle *dbv*, Fig. 146, A). The block containing the acute angle on the down-dip side of an outcropping bed may be called the *acute-angle block*, and the other, the *obtuse-angle block* (see also Fig. 146, B).

169. Omission and Repetition of Beds Defined.—Erosion after strike-faulting of stratified rocks may bring about the entire elimination of some beds (Fig. 159, A), or, on the other hand, it

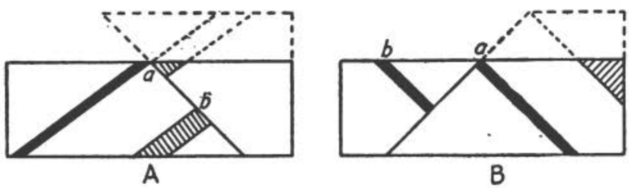


Fig. 159.—Sections showing omission (A) and repetition (B) of strata. In A, the beds between *a* and *b* are entirely concealed beneath the surface of the ground. In B, beds between *a* and *b* are exposed twice in the same succession on the surface of the ground.

may cause repetition of some beds, with the same sequence, on opposite sides of the fault (Fig. 159, B). The first is spoken of as *omission of beds* and the second as *repetition of beds*, respectively.

Geologic Evidences for Faulting

170. Principal Evidences of Faulting.—That faulting has occurred in any locality may be indicated in various ways. Sometimes slickensides or other marks of slipping may be observed on a fault surface exposed by natural or artificial means. More often the evidence is found in the relations of the rock structures on the two sides of the fault when the latter is viewed in horizontal, inclined, or vertical cross section. Or, again, the criteria may be topographic in character. These features, whether geologic or topographic, the field geologist should learn to recognize. He should know how to interpret their meaning, and in order to do this, he must be able to discriminate between them and other features that look like them but are really of very different origin.

The topographic forms related to faulting are described in Chapter XI. Their significance as evidences for dislocation is pointed out in Art. **192.** Following are the more important geologic phenomena:

1. Slickensides, polish, and other features on fault surfaces.
2. Visible displacement of veins, dikes, strata, etc., on opposite sides of an exposed fault line.
3. Zones of breccia.
4. Drag.
5. Discontinuity of linear forms along their general trend.
6. Abrupt termination of structures along their trend.
7. Repetition of strata.
8. Omission of strata.

171. Slickensides and Other Features on Fault Surfaces.—Slickensides are useful in showing the general line along which the motion took place. On a vertical fault surface, they indicate vertical slipping if they are vertical, horizontal slipping if they are horizontal, and so on; but they do not tell the relative motion, *i.e.*, if they are vertical, they do not show which block moved up with respect to the other. This relative displacement is sometimes indicated by steplike jogs that trend across the slickensides (**33, H**). The student should be careful not to place too much importance on these little irregularities. One or two are not sufficient evidence, but if they are numerous and all face in one direction, then they are fairly conclusive. Polish is of no value as a criterion for displacement.

Slickensides on outcrop surfaces may look like glacial striæ. For the most part, slickensides on any given surface are parallel, whereas striæ generally—not always—vary in direction within 10° or 15° of arc. On steeply inclined surfaces, fault scratches are apt to run up and down, whereas glacial striæ are likely to trend in a nearly horizontal direction. When the scratched surface can be traced to a place where it passes into the rock,[1] it is usually a fault surface; but exception must be made for the rare case in which ancient (pre-Pleistocene) glaciated surfaces are

[1] Not merely under superficial deposits, such as till, alluvium, etc.

found to have been rëexposed by the partial removal of the overlying younger rock. When the scratched surface is glaciated, any overlying material, consolidated or not, is apt to be of glacial or of aqueoglacial deposition. For other kinds of scratches, grooves, and polish, which may be mistaken for slickensides the reader is referred to Art. **33.**

Slickensides are not invariably accurate indices of the direction or distance of slipping. Successive movements on the same fault may have different directions, and the grinding and polishing of the last dislocation may have destroyed all traces of earlier slickensides. Thus, the total distance travelled by a point from its first position may be greater than the slickensides would lead one to believe, and the present direction between two points which were formerly in contact may be different from the course along which they acquired their ultimate positions. In making measurements on a given fault the geologist should ascertain, if possible, whether the slickensides are reliable data for obtaining the direction and amount of slip.

172. Visible Displacement of Veins, Dikes, Strata, etc.—There can be no better evidence for faulting than the case in which the two ends of a dislocated bed, dike, vein, or other structure, are visible where they abut against the fault, also exposed in section (Fig. 139). The geologist will discover few instances in which this kind of evidence is questionable; but he will also find that it is a phenomenon which is seldom seen except on a small scale.

173. Fault Breccia Zones.—This subject is reserved for Art. **204.**

174. Drag.—Drag is not observed unless in the immediate vicinity of a fault. It need not be exposed on both sides of the fracture in order to ascertain the direction of displacement, for its curvature in either block is always convex toward the direction of relative motion of that block (see Figs. 140, B, and 142). If the slipping had a vertical component, the faulted structures are turned up in the downthrown block and down in the upthrown block. There are cases known in which monoclinal folding was succeeded by faulting in the zone of the bending in such a way that the block relatively elevated by the folding was lowered by the faulting, and the consequent appearance was that of drag turned up in the upthrown block and down in the downthrown block.

175. Discontinuity of Linear Structures Along Their General Trend; Offset.—A dip fault or a diagonal fault, intersecting beds or other regular structures across their strike, is usually indicated by some type of offset. For example, a bed which has been dislocated in this way may be traced on the surface of the ground, generally in a series of separate outcrops, to a point beyond which it terminates and some other rock takes its place; but somewhere, to the right or left, the same bed will be discovered, probably trending in the original direction. The relations are essentially like those described in Art. **172**, but here the fault intersection (fault line) is concealed, so that merely its approximate position can be determined.

For the correct interpretation of offset the faulted bed, dike, vein, igneous contact, or other structure must have characters sufficiently distinctive for unquestionable recognition. On

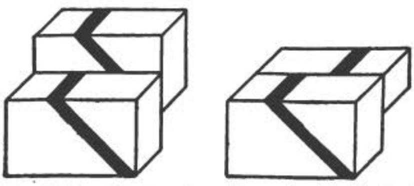


Fig. 160.—Offset produced by a dip-slip dip fault. Left, without erosion; right, after erosion.

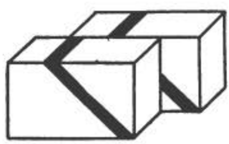


Fig. 161.—Offset produced by a strike-slip dip fault.

the assumptions (1) that inclined stratified rocks have been dislocated, (2) that the bedding has the same strike and dip on both sides of the fault, and (3) that the land surface is essentially horizontal, the conditions of offset may be classified as follows:

A. *The fault is a dip fault; there is neither gap nor overlap.* Like effects upon the outcrops of the strata may be produced by dip-slip, oblique-slip, and strike-slip faults, provided the net slip is of the proper amount. Whether the fault is vertical or inclined, the beds are offset toward the direction in which they dip in the upthrown block of a dip-slip fault (Fig. 160), and in the block which moved toward the dip of the bedding in a strike-slip fault (Fig. 161). For an oblique-slip fault (Fig. 162)

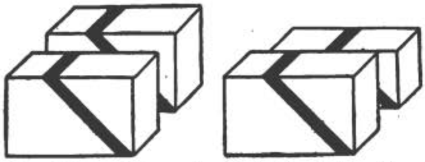


FIG. 162.—Offset produced by an oblique-slip dip fault. Left, without erosion, right, after erosion.

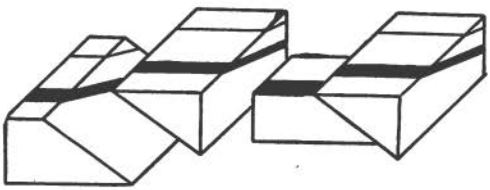


FIG. 163.—Offset toward the direction of dip of the beds in the downthrown block of an oblique-slip dip fault. Left, without erosion; right, after erosion.

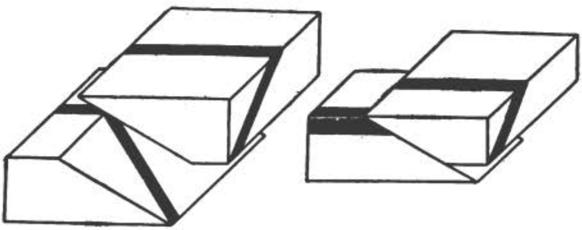


FIG. 164.—Offset toward the direction of dip of the beds in the downthrown block of an oblique-slip dip fault. Left, without erosion; right, after erosion.

the same statements hold true with the exceptions drawn in Figs. 163 and 164.

B. *The fault is a diagonal fault.* Like effects on the outcropping strata may be produced by dip-slip, oblique-slip, and strike-slip faults, provided the displacement is of the proper amount. Whether the fault is vertical or inclined, in the case of dip-slip faults, overlap results from downthrow of the acute-angle block (Figs. 165, 166), and gap from downthrow of the obtuse-angle block (Figs. 167, 168); and in the case of strike-slip faults, overlap results from the movement of the obtuse-angle block in the direction of the dip of the beds, and gap from

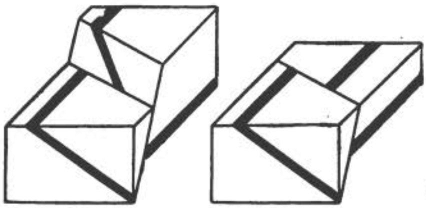


FIG. 165.—Overlap caused by a dip-slip diagonal fault. Left, without erosion; right, after erosion.

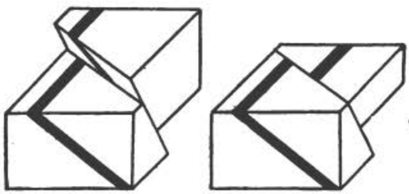


FIG. 166.—Overlap caused by a dip-slip diagonal fault. Left, without erosion; right, after erosion.

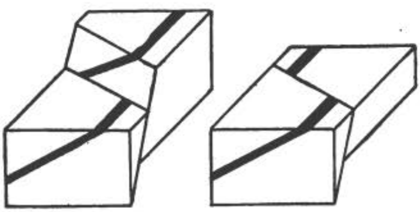


FIG. 167.—Gap produced by a dip-slip diagonal fault. Left, without erosion; right, after erosion.

the movement of the acute-angle block in this direction. The same statements hold for oblique-slip diagonal faults, except in cases analogous to those figured for dip faults.

If inclined stratified rocks have been broken by a rotational dip fault, the beds are offset in the same manner as in a dip-slip dip fault but the outcrops are broader in the block which has undergone a differential upward displacement increasing in amount in the direction of the dip of the strata (Fig. 169, front block; Fig. 170, back block). Exception to this statement may be found where the rotation has actually reversed the direction of dip of the beds.

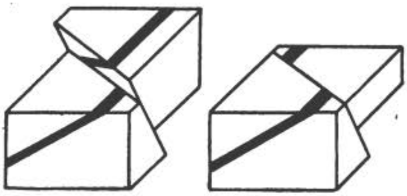


FIG. 168.—Gap produced by a dip-slip diagonal fault. Left, without erosion; right, after erosion.

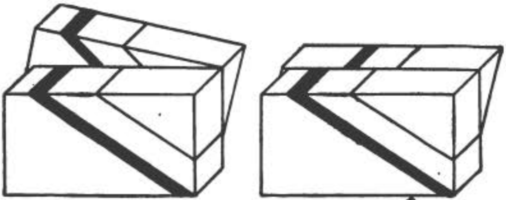


FIG. 169.—Offset by rotational faulting. Left, without erosion; right, after erosion.

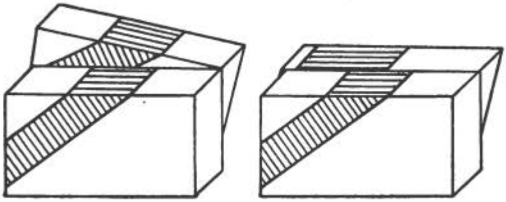


FIG. 170.—Offset by rotational faulting. Left, without erosion; right, after erosion.

176. Abrupt Termination of Structures Along Their Trend.[1]—In offset the two parts of a dislocated structure end abruptly against the fault line. If one of the parts were gone the condition would be that referred to in the title of the present article.

[1] Note that the word trend implies outcrop on the land surface.

Under these circumstances, the lost portion of the structure may be concealed under water, under alluvium, under lava, or under a later series of stratified rocks (Fig. 171); or the displacement may have been greater than at first imagined and the "lost portion" may be found by more extended search.

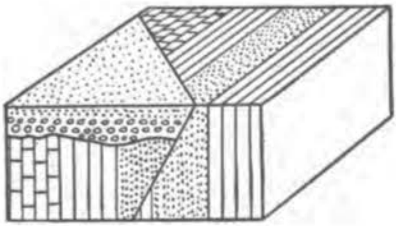


FIG. 171.—Abrupt termination of strata (right) against a fault. The same strata, on the left of the fault, are concealed beneath the body of horizontal sediments. These younger horizontal sediments have been eroded from the right fault block.

In a series of strata which have been broken by a rotational fault and then eroded the beds in one or both blocks may be truncated by the fault. On the assumption that the land is essentially horizontal, these relations may be classified as follows:

A. *The beds are horizontal in one fault block and are inclined in the other, and the inclined beds strike nearly or quite at right*

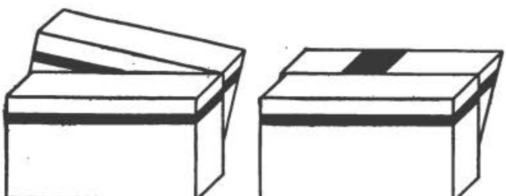


FIG. 172.—Effects of rotational faulting of horizontal strata. Left, without erosion; right, after erosion.

angles to the strike of the fault. The block with the tilted beds suffered relative uplift with increasing slip on the side away from which the strata dip. The fault surface is vertical or inclined (Fig. 172). The same relations may be brought about by rotation of a block of tilted strata on a dip fault in such a way that the layers in this block become horizontal; but this case is exceptional.

B. *On both sides of a fault the beds are inclined in the same general direction, but those on one side strike parallel to the strike of the fault and those on the other side strike so that they make an*

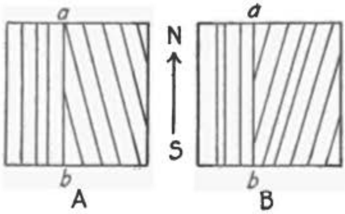


FIG. 173.—Effects of rotational faulting of inclined strata, as seen in plan.

acute angle with the fault line. The beds which are truncated at the fault line are in the tilted block. In Fig. 173, A, (1) if the fault is vertical and the beds dip to the right, the tilted block was increasingly lowered toward *a*; (2) if the fault dips to the right and the beds dip to the right, either the fault dips more steeply than the beds and the tilted block was increasingly lowered

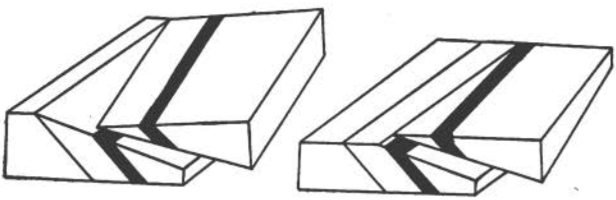


FIG. 174.—Effects of rotational faulting of inclined strata. Left, without erosion; right, after erosion of upthrown block.

toward *a*, or the fault dips less steeply than the beds and the tilted block was increasingly lowered toward *b* (see Fig. 174); (3) if the fault dips to the right and the beds dip to the left, the tilted block was increasingly lowered toward *b*. In Fig. 173, B, (1) if the fault is vertical and the beds dip to the right, the tilted block was increasingly lowered toward *b*; (2) if the fault dips to the right and the beds dip to the right, either the fault dips more steeply than the beds and the tilted block was increasingly lowered toward *b*, or the fault dips less steeply than the beds and the tilted block was increasingly lowered toward *a*; (3) if the fault dips to the right and the beds dip to the left, the tilted block was increasingly lowered toward *a*.

C. *The beds on both sides of the fault are inclined in the same general direction and strike so that they make an acute angle with the fault line* (Fig. 175). On the assumption, above made, that

FIG. 175.

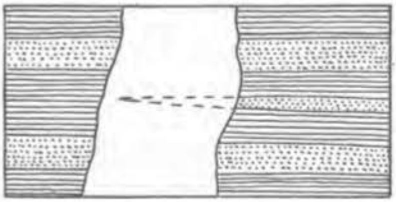


FIG. 176

FIG. 175.—Effects of rotational faulting, as seen in plan.

FIG. 176.—Sketch map of a body of inclined strata partly covered by alluvium (white). The middle sandstone bed (stippled) on the right thins out beneath the alluvium and thus looks as if it had been dislocated by a fault, also concealed beneath the alluvium; but the fact that the other beds match across the alluvium cover proves that the suggestion of a fault is incorrect.

the land surface is horizontal, these relations are caused by rotation in both blocks; but in nature the same thing is more apt to be due to the fact that the ground slopes.

The abrupt termination of structures along their trend is not necessarily a result of faulting. The same phenomenon is common in association with igneous contacts and lines of unconformity. Furthermore, one should not overlook the fact that since beds, dikes, veins, fractures, and the like, may come to an end in their original form, within short distances, apparent truncation is not always real (Fig. 176). The natural termination may be concealed and so lead one to infer the presence of a covered fault where no fault exists.

177. Repetition of Beds.—Repetition of beds is a very satisfactory indication of faulting, but it is not conclusive evidence.

It may be due to folding where an intervening limb is concealed (Fig. 177), or it may be a consequence of the repetition of a certain sequence of conditions during the deposition of the beds. Proof that folding is not the cause may often be found by wider field correlation, or, if the true succession of strata is known from observations in the vicinity, by actual measurement across the

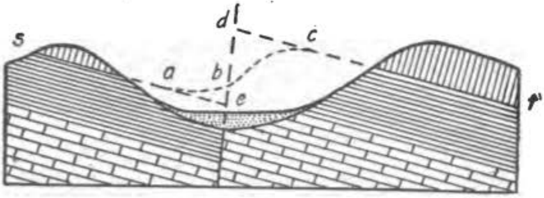


FIG. 177.—Repetition of beds explained by folding (*sabct*) or by faulting (*saedct*). The stippling represents alluvium which conceals some of the beds and likewise the fault line, if faulting is the correct explanation.

strike to determine whether there is room for the concealment of the repeated strata in an intervening limb of a fold. As for the possibility that the conditions of sedimentation were repeated, this is very unlikely, and the more beds there are in the repeated series, the more improbable does this suggestion become.

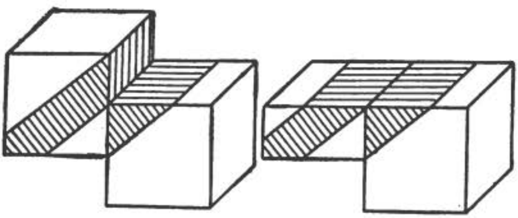


FIG. 178.—Repetition of strata caused by erosion (right diagram) succeeding dislocation by a vertical dip-slip strike fault (left diagram). (Cf. Fig. 182.)

Figs. 178 to 181 show several methods by which repetition of strata may be produced.

178. Omission of Beds.—The ability to recognize omission of beds in the field demands a thorough acquaintance with the stratigraphic sequence (**98**) in the region; for obviously, unless

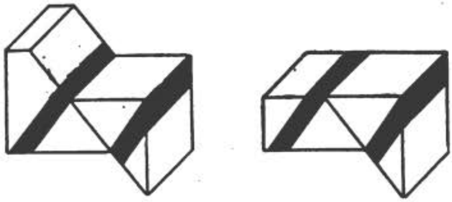


FIG. 179.—Repetition of strata caused by erosion (right block) succeeding dislocation by a dip-slip strike fault that dips in the opposite direction from the dip of the broken strata. (Cf. Fig. 183.)

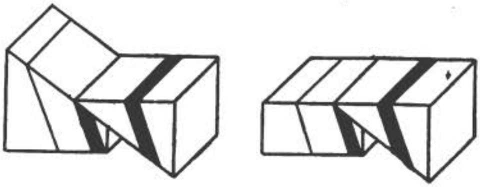


FIG. 180.—Repetition of strata caused by erosion (right block) succeeding dislocation by a dip-slip strike fault that dips in the same direction as the broken strata. (Cf. Figs. 181, 184.)

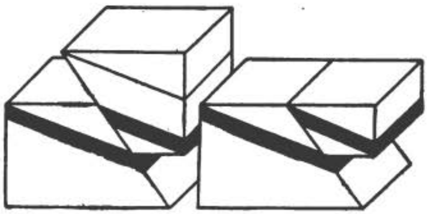


FIG. 181.—Repetition of strata caused by erosion (right block) succeeding dislocation by a dip-slip strike fault that dips in the same direction as the broken strata. (Cf. Figs. 180, 185.)

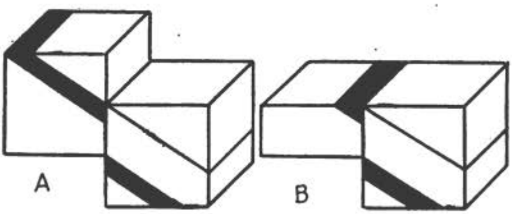


FIG. 182.—Omission of strata caused by erosion (right block) succeeding dislocation by a vertical dip-slip strike fault. (Cf. Fig. 178.)

one knows what strata to expect, one can not tell whether or not some beds are missing. In Figs. 182 to 185 are illustrated several methods by which omission of beds may be produced.

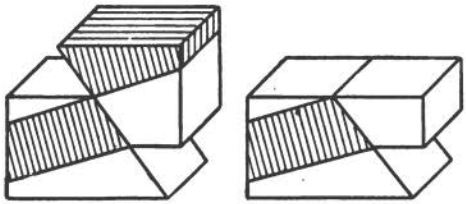


FIG. 183.—Omission of strata caused by erosion (right block) succeeding dislocation by a dip-slip strike fault that dips in the opposite direction from the dip of the broken strata. (Cf. Fig. 178.)

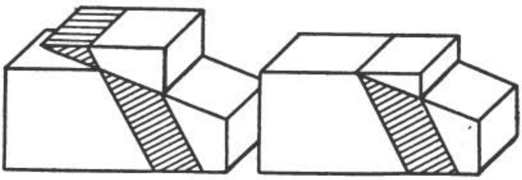


FIG. 184.—Omission of strata caused by erosion (right block) succeeding dislocation by a dip-slip strike fault that dips in the same direction as the broken strata. (Cf. Figs. 180, 185.)

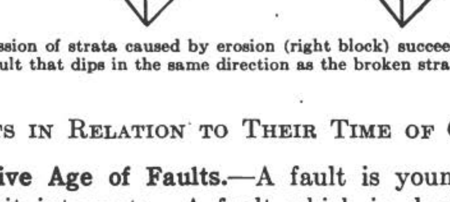


FIG. 185.—Omission of strata caused by erosion (right block) succeeding dislocation by a dip-slip strike fault that dips in the same direction as the broken strata. (Cf. Figs. 181, 184.)

FAULTS IN RELATION TO THEIR TIME OF ORIGIN

179. Relative Age of Faults.—A fault is younger than the rocks which it intersects. A fault which is clearly dislocated by an intersecting fault is older than the latter (Fig. 147, B). Yet there are many cases of intersecting faults which are essentially contemporaneous, even though some are slightly dislocated by others. Such faults generally occur in definite sets which, like intersecting joint sets (**199**), have been formed during one and the same period of deformation. In a given region tension faults are usually younger than compression faults.

180. Warped and Folded Faults.—Faults have been recorded as folded or warped; that is to say faulting is supposed to have been accompanied or followed by folding or warping. Overthrusts are particularly liable to bending, because, like most folds, they are products of compression, and they may be followed as well as preceded by folding. Tension faults are less apt to be warped unless the rocks which they intersect are buried and subjected to folding in a later geologic period. Note, however, that the fact that a fault has an undulose shape and

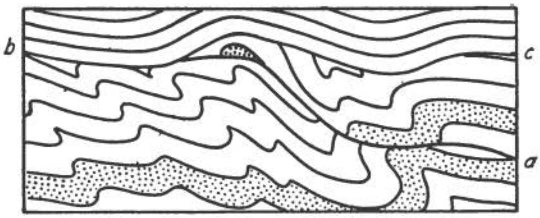


Fig. 186.—Section of a fault (*a*) which is intersected by a surface of unconformity (*bc*). Since the surface of unconformity and the beds above it have been folded, the irregularity of the subjacent fault is probably also a consequence of deformation.

looks as if it had been flat and had been bent, is no proof of subsequent deformation. A great many faults originate with such a shape. Indeed, irregular form is more typical than is flatness. Yet in most cases, no doubt, a highly undulose shape of the fault surface is significant of compression after faulting. One's conclusions must be guided largely by the degree of irregularity exhibited. The surest evidence for warping or folding of a fault includes all the following features in association (Fig. 186): (1) the fault has an undulating form; (2) it cuts a rock formation which has clearly been folded; (3) it terminates upward at a surface of unconformity which separates the dislocated formation from an overlying series of strata; (4) this younger series is likewise folded. In the absence or obscurity of one or more of these structural relations, the conclusion that the undulose fault has been bent after its origin becomes less reliable and it is often safer to believe that the shape is primary.

181. Geologic Age of Faults.—The geologic age of faults is ascertained from their relation to the adjoining rocks. An example is shown in Fig. 65.

182. Post-Pleistocene Faults in Bedrock.—In countries which were glaciated in the Pleistocene, signs of postglacial dislocation are sometimes found in low scarps or edges, of a fraction of an inch to a few inches in height, which interrupt the continuity of striated and glacially smoothed rock surfaces (Fig. 187). Although the throw of these faults may be small individually, the total displacement of several on a single ledge, all with the downthrow on the same side, may amount to a number of feet. Demonstration of the origin of these faults subsequent to the erosive work performed by the ice lies in the facts, (1) that the displaced scratches and grooves on the two sides of the fault clearly match as to their direction, shape, and size, and (2) that the edge of the upthrown block at the fault is sharp, not bevelled off as it would be had the dislocation antedated glaciation.[1]

FIG. 187.—A small postglacial fault (*ac*) which interrupts the continuity of a glaciated rock surface. The edge made by the fault is about ¼ inch high.

183. Faults That Originate in Unconsolidated Sediments.—Faults may be formed in unconsolidated sediments in all the ways described for folds (**154**). They are usually reverse faults when the deformation was produced by an overriding mass, and, like the overturned plications, they indicate by their attitude the direction in which the agent moved. If due to settling the faults are commonly normal. Settling may be induced by faulting in the underlying bedrock (Cf. 10, **154**), by decomposi-

[1] Bibliog., MATTHEW, G. F.

tion of the underlying rock and removal of the products in solution (Cf. 9, **154**), by mechanical washing out of the finer grains from a bed of sand or gravel, or by the removal of a support, such as ice. It is possible that many of the small faults in aqueoglacial sands are to be explained by one or both of the last two processes.

184. Discrimination Between Faults Originating in Sediments Before and After Consolidation.—After faulted sediments have

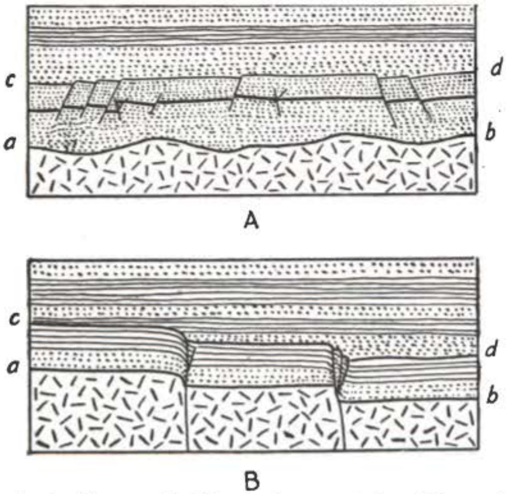


FIG. 188.—Sections to illustrate the difference between faults which were limited to superficial sediments (A) and those which, although appearing in the superficial sediments, had their origin in the underlying bedrock (B). *ab*, line of unconformity between ancient rock foundation (dash pattern) and sediments which were unconsolidated at the time when they were dislocated. *cd*, original land surface at time of faulting. In both cases this surface was later buried under younger sediments.

become consolidated, it may be difficult to decide whether the observed displacements were formed before or after lithification.

1. If such faults are thrusts, they are probably associated with crumpling, and the criteria outlined in Art. **155** for the discrimination of contemporaneous folds may be applied.

2. Gravity faults, occasioned by settling of purely superficial origin and therefore limited to sediments which were un-

consolidated at the time of the displacements, are seldom more than a few inches or a few feet in length when measured across the bedding. They are spaced typically at short intervals, their trends and mutual relations are irregular, and they are lacking in definite relations to the axes of diastrophic deformation in the rocks of the region. A fault of this kind is often slightly blurred because some of the grains of the unconsolidated deposit slipped or rolled a little way along the surface of displacement and so obscured the bedding in a thin layer. Such a layer corresponds to a fault breccia in fractured solid rocks. Usually, not always, it is indistinguishable or absent in muds or clays and their derivatives, narrow in sands and sandstones, and broader in coarse materials. These gravity faults commonly terminate upward where the original surface of the deposit was at the time of dislocation (Fig. 188, A).

3. Faults, either single or multiple, which were produced in unconsolidated sediments by displacement in the subjacent rock, intersect a regional unconformity (Fig. 188, B). In the younger formation, which was unconsolidated at the time of their origin, they exhibit many features like those mentioned for the second group, but necessarily they are definitely related to the faults in the rocks below the unconformity. In the underlying formation they are apt to have clean-cut edges, true breccia zones, and other characters such as develop in the dislocation of consolidated rocks. Sometimes the grains of the younger formation are found to have slipped down into the fault crack in the older formation.

Faults in Relation to the Land Surface

185. Classification of Topographic Forms Related to Faulting.—The topographic expression of faults may be original or subsequent. Original are all those land forms produced by faulting and not so modified by erosion but that their primary characters are still recognizable. These include fault scarps (**229**), faceted spurs due to faulting (**232**), fault valleys, fault gaps, and rifts (**245**), kernbuts and kerncols (**235**), and horsts, grabens, and structural basins bounded by faults (**168**). All topographic forms which have been derived through the extensive erosion and consequent extensive modification of original topographic features due to faulting are subsequent. Such are fault-line scarps (**231, F**), fault-line gaps (**250, E**), and the erosion modifications of horsts, grabens, and basins (**186**).

186. Topographic Expression of Horsts, Grabens, and Basins.—Horsts, grabens, and basins are included in the list just given because, if they are comparatively small, or if their characters are very pronounced, they are recognizable as topographic forms; but ordinarily they are so large and their surfaces are so varied in relief that their study can be accomplished only by extensive field investigations. Consequently, although the scarps, valleys, and other land forms are described in Chapter XI, horsts, grabens, and basins will receive consideration here.

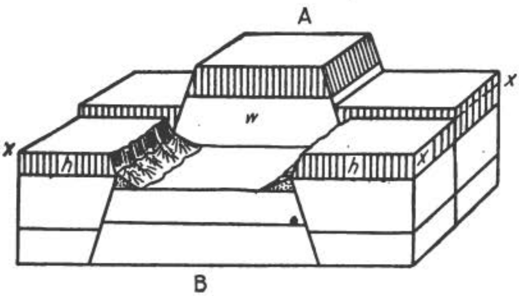


Fig. 189.—Block diagram of a horst after faulting (A) and after considerable erosion (B). The land of block A is supposed to have been reduced by erosion almost to a plain (peneplain) at the level *xxx*. Then, after a general uplift, the rivers of the region were revived. They cut away the weak rocks (*w*) much more rapidly than the resistant rocks (*h*), so that the lowlands of block A became the uplands of block B.

A horst has been defined as a relatively elevated block of the lithosphere between two downthrown blocks; that is, in its original surface form, a horst is a ridge (Fig. 189, A), or, if erosion has modified the block, it has a hilly or mountainous expression, provided the block is a large one. In the same way, the original topographic form of a graben is a lowland which may or may not have an even floor (Fig. 190, A). If a region in which there is a graben or a horst is exposed to denudation for a long period, hard and soft rocks may be so distributed in the fault blocks that the relief may become reversed. The horst may become a lowland and the graben may become an upland (see B in Figs. 189 and 190). Likewise, theoretically, the relief of a geologic basin may be reversed.

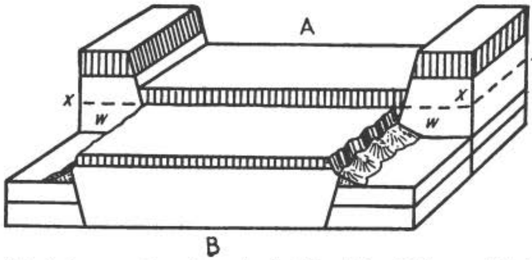


Fig. 190.—Block diagram of a graben after faulting (A) and after considerable erosion (B). The land of A was reduced to a plain at the level *xxx*. After uplift and rejuvenation of the rivers, the weaker rocks (*w*) were eroded away more rapidly than the hard rocks (lined), so that the lowland of A became the upland of B.

The student should observe that even if a basin or a graben is still a lowland, and if the horst is still an upland, this seemingly primary form may be of subsequent development. In other words the scarps which bound the basin, graben, or horst, may be fault-line scarps (**231, F**) which front in the same direction as the original fault scarps.

187. Effects of Topography on the Trend of Fault Lines.—Major faults are most apt to trend along valleys or along the bases of scarps, but where a fault runs across hills and valleys the form of its outcrop is regulated by the topography in just the same way as is that of an exposed stratum (**159**). The rules governing the outcrops of vertical, inclined, and horizontal faults are identical with those for strata with like attitudes; and the exceptions are the same. The trace of an overthrust may be highly complex and irregular (Fig. 191).

188. Inliers and Outliers Produced by Erosion of Faults.—Like low-dipping strata, the outcrop lines of overthrusts are very involved and sinuous in lands of marked relief. Cases are known in which the overlying (overthrust) block has been locally perforated by erosion so that the lower block has become uncovered (Fig. 191, *b*). An isolated exposure like this has been termed a *fenster* (German, window). With reference to the main mass of

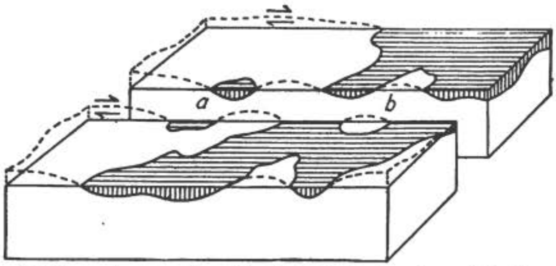


FIG. 191.—Relations of an overthrust fault to the land surface. The figure is drawn as if a single block had been cut and the pieces had been separated a short distance. The land surface (top of the blocks) is represented as flat. Erosion has removed a large part of the older overthrust block (shaded), thus exposing the underlying younger rocks (white). (Cf. Fig. 149.) The base of the shaded formation is the fault, drawn as a full line where still present, and as a dashed line where eroded. The arrows indicate the relative motion of the blocks in the faulting. *a*, a fault outlier; *b*, a fault inlier.

the overridden block, a fenster may be called a *fault inlier*. In analogous fashion, a remnant of the upper, overthrust block, separated by erosion from the main area of this block and surrounded by the worn surface of the lower block, may be termed a *fault outlier* (Fig. 191, *a*) (Cf. Fig. 158).

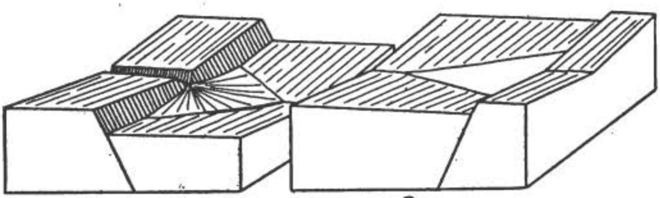


FIG. 192.—Relations of faulting to streams. A, upthrow on upstream side of fault; B, upthrow on downstream side of fault. A lake has formed upstream from the fault in B.

189. Effects of Faulting on Streams.—A and B in Fig. 192 show two cases in which dislocation has occurred across the channel of a stream. If downthrow is on the downstream side of the fault, the stream will incise its course in the upthrown block and will build a small alluvial fan in front of the scarp (Fig. 192, A). This process will continue until the river's channel is reduced to a uniform grade. Following relative upthrow of the downstream block (Fig. 192, B), the fault scarp serves as a dam above which a lake may be impounded. The lake will rise until it spills over at the old channel. The outlet will then be degraded until the lake is drained and any sediments which may have been spread over its floor will be incised.

190. Displacement Relative to Sea Level.—When we say that one fault block has moved up or down with respect to another, we do not imply anything as to the actual change of position computed from sea level. Slickensides and measured relative displacements do not solve this problem. Both fault blocks may be lowered, but if one sinks more than the other, the latter appears to have been raised. For ancient faults it is practically impossible to determine the true change of position. Recent earth movements can be studied by levelling. A comparison between old and new triangulation records may establish results as to uplift or downthrow with respect to sea level. This is really the only satisfactory method, although certain physiographic features, when observed not too far from the coast, may be significant. For instance, where there is evidence that a late young topography, adjacent to the coast, has had its valleys suddenly aggraded from the shore line inland to a fault scarp which shows downthrow toward the sea, the seaward block has probably been depressed with respect to sea level. In this, as in other problems, the correlation of geologic and physiographic phenomena is of great importance.

191. Original Inclination of a Fault Scarp.—The average inclination of a fault scarp may be less than the dip of the fault (or faults) either because the displacement is a distributive fault or because the scarp has been lowered by erosion. Professor Davis has suggested a physiographic method of determining in a rough way how steep a dissected scarp may have been before it was modified by erosion.[1] If the fault had been very

[1] Bibliog., Davis, W. M., 1909, p. 754.

steep, as in Fig. 236, talus would probably have accumulated at the base of the scarp between the notches, and this rock waste would have been conspicuous in front of each triangular facet for a long time during the erosion of the fault block. The absence of talus with these relations would therefore indicate that the scarp was originally of comparatively low inclination, perhaps not much over 30° or 35° (**227**).

192. Topographic Forms as Evidences of Faulting.—None of the land forms listed in Art. **185** can be accepted as *prima facie* evidence for faulting. Perhaps the most significant are rifts, kerncols, and kernbuts, and certainly (1) scarps which interrupt the continuity of slope on constructional surfaces (**229**) and (2) local abnormal changes in stream courses associated with transverse scarps or rifts in the banks on either side (**189**) indicate faulting; but, in general, scarps, faceted spurs, gaps, and valleys may originate in other ways than by dislocation, and rifts, kernbuts, and kerncols are not always easy to recognize. Faceted spurs may be made by glacial scour or by marine erosion (**232**); valleys may be eroded upon belts of weak rock, or along lines of igneous contact and of unconformity (**250, B**); erosion scarps often look very much like fault scarps (**229**), and raised beaches, river terraces, etc.; may resemble low fault scarps in unconsolidated gravels or in other loose deposits (**233–238**). A common fallacy is to ascribe joint-faced erosion scarps to faulting. Such scarps are especially numerous in glaciated lands and they may be very striking in their regularity and in their extent. They are often the plucked sides of roches moutonnées. As in the case of many of the geologic structures mentioned in the preceding pages, these topographic forms suggest the possibility of faulting, but they do not prove it. Before they can be attributed to faulting, the geologist must demonstrate that there is no other reason for their being. In other words, he must be able to discriminate between them and other similar features of the land surface. For the comparison between like topographic forms, the reader is referred to Chapter XI.

JOINTS

Terminology and Classification

193. Definitions.—Well-defined cracks in a rock divide it into blocks. If, along such a crack, there has been no slipping of one block on another, or if one block has slipped only a very little against the other, the crack is termed a *joint*. Slight displacement may sometimes be seen when, for instance, a pebble in conglomerate has been split by a joint and the pieces have subsequently been cemented together in their altered position by vein material. The blocks between adjacent joints, or blocks bounded by joints, are called *joint blocks*. Their breadth depends upon the *spacing* of the joints. The opposing surfaces of two blocks at a joint are the *walls* or *surfaces* of this joint. Short or long, straight or curving, regularly or irregularly distributed, joints display great variety of character. They may be arranged in definite *sets*, all those belonging to one set having the same general direction. Often the fractures of one set are better developed than those of the other set or sets in a locality, and we then call the former the *master joints* or *major joints*. The strike and dip of a joint may be taken on the outcropping edge of the crack, or, if one block has been removed, upon the joint wall that still remains *in situ*.

194. Classification.—Theoretically joints may be classified according to whether they have been formed by compression, tension, or torsion; but since torsion is a special phase of tension there is no need to include it in the classification. Due to compression are; (1) irregular cracks induced by the expansion of rocks consequent upon chemical alteration; (2) sheet structure in massive, relatively homogeneous rocks; and (3) probably a majority of the regular joint systems in stratified rocks. Tension joints include: (1) irregular cracks formed in the shrinkage accompanying certain kinds of rock alteration; (2) hexagonal columnar structure and associated fractures due to cooling; (3) small local cracks, opened in folding, in the upper parts of some anticlines and less often in the lower parts of synclines; (4) gash joints transverse to cleavage in sheared rocks; (5) fractures clearly associated with tension faulting; (6) cracks due to the drying of muds, clays, and argillaceous limestones.

To say whether the origin of this or that joint or set of joints is to be ascribed to tension or to compression is not always possible. The criteria are too indefinite and the problem is often too complex for solution. Typical tension fractures bear on their surfaces evidences of pulling apart, of disruption. From their walls project the grains or pebbles or other physical constituents of the broken rock, and each projection on one joint surface is matched by a hollow from which it was torn on the other surface. Thus, tension cracks characteristically have rough, granular walls. On the other hand, joints arising from compression are really shear surfaces along which there has been a small differential gliding of the blocks. Such fractures cut across pebbles and large grains indiscriminately, so that the joint walls are apt to be comparatively smooth. Mathematical flatness and smoothness are prevented by the imperfect elasticity of rocks, and by other interfering factors. More significant than these surface features in determining the nature of the causal force are the larger relations to folds or to adjacent igneous bodies. These will be mentioned below in describing the more important types of joints.

Description of Joints

195. Columnar and Transverse Jointing Related to Igneous Eruption.—In the consolidation of magma which has been erupted in the zone of fracture, or in the consolidation of lava, there is often an accompanying diminution of volume. A tensile stress is set up thereby in the cooling igneous body and the strain at length may become so great that the rock may crack. Since cooling and consequent increase of tensile stress begin at the contacts of the eruptive body and proceed inward, the cracks likewise open first at the outside and then grow inward. If the igneous mass is chilled uniformly over a flat contact surface, according to a well-known physical law the fissures develop in three plane directions, each at 120° to the other two, and all at right angles to the contact surface at which they started. The blocks between the fissures are hexagonal columns (Fig. 193). At the same time transverse joints form parallel to the contact and therefore perpendicular to the lengths of the columns.

This kind of tension jointing is best exemplified in some sills, dikes, and lava flows, and it is sometimes found in laccoliths and necks, but it is by no means a constant feature in these eruptive bodies, for conditions are rarely suitable for its origin. There is usually a great deal of variation in the shape and perfection of the columns. They may curve, especially if the contact surfaces are not parallel. In cross section they are irregularly hexagonal and some may be found which are pentagonal or even quadrilateral. The transverse joints may be flat or curving and one such fracture may intersect one or several columns.

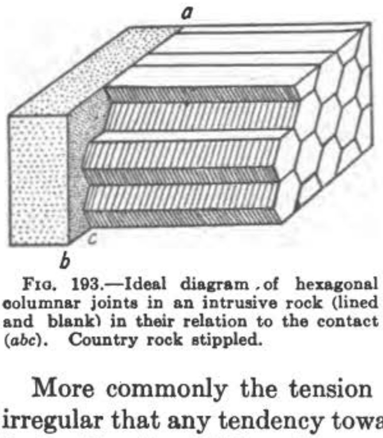


FIG. 193.—Ideal diagram of hexagonal columnar joints in an intrusive rock (lined and blank) in their relation to the contact (*abc*). Country rock stippled.

More commonly the tension cracks in eruptive bodies are so irregular that any tendency toward hexagonal columnar structure is hardly discernible. Yet, even in such cases, a master set of joints may be observed essentially parallel to the contact, while the associated fractures lie in various plane directions at right angles to it.

The joint structures resulting from cooling tension in an eruptive rock may also originate, though less frequently and with less regularity, in the adjoining country rock; for the latter, at first heated, later cools and contracts. The same relations as those above described exist here between joint directions and contact attitude.

All these tension fractures characteristically have granular, rough surfaces. Both types, columnar and transverse, whether in the eruptive or in the country rock, are best developed and have the closest spacing nearest the contact. Away from it their regularity decreases, their spacing increases, and they may actually fade away and disappear.

196. Columnar and Transverse Jointing Not Related to Igneous Eruption.—Sun cracks are an example of original or contemporaneous hexagonal columnar jointing. The tendency to open along the old fissures may persist even through the long period of burial and lithification of the mud, so that, when the consolidated rock is finally exposed to erosion, joints may form along the ancient sun-crack surfaces. These inclose short, roughly hexagonal columns just as the sun cracks did. Perpendicular to the bedding planes the columns fade away downward, but terminate abruptly upward. (Why?) These revived original fractures are seldom found. They have been noted not only in mudstones, but also in limestones which suffered exposure to the atmosphere at intervals during their accumulation.

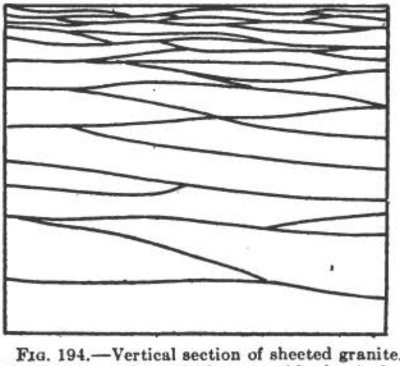


FIG. 194.—Vertical section of sheeted granite. The joints or sheets inclose roughly lenticular slabs of the rock between them.

197. Sheet Jointing in Massive Rocks.—Sheet structure, sheet jointing, or sheeting may be seen to good advantage in granite and other massive, homogeneous rocks. The joints are broadly undulating and are roughly parallel to the surface of the ground. They divide the rock into flat sheets, or into lenticular slabs that lie so that the thick part of one rests upon the thin ends of two underlying lenses (Fig. 194). The vertical spacing of the blocks, *i.e.*, the thickness of the slabs, increases downward. The fracturing is believed to be due to relief of pressure, and consequent vertical expansion, through removal of the overlying rock by erosion.[1]

[1] Bibliog., DALE, T. N., 1907, pp. 30–38.

When sheet jointing is present in massive sedimentary rocks considerable care is sometimes necessary to distinguish between it and stratification. Even granites and other igneous rocks that are well sheeted may look very much like strata from a distance.

198. Vertical and Irregular Joint Systems in Igneous Rocks.—Some granite quarries display two vertical joint sets which are approximately perpendicular to one another. They are thought to be effects of compression or of torsion, and, in respect to origin, may resemble the similar rectangular fracture systems in some strata (**199**). Irregular jointing is more common. In some places, called "headings," the cracks are so closely spaced that the rock breaks into many small blocks when quarried. All these fissures become less abundant downward from the earth's surface.

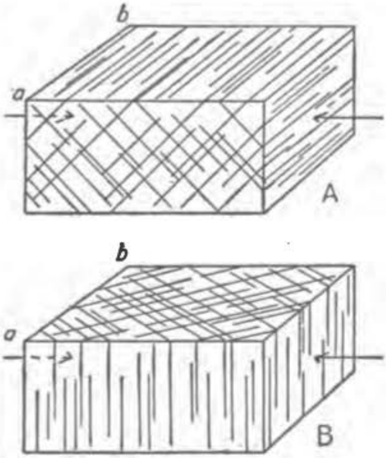


Fig. 195.—Compression joints made by forces acting in the direction of the arrows. *ab* would be the approximate strike of beds folded by these forces. In A both sets of fractures are strike joints; in B both sets are diagonal joints. All four sets might well be produced in a single rock mass. They are shown separately here merely for comparison.

199. Intersecting Joint Systems in Stratified Rocks.—In the stratified rocks of any district joints may be seen striking in all the directions of the compass, but among these a large proportion usually fall into two or more distinct sets. These are the major joints, and it is these that the following description concerns. The minor fractures are merely the outcome of the complex conditions of force and resistance that must obtain in a strained series of variable beds. Probably the majority of joints in stratified rocks are the result of compression or of torsion, seldom of simple tension.

1. Compression along a single axis may produce two, four, or more joint sets, and there is a tendency for fractures in intersecting sets to be perpendicular to one another and for all the sets to be approximately at 45° to the direction of compression (Fig. 195). All such joints are apt to show on their surfaces indications of slight shearing, and close inspection may reveal minute displacements between the severed parts of fractured objects in the rock. In a region of folding, if two joint sets only are well developed, both may strike roughly parallel to the fold axis (*strike joints*), or at an average angle of 45° to this direction (Cf. A and B, Fig. 195). If parallel to the axes, these joints dip so that they converge above anticlines and below synclines (Figs. 196; 197, A). It is possible also for joint systems to result from compression acting along the fold axes in the condition of strain for the formation of complex folds (**143**). If, through this *minimum* compression, fractures arise striking perpendicular to these lines of force, their average strike will be nearly in the plane of the dip of the main folds. They will be *dip joints*.

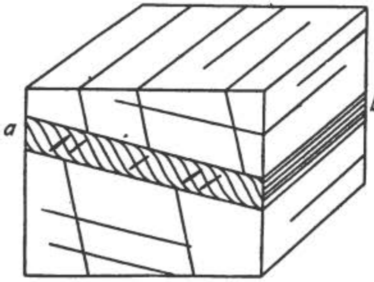


FIG. 196.—Block diagram of a thin, weak bed (*ab*) between two thick, strong beds. The fractures in the strong beds are strike joints formed by compression. Those which are parallel to the bedding are bedding joints. In the weak bed the curved fractures are fracture cleavage, and the five short cracks are gash joints formed by tension. (After E. Steidtmann, with modification.)

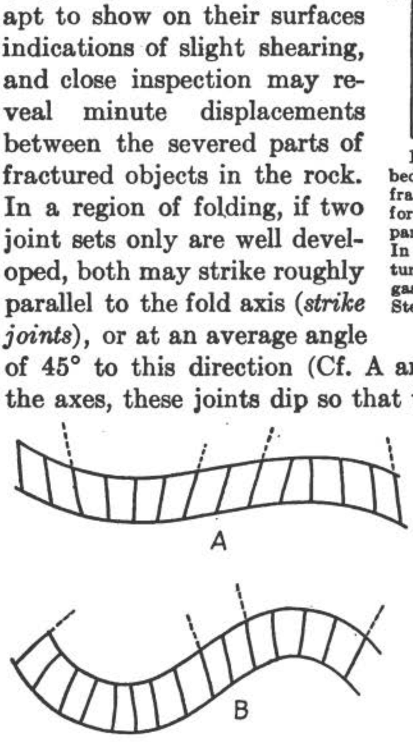


FIG. 197.—Sections of folded strata intersected by strike joints. In A the fractures are compression joints, and in B they are tension joints.

2. Torsion, like compression, may give rise to two, four, or more sets of joints which bear similar relations to one an-

other, and which tend to make an angle of 45° with the axis of twisting. Torsional strain probably accompanies the warping and compression that produce complex folds.

3. Sometimes tension may lead to the formation of cracks at the crests of anticlines and less often at the troughs of synclines, where stretching results from folding; but it is doubtful whether joints of this nature are common. In simple folds tension joints strike parallel to the fold axes, and in complex folds there are two sets, one striking parallel, and the other transverse, to the axes. These joints, unlike the fractures made in analagous positions by compression, dip so as to diverge above anticlines and below synclines (Fig. 197, B). Gash joints are short, local tension fractures (Fig. 196).

The geologist may take for granted that lithified, flat-lying strata have nearly always suffered broad-scale warping, although in small areas no dip may be apparent. These "horizontal" beds are commonly intersected by two main vertical joint sets approximately perpendicular to one another. Extended field work in some regions has demonstrated not only the existence of broad undulations in such strata, but also the fact that the two master fracture sets strike respectively perpendicular and parallel to the axes of the low folds and dip so as to converge above anticlines and below synclines. For these particular areas, then, the joints would seem to be of compressional origin.

In distinctly folded rocks conspicuous joint sets are more numerous and more closely spaced, and their study is correspondingly more difficult.

No individual joints, not even the master ones, are continuous for long distances. When a fracture ends it is usually replaced, on one or the other side, often with a few inches or a few feet of overlap, by other joints having the same trend. In strata of variable resistance, joints in one bed often end abruptly against an adjacent bed or they may turn and pass through the latter bed in a different direction.

Interpretation of Joints

200. Interpretation of Joints.—Our knowledge of joints is still so incomplete that we can seldom found general inferences upon field observations of their characters and mutual relations. To this statement hexagonal columnar structure is an exception. We know that the columns are apt to develop perpendicular to the igneous contact at which their growth commences. Therefore, if a rock has vertical columnar jointing, the contact is probably horizontal, and if the columns are horizontal the contact is vertical. If such columns are present, they are apt to be vertical or steeply inclined in recent lava flows, perpendicular to the adjacent strata in sills and laccoliths, and in dikes that cut stratified rocks they are parallel or inclined to the bedding.

In proportion as the columnar structure is less perfect, the transverse joints become more conspicuous. They may be of use because of their approximate parallelism with the contact. Following is an actual example: A certain outcrop of trap was intersected by what appeared to be a very complex system of joints. Upon close examination one fracture set seemed to be better developed than the rest. It had a definite trend and the cracks belonging to it were, many of them, continuous for several yards. They had a strike between N. 10° W. and N. 10° E. and a dip of about 50° eastward. There were several other less prominent joint sets more or less perpendicular to the master set. Knowing that trap occurred in this region generally in straight-edged dikes and assuming that the fissures were of the tension class, the geologist inferred that the master set corresponded to the transverse variety of joints, that the contact might have approximately the same attitude, and that therefore search should be made on the eastern and western edges of the outcrop. By removing the sod here and there this conclusion was proved to be correct. The country rock was found, the igneous rock was shown to be a dike, and the attitude of the dike was obtained. The value of this method lies, not in its infallibility, for it is by no means certain, but in its suggestiveness where contacts are hidden.

For the significance of certain kinds of joints in folded strata refer to Art. **209.**

Joints in Relation to their Time of Origin

201. Age of Joints.—From what has been stated above certain important conclusions may be drawn: (1) Joints having different attitudes may be of the same age, whether they are intersecting or not. (2) If, in homogeneous rocks, the joints of one set (A) are relatively short and always terminate against the fractures of another set (B), (A) may be younger than (B). (3) If joints in a given bed terminate abruptly against an overlying bed, they are not necessarily older than the latter; rather, they are almost surely younger. (4) Many joints are contemporaneous with folding that is accomplished in the zone of fracture. (5) Joints due to the cooling of an intrusive rock are younger than the adjacent country rock (**195**). (6) Joints due to the cooling of a lava flow are younger than the underlying rock. (7) Joints that are due either to drying or to cooling are essentially contemporaneous with the origin of the material in which they occur. (8) All other kinds of joints herein described are subsequent, *i.e.*, they are of much later date than the rocks intersected by them. To these statements may be added the following: (9) Joints may be synchronous with cleavage (*q.v.*). (10) Compression joints may be contemporaneous with compression faults (*q.v.*), and tension joints may be contemporaneous with tension faults (*q.v.*).

The geologic age of joints may sometimes be ascertained by their relations to dikes. For instance, in a certain region where late Carboniferous strata were folded before the Triassic period commenced, the beds are abundantly cut by several prominent sets of fractures. Parallel with these fractures and showing every sign of having been intruded into some of them, are numerous dikes of Triassic age. Obviously the joints are pre-

Triassic and post-Carboniferous, and they must therefore have been contemporaneous with the folding, or a little later.

Joints were no doubt developed near the earth's surface in the past just as they are today, and we might therefore expect to find signs of old fracture systems at surfaces of regional unconformity. However, it would require a shrewd geologist to prove that existing cracks in the underlying formation (below the unconformity) are old fissures reopened and are not joints of the same series as those in the overlying younger formation.

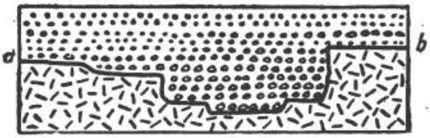


FIG. 198.—A line of unconformity (*ab*) which indicates by its form that the older formation (dash pattern) had vertical and horizontal joint sets prior to the deposition of the overlying sediments.

More satisfactory evidence is necessary. This may be found where the old joints were filled, previous to the first erosion period, by vein material or by dikes, or later, at the close of the erosion period, by sediments belonging to the overlying formation.[1] By their shape and relations to the surface of unconformity, these joint fillings may indicate something of the original character and arrangement of the fractures in which they were formed (Fig. 198).

JOINTS IN RELATION TO THE LAND SURFACE

202. Relations of Joints to Erosion and Topography.—Joints are the commonest kind of fractures in rocks. In promoting erosion they are of the utmost importance, for they serve as channels for waters that cause decomposition, they facilitate the wedge action of ice in disintegration and in glacial quarrying, and they invite concentrated attack by abrasive agents. Many erosional processes are accomplished by the removal of joint

[1] It must be clear that the old fissures were not opened along faults.

blocks. The surface configurations of ledges, cliffs, and mountain summits are generally conditioned by joints. Indeed, it has been demonstrated that the pattern of drainage and topography in a region often reveals a marked dependence upon the existing fracture systems. Thus, the elbow turns in many young streams are not infrequently due to a shift of the current from one joint set to another. The student should be on the lookout for this kind of topographic control, not only in the field, but also by comparing joint directions as plotted on a contour map with the pattern of rivers, lakes, and divides.[1]

FIG. 199.—Microscopic section of fracture cleavage (diagonal) crossing flow cleavage (horizontal). (After T. N. Dale.)

FRACTURE CLEAVAGE

203. Definition and Origin.—*Rock cleavage* has been defined by Leith as a "structure by virtue of which the rock has the capacity to part along certain parallel surfaces more easily than along others."[2] He goes so far as to include within the definition such primary parallel structures as bedding, flow structure in

[1] Bibliog., Hobbs, W. H.
[2] Bibliog., Leith, C. K., 1905, p. 11.

igneous rocks, etc. Ordinarily, however, in speaking of rocks, geologists apply the term "cleavage" to secondary structures only. This is the sense in which it is used in the present book.

Cleavage may be induced by fracture or by flowage. The discussion of flow cleavage is reserved for Chapter IX. *Fracture cleavage*, also called *fissility*, may be regarded as a special case of jointing or of faulting in which the displacements are minute and the "blocks" are thin sheets. Not infrequently it occurs in two or more intersecting sets that divide the rock into small polygonal blocks. In thin sections, for microscopic examination, fracture cleavage is seen to consist of true fissures (Fig. 199). Sometimes the microscope reveals columnar or platy minerals distributed in the planes of the fracture, with their long dimensions parallel to it, so that they give the appearance of flow cleavage (*q.v.*). They may have acquired this arrangement by growth after the origin of the fracture cleavage or by rotation of the parallel mineral grains of flow cleavage into parallelism with a subsequent fracture cleavage.

For further details on fracture cleavage refer to Chapter IX.

BRECCIAS AND AUTOCLASTIC STRUCTURES

204. Definition and Classification.—The term *breccia* (pron., bretchia, not breck-chia) is derived from a root which means to break. As far as its origin is concerned, it might be applied to a rock which is intersected by closely spaced joints, but this use is not accepted. The word is best employed for rocks which have the following qualifications: (1) the rock consists of an unsorted mass of angular fragments contained in a matrix of the same or of different material; (2) these fragments have acquired their angularity through breaking, not by abrasion; (3) the materials may have been somewhat shifted from their position before breaking, but ordinarily the change of position is not great. To these qualifications there are some exceptions which will be noted below. The class of breccias includes fault and other friction breccias, talus breccias, breccias resulting from change of volume, explosion breccias, flow breccias, and intrusive breccias.

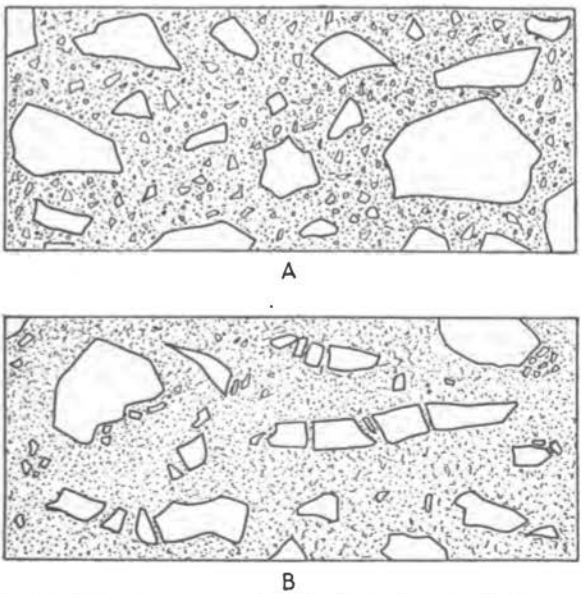
1. To friction breccias belong fault breccias and shatter zones caused by mechanical stresses acting through the earth. They grade into cataclastic structure, a microscopic kind of brecciation present in many gneisses and schists. Both compressional (thrust) and tensional (gravitational) faulting may cause irregular fracturing by the grinding of the blocks against one another, and sometimes the fragments may show evidences of rubbing (**44**). By excessive attrition due to shearing such fragments may become more or less rounded. The matrix of a friction breccia generally consists of the same substance as the larger fragments, but in a more finely pulverized condition. Friction breccias such as those just described are called *autoclastic* ("self-broken") rocks. In general, as contrasted with normal clastics, they are apt (*a*) to consist of homogenous material like that of the adjacent rocks, (*b*) to contain a large proportion of vein cementing substance, and (*c*), when in strata, to trend across the bedding; but none of these criteria is decisive.

Under friction breccias may be put certain fracture structures of superficial origin. Breccia structures may result from overriding ice. The disrupted material may have been solid rock or unconsolidated gravel, sand, or mud, temporarily cemented by interstitial ice (**84a**). Evidences of associated glacial deposits and signs of ice abrasion should be sought. Landslide débris and breccia structures caused by other kinds of gravity slipping of essentially superficial origin may also be listed here.

2. Since talus débris is the product of a disruptive process it is properly classified as a breccia; but it differs from friction breccias in that the fragments accumulate many feet or even several hundreds of feet from their source. Coarse-grained rocks may suffer rounding by disintegration so that the talus fragments may lose their angularity. Criteria for consolidated talus are: (*a*) the materials show different degrees of weathering; (*b*) the matrix is of the same materials as the larger blocks; (*c*) the deposit is often associated with other sediments as a basal accumulation above a regional unconformity; (*d*) the deposit is banked up against a cliff (usually buried if the talus is con-

solidated rock). The materials of talus are homogeneous or heterogeneous, depending upon the nature of the cliff rock from which they were derived.

3. Rocks may be broken as well as folded (9 in **154**) by change of volume effected by decomposition. Breccia structure of this origin does not in itself cause removal of the fragments.



Fid. 200.—Breccia structures. A, agglomerate; B, flow breccia. In B many of the fragments seem to have fitted together and to have been separated by only a little distance. This is because they were broken essentially *in situ*. The fragments in A were thrown by volcanic explosion some distance from the place of their shattering.

If they remain essentially in place, they constitute a mass which grades down into the subjacent unshattered rock of the same kind. Being for the most part only slightly dislodged, they can often be seen to have once fitted together. There are no signs of faulting. Interstitial material between the fragments is in relatively small amount and is apt to be foreign.

4. Tuff and agglomerate are varieties of breccia, the fragments

having been broken and thrown up by volcanic explosion. The larger blocks in agglomerate may be of lava or of the country rock which was pierced by the conduit, and the matrix may consist of tuff, with or without finely comminuted country rock (Fig. 200, A). Vein cementing substances are common. The best criterion for pyroclastics, aside from their lithologic characters, is their interstratification with recognized lavas.

5. Flow breccias (Fig. 200, B) are formed by hardening and breaking of the surface of a lava sheet while still flowing. The fragments and the matrix are of the same material, the matrix having frozen about the fragments from a molten condition. Various lava structures are usually present both in the fragments and in the matrix.

6. The process of intrusion may be accompanied by brecciation of the country rock, or brecciation by some other method may be followed by invasion of the shattered zone by magma, and in either event the injected magma will congeal as a matrix round the fragments of the country rock. Plutonic differentiates may harden and then be broken by movements of the residual magma which subsequently freezes about the inclusions. Again, by magmatic stoping, blocks split from the roof of a magmatic chamber (batholith, etc.) may be preserved as angular masses in the marginal parts of plutonic bodies. All these are ordinarily classed as intrusive breccias (plutonic breccias, shatter breccias, neck breccias, etc.) (refer to Arts. **123–126**). The only rocks with which they are likely to be confused are flow breccias. Their recognition depends upon the determination of the matrix rock as unquestionably intrusive in its relations.

CHAPTER IX

METAMORPHIC ROCKS

Metamorphism in General

205. General Conditions and Effects of Metamorphism.—It has been pointed out in Art. **140** that the lithosphere is divisible into a lower zone of flowage and an upper zone of fracture. All through the lithosphere water is present, but it is in relatively small amount in the lower zone. In the upper zone it occupies fractures and other open spaces. From the zone of flowage upward to a level near the earth's surface, called *ground-water level* or the *water table*, the rocks are saturated with moisture. Above the water table is a thin shell which has a variable water content and in which the principal movement of the water is downward. This outer shell of the zone of fracture is known as the *belt of weathering*, for processes of weathering are here predominant. Since the water table may fluctuate, rising in wet weather and falling in dry seasons, and since, locally, it may even reach above the earth's surface, as seen in ponds and rivers, the belt of weathering has a thickness which varies from zero to several hundred feet. The saturated rocks between the water table and the zone of flowage are in the *belt of cementation*, so called because many substances dissolved in the belt of weathering are carried down and deposited in this underlying region, thus cementing grains together and filling open spaces. It is here that most vein deposits originate (see Chapter X).

Now, all rocks are more or less subject to alteration if the conditions under which they were formed are changed. Such alteration is called *metamorphism*. It may be induced chemically or mechanically. *Gases* and *liquids, heat, static pressure* (simple downward pressure), *stress*, and *duration of time* are the important factors concerned in both chemical and mechanical changes. On account of the different conditions existing at various depths within the lithosphere, different chemical processes assume chief importance in the zones and belts referred to above. In the zone of fracture, oxidation, hydration, and carbonation prevail, the first being particularly characteristic of the belt of weathering and the other two, of the belt of cementation. Complex silicates break down and simpler, less dense minerals form. These processes are therefore said to be katamorphic (*κατά, down*, and *μορφή, form*) and the zone is called the *zone of katamorphism*. In contrast to this, reactions in the zone of flowage may involve deoxidation, dehydration, and decarbonation. Here silicates are built up, and the great pressure leads to the formation of denser minerals and a compact crystalline structure. This is known as the *zone of anamorphism* (*ἀνά, up*, and *μορφή, form*).[1] According to definition, any kind of alteration that any rock has undergone, whether katamorphic or anamorphic, comes under the head of metamorphism, but there are many geologists who prefer to restrict the meaning of the more general term so that it does not include weathering. It will be used in this restricted sense in the present book.

Four important processes leading to change of the conditions under which rocks originate are erosion, sedimentation, eruption, and mountain building.

1. Through erosion rocks that were once at great depths are brought into regions of lower temperatures and pressures than those which prevail farther down in the lithosphere.

2. Sedimentation works in the opposite direction. Materials accumulated on the earth's surface, volcanic products, and high level intrusive bodies (after their crystallization) suffer a gradual increase in temperature and pressure as they become more and more deeply buried, and ultimately they may enter the influence of anamorphic conditions. The weight of the overlying rocks is to be regarded as a simple downward static pressure which induces

[1] The reader is referred to Bibliog., LEITH, C. K., and MEAD, W. J., for a general discussion of the subject.

little or no rock flowage. Hence the new minerals that develop are apt to be those with equidimensional forms (*e.g.*, garnet) or, if they are bladed or tabular (hornblende, staurolite, ottrelite, biotite, etc.), they grow in all sorts of positions (Fig. 201). This is *static metamorphism* (Cf. 4, below). The increasing weight of accumulating sediments may sometimes so far compress the strata, vertically, that there is some differential lateral slipping and the consequent growth of mica plates parallel to this slight motion (Cf. 4, below).

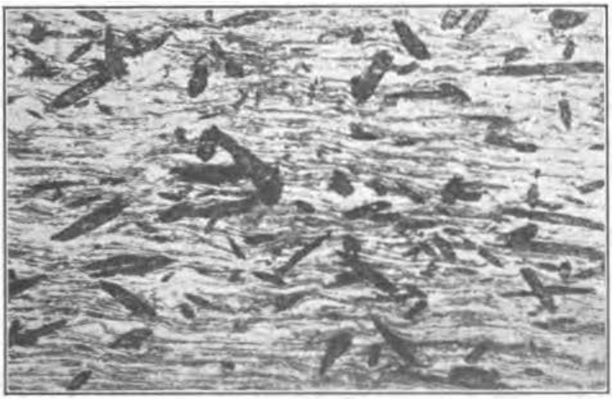


FIG. 201.—Metacrysts of hornblende in a gneissic rock. The metacrysts were formed after the development of the parallel gneissic structure. (About ⅓ natural size.)

3. Through intrusion of magma or overflow of lava the adjacent materials may be heated, invaded by gases and liquids, and otherwise affected. Of the several agents concerned, pressure is usually of least importance. For the most part the alterations are chemical and mineralogical and they are often of the anamorphic type, even within the zone of katamorphism. They come under the head of *contact metamorphism* (see Arts. **118–122**).

4. The forces which give rise to folds and compressional faults in the processes of mountain building are very effective agents

of metamorphism. At any given point in a rock subjected to stress, the forces may be regarded as resolvable into three components at right angles to one another, the maximum, mean, and minimum stresses. A rock under this kind of unequal compression may be deformed by fracture or flowage. The metamorphism is said to be *dynamic*.

Rock cleavage (**203**) is a common result of dynamic metamorphism. That which is developed in the zone of fracture is

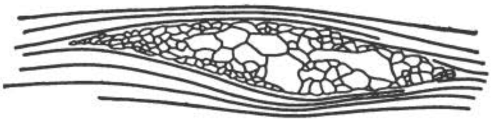


Fig. 202.—Lens of quartz granules in schist. (Enlarged 15 diameters.) The curving lines represent layers of mica, which wrap round the quartz. The lens originated through crushing of a large quartz grain. The mica was formed by recrystallization of substances which were present in the rock before metamorphism.

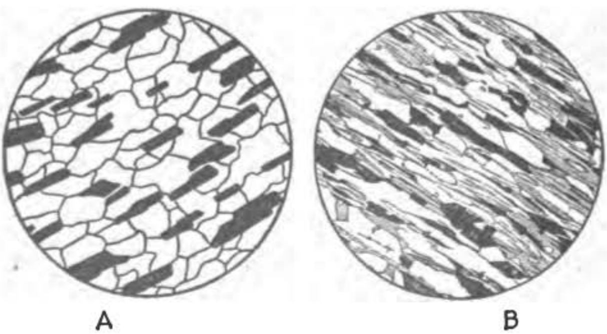


Fig. 203.—Microscopic sections of cleavage structure developed through rock flowage. In A the biotite (black) is arranged with its laths all parallel and the quartz grains (white) have a slight tendency to be elongate parallel to the mica. In B there are three different minerals, all of which are oriented in parallel position. Which rock would probably have the better cleavage? (B is after Blackwelder and Barrows.)

fracture cleavage. In the lower zone, flowage is itself a metamorphic process. It leads to the origin of *flow cleavage*, a structure consequent upon the parallel orientation of platy and columnar minerals and of minute lenticular aggregates of grains (Figs. 202 and 203). Locally, along surfaces of slipping, a parallel arrangement of minerals may be produced in the zone of fracture. Flow cleavage is called *slaty cleavage* when it is so perfect that the rock splits into thin plates of uniform thickness, and it is called *schistosity* when the rock splits easily, but not

FIG. 204.—Microscopic section of "sliced" feldspars (white) in mica schist. (After C. K. Leith.)

always very regularly. Rocks exhibiting these features are called slates and schists, respectively. Micas are the commonest of the thin, flat minerals that give rise to flow cleavage. They often cause a distinct sheen on the broad surfaces of the cleavage frag-

FIG. 205.—Side view of a specimen of gneiss having parallel linear structure. (Cf. Fig. 206.)

ments. Many schists have the mica flakes distributed in wavy lines (seen in cross section) which alternately meet and separate, and so inclose lenticular areas in which the constituents other than the mica predominate. These lenses range from a few inches to many feet in length. A *gneiss* is a metamorphic rock in which a banded distribution of its constituents is more conspicuous than a parallel orientation of the individual grains. Many gneisses contain feldspar, quartz, and mica, so that they look like granitic rocks, especially if their banding is not pronounced (**214**).

Flow cleavage is produced, *i.e.*, rock flowage is accomplished, by granulation, recrystallization, and rotation, thus: (1) Brittle minerals are crushed and the aggregates of minute fragments are flattened in planes at right angles to the maximum stress (Figs. 202, 204). This is *cataclastic structure.* (2) From the old constituents new minerals are built and these are apt to be species with tabular or columnar shapes (Figs. 203, 204). If tabular, they grow with their flatness normal to the maximum stress, and if columnar, they grow in various directions in planes normal to the maximum stress (*plane schistosity*), or, if the mean and maximum forces are approximately equal, such crystals may develop with their lengths parallel and in line with the minimum stress (*linear schistosity, linear parallel structure*) (Figs. 205, 206). (3) Old or new constituents may be rotated into approximate parallelism.

FIG. 206.—End view of a specimen of gneiss having parallel linear structure. (Cf. Fig. 205, another view of the same specimen.)

After flowage has ceased and static conditions have been resumed, heat, moisture, etc., may still continue to operate and so produce minerals without parallel arrangement. These will lie scattered in various positions through the schist or slate; that is to say, the features of static metamorphism will be superposed upon those of dynamic metamorphism. Often these later crystals are large and conspicuous. Being of origin *subsequent* to that of their inclosing matrix, they are termed *pseudophenocrysts* or *metacrysts*, and the structure is *pseudoporphyritic* (Fig. 201).

Quartzite and marble deserve mention here. Both rocks are not infrequently seen interbedded with schists, yet as a general rule neither displays much evidence of flow cleavage. Both may originate under either static or dynamic conditions, through pressure or through contact metamorphism. In quartzite that was formed under dynamic conditions, the quartz grains are usually a little longer than wide, and they are oriented in parallel position, but the elongation is not enough to be recognized by the eye. The massive character of marble is probably to be accounted for by the ease of recrystallization of calcite. Under static conditions following the cessation of differential pressure, the calcite readily recrystallizes without linear arrangement of its grains. If impurities are sufficiently abundant in these rocks, minerals such as the micas, amphiboles, etc., may be developed with distinctly parallel orientation in dynamic metamorphism, but without orientation in static metamorphism.

Several kinds of metamorphism have already been mentioned. Such are static, dynamic, and contact metamorphism, anamorphism, and katamorphism. *Regional metamorphism* is a term often used in contrast with contact metamorphism, because the latter is generally rather local; but this distinction is unfortunate for alterations caused by intrusion are sometimes very extensive in their distribution. It would be less confusing further to qualify the word "regional" by "static," "dynamic," or "contact," when the discrimination is necessary.

Study of Cleavage

206. Relations of Flow Cleavage and Fracture Cleavage.— Fracture cleavage may originate in rocks which have not been below their zone of fracture, or it may be developed in rocks which have already been folded and had a flow cleavage induced upon them in the zone of flowage and which have later been subjected to further compression in the zone of fracture. In the latter case the fracture cleavage is nearly always preceded by minute folding (crenulation) of the older flow cleavage. These relations are represented in Fig. 207. In rocks which have had fracture cleavage induced upon them and then flow cleavage, the earlier cleavage is destroyed.

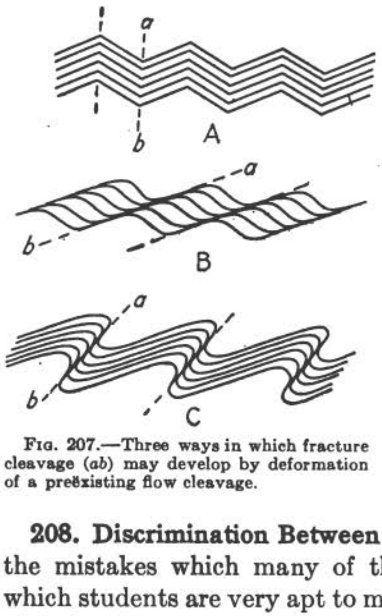


FIG. 207.—Three ways in which fracture cleavage (*ab*) may develop by deformation of a preëxisting flow cleavage.

207. Discrimination Between Flow Cleavage and Fracture Cleavage.—When fracture cleavage occurs in several sets, the planes of parting are equally good in different directions, whereas if flow cleavage is found in intersecting planes, one set is usually much smoother and better developed than the other. For further distinctions between the two varieties of cleavage the reader is referred to Bibliog., Leith, C.K., 1905, page 125.

208. Discrimination Between Bedding and Cleavage.—One of the mistakes which many of the old-time geologists made and which students are very apt to make at first, is to confuse cleavage with bedding. The error is most natural, for on weathered rock surfaces both structures may look much alike. But cleavage, in its superficial expression, often appears as parallel fractures, whereas bedding consists of parallel layers of different textures and often of different colors. If there is doubt, study the rock closely and see whether its parallel structure is due to cracks or to layers of varying character. The strike and dip of cleavage may be recorded on a map, but on such a map there must be clear indication which symbols are for cleavage and which for stratification.

209. Relations of Cleavage and Bedding in Folds.—It has been stated (**143**) that in parallel folding adjustment is ac-

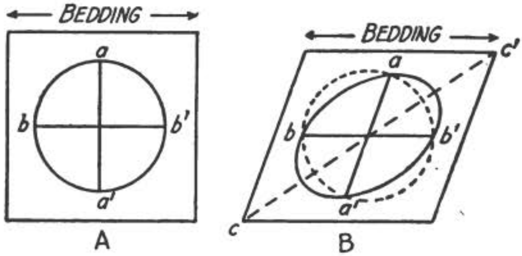


FIG. 208.—Relations of flow cleavage and compression joints to deformation. The diagrams are supposed to be drawn on the edge of a bed, as seen in section. A, before folding; B, after folding. The square and circle of A become a rhombus and an ellipse in B. In its proper position in the fold, *aa'* in B should be vertical. The bedding and the line *bb'* would then be inclined toward the left. B has been placed in its present position to emphasize the relations between it and A. The lines *aa'* and *bb'* in B indicate the positions of compression joints and fracture cleavage which may be produced in the deformation. *cc'*, the direction of greatest elongation of the rock, is the position for flow cleavage. (Cf. Fig. 209.)

complished by the shearing of contiguous strata on one another. Each bed on the limb of a fold slips on the next underlying bed *toward the nearest anticlinal axis.* This differential movement has a tendency to produce cleavage planes or joints either parallel to the stratification or at an acute angle to it (Figs. 208, 209). In the latter case the cleavage planes "lean toward the direction of motion." They dip so as to converge upward in anticlines, like the axial planes of drag folds (**145, 150**). When beds differ in their competency, cleavage may be developed in this way in the weaker layers only (Fig. 209). It may change a

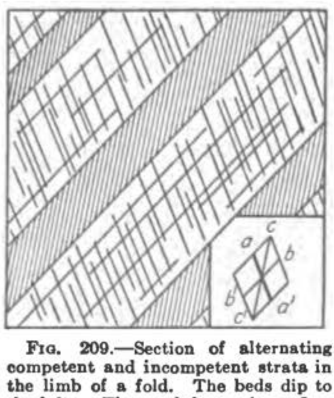


FIG. 209.—Section of alternating competent and incompetent strata in the limb of a fold. The beds dip to the left. The weak layers have flow cleavage, parallel to *cc'*: the strong layers are intersected by two sets of compression joints, parallel to *aa'* and *bb'*. (Cf. Figs. 196, 208.)

little in direction where it approaches the contacts between beds of different resistance (Fig. 196), and its average attitude in one stratum may vary several degrees from its average attitude in an adjacent stratum.

In similar folds, with which flow cleavage is usually associated, since both are produced in the zone of flowage, this cleavage may be extensively developed with a uniform dip regardless of its position in the folds. It is approximately parallel to their axial planes (Fig. 210). Hence, while it is nearly or quite perpendicular to the bedding in the axial parts of the folds, it may be essentially parallel to the bedding on the limbs. As a matter of fact these are the relations which exist on a much smaller scale between minor drag folds and cleavage when both structures occur together (Cf. Figs. 126, 211). It would seem, then, that the major folding and its associated monoclinal cleavage might be concomitant effects of a powerful control, such as the overriding of a great rock mass in the process of overthrusting, just as the drag folds are a smaller product of differential shearing between separate beds.

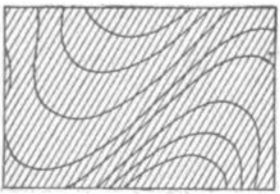


Fig. 210.—Relations of flow cleavage to folds.

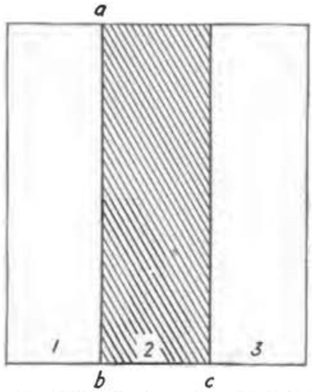


Fig. 211.—Section of vertical strata. 1 and 3 are competent beds; 2 is an incompetent bed with cleavage.

210. Uses of Cleavage in Geologic Interpretation.[1]—The relations between bedding and cleavage as described in the last section are useful as criteria in the interpretation of geologic

[1] See Bibliog., Leith, C. K., 1913, p. 129, the source for many of the following statements.

structure. An outcrop in which cleavage is perpendicular to the bedding is probably near the axial region of a fold, and one where cleavage is inclined to the bedding at an acute angle is probably in the limb of a fold. Of great importance in this connection are the two rules which have been stated before with reference to parallel folding, namely, (1) the cleavage planes lean in the direction of differential movement between adjacent beds (Fig. 209), and (2) this differential motion is such that any bed slips over the next underlying bed upward toward anticlinal axes (**145**). By the application of these rules the geologist can tell on which limb of a fold an outcrop is situated, and which are the upper and lower beds in cleaved vertical strata. Thus, in Fig. 211, at the contact *a–b* the cleavage cracks in bed 2 lean toward *a* and so indicate that 1 moved over 2 in this direction. Similarly, 3 slipped along 2 toward *c*. This section, then, must be a part of a limb between an anticline on the right and a syncline on the left. Successively younger beds are crossed up to the axial region of the syncline in passing from right to left across the outcrops (Cf. **151**). "Cleavage in a slate area may strike east and west and dip south at an angle of 45°. The inference is that here are similar composite folds with east-west trend and axial planes dipping to south; further, that the structure was developed by the relatively northward movement of some overlying competent rocks which have been removed; finally this inferred major control suggests a major anticline to the north."[1]

211. Distortion of Original Structures, Fossils, Pebbles, etc.— Of the two kinds of metamorphism, static and dynamic, the former is least apt to blur and destroy original structures in a rock. Pebbles, fossils, and such lithologic features as ripple-mark and cross-bedding are little, if at all, altered in shape, except in so far as they are flattened by compression of the rock as a whole (Fig. 212). Indeed, the lithologic structures may be made more conspicuous by the growth of new minerals in layers or lines such as to emphasize contrasts. Dynamic meta-

[1] Bibliog., LEITH, C. K., 1913, p. 132.

morphism, and especially rock flowage, has a marked distorting effect. In similar folding, beds are thinned on the limbs and thickened in the axial regions (**143**). Sometimes strata are irregularly thinned and thickened so that they "pinch and swell," as seen in cross section. Pinching may go so far that a bed

Fig. 212.—Section of the trunk of an ancient tree (Sigillaria), flattened by simple compression. (About ⅓ natural size.)

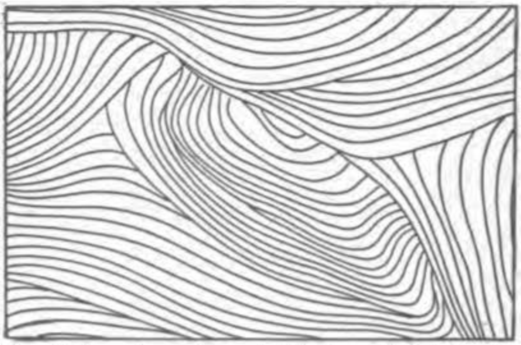


Fig. 213.—Section of deformed curved cross-bedding in vertical strata. By the rule stated in Art. 151, in which direction would one go to find younger strata?

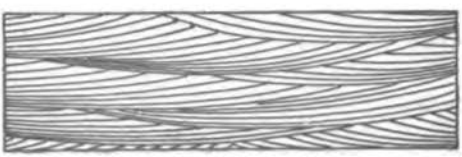


Fig. 214.—Section of curved cross-bedding which has been somewhat flattened by compression.

which was once continuous now consists of a series of detached lenses.

Obviously distortion which can have these results must seriously modify the forms of original minor structures. The laminæ in cross-bedding may be folded (Fig. 213) or their curvature may be flattened (Fig. 214).[1] In proportion as they suffer deformation, their usefulness in determining stratigraphic sequence lessens (**151**); and the same is true of ripple-mark. Pebbles may be squeezed into spindle-shaped rods (linear

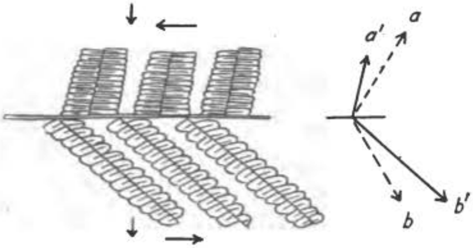


Fig. 215.—Part of a fossil frond deformed by shearing. The midribs of the leaflets once had the positions *a* and *b*. By the shearing the leaflets above have been shortened and rotated toward the left (*a'*), and the leaflets below have been lengthened and rotated toward the right (*b'*). (About ½ natural size.)

Fig. 216.—Deformed impression of the shell of a Spirifer. (About natural size.)

schistosity) (Figs. 20, 21) or they may be flattened into thin sheets (plane schistosity), the deformation in both cases being accomplished by rock flowage. Fossils also may be distorted

[1] Schists sometimes have a wavy streaking of their constituents in thin lines that may be mistaken for cross-bedding.

(Figs. 215, 216), and unfortunately only a little shearing is enough to deprive them of their value so far as this depends upon the recognition of species.

In the deformation of any lithologic feature, all stages may exist between very slight change and very great change (**212**), and in rocks that have been intensely metamorphosed such original features may have been obliterated. Thus, curious though it may seem, the distinction between sheared quartz veins and sheared quartzite pebbles may be almost impossible in cases of extreme metamorphism. Lithologic structures in igneous rocks may likewise be deformed, but here one must be careful not to confuse phenomena due to magmatic flow with those which are of truly metamorphic nature (**214**). If possible it is good policy for the beginner to postpone studying highly metamorphosed rocks in the field until he has first become familiar with the primary characters of sediments and igneous rocks.

212. Degrees of Dynamic Metamorphism in Clastic Sedimentary Rocks.—Like contact metamorphism, dynamic metamorphism exhibits various degrees of intensity (**121**). To be sure there is great complexity in the latter type of alteration on account of many factors, such as the composition and texture of the rock, yet certain stages can be recognized. (1) The first indications of metamorphism, as seen in hand specimens, are a poor secondary cleavage and a faint gloss on the cleavage surfaces, both due to the presence of a little white mica (sericite or paragonite) in fine laths that have roughly parallel orientation. (2) When shearing has been somewhat more intense, the white mica laths have more perfect parallelism and there are more of them, so that the rock cleavage is better and the sheen on the fracture surfaces is more conspicuous. Sometimes other secondary minerals, like biotite and ilmenite, are found, although these may have originated under static conditions after the cessation of rock flowage (page 234). Fossils are somewhat distorted. Pebbles are slightly, if at all, deformed, but they have thin coats of mica. (3) In what may be called the third stage, secondary cleavage is good and is often consequent upon the parallelism, not only of the white mica, but also of ilmenite, biotite, etc.; that is, all these cleavage minerals grew during rock flowage. Fossils are much distorted. Pebbles, too, are distorted and are thickly coated by white mica. (4) Maximum metamorphism is represented in the fourth stage. Original structures and fossils are largely obliterated and pebbles have been very much deformed. All the minerals in the rock are secondary.

These stages are not sharply defined, nor do they hold for all classes of rock. As they have been described above, they are applicable to many metamorphosed clastic sediments. Other things being equal, flowage is easier in mudstone than in sandstone and in sandstone it is easier than in conglomerate; that is to say, under similar conditions of pressure, etc., mudstones may acquire a higher degree of metamorphism than sandstones, and sandstones reach a higher stage than conglomerates.

Recognition of the Ultimate Origin of Metamorphic Rocks

213. Discrimination Between Metamorphosed Sedimentary Rocks and Metamorphosed Igneous Rocks.—The facility with which the original classification of a metamorphic rock can be ascertained depends largely on how much the rock has been modified. Seldom is this problem insoluble. Even in cases of extreme metamorphism there are generally some characters, physical or chemical, local or regional, which give intimation of the primary nature of the rock. Some of the more useful points of distinction are noted below.

(1) An important field evidence is an observed gradation in the exposures of a rock from its highly metamorphosed condition to less altered phases where its source is recognizable. In deformed sediments the least altered portions are likely to be found in the axial regions of the folds. (2) Look for original structures that are surely identifiable, such as contacts in the case of igneous rocks, and pebbles, fossils, cross-bedding, etc., in sedimentary rocks. Faults and unconformities must not be

mistaken for igneous contacts (**288**). (3) Original textures, such as porphyritic texture, may be preserved. (4) Igneous rocks may be uniform over large areas; sedimentary rocks often have a regular and continuous banding. (5) Intercalation of beds of limestone or quartzite is good evidence for sediments, but sometimes calcite and quartz veins may be misinterpreted for beds. (6) Graphite may be sparsely distributed through an igneous rock or it may occur in veins. However, if it is uniformly disseminated in distinctly argillaceous or quartzose layers, or if it forms beds intercalated between such layers, it and its associated rocks are probably of sedimentary origin. (7) Great preponderance of quartz is characteristic of some sediments. Confusion may arise in the case of sheared quartz veins and highly quartzose pegmatite dikes. For other criteria, which are mostly microscopical and chemical, the reader is referred to Trueman and to Leith.[1]

214. Discrimination Between Primary and Secondary Gneisses.—Primary gneisses are igneous rocks which possess a foliation produced before crystallization was complete. Secondary gneisses are those which acquired their structure through true rock flowage and not through the viscous flow of a stiff magma. Certain characters of primary gneisses, useful as criteria for distinguishing between the two classes of rock, are noted in the following quotation from Trueman:[2] "Field evidence: Banding in apophyses from the gneiss parallel to the walls and at an angle to the schistosity of the inclosing rock; dikes of pegmatite belonging to the same magmatic series as the gneiss and either parallel to the gneissic structure and foliated with it or cutting the gneissic structure and undisturbed; lack of sharp contact between the acidic and more basic portions of the gneiss, indicating high temperature during the solidifications of the different bands; presence of inclusions of foreign rocks, which are but slightly deformed, in a matrix of well-banded gneiss; presence of distinct bands of widely different composition, none of which may show

[1] Bibliog., Trueman, J. D.; Leith, C. K., 1913.

[2] Bibliog., Trueman, J. D., p. 231.

evidence of shearing; flow-like curves of the banding, some of which may close in a circle.

"Mineralogical evidence: Presence of minerals formed characteristically only from igneous melts and arranged in a manner impossible of formation from solid rocks by metamorphism, *e.g.*, nepheline and olivine; textures due to crystallization from an igneous melt."

Metamorphic Rocks in Relation to their Time of Origin

215. Relative and Geologic Age.—Since metamorphosed rocks were once typical sediments or typical igneous rocks, their age relations are in general similar to those of the rocks from which they were derived. That these relations are more difficult to recognize in their case, however, is suggested in the preceding paragraphs.

The geologic age of metamorphic rocks can seldom be determined directly by fossil contents. Ordinarily it must be obtained by correlation with other rocks whose age is known.

Metamorphic Rocks in Relation to the Land Surface

216. Original Depth of Metamorphic Rocks.—A rock which has characteristics due to rock flowage must have once been within its zone of flowage. A comparatively weak rock, like shale, may have undergone anamorphic changes at a moderate depth; but if all the rocks in a formation, even the most resistant types, have flow cleavage or other features unquestionably of anamorphic origin (not contact metamorphism), probably these rocks were altered in the zone of flowage, that is, below the region where both fracture and flowage are possible. On the assumption that the upper part of the zone of flowage is several miles below the earth's surface (**140**), this would mean that these rocks have been exposed through the erosion of a cover of that thickness.

CHAPTER X

MINERAL DEPOSITS

Mineral Deposits in General

217. Terminology and Classification.—A mineral deposit is a natural concentration of one or more mineral species. The concentration may be brought about by sedimentary, igneous, or metamorphic processes. Such deposits are *primary* if they still preserve their original characters and relations to adjoining rocks, and they are *secondary* if they have suffered partial or complete chemical or mechanical alteration since their origin. In the formation of a secondary deposit the materials often change their position. With reference to the time of their origin as compared with that of the inclosing rock (country rock), primary bodies are either *contemporaneous* (*syngenetic*) or *subsequent* (*epigenetic*). The contemporaneous varieties are further divided into those which are *igneous* and those which are *sedimentary*. Subsequent mineral deposits include *open space deposits* and *replacement deposits*. Secondary deposits, produced by various processes of erosion, may be concentrated by chemical or mechanical means.

It is not the author's purpose to enter into detail concerning mineral deposits. All classes are abundantly represented by ores, *i.e.*, by deposits which are of economic importance, and therefore, if the student wishes full information on the subject he should consult books devoted to economic geology. We are here interested particularly in structural and field relations. With respect to the different types noted above, all discussion of contemporaneous primary mineral deposits and of secondary mineral deposits will be omitted from this chapter. Igneous primary deposits, resulting from processes of magmatic differentiation and segregation, answer to statements made in Chapter VI; sedimentary primary deposits are merely beds which, in general, have structural and field relations like those described for stratified rocks in Chapter V; and many of the facts outlined in Chapters V and IX are applicable to secondary mineral deposits. The only types left for description here are open space and replacement deposits.

Study of Subsequent Mineral Deposits

218. Origin of Subsequent Deposits.—Underground waters, whether they have descended into the lithosphere from the earth's surface or have been given off by intruded magmas, contain a variable proportion of mineral substances in solution. In their circulation these waters may come under certain influences which induce the deposition of some of the solutes. Precipitation may be caused by cooling, by the mingling of different solutions, by chemical reactions between a solution and the rock through which it is passing, and in other ways. The same is true of gaseous solutions which probably emanate from magmas in considerable quantities (121). In the zone of fracture the precipitated minerals may incrust the walls of open spaces and line them with layer upon layer until the openings are partly or wholly filled. Thus originate open space deposits (Fig. 217). Under certain circumstances mineral-bearing solutions may attack a rock, removing its constituents in

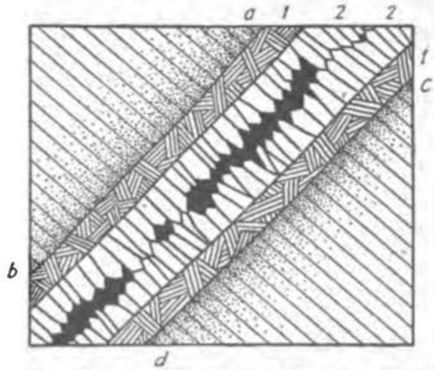


Fig. 217.—Section of an open space vein. The mineral numbered 1 was deposited before that numbered 2. The black represents spaces still unfilled. *ab* is the hanging wall and *cd* is the foot wall. The stippled part of the country rock adjacent to the vein has been metasomatized.

solution and precipitating new ones by a process of substitution or *replacement*. This is also known as *metasomatism*. Such *replacement deposits* may be formed either in the zone of fracture or in the zone of flowage. Metasomatism is often associated with intrusion as one of the important phases of contact metamorphism (Fig. 218).

Although any rock may be altered by replacement if the conditions are favorable, some kinds are much more susceptible than others. Limestone is one of the types that are metasomatized

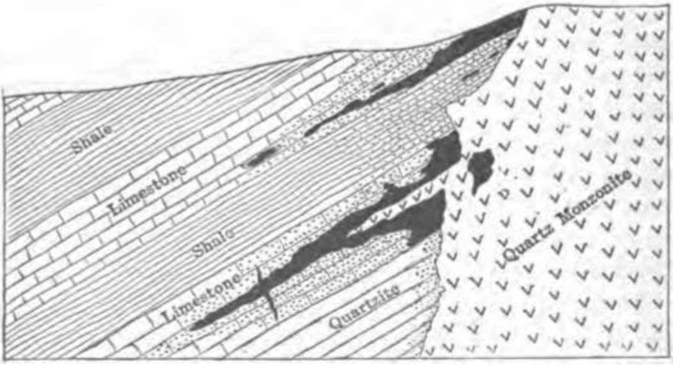


Fig. 218.—Vertical section of a contact metamorphic deposit. Ore, black; altered country rock beyond ore, stippled. The alteration was induced by the intrusion of the quartz monzonite. The ore is almost entirely limited to the limestone. (After W. Lindgren.)

with comparative readiness (Fig. 218). Fossils are often preserved because their constituents have been replaced by more stable compounds. Not uncommonly the wall rocks of open space fillings are more or less metasomatized in the vicinity of these deposits (Fig. 217).

219. Forms of Subsequent Mineral Deposits.—Subsequent mineral bodies with tabular or sheetlike form and genetically associated with fractures are called *veins* (Fig. 217). They may originate by the filling of a fissure (joint, fault, cleavage plane, etc.) or by more or less replacement of its wall rocks, or by a combination of both processes. Simple open space fillings of any variety naturally have the shape of their inclosing chambers or fissures. Examples are amygdales (page 111); geodes, which are incrustations in cavities a few inches in diameter; and gash veins, occupying gash joints (Fig. 196) and some other kinds of tension fractures. Stalactites and stalagmites are peculiar types belonging to the group of open space deposits. Replacement bodies are usually very irregular in shape. This is true even of replacement veins, although in the main they are tabular. Veins of any kind may widen or pinch; they may turn in their course, branch, and sometimes form networks; indeed, as a class they display every conceivable irregularity. In schistose rocks they are frequently lenticular.

220. Distribution of Subsequent Deposits.—The fillings of primary open spaces are limited in their distribution to the rocks in which the chambers were present; *e.g.*, amygdales in certain lavas. Deposits in secondary openings, especially fissure fillings, are found in nearly all rocks. They are exceedingly common. Such deposits bear the same relations to geologic structures (folds, contacts, strata, etc.) as do the joints or faults in which they were formed. Sometimes they may be localized in particular rocks. Thus, in a folded stratified series, fissure veins may be found only in the harder, more brittle members which suffered prominent fracturing (**145**), whereas the less competent beds, which were deformed by flowage, are barren or have only thin, poorly defined veinlets.

Replacement deposits are apt to be associated with igneous contacts or with fractures, shear zones, or other structures which functioned as channels for the mineralizing solutions. Like open space deposits, they too may have a distribution restricted in certain regions to special kinds of rock. Their localization may be caused by some definite control over the migration of the solutions, or to the fact that the altered rocks were relatively very susceptible to metasomatism under the influence of the particular solutions in circulation at the time; *e.g.*, some limestones.

221. Composition of Subsequent Deposits.—The composition of veins and other subsequent deposits is exceedingly varied.

Among the commonest constituents are quartz, calcite, epidote, pyrite, chalcopyrite, hematite, barite, prehnite, and the like. Ore-bearing veins generally consist of one or more minerals which have a commercial value associated with other substances, known as *gangue minerals*, which have no value. Within the gangue the ore minerals may be disseminated as fine particles, or distributed in threads, or segregated in masses, or otherwise arranged. Although ore minerals are sometimes native, as gold, copper, platinum, and mercury, they are usually sulphides, oxides, carbonates, sulphates, chlorides, or other compounds.

222. Size of Vein Deposits.—In thickness veins may range from a fraction of an inch to many yards, and in length they may range from a fraction of an inch to several miles. Many have been followed downward to depths of 3000 or 4000 ft.

223. General Field Relations of Veins.—The attitude of a vein is referred to in the same terms as that of a fault, a dike, or a bed. Strike, dip, and hade are used with the same significance as defined in Art. **165.** A majority of veins have dips steeper than 50°. When a vein is inclined the wall above it is the *hanging wall* and that below is the *foot wall* (Fig. 217).

The geologic age of a mineral deposit is determined by correlation with fossiliferous strata or with other rocks whose age has been established.

With reference to their relations to the land surface, veins may be more resistant or less resistant to the influences of weathering than their wall rocks. If stronger, they project as ridges. When small and numerous, they give to an outcrop a ribbed surface or a honeycombed appearance according as they are in parallel or intersecting sets. If they are less resistant than their country rock, they weather down below the general level and become covered with their own residual débris (gossan, etc.).

The trends of outcropping veins conform to the rules which have been set forth in Art. **159** for strata.

224. Discrimination Between Open Space Deposits and Replacement Deposits.—No infallible rule can be laid down for ready discrimination between open space and replacement deposits. There is generally some alteration in the walls of open space deposits and, on the other hand, replacement bodies may be situated along fissures which conducted the mineralizing solutions. Every gradation exists between the two classes. Nevertheless there are certain features which are especially characteristic of one group or the other, and these, when properly interpreted, may be of considerable assistance as distinguishing marks. (1) Usually, not always, replacement deposits have rather indistinct or blended contacts

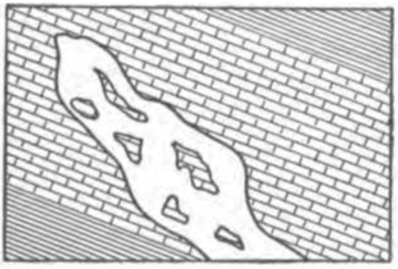


FIG. 219.—Section of a replacement mineral deposit (white) containing isolated blocks of the country rock in their original position.

and open space deposits have sharply defined boundaries. (2) Open space bodies ordinarily have a banded or crustiform structure parallel to the walls of the original chamber, this being due to the deposition, one upon another, of successive layers of varying mineral composition. Banding, if present in replacement deposits, is rarely symmetrical. (3) Replacement veins are apt to be less regular in shape than fissure veins. The latter often exhibit matched walls. (4) Blocks, or "horses," of the wall rock, completely detached and with their original structures unchanged in position, have been isolated by replacement of the intervening rock (Fig. 219). If detached fragments of the wall rock are found in an open space deposit, they usually touch one another and they have altered their position as shown by the various orientations of their structures.

225. Discrimination Between Veins and Dikes.—In their field occurrence dikes and veins are very much alike. Typically they are sheetlike and their irregularities of shape are of similar nature, so that they can not be distinguished by their form and structural relations. As for their manner of origin, there is a complete gradation between them. Vein materials are deposited from solutions. Dikes are formed by the consolidation, usually the crystallization, of magma in which is present a variable quantity of gases and vapors. The greater the proportion of these mineralizers, the more mobile is the magma and the more nearly does it resemble a hot solution from which certain types of vein are precipitated. Pegmatite dikes (or veins) are on the border line in the classification. Pegmatite apophyses from granitoid bodies often verge into true quartz veins at their outer extremities.

From these facts it is evident that a satisfactory code of rules for the discrimination of dikes and veins can not be made. There are too many exceptions. However, texture, lithologic structure, and mineral composition are often helpful guides. Dikes are usually compact without visible open spaces, and not uncommonly they have porphyritic texture. Chilled margins are typical of many. On the contrary, veins are apt to have open spaces into which numerous crystal ends project (drusy cavities), and they may have a banded distribution of their mineral constituents parallel to the walls. Perhaps the most important criteria are mineral composition and especially the relative proportions of the different species. There are certain minerals which, while sometimes found in dikes, are of much more frequent occurrence in veins; and *vice versa*. For example, characteristic of veins are calcite, epidote, and the other minerals cited in Art. **221,** and species more typical of dike rocks are feldspar, hornblende, augite, biotite, and muscovite. Yet, even in this case, great care must be exercised not to confuse calcite, epidote, and the like, in veins with the same minerals occurring as secondary constituents of dike rocks.

CHAPTER XI

TOPOGRAPHIC FORMS

Land Forms in General

226. Land Forms and Their Recognition.—Hills, valleys, plains, beaches, cliffs, and the like, are classed as *topographic forms* or *land forms*. Although most of them are products of the erosional agents which are working at the earth's surface, some have been made through the operation of subterranean forces. To the latter category belong volcanoes, lava flows, fault scarps, etc.

Of the topographic forms resulting from erosion, those which project upward (hills, etc.) are *positive*, and those which have the nature of depressions are *negative*. Those which are direct effects of wearing down are *destructional*, and those which have been built by processes of accumulation are *constructional*. Destructional land forms are immediately dependent upon the relative resistance of the materials eroded. Underlying structure is of secondary account, although it naturally governs the shape and distribution of the topographic elements. Constructional forms are nearly always situated in regions lower than the sources of the materials. This, of course, is because the products of erosion are generally carried downward.

The ability to recognize land forms is not only indispensable for the geologist, but it is also a valuable acquisition for persons engaged in many other pursuits. One should be able to tell the difference between valleys made by ice and those made by rivers; between hills of eolian, glacial, or volcanic origin; between plains built by rivers and plains due to the work of waves; and so on. The criteria are included for the most part among the following characters of topographic forms: (1) surface features; (2) general shape, including ground plan and profiles in significant directions; and (3) position with reference to topographic surroundings. For constructional deposits, (4) original internal structure, and (5) the characters of constituent grains or fragments are additional features of importance.

Slopes

227. Significance of the Inclination of Land Surfaces.—Topography may be said to consist of sloping surfaces. Even plains have some undulations, and those which are essentially flat often have an inclination one way or another. The slope of any such surface is a feature which deserves an explanation, for it is related to the mode of development of the topographic form with which it is associated.

Land surfaces may be on consolidated or on unconsolidated rocks. The average inclination of the surface of a lava sheet, or a lava cone, is indicative of the original viscosity of the liquid

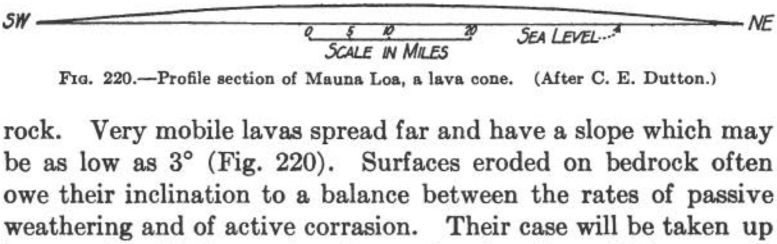


FIG. 220.—Profile section of Mauna Loa, a lava cone. (After C. E. Dutton.)

rock. Very mobile lavas spread far and have a slope which may be as low as 3° (Fig. 220). Surfaces eroded on bedrock often owe their inclination to a balance between the rates of passive weathering and of active corrasion. Their case will be taken up in more detail below. Any destructional surface which approximately coincides with the stratification of dipping beds is called a *dip slope*. It is due to natural stripping of an overlying weak stratum from an underlying resistant layer (**258, C**).

Surfaces on unconsolidated sediments may be either destructional or constructional. In the case of stratified deposits, a surface coincident with the bedding is probably constructional, and one intersecting the bedding is probably destructional. The most important angle of slope in unconsolidated deposits is that known as the *angle of repose*. If sand or gravel has been held up by a support, and this support be removed, the sediments will slump down of their own weight and will continue to slide until friction between the particles prevents further slipping. The vertical angle between a horizontal plane and the surface in which sliding ceased is the angle of repose for these materials (Fig. 221). The maximum angle of repose for coarse gravels consisting of angular fragments is about 35°. Even 40° has been recorded. Volcanic lapilli and ash may stand with slopes of 35° to 40° (Fig. 222). The angle of repose for rounded gravels is lower. For mixed sand and gravel and for sand alone, 28° to 30° is common. Damp sand can stand more steeply than dry, and angular sand more steeply than well-rounded sand. The angle of repose for sand is somewhat higher under water, provided there is no current, for a current can easily reduce the slope to a much lower inclination. Clay, loess, and similar materials,

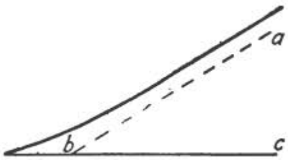


FIG. 221.—Profile section of a slope on loose gravel. *abc*, angle of repose. The larger bowlders accumulate at the foot of the slope.

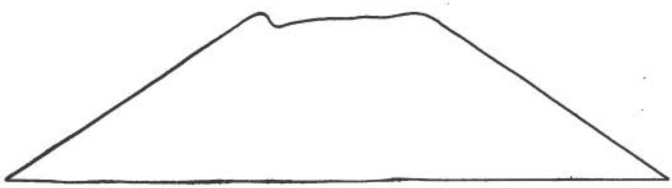


FIG. 222.—Profile of a volcanic cinder cone. The breadth at the base is a few hundred feet. (After J. S. Diller.)

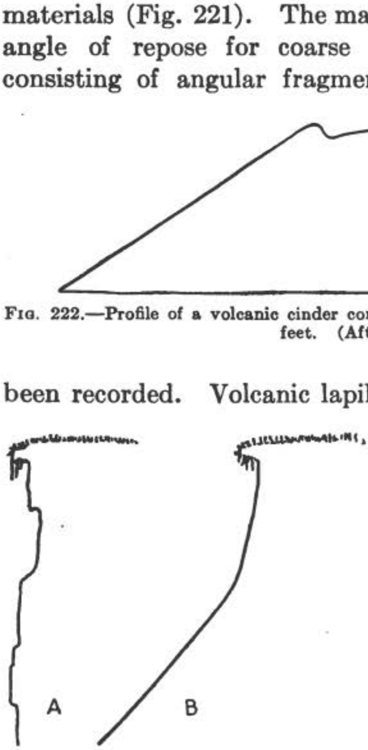


FIG. 223.—A, profile of a bluff in loess; B, profile of a bluff in till. The upper steep slope in B is due to rain erosion; the lower more gentle slope is due to a balance between deposition by rainwash and landslips, on the one hand, and erosion by rain, on the other hand.

which are capable of a sort of semiconsolidation, may stand in vertical cliffs (Fig. 223), but, when well soaked with water, mud and clay may slide on slopes of only 2° or 3°.

Cliffs

228. Cliffs in General.—To vertical or very steep faces of rock and partially consolidated sediments are given such names as cliffs, scarps, escarpments, precipices, bluffs, etc. The word cliff will be used here in a general sense. The more common varieties may be classified as follows:[1]

Key for the Identification of Cliffs

If a cliff

A. Bears scratches and grooves which
   1. Trend principally along the cliff, either horizontal or with a low inclination, the cliff was probably made by glacial abrasion (**231, D**).
   2. Trend up and down the slope, being vertical or steeply inclined, the cliff may be a fault scarp (**229**) or a landslide scar (**231, G**).

B. Bears no scratches or grooves, but is rough on account of the separation of grains or joint blocks (**32**), and
   1. Evidence is found of dislocation (faulting) of bedrock structures,
      a. And of topographic forms, along the cliff, the latter is probably a fault scarp, somewhat weathered (**229**).
      b. But not of topographic forms, along the cliff, the latter is probably a fault-line cliff (**231, F**).
   2. No evidence of dislocation is found along the cliff, the latter
      a. Being situated along an existing shore line or, if not so situated, being associated with a wave-cut bench at its base (**237**), this cliff is a wave-cut cliff (**231, A**).
      b. Not being associated with a shore line or with a wave-cut bench, and if
         (1) The cliff truncates a particular stratum or layer in a series of eroded horizontal or inclined layers, this cliff is an erosion scarp produced largely by weathering (**32**).
         (2) The cliff is the front edge of a recent lava flow, this cliff may be original (**230**).
         (3) The cliff is the inclosing rim of a crater or of a caldera, and intersects rocks of volcanic origin, this cliff may be a consequence of volcanic explosion, or of the infall of blocks from the

[1] Faceted spurs (**232**) are not included.

sides, accompanied or not accompanied by fusion at the base, or by these processes in coöperation (**246**).

(4) The cliff is not related to any particular kind of rock, but
   (*a*) Forms the wall of a river valley (or channel), this cliff is probably due to weathering assisted by basal undermining accomplished by the river (**231, B**).
   (*b*) Forms the wall of a glacial valley or of a cirque, the cliff may be the result of glacial scour, somewhat weathered, or of glacial sapping (**231, D and E**).
   (*c*) Forms the lee side of a roche moutonnée, the cliff is probably a result of glacial plucking (**231, E**).

229. Fault Cliffs.—Fault scarps are cliffs of varying height and length, formed by faulting. The scarp always fronts upon the lower land of the downthrown block. Most fault scarps, especially the high ones, are the result of recurrent dislocation along the same surface of fracture or along close, parallel frac-

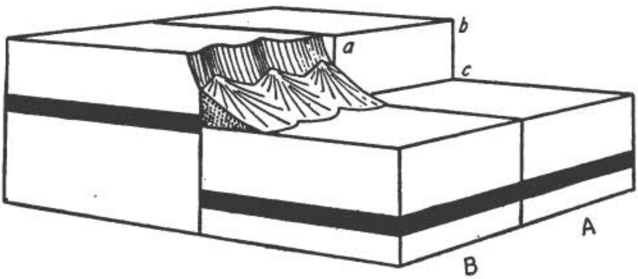


FIG. 224.—Fault scarp interrupting a level land surface. A, hypothetical condition before erosion; B, aspect after moderate erosion. Talus cones have accumulated at the base of the fault cliff.

tures. The shape of the original scarp depends upon the topography of the land mass that was broken. If the ground was level, the cliff is pretty regular in height (Fig. 224), but if a rugged surface was intersected by a fault transverse to the trend of the ridges and valleys, the scarp crest zigzags up and down (Fig. 225). In some cases the scarp may be the actual fault surface, but generally all marks of slipping are destroyed by weathering soon after their exposure. Fault scarps in sands, gravels, and

FIG. 225.—Fault scarps in a mountainous region. (After W. M. Davis.)

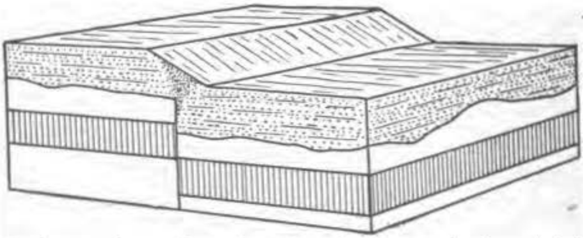


FIG. 226.—Fault scarp in gravel, produced by a displacement in the underlying bedrock. The slope of the scarp is the angle of repose of the gravel.

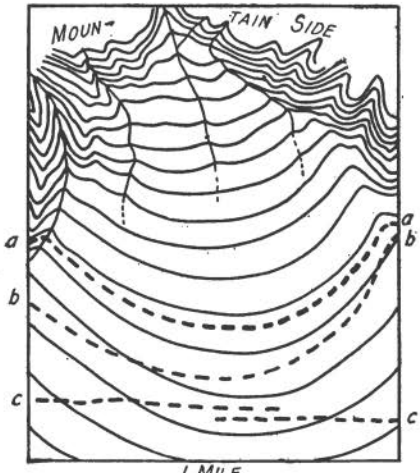


FIG. 227.—Contour map of an alluvial cone at the base of a mountain range. The dashed lines indicate the relations between the contours and the hypothetical positions of an abandoned shore line (*aa*), a tilted, abandoned shore line (*bb*), and an interrupted fault scarp (*cc*).

the like, are seldom steeper than the angle of repose, because such materials are prone to slump (Fig. 226).

When on alluvial cones and other deposits with definite constructional slopes, fault scarps may be distinguished from abandoned shore-line cliffs (**266**) by their lack of relation to the contours. Shore-line features follow the contours (Fig. 227).

230. Volcanic Cliffs.—The front edges of lava flows are often abrupt and may be fairly straight for many hundred feet, so that they resemble fault scarps. Indeed, it is sometimes a difficult matter to determine whether or not such a steep face in lava is a product of faulting. Evidence for the continuation of a line of displacement must be sought beyond the edge of the lava flow. The inner rims of explosion craters might also be mentioned here. They are steep slopes on which are usually exposed the truncated ends of the outward dipping ash deposits and interbedded flows which constitute the volcanic cone. They are distinguished with some difficulty from the bounding walls of volcanic sinks (**245**).

231. Destructional Cliffs.—Erosion cliffs include sea cliffs, river cliffs and bluffs, cuesta scarps, ice-scoured rock walls,

Fig 228.—Profile section of a sea cliff. *ab*, overhang; *bc*, undercut; *cd*, wave-cut bench.

ice-quarried cliffs, fault-line cliffs, and landslide scars. Some are made by weathering, some by abrasion, and some by both. Ordinarily one may assume that a cliff exists either because it is still in process of formation or because it was made so recently that the forces of erosion have not yet had time to erase it.

——**A.** Sea cliffs are maintained by cutting at the base. In hard rock the "locus of attack," or place where the waves do their principal work, is seen in an undercut at about high tide level (Fig. 228). From time to time joint blocks are dislodged from the overhanging rock by frost or by other agents of disintegration. Where weak dikes or strata offer less resistance to the onslaught of the waves than do the adjacent rocks, fissures and cliffs may be cut landward. This is a case of differential erosion. In materials like till, which are apt to slip if undermined, the cliff may be steep, but rarely has the compound nature of undercut and overhang (Fig. 223, B). Gravels and sand slump to their angle of repose just as fast as they are attacked below.

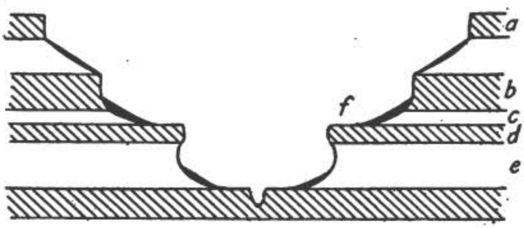


FIG. 229.—Profile section of a valley in alternating strong and weak horizontal strata. *a* and *b* weather back equally fast; *d* weathers more slowly than *b* and therefore a rock bench is developed at *f*; *c* is so thin that the talus (black) overlaps the base of *b*. Cf. *e*.

——**B.** River cliffs are cut by the lateral swinging of the stream. In respect to basal undercutting, dislodgment of blocks from the cliff face, and relation of materials to slope and form, they correspond to sea cliffs. Wherever streams are rapidly incising their channels in horizontal strata of varying resistance to erosion, the valley walls usually consist of alternating vertical cliffs on the more resistant rocks, and talus slopes with the angle of repose on the weaker strata (Fig. 229). This type of valley wall may be seen in the Colorado Canyon.

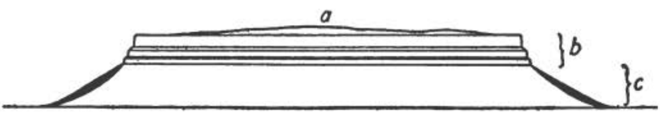


FIG. 230.—Profile section of a mesa. *a*, remains of a weak stratum, nearly worn away; *b*, alternating strong and thin weak beds; *c*, weak stratum with its edges covered by talus (black).

——**C.** Cliffs like those just mentioned form the sides of mesas and mesa-buttes (Fig. 230). Each hard layer serves as a protective cover for the underlying softer rock. To some extent erosion may undermine the weak stratum beyond the edge of the strong, but if undermining goes too far, masses of the over-

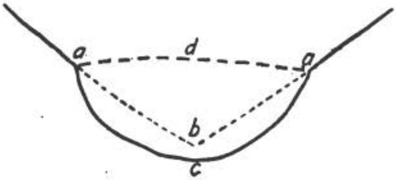


FIG. 231.—Transverse profile section of a glaciated valley (*aca*). *aba*, valley before glaciation; *ada*, original surface of ice. Note the shoulders at *a*.

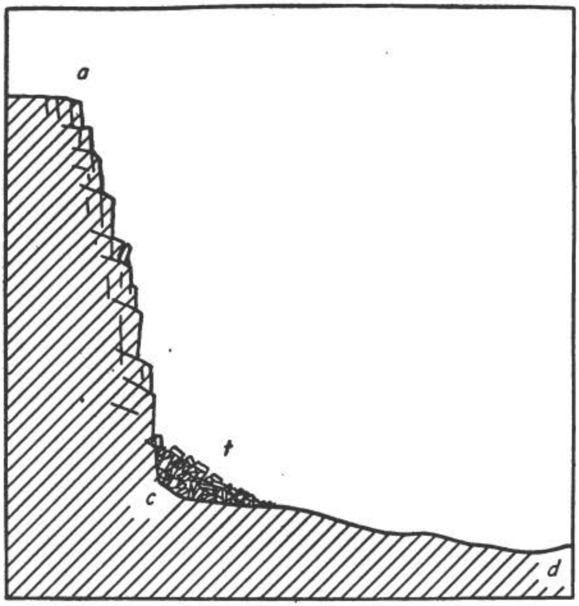


FIG. 232.—Profile section of the ice-sapped cliff (*ac*) and the ice-scoured floor (*cd*) at the head of a glacial cirque. *t*, talus.

lying rock fall off. Thus, while the cliff or escarpment is gradually worn back, its steepness is maintained as long as the hard stratum, or cliff-maker, stands well above the level attained by the streams of the region when they reach grade (**261**). If the layers have a low inclination (say up to 20° or 25°), the escarpment is called a *cuesta face* or a *cuesta scarp*, and the cliff-making rock is spoken of as a *cuesta-maker*.

——**D.** The ice of mountain glaciers scours deep the valleys through which it moves and, in so doing, greatly steepens the

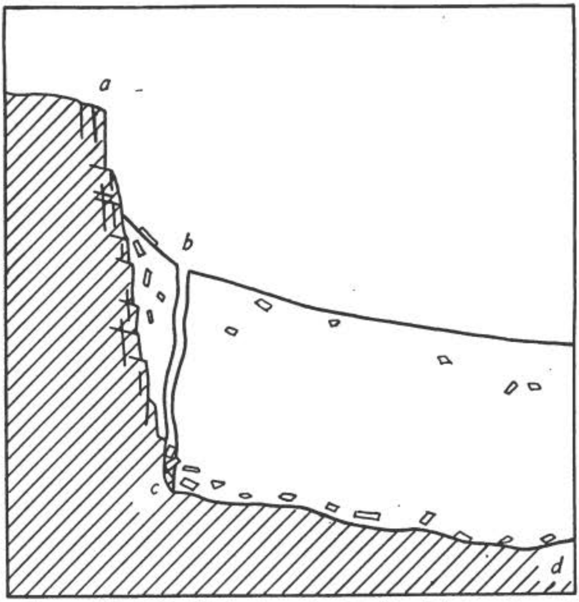


FIG. 233.—Same as Fig. 232, with the ice restored to its original position. *b* is the bergschrund. Angular fragments of rock are contained in the ice. Some have fallen to the bottom of the bergschrund.

valley walls. This is called "oversteepening" (Fig. 231). Such oversteepened, ice-scoured rock walls are polished and striated unless postglacial weathering has effaced the marks of glaciation. In the latter event the origin by ice abrasion may be demonstrated by other signs of glacial erosion in the vicinity, or by associated glacial deposits.

——**E.** Ice-quarried cliffs (Fig. 232) are quite different from the preceding type. At the head of a mountain glacier, where abrasion is little or nil, alternate thawing and freezing operate exactly as does the frost action of disintegration, but on a larger scale, and blocks are riven off along the joints. This process of *sapping* or *quarrying* is thought to be effective chiefly within a crevice, known as the *bergschrund*, which is situated near the edge of the ice and which extends down through the ice to the base of the cliff (Fig. 233). During the day water trickles down in the joints; at night it freezes and from time to time rock fragments, wedged off by the force of expansion of freezing, fall into the bergschrund and are incorporated in the ice. The bergschrund is situated about where the glacier commences its downward motion. If long continued, this process may develop cliffs up to many hundreds of feet in height, but they are not exposed, except to a certain extent within the bergschrund, until after the glacier has dwindled away and disappeared. They form the walls of cirques (**250, H**).

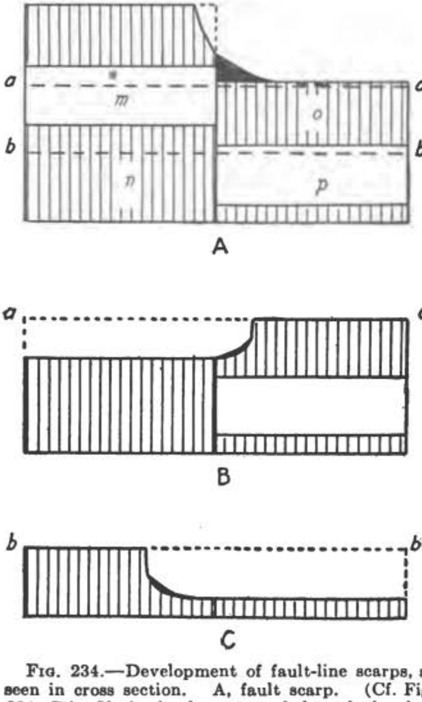


FIG. 234.—Development of fault-line scarps, as seen in cross section. A, fault scarp. (Cf. Fig. 224, B.) If the land were eroded to the level *aa* and were then uplifted, the weak rock (*m*) would be removed more rapidly than the resistant rock (*o*). Hence a fault-line scarp would be produced in *o*, facing *m*, as shown in B. In the same way, following erosion to the level *bb* (see A), uplift would result in the formation of a fault-line scarp in the resistant rock (*n*) facing the weak rock (*p*), as depicted in C. The black is talus.

Smaller cliffs of somewhat similar origin may be seen on roches moutonnées, and on hills of like nature, where moving ice detached or *plucked* joint blocks from the lee sides of the rock masses over which it rode (258). Sapping or quarrying is accomplished entirely by the passive process of wedging, whereas plucking, although more or less assisted by wedging, is largely dependent upon the overriding of a moving body.

——F. Fault-line scarps are erosion scarps developed along lines of faulting. They are not direct effects of displacement. They are phenomena belonging to a second cycle of erosion (265). The original fault scarp was eroded to low relief, the land was then uplifted and a second cycle was inaugurated, in which weaker rocks on one side of the fault were worn away more rapidly than more resistant rocks on the other side. Thus, a scarp was developed along the line of faulting. Two conditions are possible: the lower land toward which the fault-line scarp faces may be (1) on the block which was the downthrown side of the fault

FIG. 235.—Section of a fault scarp and a fault-line scarp. Strong beds, ruled; weak beds, blank; talus, black. *a* has been worn back faster than *c* because the weak rocks are exposed in *a*. Before the faulting, the strong rock stratum at *a* and *c* was continuous.

(Fig. 234, C) or (2) on that which was the upthrown side (Fig. 234, B). In other words, a fault-line scarp may face the same way as the original fault scarp or in the opposite direction. Fig. 235 represents a fault-line scarp formed in the first cycle of erosion.

——G. Landslide scars are the bare surfaces left by the fall of masses of rock or of unconsolidated materials. The greatest dimension of a landslide scar is generally up and down the slope.

232. Faceted Spurs.—Let us consider the topographic development of a fault scarp in a land mass that was essentially level before its displacement. Take "the ideal case of a faulted block of homogeneous structure whose faulting has progressed at a slow and relatively uniform rate, so that the sides of the ravines that are eroded in it shall be weathered back to graded slopes about as fast as the fault block is raised. . . . . . In an early stage (Fig. 236, A) the low fault scarp is notched by ravines whose location and length are determined by the site of pre-faulting inequalities in the upper surface of the block. Adjacent ravines have not yet widened sufficiently to consume the edge at the top of the block between them. In a later stage (Fig. 236, B) the block is raised higher, the ravines are worn deeper and farther back, some of them being larger than others. Nothing of the upper front edge of the block now remains, for the flaring walls of the ravines now meet in a sharp ridge crest that rises backward from the vertex of a *triangular facet on the block front*,[1] toward the top of the block. In the third stage (Fig. 236, C) the block is raised still higher, and the ravines have become still longer and deeper; at this stage the mountain crest

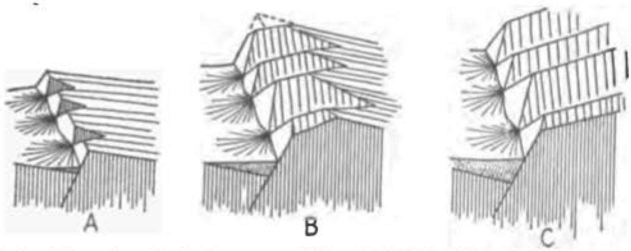


Fig. 236.—Dissection of a fault scarp. (After W. M. Davis.) A, displacement moderate; gorges short; part of the original front edge of the uplifted block remains. B, the same region after more displacement and erosion; none of the front edge of the uplifted block is left; the fault scarp still persists in a series of triangular facets. C, spurs and deep ravines in the uplifted block after further displacement and erosion. The upper surface of the block is not shown in C.

might become serrate, and its back slope would be well dissected. The long, sharp-crested ridges between the larger front ravines are still terminated by triangular facets, very systematic in form and position, with their bases aligned along the mountain front. The spur sides and the facets themselves will have suffered some carving, as is shown in Fig. 237, where some of the terminal facets are enlarged. The moderate dissection of

[1] The italics in the quotation are not original.

the large facet by small ravines results in the development of several little basal facets along the fault line, where they form the truncating terminals of several little spurs. These basal facets are of importance in this stage of dissection, for they have suffered the least change of any part of the mountain front.

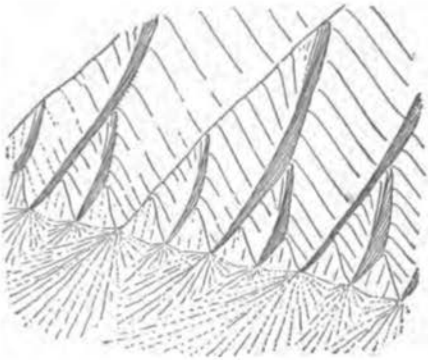


Fig. 237.—Dissected terminal facets of main spurs. Drawn on a larger scale than Fig. 236. (After W. M. Davis.)

"We are thus led to conclude that the features of special significance as the necessary result of long-continued faulting, persistent into the recent period, are, first, the sharp-cut, narrow-floored valleys which have already been considered; and secondly, the large and small terminal facets of the spurs, whose bases show a notable alignment along the mountain front.

"If faulting be supposed to cease after the stage of Fig. 236 is reached, the valleys will widen without much deepening at their mouths, the spurs will be narrowed, and the truncating terminal facets will in time be so far consumed that the spurs will become pointed."[1]

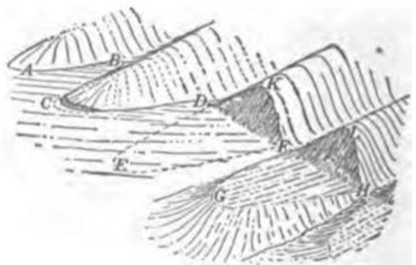


Fig. 238.—Triangular facets due to wave erosion. *ABCD*, initial shore line at time of submergence; *DKF*, cliff facet cut back in spur *DEF: FGH*, spur platform fronting its cliff facet, *FLH*, after withdrawal of the water. (After W. M. Davis.)

Faceted spurs may be made also by glacial erosion, or by wave erosion upon a submerged ridge-and-valley topography along

[1] Bibliog., Davis, W. M., 1909, pp. 745–747.

a lake shore or a sea coast. If the ice should retreat or if the lake waters or the sea should withdraw, these triangular spur terminations might be mistaken for fault facets. Wave-cut triangular facets, however, would rise from the inner margins of triangular wave-cut benches (**237**) (Fig. 238), and the valleys would show evidences of aggradation succeeded by rejuvenation, caused, respectively, by the advance and later by the retreat of the waters. Triangular facets made by ice are sometimes found terminating the ridges between adjacent tributary glacial valleys where they enter the trunk glacial trough (Fig. 239). In this

FIG. 239.—Triangular facets due to glaciation. The lowland in the foreground is part of a broad trunk glacial valley. (Drawn from a photograph, after F. H. Moffit.)

case marks of ice scour (**30, 33, 34**) are generally present on the walls and floors of the valleys and on the facets, and more or less glacial débris is distributed in the neighborhood.

A more complex type of faceted spur is developed by a series of transverse, essentially parallel step faults. On such divides downdropped strips of the old upland surface may be preserved at different levels (**235**).

Beaches

233. Classification and General Characters.—All constructional shore-line deposits, built principally by the work of waves and longshore currents, and consisting of sand or of pebbles and bowlders, are herein classed as "beaches." Under this head may be listed barrier beaches, bay-head or pocket beaches, spits, bay-mouth bars, tiebars, and cuspate forelands.

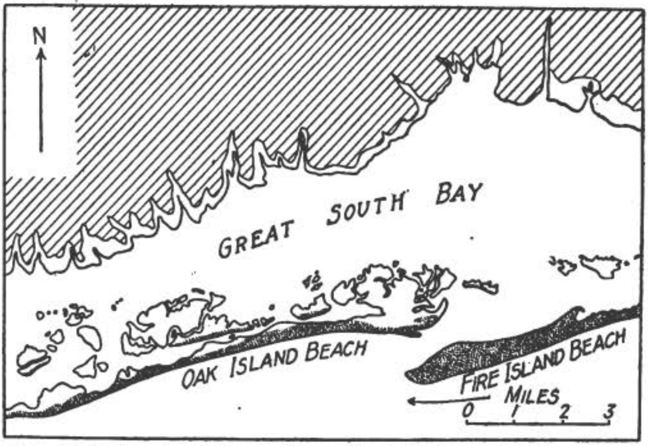


FIG. 240.—Barrier beach and lagoon (Great South Bay), south of Long Island, N. Y. The overlap of Fire Island Beach south of Oak Island Beach indicates transportation of sand in the direction of the arrow. Shaded, dry land; stippled, sand beach; unshaded land area, marsh. (Islip quadrangle, N. Y.)

Along a coast where the mainland is very low (coast of elevation), the waves break some little distance offshore. They churn up the bottom sand and build up a *sand reef* or *barrier beach* (Fig. 240), between which and the main shore there is a strip of quiet water called a *lagoon*. Reefs of this kind are well represented along the Atlantic coast from Long Island southward. Along steeper coasts, where the shore line is comparatively straight, a beach often lies at the foot of the sea cliff, forming a thin cover over the wave-cut bench.

FIG. 241.—Bay-head beach (stippled) consisting of wave-washed sediments. The land is to the right. The arrows show the direction of transportation. Sea cliffs are represented by short hachures.

Beach construction on irregular coasts is varied. At the heads of the bays there is a tendency for the accumulation of débris worn from the neighboring headlands. These deposits are *bay-head beaches* (Fig. 241). Sometimes currents sweeping by

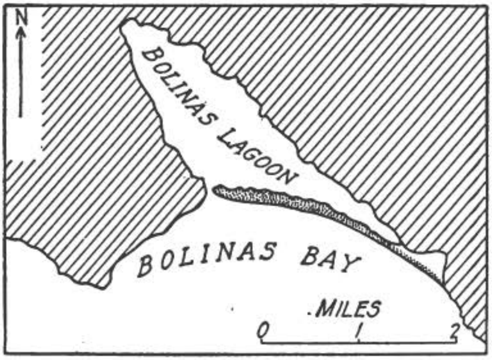


FIG. 242.—Spit (stippled) at the head of Bolinas Bay, Cal. (Tamalpais sheet, Cal.) In which direction were the materials of the spit transported?

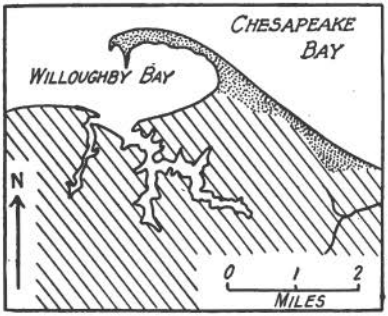


FIG. 243.—Willoughby Spit, Va. (Norfolk quadrangle, Va.-No. Car.)

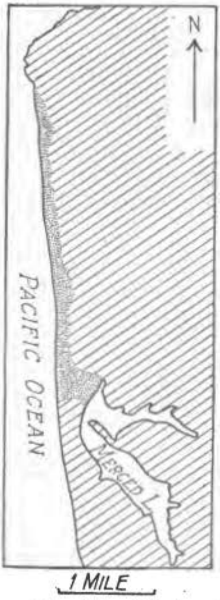


FIG. 244.—Merced Lake, Cal., a bay closed by the forward growth of a spit. (San Mateo and San Francisco sheets, Cal.)

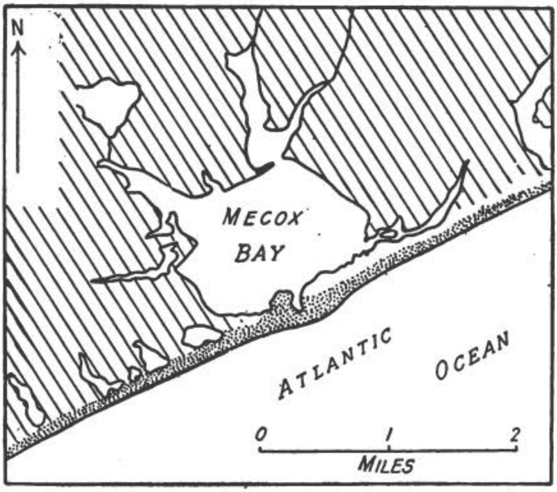


FIG. 245.—Mecox Bay, L. I., a bay closed by the landward advance of a barrier beach. (Sag Harbor quadrangle, N. Y.)

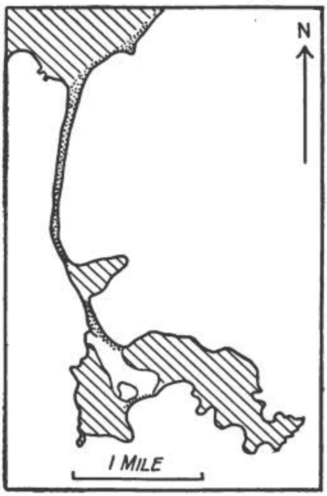


FIG. 246.

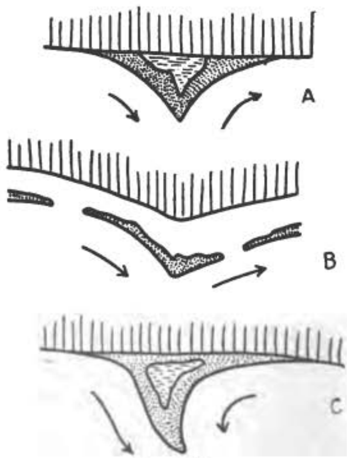


FIG. 247.

FIG. 246.—Lynn Beach (the long narrow stippled area) connecting Nahant (shaded areas on the south) with the mainland (NW. shaded area). Lynn Beach is a tiebar. Nahant once consisted of two islands, now themselves united by a tiebar. (Boston Bay sheet, Mass.)

FIG. 247.—Three varieties of cuspate foreland (stippled). The mainland is shaded. In A and C the forelands inclose lagoons. The arrows indicate current directions.

headlands or islands distribute the rock fragments and sand in *spits* which tail off into deep water (Fig. 242). Spits may be hooked, or recurved (Fig. 243). If a spit or a barrier beach finally closes in the entrance to a bay, it is termed a *bay-mouth bar* (Figs. 244, 245). If it is carried out so far as to join an island with another island, or with the mainland, it is a *tiebar* (Fig. 246). A *cuspate foreland* is a triangular point of land, often inclosing a small triangular lagoon, built out from a shore line by currents (Fig. 247).

In general beaches are coarser at the top than they are near the water. Sea beaches often consist of pebbles above high tide level, grading downward into sand, and, below low tide level, into mud. On very low, shelving shores, mud flats are exposed at low tide. Coarse pebble beaches are usually situated near cliffs from which the materials are supplied. A sand beach may have its surface diversified by ripple marks, rill marks, wave marks, and other features which have been described in Chapter IV.

Benches and Terraces

234. Definitions and Identification.—Benches and terraces are relatively flat, horizontal or gently inclined surfaces, sometimes long and narrow, which are bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side. Both forms, when typically developed, are steplike in character. By increase in breadth they grade into plains. In this book the term *bench* will be used to denote forms in solid rock, and *terrace*, forms in unconsolidated materials.

Key for the Identification of Terrace-like Land Forms

The land surface has the form of a bench or a terrace. If

A. The terrace-like form is definitely related to horizontal strata in the underlying bedrock, being situated between two abrupt slopes or cliffs which truncate relatively hard strata, it is probably a bench or a step produced by differential erosion (**237**).

B. The terrace-like form is not definitely related to horizontal strata in the underlying bedrock, and
  1. Is situated along an existing shore line, beachlike, usually just above high water level, it may be a wave-built terrace or an ice-pushed terrace (**236**).
  2. Is not situated along an existing shore line, but
    a. Is situated on a valley side or a hillside, and
      (1) Has a rather irregular shape, seldom with a flat or level surface, and although, perhaps, appearing on the flanks of several adjacent hills (or mountains), never follows up the intervening valleys, the terrace-like form may be a fault bench or terrace (**235**).
      (2) Has a shape which is conspicuous for its regularity, generally with a comparatively flat surface, and
        (a) With the appearance of having been *built out upon* the original sloping surface, the terrace-like form may be a marginal terrace (**236**), or an alluvial terrace (**238**), or one of several varieties of abandoned beach (**233, 266**), in any case bounded downhill by a relatively steep slope.
        (b) With the appearance of having been *cut into* the original sloping surface, the terrace-like form may be a wave-cut bench (**237**) or a wave-cut terrace (**238**), in either case bounded uphill by a steep wave-cut cliff (**231**) at the base of which wave-worn pebbles and bowlders may be present.
        (c) With the appearance of having been *both built out upon, and cut into*, the original sloping surface, the terrace-like form may be an abandoned wave-cut bench or terrace (cut in) in association with an abandoned offshore terrace (built out) (**266**).
    b. Is situated on the floor of a valley, it is probably an alluvial terrace (**238**).

235. Fault Benches.—Irregular benches are produced on the sides of hills and mountains by certain kinds of faulting. These are *fault benches*. Their surfaces may be undulating or hummocky and need not be horizontal along their length. There may be a slight depression—indeed, sometimes quite a marked saddle—between the outer edge of such a bench and its inner edge where it meets the hillside (Fig. 248). Lawson has called the outer, ridge-like edge a "kernbut," and the inner sag a "kerncol."[1] Two explanations for the origin of these features are illustrated in Fig. 249. Such benches are not to be confused with similar forms of landslide origin and therefore purely superficial (Fig. 250).

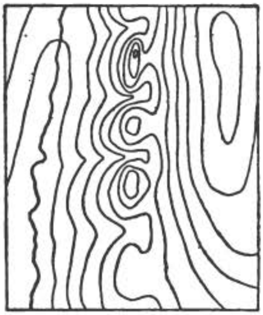


FIG. 248.—Map of a hillside ridge made by faulting. (After the California State Earthquake Investigation Commission.)

236. Constructional Terraces.—Constructional terraces include offshore terraces (also called wave-built terraces), marginal deposits, and abandoned beaches. An *offshore terrace* (Fig. 251) is a deposit of sand which is built out into deep water by the combined action of waves and currents. It trends parallel to the shore. The materials are dumped over its outer edge. Its upper surface is a continuation of the shore bench or wave-cut bench with which it is associated. Shore terraces are not exposed except by sufficient subsidence of the water level.

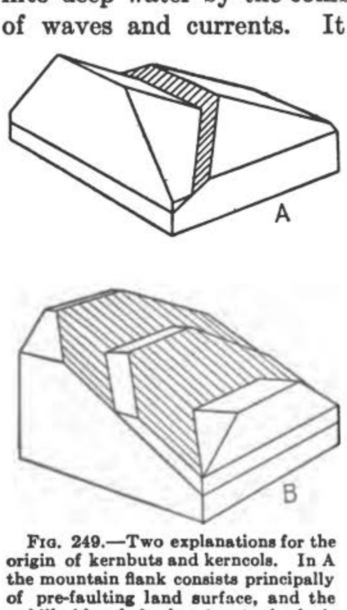


FIG. 249.—Two explanations for the origin of kernbuts and kerncols. In A the mountain flank consists principally of pre-faulting land surface, and the uphill side of the kernbut is the fault surface (lined). In B the mountain flank is chiefly fault surface (lined), and the uphill side of the kernbut is the pre-faulting land surface.

"*Wave-built terrace*" is a term sometimes given to the upper coarser portion of a beach where the waves have thrown the pebbles up in low ridges parallel to the shore line and a few feet above mean high water level. An *ice-pushed terrace* is made along some lake shores by the thrust of ice up the beach.

During the later Pleistocene, when the ice was fast melting away, gravels and sands were sometimes deposited between

[1] Bibliog., LAWSON, A. C., 1902–4, p. 331 *et seq.*

withering ice tongues and the adjacent valley walls. After the complete disappearance of the ice, these *marginal deposits* were left as terraces on the hillsides. While, for several reasons, they are not common, the chance of their existence should not be forgotten when studying terraces in regions of past glaciation.

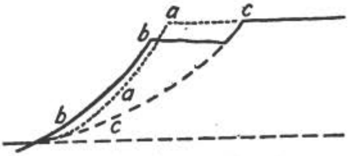


Fig. 250.—Bench caused by a landslide. *aa*, original profile; *bb*, profile after slipping; *cc*, surface of slipping. (After M. L. Fuller.)

Beaches and other associated shore-line deposits which have been abandoned by the water body at whose margin they were formed, may constitute terraces which may be difficult to distinguish from alluvial terraces. They are discussed in a separate section below (**266**).

237. Destructional Benches.—Wave-cut benches, canyon benches, and plateau steps are destructional forms in bedrock. The *wave-cut bench* (*marine bench*) has a rock floor, and terminates inland in a marine cliff and seaward in a shore terrace (Fig. 251). It is made by the gradual landward erosion of the cliff and may be more or less covered by a thin layer of rock débris.

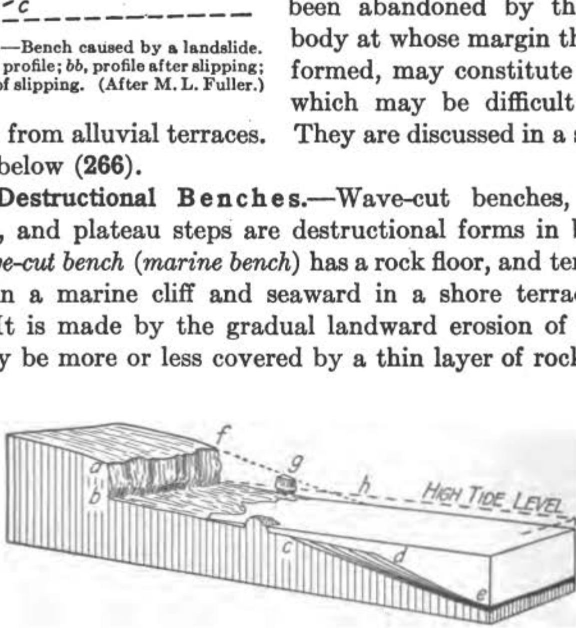


Fig. 251.—Shore-line features. *ab*, sea cliff; *bc*, wave-cut bench; *cde*, wave-built terrace; *fgh*, outline of land surface before wave erosion; the same surface lies beneath the terrace; *g*, a stack.

Stacks (**258, F**) may rise above the bench near its inner margin. If the land rises or the sea level falls, such a bench becomes *abandoned* (**266**). Its associated terrace will be quickly destroyed, wholly or in part, and a new sea cliff and sea bench may be cut into the rocks. The abandoned bench will then be bounded both landward and seaward by sea cliffs (Fig. 252). It may be incised by streams that traverse it to the new shore line.

In regions of horizontal strata the walls of deep valleys are steplike. The cliffs between the "treads" or bench levels are in hard strata. In each case the upper surface of the hard layer

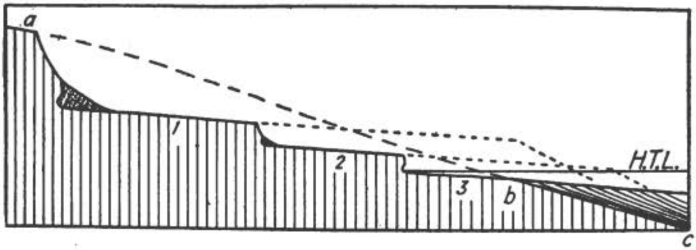


FIG. 252.—Profile section of abandoned (probably elevated) wave-cut cliffs and benches. Stippled, talus; *abc*, outline of land before erosion; *H.T.L.*, high tide level. The oldest bench is 1, the next is 2, and the youngest is 3.

roughly coincides with the tread above a cliff (Fig. 229). These *canyon benches* are often classed as terraces.

Where erosion of wind or water has greatly broadened benches like those just described, they are called *steps* (German, stufe) (Fig. 253). They are characteristic of the high plateaus of western America. Exact counterparts of these steps, as far as

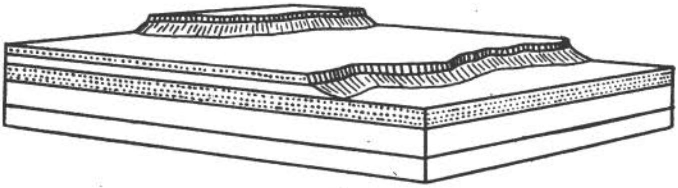


FIG. 253.—Steps, or "stufe," made by erosion of alternating strong (stippled) and weak (blank) horizontal strata.

their origin is concerned, are the cuesta in low-dipping strata and the hogback in steeply dipping strata (**258, C**).

238. Destructional Terraces.—Wave-cut terraces and alluvial terraces are of destructional origin. The *wave-cut terrace* is identical with the wave-cut bench, but is in unconsolidated materials. A succession of these terraces may result by interrupted uplift of the land with respect to the sea or by interrupted subsidence of the water of a lake. *Alluvial terraces* are common features along the courses of many rivers. They are often formed, in any given region, where a period of downcutting or *degradation* by a stream follows a period of upbuilding, known as *alluviation* or *aggradation*. There are several reasons why degradation may succeed aggradation. (1) In its normal development a river constructs an alluvial plain in its lower course. The surface of this plain is above the level to which the stream can cut in a later stage. Subsequently, therefore, the river incises its channel in the alluvial deposit and, by meandering, may broaden its flood plain (**241, A**) until only remnants of the old, higher plain are left. These remnants appear as terraces on either side or on both sides of the flood plain. They are usually not very conspicuous features. (2) Much more striking are the

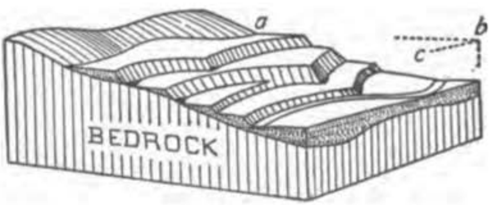


FIG. 254.—River terraces. Black spots at the terrace cusps represent bedrock exposures. *abc*, former level of terrace gravels.

terraces formed by the downcutting of a stream into thick alluvial deposits which it laid down during a period when it carried an excessive load. Many of the rivers of northern regions were thus overloaded by abundant débris derived from melting ice in the waning stages of glaciation. With the disappearance of the ice, the supply decreased so much that aggradation gave place to degradation. Terraces made in this way may be preserved for long periods of time when the river, in swinging from side to side, encounters projections of the bedrock below the alluvium. The rock outcrops are generally situated near the terrace cusps (Fig. 254). (3) If the volume of a stream is augmented while the load remains unchanged, the stream will incise its channel. (4) By uplift of the land, rivers may be rejuvenated and so forced to cut into their old alluvial deposits. Of the four cases cited above, the second is the most probable in regions within, and not far south of, the glacial limit.

PLAINS

239. Terminology and Identification.—Land forms which are comparatively flat and of low inclination and which are not better classified under the head of benches or terraces are placed here under *plains*. They vary in area from a few acres to many square miles. While their continuity may be interrupted by isolated hills or by occasional valleys, flatness is their predominating quality.

KEY FOR THE IDENTIFICATION OF PLAINS

The land surface is a flat, or nearly flat,[1] plain which may be horizontal or gently inclined. If

A. The materials beneath the plain are till, the plain is a till plain (**241, D**).

B. The materials beneath the plain have a stratiform structure with which the plain is essentially parallel, and these materials consist principally of

  1. Superposed lava sheets, often with intercalated beds of volcanic ash, etc., the plain is of volcanic origin (**240**).

  2. Stratified muds, sands, or gravels, and if

    a. The plain constitutes the floor of a basin which

      (1) Is intermittently more or less covered by shallow alkaline lakes, the plain is probably a playa (**241, F**) and is situated in the lower central part of a desert region.

      (2) May or may not be flooded from time to time, and which is bordered by such shore-line phenomena as beaches, deltas, wave-cut cliffs, etc., now all abandoned and more or less destroyed, the plain may be the floor of an old lake (**241, E**).[2]

[1] Such a flat plain need not be continuous. It may be incised by valleys or broken by faults, or perhaps diversified by an occasional volcanic cone, sessile upon its surface; but provided its original character is still recognizable, its remaining visible portions may be classified as if it had not been modified since its origin.

[2] Such features may be found in valleys which were once basins produced by some temporary natural barrier (**266**).

b. The plain borders a range of hills or mountains away from which it slopes downward with an inclination of 5° to 8° at its upper margin, this angle decreasing inversely as the distance from the range, the plain may be a piedmont alluvial cone or a piedmont alluvial plain (**241, A**).

c. The plain constitutes the floor of a valley along which a stream flows, the plain may be a valley train (**241, C**) or a flood plain (**241, A**).

d. The plain borders upon a lake, down to which it has a gentle inclination, and

(1) Is local, being situated at the mouth of a stream which empties into the lake, the plain is probably the exposed upper surface of a delta (**241, B**).

(2) Is continuous round a large fraction or the whole of the periphery of the lake, and is underlain by mud or clay, the plain may be an exposed portion of the lake bottom at time of low water.

e. The plain borders upon the sea, down to which it has a gentle inclination, and

(1) Is local, being

(*a*) Situated at the mouth of a stream and not being inundated except, perhaps, in rare instances and then only at its outer margin, the plain is probably the exposed surface of a delta (**241, B**).

(*b*) Part of the floor of a bay, and being inundated at high tide, the plain is probably an estuarine flat (**241, E**).

(2) Is continuous for many miles along the coast and is not inundated at high tide, the plain may be a coastal plain (**241, E**).[1]

f. The plain, having a gentle southward inclination, is bordered on the north by an irregular hummock-and-hollow topography of glacial origin (refer to the key in **254**), it may be a frontal apron or a sand plain (**241, C**).

C. The materials beneath the plain are rocks of various kinds and often with diverse structure, and these rocks and structures are truncated by the plain, the latter may be a plain of marine denudation, a peneplain, or a plain of eolation (**242**).

240. Volcanic Plains.—Volcanic plains are the surfaces of broad sheets of lava or of volcanic ejectamenta. They may be

[1] A coastal plain may consist of isolated portions at the heads of the bays on an irregular coast which has suffered only a small emergence.

many square miles in area. They are usually diversified by other volcanic forms.

241. Constructional Plains.—River flood plains, alluvial cones, piedmont alluvial plains, delta plains, glacial frontal aprons, outwash plains, valley trains, till plains, lake-floor plains, estuarine flats, coastal plains, and playas are all constructional in their mode of origin. Swamps might also be listed here, but they are treated in Art. **243**. All have been built up in one way or another.

——**A.** Plains of several kinds are constructed by rivers. When a stream has its volume diminished (as by evaporation in deserts) or has its efficiency lowered by a decrease in its velocity, it may become overburdened with detritus so that it will have to

Fig. 255.—Radial profile section of an alluvial cone. The distance from *a* to *b* is about 8 miles.

deposit part of its load. *Flood plains,* characteristic of mature rivers (**261**), are alluvial flats which are often covered by water at times of flood. When the waters subside a new layer of sediment is deposited on the plain. On piedmont slopes streams are forced to deposit where they pass out from their steeply graded mountain valleys on to broad lowlands. Each stream builds an *alluvial fan* or *cone,* a gently sloping deposit (Fig. 255), which focusses at the point where the stream leaves the mountains. Ordinarily the channel is not so deep but that the stream can break out at times of high water and take a new route on a lower part of the cone. When deposition has gone too far in one place there is a shift in the water course to a new position, so that the cone is formed symmetrically, banked up against the mountain side. If these cones coalesce, they make a *piedmont alluvial plain* or *bajada,* (pronounced bahada), which spreads like an apron along the front of the range.

——**B.** A delta is a familiar type of river deposit. It is made where a stream loses carrying power by passing into a body of water with little or no current. Topographically it consists of three parts (Fig. 256), (1) a broad, gently sloping upper surface most of which is above the level of the quiet water body, (2) the steeper front slope which is submerged and has the angle of repose of materials under water, and (3) the submerged muds

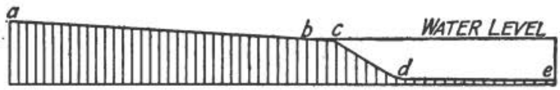


FIG. 256.—Radial profile section of a delta, *abc*, top surface, of which *ab* is exposed and *bc* is submerged; *cd*, front slope; *de*, prodelta clays and muds.

and silts (*prodelta clays*) which extend out in a gently undulating sheet from the foot of the front slope. Deltas are described here because the exposed portion, (1) above, is conspicuous as a plain. On this surface the river may split into distributaries which reach the front at different points on the periphery (Fig. 257, A). The plan of a delta depends on several factors among which the presence or absence of longshore currents and variations in the load transported by the river are important. Were it not for these disturbing factors the delta would be semicircular in outline. Longshore currents sweep away much of the material dumped by the stream, and so truncate the delta (Fig. 257, B). When the load of the river is diminished, the several distributaries may temporarily degrade their channels, bear the resulting sediments to the front, and drop them there as small deltas. This makes the main delta lobate.[1] Highly irregular delta fronts show that river construction dominates over wave erosion. Delta structure has been described in Art. 80.

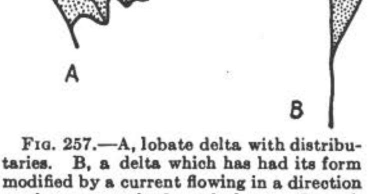


FIG. 257.—A, lobate delta with distributaries. B, a delta which has had its form modified by a current flowing in a direction up the page, as the figure is drawn. In each case the mainland is on the left and the water body on the right of the shore line.

[1] Bibliog., SMITH, A. L.

——C. The construction of outwash plains was an important accomplishment of aqueoglacial waters just outside the margin of the continental ice sheet. Frontal aprons, valley trains, and sand plains were so formed. *Frontal aprons* correspond to alluvial plains. They consist of sands and gravels which were spread out in front of the ice. Their length is parallel to the ice margin and they often head northward against frontal moraines. The largest ones were made south of the main terminal moraine. Probably those portions of the loess plains of central United States which were water-laid constitute parts of very large outwash plains. *Valley trains* are nothing more than restricted frontal aprons. They are valley floor deposits of sand and gravel laid down by heavily overloaded streams that flowed from the melting ice. Some of them are many miles long. Many have since been terraced. *Sand plains*, sometimes also called *delta plains*, are small deltas that were built by aqueoglacial streams in temporary lakes. For their construction the ice front must have been stationary (Cf. **257, E**). Subsequently they were exposed by the natural draining of these lakes. There are a great many of them in New England, New York, etc. They consist of the three parts mentioned above for modern deltas. The prodelta clays are now often covered by marsh. At their northern edge, these sand plains usually terminate in ice-contact slopes where formerly the

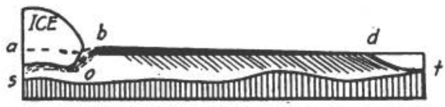


FIG. 258.—Ideal radial section of a glacial sand plain showing its relation to the ice mass and the water level. Both ice and lake were temporary. *ab*, esker channel; *b*, head of sand plain; *d*, front of sand plain at water level; *o*, backset beds; *st*, line of unconformity between rock floor and overlying unconsolidated deposits. (After W. M. Davis.)

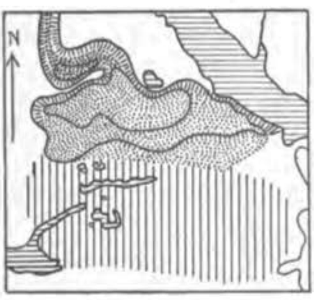


FIG. 259.—Map of the Barrington sand plain, R. I. Stippled, esker and sand plain; vertical ruling, brick clays, largely marsh land; horizontal ruling, water. Scale, approximately 1 inch to 1 mile. (After J. B. Woodworth.)

deposits rested against the ice (Fig. 258). Often an esker north of a sand plain marks the course of the original stream (Fig. 259). Some sand plains are *pitted* by kettle holes (**247**) and some show the old stream channels, or *creases*.

——**D.** Till plains are produced by more or less uniform deposition of till, usually in lands of low relief. The ice must retreat at a fairly constant rate, for otherwise the débris is apt to be heaped up in morainal ridges. The till of these plains is no doubt partly subglacial (ground moraine), partly englacial, and partly superglacial. In sections the deposit is seen to have no stratification (**62**).

——**E.** While silts and muds are in process of accumulation on the floor of a lake there is a tendency to fill depressions and thus to make the bottom more even. The same thing may be said of sea floors. If the lake is drained or evaporated away, the exposed floor will be a *lake-floor plain.* In section the underlying deposits will be seen to be very fine and evenly stratified (**82**). They may carry fresh water fossils. If the floor of a bay is laid bare at low tide we speak of it as a *mud flat* or an *estuarine flat.* If the land should suffer relative uplift with respect to sea level, a larger area of sea floor would be exposed as a *coastal plain.* The underlying sediments would show features characteristic of marine offshore deposition (**74, 80, F, 82**).

——**F.** *Playas* are thin, flat sheets of fine clay and sand laid down in shallow basins of desert regions. Deposition is intermittent. It is accomplished by inflowing mud-laden streams after local cloudbursts. Drought of many months duration may succeed a short period of accumulation, and in this dry season the muds may crack and peel under the sun's rays and undergo a considerable amount of eolian erosion. While dry, playas are often whitened by a crust of soluble salts. (Where did these salts come from and why are they found here?)

242. Destructional Plains.—The plain of marine denudation, the peneplain, and the plain of eolation, are the three principal members of this group. The *plain of marine denudation* is merely an enlarged marine bench (**237**), a level area cut by the waves. Its distinguishing characters are as follows: (1) a sea cliff surrounds any residual stacks or other elevations that rise above the plain; (2) there is a scanty covering of wave-worn pebbles and beach sand; (3) the surface bevels across rock structures. The sand and gravel, being poor supporters of plant growth, are not likely to be densely covered by vegetation even in old uplifted plains.

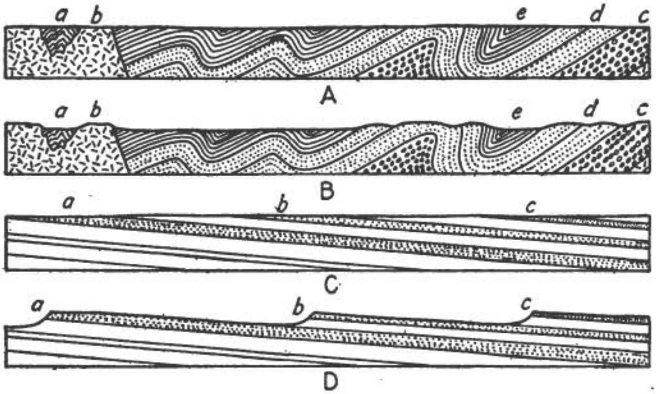


FIG. 260.—A represents the section of a peneplain upon rocks of varying hardness and with complicated structure. B is the same region after moderate uplift, revival of erosion, and removal of the weaker rocks to a level below that of the old peneplain which is now preserved in the hill tops. *a*, schists, intruded by *b*; *c*, basal conglomerate laid down unconformably on *b* and overlain by sandstone (*d*) and shale (*e*). C shows a peneplain bevelling inclined strata. D represents the same region after uplift and erosion. Here the harder rocks (*a*, *b*, and *c*) form cuestas.

A peneplain (*pene*, almost), is a nearly flat or broadly undulating land surface produced by normal subaerial erosion, that is, by erosion which is accomplished chiefly by the work of rivers assisted by weathering. A stream-made topography passes through a series of stages of development, known as youth, maturity, and old age (**261**). The valleys, at first narrow, become broad; the hill slopes grow gentler; the relief as a whole becomes less and less rugged; and finally the rivers with their branches, aided by weathering, reduce the land to an almost level plain. This is the peneplain. It is the ultimate stage of the erosion cycle. A true peneplain has the following characters: (1) the relief is very low, but there may be a few scattered residual hills (monadnocks) which have not yet been cut down to the level of the surrounding country; (2) the streams meander at grade (**261**) in broad, shallow valleys; (3) thick residual soils carpet the interstream areas, for slopes are so low that weathering is more rapid than removal of the débris; (4) the surface of the plain bevels across the underlying rocks without regard to variations in their hardness and structure (Fig. 260, A). Peneplains on nearly horizontal strata are difficult to determine as such, but the geologist usually finds that, by travelling across the plain in certain directions he traverses different strata or formations which successively come to the surface (Fig. 260, C). A peneplain is first completed near the sea coast and its development progresses inland, for rivers generally reduce the land to late stages of erosion in their lower courses long before they have lost even their youthful appearance up in the hill country. A peneplaned surface of great extent is rare because erosion becomes excessively slow in advanced maturity and old age. Relative depression of the sea level, tilting, crustal warping, and other changes may interrupt the cycle of erosion before it has reached its normal conclusion.

If a peneplaned land mass is uplifted with respect to sea level, a new cycle is inaugurated. Beginning at the shore line and cutting headward, the rivers will incise their channels as young valleys below the upland surface. They will have a new base level (**261**) toward which they will work. As time goes on, the upland area, the old peneplain, will be diminished until, in the mature topography of the new cycle, it is represented perhaps merely by the crests of the hills. Yet it will still be called a peneplain—*a dissected peneplain.* It will be recognized by the fact that a majority of the hills rise to about the same level (Fig. 260, B, D). In the distance it will be indicated, though not demonstrated, by the "even sky line." We say "not demonstrated," for an even sky line in a hilly topography may be due to the dissection of some other kind of plain, or it may be the result of differential erosion on strata which have been folded so that the anticlinal crests reached approximately to the same level. The student must take great care to investigate each case by itself before concluding that he has discovered a peneplain.

The third type of destructional plain, the *plain of eolation*, is limited to desert regions.[1] It is the product of wind abrasion, assisted by sheetflood erosion.[2] Often these plains are great saucer-shaped areas, rimmed by mountain ranges. They are then known as *bolsons* (Fig. 261). Students of desert conditions have shown that many square miles of nearly level country in arid regions are really floored by bedrock concealed by only a

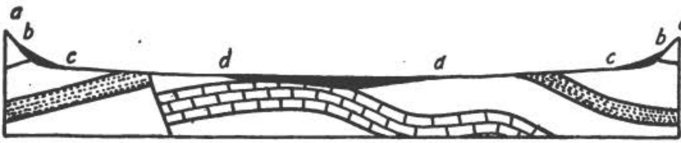


FIG. 261.—Ideal cross section of a bolson. *ab*, exposed mountain flanks in process of erosion; *bc*, relatively thick piedmont waste; *cd*, rock-floored plains thinly veneered with rock waste; *dd*, accumulating deposits of the lower central part of the basin.

thin veneer of rock waste. During storms and during the movement of the sheetflood, this rock waste is carried forward and, in its transportation, it accomplishes erosion; but, after wind or flood subsides, it comes to rest for a while until the next storm urges it forward again. In this manner a plain may be worn on the bevelled edges of rock strata so that the relations resemble those of true peneplanation. The plain of eolation may be distinguished by the fact that the bevelled rock surface and likewise the particles of the overlying cover of débris bear signs of eolian wear (**46**). (In what other ways would the plain of eolation differ from the peneplain?) Residual hills and

[1] Bibliog., KEYES, C. R.

[2] A sheetflood is a broad, shallow sheet of running water, which rises rapidly, generally following a cloudburst, and soon subsides again and disappears. Temporary streams of this kind are characteristic of some semiarid regions.

ranges of relatively resistant rock may rise as monadnocks above the plain of eolation.

SWAMPS

243. Definition and Classification.—A large proportion of the land surface receives its moisture in the form of rain, snow, hail, dew, or frost, but there are some places which are watered by springs, and there are others which are periodically or occasionally flooded. Whatever may be the source of supply, the water ordinarily passes away within a very short time. Some of it runs off over the ground in thin sheets or in little rills; some of it sinks into the soil and into fissures in the bedrock, and so becomes groundwater; part of the underground water combines with part of the "run-off" to form streams; and, last, a considerable quantity of moisture is evaporated. These modes of removal may be referred to as drainage (including run-off and streams), percolation, and evaporation. Thorough drainage may be prevented by the levelness of the land; percolation may be impeded by a relatively impervious soil, subsoil, or underlying bedrock, or by a thick mat of plant roots and plant remains; and evaporation may be checked by a dense foliage. If, in any region, these processes are incompetent to carry away all the water that is supplied, the ground may become swampy and perhaps stay so for an indefinite time. A *swamp* may be defined as a land area where the soil contains an excess of moisture.

A majority of swamps are nearly or quite level, yet the soil on mountain sides and hillsides is sometimes soggy either because of the constant downslope percolation of moisture from melting snow fields above or because of a local subsurface discharge of underground water. These may be termed *hillside swamps. Coastal plain swamps*, like the Everglades, owe their existence primarily to their flatness and consequent poor drainage. Although they are situated on uplifted portions of the sea floor, they are usually fresh, most of the original salinity having long ago disappeared. *Delta-plain swamps* and *river flood-plain* *swamps* are due as much to frequent overflow as to their levelness. In glaciated countries inland swamps are often the sites of lakes which have been choked by vegetation and soil, or they are located upon a clayey subsoil that does not allow free percolation. The latter variety is not uncommon on the prodelta clays of glacial sand plains (Fig. 259). The lake-basin bogs are sometimes called *muskegs*. Portions of the tundra in northern climates are kept saturated by melting snow. Small boggy places may be found even in deserts. For instance, the ground is moist and there is generally some vegetation in the vicinity of springs, and at points where intermittent streams sink into the ground, or where they come near the surface in their subterranean course. A swampy belt may be situated in soil that conceals a bedrock fault, if the fault serves as a conduit for ascending underground waters. Along sea coasts several kinds of salt marsh are recognized. Some are caused by the filling of lagoons with mud, sand, and plant remains (**263**); others are due to the slow uplift of the sea floor; and others, on the contrary, are indicative of subsidence. The evidence for the origin of this last type rests on these facts: (1) the marsh deposit is relatively thick and consists of mud mixed with the relics of plants (mostly grasses) which can exist only if they are moistened by salt water for a short period each day; (2) this marsh deposit rests upon a floor which was once undoubtedly under subaerial conditions; and, (3) the present upper surface of the marsh is just within reach of the high tide.

In many cases the origin of a swamp is suggested by its topographic surroundings, but whenever possible corroborative proofs should be looked for in the structure of the marsh deposit itself. This can be done with an instrument for cutting test holes.

Valleys and Basins

244. Terminology and Identification.—The word *basin* is here used for topographic depressions which are rimmed round on all sides. They may be deep or shallow, large or small, and they may or may not contain water. *Valleys* are topographic depressions that are open, although in some cases their floors may be diversified by small basins. They may or may not be occupied by streams.

In attempting to draw up a table for the recognition of valleys and basins, it has been thought best to treat them separately, as follows:

Key for the Identification of Topographic Basins

The land has the form of a basin, being rimmed on all sides. If

A. The basin is due to the damming of a valley by a barrier of lava, morainic débris, ice, or landslide débris, or if it is situated near the sea coast and is separated from the ocean merely by a sand or gravel beach, it is a barrier basin (247).

B. The basin is not the consequence of the construction of a barrier across a valley, and

1. Is entirely rimmed by bedrock,[1]

***a.* Being generally shallow and**

(1) Veneered by a thin deposit of transported (wind-blown) dust or sand, it may be a wind-scoured basin (248).

(2) Covered by a deposit of residual material, it may be a basin due to some localized process of weathering (248).

***b.* Being comparatively deep, but generally not as deep as it is wide or long, and if it**

(1) Has steep inward facing walls which are rough and irregular and have no scratches or grooves, or, if exhibiting such marks of abrasion, have them trending up and down, the basin may be a volcanic crater (246), a caldera (246), or a volcanic sink (245), and the surrounding rock is probably lava.[2]

(2) Has walls which are steep in some places and of gentler declivity in others, showing marks of abrasion which trend, for the most part, along the walls and parallel to the length of the basin, the latter is probably an ice-scoured basin (248).

***c.* Having a depth generally equal to, or greater than, its horizontal dimensions, and if it**

(1) Has smooth, often polished, rock walls which may bear irregular circumferential grooves, the basin may be a large pot-hole (34).

[1] Sometimes this fact is obscure because the bedrock is more or less covered by surface débris.

[2] The lava may have intercalated beds of volcanic ash, etc.

(2) Has walls which are rough or, if somewhat smooth, have vertical channels due to solution (**33**), and is in limestone, the basin may be the upper end of a sink hole (**249**).

2. Is entirely rimmed by unconsolidated materials, and
   a. Is situated at the crest of a conical hill which consists of volcanic ash, etc., the basin is probably a volcanic crater.
   b. Is situated in an irregular hummocky land area which is
      (1) Underlain by glacial till, the basin is probably a kettle hole in a moraine (**247**).
      (2) Underlain by rather poorly stratified gravel and coarse sand with subangular pebbles predominating, the basin is probably a kettle hole associated with kames and eskers (**247**).
      (3) Underlain by fine, cross-bedded, wind-blown sand, the basin is probably a "blow-out" (**248**), or less probably a constructional depression, between sand dunes (**247**).
   c. Is situated on a nearly flat plain, which is
      (1) Underlain by well-bedded, often cross-bedded sands, not infrequently overlain by gravel, the basin is probably a kettle hole in a sand plain or a frontal apron (**247**).
      (2) Underlain by gravel, sand, or mud, the basin being crescentic in form and associated with a meandering stream, the basin is probably a deserted meander (**247**).

Key for the Identification of Valleys

The land surface has the form of a valley. If

A. The valley has rock walls,[1] and
   1. Its floor bears evidences of glacial abrasion, with more or less glacial deposition, and its cross section is U-shaped, the valley is probably of glacial origin (**250, G, H**).
   2. Its floor bears no evidence of glacial erosion or deposition, and it is
      a. Definitely related to, or controlled by, the underlying rock structure, in this respect, that
         (1) The valley crosses or intersects a ridge across its trend,
            (*a*) The ridge being a cuesta, the valley is a transverse valley and is probably "consequent" in the sense that its stream originally flowed down the constructional surface of the dipping beds.
            (*b*) The ridge being a hogback or a similar exposed edge of a steeply dipping stratum or other layer, the valley may be some variety of gap (**245; 250, E**).

[1] This fact is not always clear at once, for the bedrock may be more or less concealed by surface débris.

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(2) The valley trends along the course of one or more of a series of parallel rock layers, it is a longitudinal valley and may be
(*a*) Due to corrosion, particularly if the underlying rock is not markedly soluble, or
(*b*) Due to solution, if the underlying rock is soluble, *e.g.*, limestone (**250, D**).
(3) The valley is situated above a fault (single or multiple), this valley may be a rift (**245**) or a fault-line valley (**250, B**).
(4) The valley is bounded on one side by a fault scarp or a fault-line scarp, this may be a fault valley (**245**), or a fault-line valley (**250, B**), respectively.
(5) The valley is bounded on both sides by fault scarps or by fault-line scarps, this valley may be situated upon a graben, or upon a horst of which the relief has been reversed by erosion (**186**).

b. Not definitely related to, or controlled by, the underlying rock structure, it is probably a river valley in a region of complex geologic structure or in a region of horizontal strata.

B. The valley lies between a rock wall on one side and a wall of unconsolidated materials on the other side, this valley is probably a result of construction, and the unconsolidated materials may belong to a moraine (**257, E**), an esker (**257, C**), etc.

C. The valley has walls of unconsolidated materials, and
1. Lies between two typical constructional deposits (two moraines, two eskers, an esker and a drumlin, etc., etc.), the valley is of constructional origin (**247**).
2. Interrupts the continuity of an otherwise essentially flat surface, the valley may be a stream channel
a. Associated with the upbuilding of the deposit (channels on alluvial cones, deltas, etc., and creases; refer to **247**).
b. Of purely destructional origin (**250, F**), (rainwash gullies, etc.).

245. Fault Valleys and Basins.—In faulting the blocks may be tilted in such a way that a depression lies at the base of the fault scarp (Fig. 236), or a block may slip down between two opposing fault scarps (Fig. 190, A). Sometimes long, relatively narrow depressions or *rifts* are formed along lines of multiple fracture (Figs. 262, 263). The San Andreas rift in California, along which differential movement occurred in the earthquake of 1906, is "a trough coinciding in general trend with the Coast Ranges, but crossing various mountain ridges obliquely, or even following their crests. In detail it comprises many small ridges and hollows, approximately parallel but otherwise irregularly disposed, and evidently caused by splintery dislocation. Streams zigzag more or less about the ridges, and the hollows contain many small ponds and marshes."[1] This rift is traceable for several hundred miles.

Another possible phase of fault valley is the *fault gap*, a depression between the offset ends of a ridge developed on a resistant rock layer that has been displaced by a transverse fault (Fig. 264). *Fault-line gaps* are more common than fault gaps (**250, E**).

In volcanic regions roughly circular or oval depressions, called *volcanic sinks*, may be formed by broad scale downfaulting of the land surrounding an old vent. The settling may be caused by subterranean removal of lava which had served as a support. These sinks are bounded by steep fault scarps upon which slickensides or other evidences may sometimes be found, indicating the direction of the slipping (**33, 171**). The floor of a volcanic sink is of much larger area than the cross section of any associated vent.

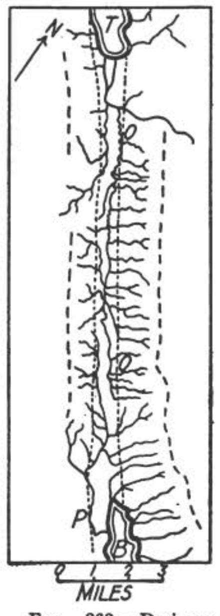


FIG. 262.—Drainage map of the Bolinas-Tomales valley, Cal. Heavy broken lines, crests of bounding ridges; light broken lines, limits of rift topography; *T*, Tomales Bay; *O*, Olema Creek; *P*, Pine Gulch Creek; *B*, Bolinas Lagoon. (After the California State Earthquake Investigation Commission.)

246. Volcanic Basins.—By volcanic outbursts craters are formed, either as holes in more or less level ground (pit craters), or as cup-shaped depressions on the summits of volcanic peaks. The floor of such a crater is of the same size as the cross section of the vent through which the explosions occurred. Explosion-made depressions of considerably larger size than the accompanying associated volcanic vents are called *calderas* (sing., caldera) (cf. volcanic sink, Art. **245**). Lakes may gather in the craters of extinct volcanoes.

[1] Bibliog., GILBERT, G. K., 1909, p. 48.

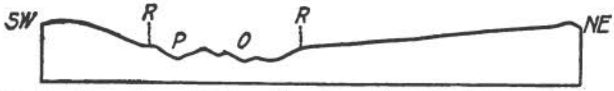


FIG. 263.—Profile section of Bolinas-Tomales valley. Vertical and horizontal scales are equal. *RR*, limits of rift; *P*, valley of Pine Gulch Creek, running SE.; *O*, valley of Olema Creek, running NW. (After the California State Earthquake Investigation Commission.)

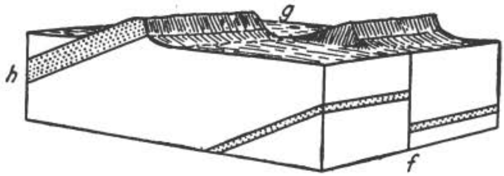


FIG. 264.—Diagram of a fault gap (*g*), caused here by horizontal movement on a vertical fault (*f*) with consequent displacement of the ridge of hard rock (*h*).

FIG. 265.—Dunes and dune hollows. Contour interval, 20′. (Lakin sheet, Kan.)

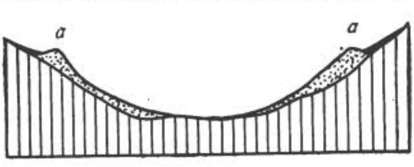


FIG. 266.—Section of a glaciated valley with lateral moraines (stippled). Talus (black) has partly filled the small valleys between the moraines and the bedrock (vertical lining).

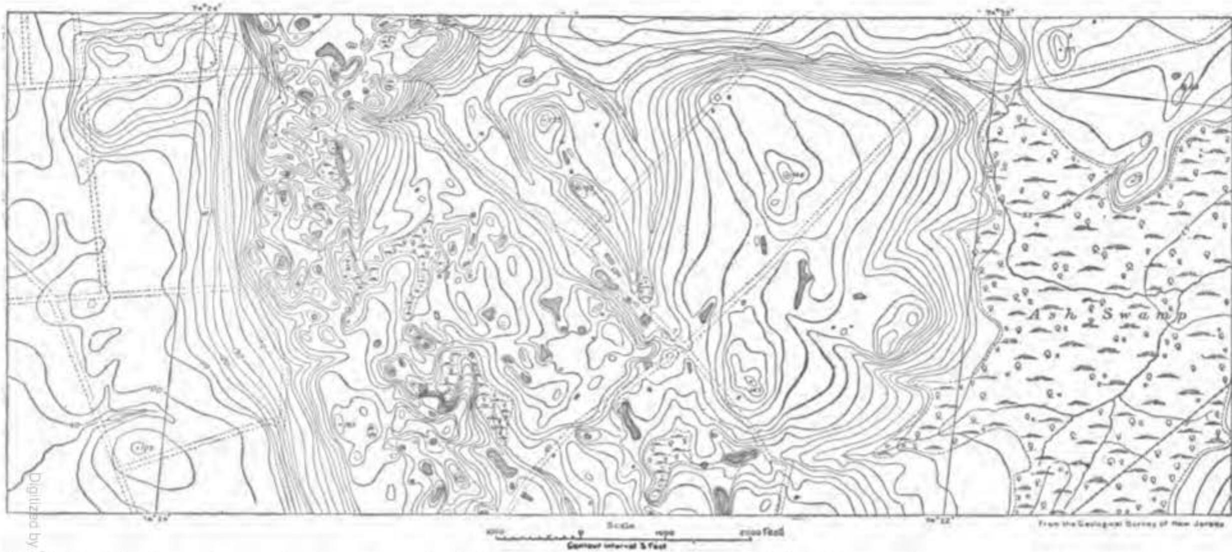


FIG. 267.—Moraine and outwash-plain topography in Union Co., N. J. The eastern half of the map shows ground-moraine topography. The rough belt of country just east of meridian 74° 24′ is a terminal moraine. The land sloping westward from the terminal moraine is an outwash plain. Ponds are represented by horizontal ruling. (After R. D. Salisbury and W. W. Atwood.)

247. Constructional Valleys and Basins.—When deposition by wind, water, ice, or vulcanism is irregular, or when natural barriers are thrown up across valleys, constructional valleys and basins may result. Basins, some constructional and some de-

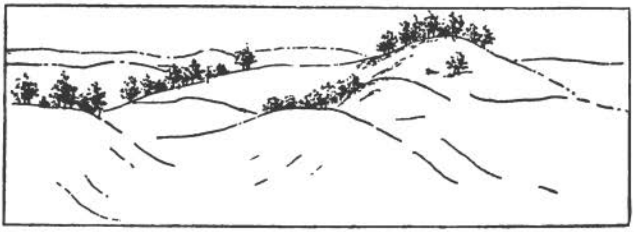


FIG. 268.—Characteristic terminal moraine topography. (Passaic Folio, N. J.-N. Y., No. 157, U. S. G. S., 1908.)

structional are typical elements in the topography of dune areas (Fig. 265). Valleys may be formed between parallel morainal ridges of mountain glaciers, or between the lateral moraines (**257, E**) and the adjacent valley walls (Fig. 266). They

FIG. 269.—Section showing a mass of ice (*a*) surrounded by aqueoglacial deposits, and a kettle hole (*b*) resulting from the melting of a similar projecting ice block. (After M. L. Fuller.)

may be formed also between parallel ridges deposited by a continental ice sheet. Terminal moraines especially are characterized by numerous hollows of all sizes and shapes (Figs. 267, 268). At the ragged edge of the melted ice sheet, outwash sands and

FIG. 270.—Section showing a block of ice (*a*) covered by aqueoglacial deposits, and a kettle hole (*d*) formed by the melting of a similar buried ice block. Under the kettle hole structureless sands (*c*) occupy the space of the melted ice. (After M. L. Fuller.)

gravels (kames, eskers, sand plains, etc.; see **257**) may be spread round and even over detached ice blocks, which, by subsequent melting, leave depressions (kettle holes, ice-block holes) to mark their sites (Figs. 269, 270). When such kettle holes are in outwash plains (**241, C**), dry channels or "creases" may sometimes be seen to extend out from them, channels by which water was conducted away from the melting ice block. If the wash deposit did cover the ice, melting caused the materials to sag and so more or less destroy their internal structure. The sides of the resulting kettle hole may have any inclination between 0° and 30° or 35° (angle of repose), according to how much sagging there was, and there can be no accompanying drainage creases on a surrounding outwash plain. If a kettle hole has a notably flat, even floor, it has probably been alluviated.

Barrier basins are produced by natural damming. Landslide débris may choke up a narrow valley for a while and a lake may be formed upstream from it. Many of the lakes in glaciated countries lie in hollows behind morainic barriers (Fig. 271, A). Ice itself has sometimes served as a temporary dam, particularly in the valleys of northward-flowing streams. Two bends of a meandering stream sometimes meet, and the stream, breaking through the narrow neck, adopts the shorter course. The deserted meander, at length silted up at its cut-off ends, becomes an oxbow lake (Fig. 272). When a side stream brings down more detritus than the main stream can handle, the latter may be ponded upstream from the confluence; and, *vice versa*, if a river carries an excess of load, it may aggrade its bed and impound the lower reaches of its branches just above its confluence with them. (Under what topographic conditions might these events occur?) Another type of barrier basin may be made by a sheet of lava which blocks a main valley, or, by moving down a main valley, dams up the side valleys. Barrier basins include lagoons (**263**) and bays which have been closed in by bay-mouth bars (**233**).

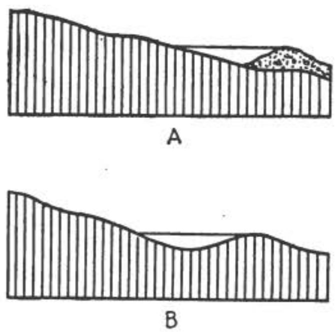


FIG. 271.—Section to illustrate the nature of glacial lake basins. A, lake retained by moraine dam; B, lake held in rock basin.

248. Destructional Basins.—Basins of destructional origin are comparatively rare. Some are made by ice, some by wind, and some by unequal weathering. In glaciated districts these rock basins are not infrequently occupied by lakes which may be very deep (Fig. 271, B). The process by which they are

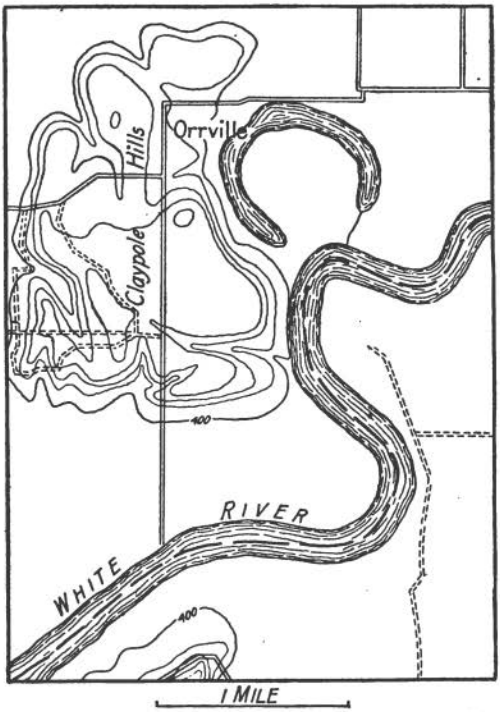


FIG. 272.—An oxbow lake in the site of a deserted meander of the White River, Indiana. Contour interval, 20′. (Princeton sheet, Ind.-Ill.)

gouged out by the ice is often called *overdeepening*. On their rocky rims are unmistakable signs of their glacial origin, in striæ, grooves, and numerous knobs or roches moutonnées (**258, E**). *Wind-scoured basins* are shallow, but they may cover large areas. They are characteristic of deserts. At irregular intervals they become the seats of broad, shallow sheets of water called *playa lakes*, which quickly gather and almost as quickly evaporate, leaving mud flats, or *playas*, to mark their sites. Destructional hollows carved out by wind in dune areas are called *blow-outs*. Their sides are often steep and intersect the bedding of the adjacent dunes. Shallow basins are sometimes produced by unequal weathering (chiefly decomposition) in uniform rocks, or by differential weathering in rocks of varying resistance, where the surface of the ground is too level for thorough drainage.

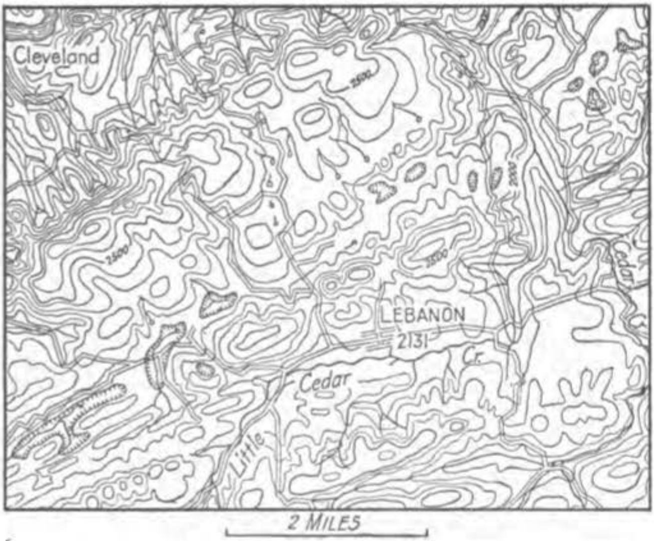


FIG. 273.—Sink holes in limestone. The depressions are situated on the NE.-SW. diagonal of the map. Contour interval, 100′. (Bristol quadrangle, Va.)

Moisture, collecting in the hollows, maintains a luxuriant vegetation and, with the help of soil acids, brings about the decay of the underlying rock. Such basins may broaden more rapidly than they can deepen, for decomposition is greatly retarded by increase of depth.

249. Destructional Sinks.—The word "*sink*" is applied to pipe-like vertical holes in the ground, which lead downward into subterranean passages and chambers that have been formed by the solution of a soluble rock. It should not be confused with the volcanic sink (**245**), which is of diastrophic origin. Sinks are generally limited to countries where limestone underlies the soil and the climate is humid (Fig. 273). They are of two kinds: some are produced by the caving in of the roofs of subterranean chambers, and others are channels which were opened up along joints and which have been enlarged through solution by descending surface waters. The cave-in type of sink reveals signs of fracture on the edges of the hole, generally increase in diameter downward from the surface, and contains

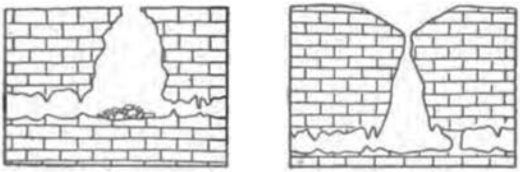


Fig. 274.—Sections of sink holes. In A the roof has fallen in; in B the upper opening has been made entirely by solution.

shattered débris of the roof rock on the cave floor beneath the opening (Fig. 274, A). On the other hand, solution sinks often flare, funnel-like, at the surface, and the edges and walls of the hole bear marks of corrosion, not of fracture (Fig. 274, B. (Chapter II).

250. Destructional Valleys. A. In General.—Valleys carved by erosion differ very greatly in respect to size, shape, and pattern. In size they grade down into grooves (*q.v.*). Their shape may be considered in terms of their profile sections, their longitudinal sections, and their plan. These characters depend upon a number of factors, the most important of which are the agent of erosion, the nature of the material or rock eroded, and the stage of erosion (**260**).

——**B. Valleys of Differential Erosion; Contact Valleys.**—Where rocks differ in their resistance to erosion, the weaker ones become the sites of valleys and lowlands, while the stronger ones remain as uplands. It may be that the difference in resistance is merely mechanical, the weaker ones perhaps being softer or more closely jointed, or the weaker rock may be more soluble or otherwise more easily decomposable than the hill-maker (Figs. 275, 276). Valleys are often opened up along the

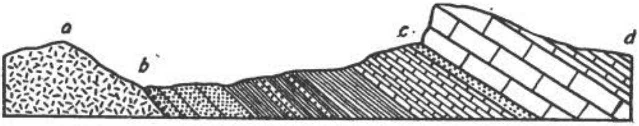


FIG. 275.—Section of a valley due largely to the disintegration of the weaker rocks which are principally sandstones and shales. Here granite (*a*) and the massive Bighorn limestone (*cd*) form the uplands. The section is roughly 1500 feet long. (Cloud Peak-Fort McKinney Folio, Wyoming, No. 142, U. S. G. S., 1906.)

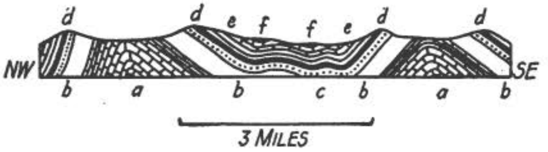


FIG. 276.—Section across the Appalachian Mts. in Virginia. The principal valleys are situated on limestone. The ridges are on sandstone and quartzite. *a*, Shenandoah limestone; *b*, Martinsburg shale; *c*, Juniata formation; *d*, Tuscarora quartzite; *e*, Lewistown limestone; *f*, Monterey sandstone. (Monterey Folio, Va.-W. Va., No. 61, U. S. G. S., 1899.)

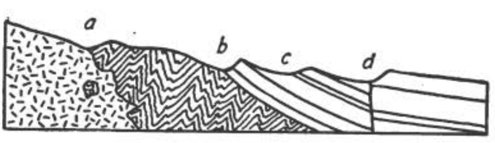


FIG. 277.—Geologic section illustrating valleys situated upon contacts as follows: *a*, intrusive contact; *b*, unconformity; *c*, conformable bedding contact; *d*, fault. Note that the contact localizes the valley, but often because resistant and weak rocks are there in juxtaposition.

outcropping edges of such surfaces of weakness as igneous contacts, upturned unconformities, conformable bedding contacts, and faults (Fig. 277). These may be called *contact erosion valleys*, and those on fault lines are further defined as *fault-line valleys*. The fault-line gap is a special variety of fault-line valley.

——**C. V-shaped Valleys.**—Gully, gorge, ravine, and canyon, are all general names applied to destructional valleys with comparatively steep sides. Those which are stream-made are characterized by two important features: they are V-shaped in cross section, and their plan is more or less sinuous or zigzag, so that a person standing near the stream and looking along the valley can not see far because of overlapping upland spurs (Fig. 278). The breadth or angle of the V is largely dependent upon the stage of erosion (**260**). In young valleys it is narrow and relatively deep. In valleys which are said to be in early maturity it is broader, and it opens wider and wider and becomes more and more shallow as maturity advances to old age.

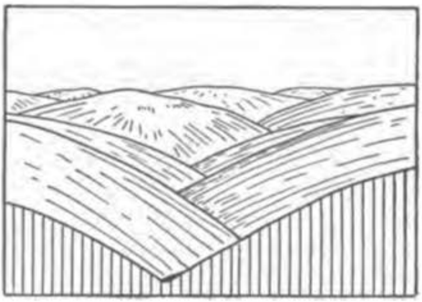


FIG. 278.—A river valley showing overlapping spurs. The line at the top of the vertical ruling is a profile line, the ruling being a section of the ground.

——**D. Solution Valleys.**—The V-shaped types of valley just described are due to corrasion. In moist climates soluble rocks, like limestone, may wear chemically with greater facility than they wear mechanically. The resulting *solution valleys* are often broadly U-shaped in cross section, and their trend parallels the outcrop of the soluble rock. There is the possibility that these valleys may be confused at first glance with those of glacial origin; but, in general, solution valleys are seen only south of the limits of continental glaciation. Within the glaciated area examples may be found of valleys started by solution, but subsequently deepened by ice abrasion.

——**E. Destructional Gaps.**—A short valley which opens across a ridge and connects lowlands on opposite sides of the ridge is termed a *gap*. The fault gap has already been described and figured (**245**).

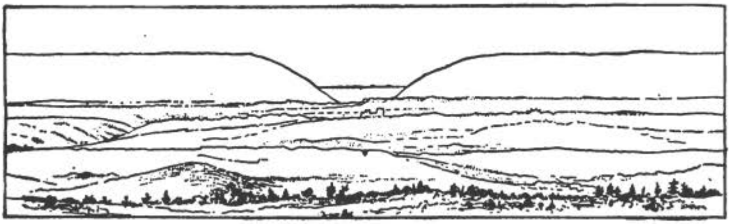


FIG. 279.—The Delaware Water Gap, from Jenny Jump Mt. The high ridge in the background, interrupted by the gap, is Kittatinny Mt. Its top marks the level of an ancient uplifted peneplain. (After W. M. Davis.)

Under certain conditions a river may be forced to incise its course as a narrow gorge in a hard rock ridge while it opens out a broad lowland in the less resistant rocks on each side. This gorge is called a *water gap* as long as the stream flows through it (Fig. 279); but if, for any reason, the water is diverted, the original water gap becomes a *wind gap*. A gap, whether or not containing a stream, is called a *fault-line gap* provided it is due primarily to erosion and is located along the line of outcrop of a dip fault or a diagonal fault that intersects the ridge-making rock layer (Fig. 280).

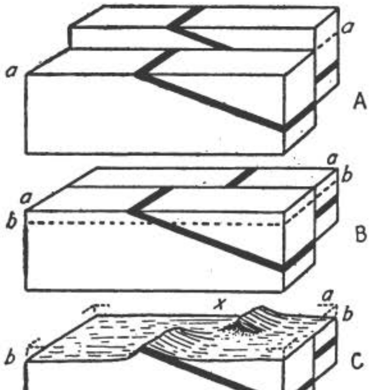


FIG. 280.—Origin of a fault-line gap. A, a region after faulting and before erosion; B, the same region after erosion to a plain at the level *aa*; C, the same region after revival of erosion and removal of the weak rocks to the level *bb*. The fault-line gap is at *x* in C. Hard rocks are black.

——**F. Valleys and Channels Without Streams.**—Two cases have already been noted of channels which have been abandoned by the streams that made them. These are the wind gap (**E**) and the glacial crease (**247**). Further comment on them is unnecessary; but there are several other types of channel, gorge, or valley, which are temporarily or permanently without streams.

By differential weathering steeply inclined dikes and strata may be eroded so much faster than the rocks on each side that clefts and even considerable valleys may be produced. Often there is no stream in these depressions. The rock waste is removed by rainwash or, in dry countries, by the wind.

In deserts dry channels or *arroyos*, some of them many feet deep, are normal features in the landscape. Occasionally these arroyos are filled by roaring torrents which are supplied by

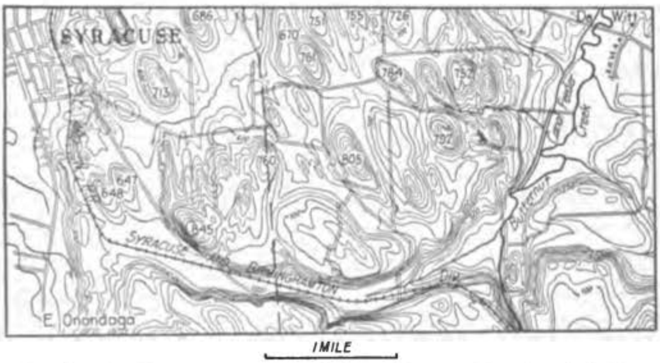


Fig. 281.—An abandoned stream channel, formerly an outlet of a glacial lake. The Syracuse and Birminghamton Division of the railroad follows the channel. Contour interval, 20′. (Syracuse sheet, N. Y.)

cloudbursts in adjoining mountains, but the water runs usually for only a short time because it soon sinks into the ground or is evaporated. The typical arroyo has a flat floor and almost, if not quite, vertical walls, for the effects of the excessive erosion performed by the torrents are scarcely modified in the intervals between successive floods.

Alluvial fans in dry regions are built intermittently. The streams pass into the loose sand or gravel far up on the deposit and abandon their lower channels except at times of heavy rainfall in the mountains. Shallow depressions are common on alluvial plains where the streams, in their meandering, have deserted their former courses.

Above the level of saline lakes, in relatively low places in the rims about their basins, abandoned outlets may exist by which the lake waters once drained out. More common, however, are the abandoned channels in lands which have been under the influence of continental glaciation, channels which served for a while as main drainage lines for the glacial waters (Fig. 281). They were made where the lower, older valleys were blocked by ice or moraine and the water was forced to follow new routes. They often start at the level of abandoned shore lines, showing that they were the outlets of temporary lakes. Some of these gorges were subsequently buried under later drift, but those that were not so filled display many of the normal characters of destructional stream courses, except that they are often out of harmony with the present drainage systems.

——**G. Glacial Valleys.**—Glaciated valleys have been scoured either by mountain glaciers or by ice sheets. In both cases it is probable that many of the valleys were formerly made by streams and were then modified by ice. The glaciated valleys of mountain districts are characterized by several or all of the following features: (1) the transverse profile is U-shaped, not V-shaped as in a majority of stream valleys; (2) the valley is straight or broadly curving, without overlapping spurs; (3) its rock walls are steep (oversteepened stream valley walls) and are more or less polished, striated, and grooved by ice abrasion; (4) the ice-scoured walls sometimes terminate upward in an obtuse angle or *shoulder* above which the mountain slope is less steep; (5) the valley's longitudinal profile is broadly steplike, the "treads" being of gentle grade and sometimes holding lakes in rock-rimmed or moraine-dammed basins, and the "risers" being steep, ice-plucked cliffs, sometimes well nigh impassable (Fig. 282); (6) the rock floor of the valley bears evidence of powerful ice abrasion in polish, striæ, grooves, etc., and is often irregular with roches moutonnées; (7) ground moraine and recessional moraines (**257, E**) rest on the valley floor, and lateral moraines are plastered up against the valley sides; (8) tributary valleys usually enter at levels considerably above the main valley floor (**251**).

Valleys overrun by ice sheets do not possess so many distinguishing marks of their origin. Their profile is U-shaped

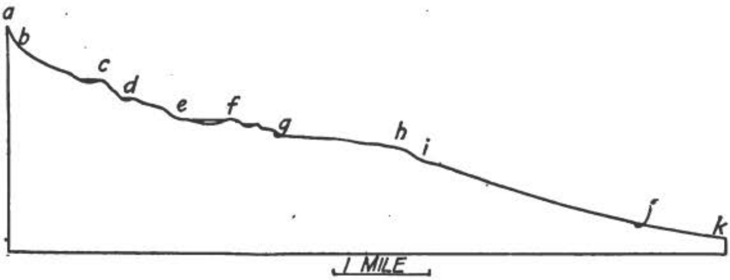


FIG. 282.—Longitudinal profile section of a glacial valley in the Sierra Nevada, Cal. *ab*, cirque wall; *c*, *d*, *ef*, lakes; *gh*, tread; *hi*, riser; *jk*, head of alluvial cone at foot of mountains. The vertical scale is twice the horizontal scale.

if they happened to trend about parallel to the ice motion, but those which lay athwart this direction often suffered plucking (and therefore steepening) on the side toward the source of the ice and abrasion (hence reduction of slope) on the other side (Fig. 283). Although an ice sheet tends to straighten original valleys parallel to its advance, although it polishes, striates,

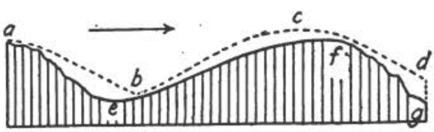


FIG. 283.—Transverse profile of a valley overrun by an ice sheet in the direction of the arrow. *abcd*, profile of valley before ice erosion.

and grooves their floors and walls, and here and there scours out rock basins or forms roches moutonnées, it does not have a special propensity to oversteepen these walls, nor to produce "shoulders", nor to erode "giant steps." There are no true lateral moraines. In fact, the distribution of morainic material shows regional rather than local control. Outwash sediments very often cover the bedrock floors of these valleys, sometimes to considerable depths.

Glacial valleys may lose their distinctive marks so that there may be some trouble in distinguishing them from solution valleys on the one hand, and from certain mature stream valleys on the other hand. For instance, weathering may remove striæ and other tokens of glacial abrasion, and, in mountain valleys, talus accumulations may obscure the U-profile or conceal morainic deposits. As with solution valleys, so too with U-shaped mature stream valleys, they are not found in areas which have suffered continental glaciation because there has not been time enough for their development since the ice retired. All such original valleys in the glaciated area were modified by the ice.

——**H. Cirques and Drift Hollows.**—At its head the valley made by a mountain glacier normally opens out into a broad amphitheater bounded by steep precipices on all sides except at the junction with the valley. This is a *cirque*. Its floor resembles the floor of the associated valley in bearing evidences of very powerful ice abrasion, but its walls, unlike those of the valley, are generally free from marks of scour. They are cliffs made by sapping (**231**). They are bounded by joint faces.

The earliest phase of the cirque is to be seen in the small drift hollow on a hillside. During the day the snow melts. At night the water freezes in the interstices of the underlying rock and wedges off a few small chips. The next day these chips are washed away down the slope Thus, as the process (called *nivation*) is repeated from day to day, the snowdrift comes to rest in a hollow of its own making. When the drift hollow grows larger it becomes a small cirque and the deeper snow changes to névé.

Hanging Valleys

251. Definition and Classification.—A *hanging valley* may be defined as a valley whose floor "is not in even adjustment with the bottom of the lower depression with which it unites."[1] Between it and this lower depression—valley or basin as the case may be—there is a steep, generally precipitous slope over which the stream of the hanging valley plunges. (1) A majority

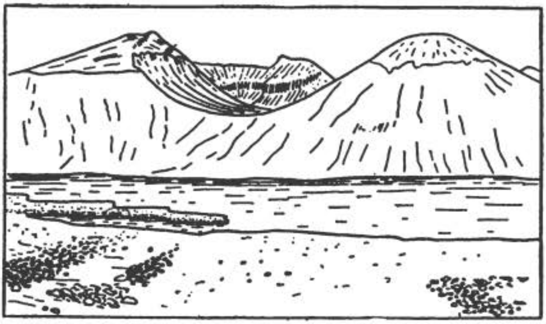


FIG. 284.—View of a glacial hanging valley on the south side of Nunatak Fiord, Alaska. (From a photograph, after R. S. Tarr and B. S. Butler.)

of hanging valleys owe their origin to glaciation (Fig. 284). This is because a trunk glacier cuts its bed to a lower level than do its tributary glaciers, and when the ice disappears the tributary valleys are left hanging above the main valley.

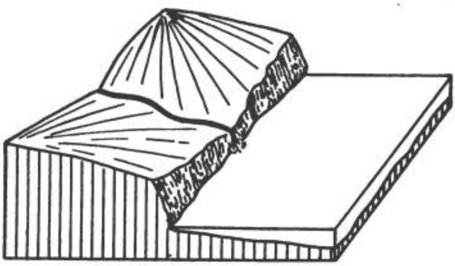


FIG. 285.—A hanging valley resulting from rapid wave erosion.

In like manner cirques may be hanging. However, there are methods other than ice erosion, by which valleys may be made to hang. (2) If waves wear back a coast line more rapidly than

[1] Bibliog., Russell, I. C., p. 76.

the inflowing rivers can cut down their channels, the latter become hanging with respect to sea level (Fig. 285). (3) A river may erode faster than its side streams so that their valleys are made to hang with respect to the main valley. (4) Finally, if a fault crosses a valley, the part of the valley in the upthrown block may be hanging above the lowland of the downthrown block, provided the displacement was more rapid than the stream erosion. From the foregoing it is clear that any kind of a valley may become hanging under the proper conditions.

Caves and Natural Bridges

252. Caves.—Caverns in lava, which result from the very irregular way in which viscous lava moves, may be classed as volcanic. Most caves are destructional. Among these, the largest are formed by solution and they, like sink holes, are characteristic of limestone countries in humid climates. The Mammoth Caves of Kentucky are the best known example. Eolian fretwork weathering may sometimes go so far that individual holes become large enough to call caves. In regions of horizontal strata weathering may locally gnaw back the weak rock underlying a cliff-maker and thus produce broad, shallow caves. Of somewhat similar nature are undercut caves formed at the base of an abrasion cliff, where winds, stream currents, or waves, deliver their most efficient attack. Such caves are especially liable to occur in weak rocks or along joints or faults that invite concentrated erosion.

253. Natural Bridges.—Natural bridges may be found in irregular lava sheets. The majority, like caves, are destructional products of denudation, and as such they are merely a later stage of cave erosion. They are remnants of cave roofs of which the main portion has fallen in or has been eroded away. Consequently, they may result from solution or from abrasion. Some are cut by wind and some by water. In regions of flat-lying strata, the undercut soft rock on opposite sides of a divide may at last be removed, leaving the hard capping layer to span the opening.

Hills, Ridges, and Other Positive Land Forms

254. Terminology and Identification.—According to the definition previously given (**226**), positive land forms include hills, ridges, pinnacles, and any other relief forms which project upward and are surrounded on all sides by lower land.[1] Following is a key to aid in their identification:

Key for the Identification of Positive Land Forms

If the land surface has the form of

A. An isolated knoll or hill, not much longer than wide, and, in general,
- 1. With its height less than its ground plan dimensions, and
  - *a*. The underlying rock materials are unconsolidated, consisting of
    - (1) Volcanic ash, scoriæ, bombs, etc. (sometimes associated with flows), with their bedding parallel to the slopes of the hill, the latter is probably a volcanic cone (**256**).
    - (2) Glacial till (**62**), the hill is probably a drumlin, if it is more or less oval in ground plan and (usually) has its length nearly parallel to the glacial striæ on bedrock in the vicinity (**257, B**).
  - *b*. The underlying rock materials are consolidated, and consist of
    - (1) A particular rock association composed of
      - (*a*) Lava in flows (sometimes interbedded with volcanic ash, etc.), the flows being parallel to the surface of the hill, the latter is probably a volcanic cone (**256**).
      - (*b*) Flat-lying strata, the hill is
        - (a_1) A mesa if its top is flat (**258, B**).
        - (b_1) A mesa-butte if its top is peaked (**258, B**).
      - (*c*) Igneous rock which has the shape of a neck, cutting across the rocks of the surrounding region, the hill is probably a volcanic butte (**258, B**).
    - (2) Not necessarily a particular rock association, and if
      - (*a*) The rock knob or hill is more or less well rounded and
        - (a_1) Has glacial scratches and grooves on its surface, the knob or hill is probably a roche moutonnée (**258, E**).
        - (b_1) Has no glacial scratches or grooves, but shows evidence of the separation of spalls or slabs from its surface and is more or less surrounded at its foot by talus of these spalls, the hill is probably an exfoliation dome (**258, D**).
      - (*b*) The knob is usually rugged, and is surrounded by a wave-cut cliff and bench, it is probably a stack (**258, F**).

[1] Islands are not treated here as a separate class.

2. With its height often several times greater than its ground plan dimensions, the elevation may be a stack (**258, F**), a rain pillar (**258, G**) or any sharp, pinnacle-like remnant of erosion (**258, H**).

B. A definite ridge, usually many times longer than wide, and either continuous or broken by transverse valleys, and if

1. The underlying rock materials are unconsolidated, consisting of

a. Loose bowlders with no, or little, intervening finer débris, the ridge may be a bowlder belt (**257, E**), or a winter talus ridge (**257, G**), or a wave-built terrace (**236**)

b. Glacial till, the hill is probably a moraine of one kind or another (**257, E**).

c. Rather poorly stratified sand and gravel, many of the pebbles and bowlders being subangular, the ridge may be an esker (**257, C**), especially if it is associated with kames and kettle holes (**257, D**).

2. The underlying rock materials are consolidated, consisting of inclined strata which dip nearly parallel to the land surface on one side of the ridge, but are truncated by the other side of the ridge, the latter may be a cuesta or a hogback (**258, C**).

C. A group of hummocks and hollows, generally with a relief of 150 ft. or less, and the underlying materials, which are unconsolidated, are

1. Fine, cross-bedded sands, the hummocks may be dunes (**257, A**).
2. Coarse sand and gravel, rudely stratified, the hummocks may be kames and the hollows kettle holes (**257, D**).
3. Unstratified, heterogeneous débris, the deposit as a whole may be of landslide origin or of glacial till (**257, B, E, F**).

D. A range of hills or mountains, with intervening valleys, the hills are the interstream divides left in the process of erosion of the valleys which have been incised into a broad upfaulted or uparched land mass.

255. Fault Mountains.—*Block mountains* are ridges due to faulting. Ordinarily one slope is gentle (back slope) and the

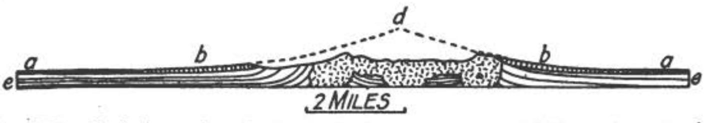


FIG. 286.—Geologic section of Marysville Buttes, a group of hills resulting from the denudation of a volcanic cone. *a*, alluvium resting on volcanic tuffs (*b*); *e*, Tertiary sedimentary rocks; *bdb*, hypothetical original profile of volcano. (Marysville Folio, Cal., No. 17, U. S. G. S., 1895.)

other is steep, the latter being a fault scarp (**229**). Since the uplift of a block mountain is generally slow and erosive agents are constantly working, the ridge is seldom seen as an unbroken unit. It is usually dissected by valleys, and, when very old, it becomes a low range of hills (Fig. 236). The same remark applies to the horst (**186**).

256. Volcanic Cones.—A volcanic peak consists principally of volcanic materials—lava, or ash and other fragmentals, or lava and fragmentals interbedded. Typically it is conical in form, often quite symmetrical, and if sufficiently recent, it may have a crater at its summit. Its slopes may vary between 2° or 3° and 40° (**227**). Denudation may eventually destroy the crater and reduce the original elevation of the peak (Fig. 286).

257. Constructional Hills and Ridges.—Constructional hills and ridges built of materials derived through erosion include dunes, drumlins, kames, eskers, several types of moraine, landslide hummocks, and winter talus ridges.

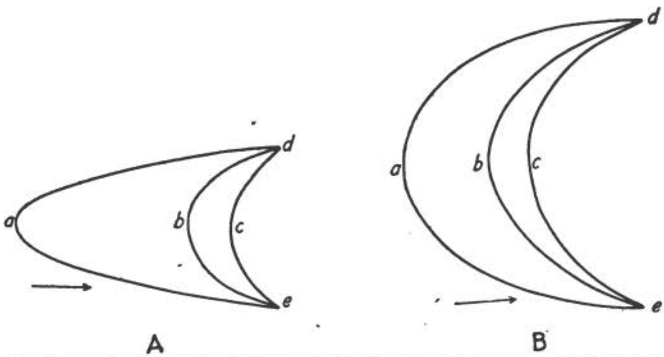


FIG. 287.—Dunes in plan. The wind blew in the direction of the arrow. (After V. Cornish.)

——**A.** *Sand dunes* are typically crescentic in plan with the horns pointing in the direction in which the prevailing wind blows (Fig. 287). The windward slope is gentle and the lee slope is steeper, with an angle of 25° to 35° (Fig. 288). Sand is blown up the gentle slope and is dropped over the crest, whence it slides down the lee slope. In this way the dune migrates with the wind. There are records of dunes consisting of clay[1]. Built of clay chips drifted together during the dry

[1] Bibliog., COFFREY, G. N.

season, these dunes become moistened during the rainy season and the clay particles break and coalesce. In the following hot spell the clay hardens into compact mounds. Sand dunes may be grassed over and covered with vegetation to such an extent that their identity is very obscure. Examination should then be made for their internal structure (**80, G**).

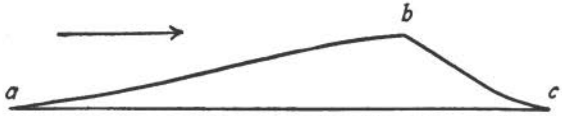


FIG. 288.—Profile section of a dune taken in the direction of the wind (see arrow). *a, b,* and *c* correspond to the same letters in Fig. 287.

——**B.** *Drumlins*[1] are hills consisting of glacial bowlder clay (till). At the time of Pleistocene continental glaciation, they were formed under the ice while it was in motion, and so they have a trend parallel to its direction of flow. The slope toward the source of the ice is often of gentler inclination than the lee side (Why?) (Fig. 289). In plan drumlins are typically oval,

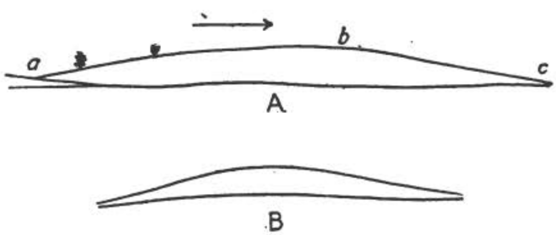


FIG. 289.—Longitudinal (A) and transverse (B) profiles of a drumlin. The arrow points in the direction of ice motion. (After W. C. Alden.)

although irregularities in shape are not uncommon (Fig. 290). Few have a relief of more than 200 ft. While some were evidently built round projecting rock ledges, many have no such rocky cores. In cross sections isolated strata may occasionally be seen in the till, and these may be contorted (**85**). At the time of their formation drumlins are thought to have been between

[1] Bibliog., ALDEN, W. C.

5 and 30 miles north of the ice front. As for their distribution, they are numerous in many States within 100 miles or so north of the southern limit of Pleistocene glaciation (Fig. 291).

FIG. 290.—Drumlins in Wisconsin. The ice moved a little west of south. Contour interval 20′. (Waterloo sheet, Wisc.)

——C. *Eskers* are relatively long, narrow, winding ridges of mixed sand and gravel. In longitudinal profile their crests are seen to be sinuous (Fig. 292, A). They range in height from 10 or 15 ft., to 100 ft. or even more. They may cross valleys or bend round hills, seldom more than 200 ft. above the valley floor.

Fig. 291.—Map of North America showing area covered by the Pleistocene ice sheet at its maximum extension. (Passaic Folio, N. J.-N. Y., No. 157, U. S. G. S., 1908.)

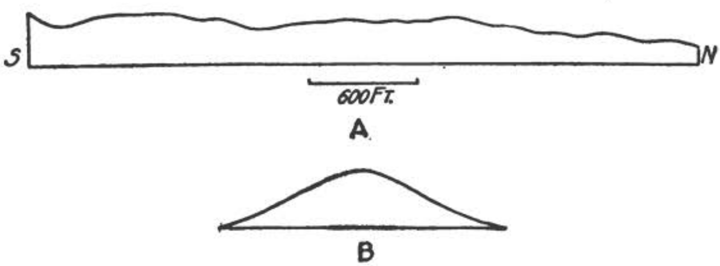


Fig. 292.—Longitudinal (A) and transverse (B) profile sections of an esker. B is drawn on a somewhat larger scale than A.

Usually they terminate in outwash plains (**241, C**). Cuttings in them show that they consist of somewhat waterworn, rudely stratified materials. The pebbles range up to 18 in. or 2 ft. in diameter and are typically subangular, although sometimes pretty well rounded. These esker ridges were laid as stream bed deposits in channels in the ice during the retreat of the glacial sheet. Their shape, their structure, and their relations to outwash plains, prove that the ice was stagnant when they were formed. After the supporting ice walls melted away, the deposits slumped down to the angle of repose for gravel (**227**). It is on account of their rapid accumulation and their later settling that their stratification is generally so poor.

——**D.** *Kames* are similar to eskers in composition, structure, and origin, but in shape they differ. Instead of being long, narrow ridges, they are more or less oval or irregular knolls and hummocks. They were deposited in irregular openings in the ice. Eskers and kames are associated with kettle holes.

——**E.** Ridges and irregular deposits laid down by ice are spoken of as *moraines*. Some are associated with valley glaciers

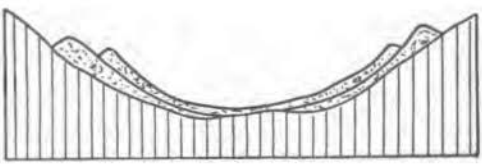


Fig. 293.—Lateral and ground moraines deposited in two successive advances of a valley glacier.

and others with ice sheets. Lateral, medial, terminal, and recessional moraines are made by valley glaciers. *Lateral moraines* are built of débris, part of which falls upon the ice as talus from the mountain sides, and part of which, having been carried for some distance within the ice, is returned to the surface by shearing or by surface melting (ablation). When the glacier retreats, it leaves these lateral moraines as embankments on either side of the valley. They consist of till or of great agglomerations of bowlders (**62**). They may rise above the valley

floor to heights of over 1000 ft. Frequently there is a descent of a few score feet from the crest of the moraine to the original valley side. A readvance of the glacier, if of great extent, may destroy the moraines of the earlier advance; but if the returning ice tongue is not as large as the first glacier, lateral moraines of

Moraines of earlier epoch. Moraines of later epoch.

FIG. 294.—Sketch map showing the distribution of moraines deposited in two successive advances of a group of valley glaciers. (After W. W. Atwood.)

the second may be constructed, terrace-like, against the inner sides of the older moraines (Fig. 293). On account of the tendency of glaciers to oscillate up and down their valleys, this superposition of lateral moraines is not uncommon, and care must be taken to discriminate between the minor variations of one ice epoch and the much more significant effects of distinct

glacial epochs. The two sets of moraines shown in Fig. 294 might belong to two ice oscillations during one epoch were it not for the fact that criteria other than relative position proved them to represent two epochs widely separated by an interglacial interval (**101**).

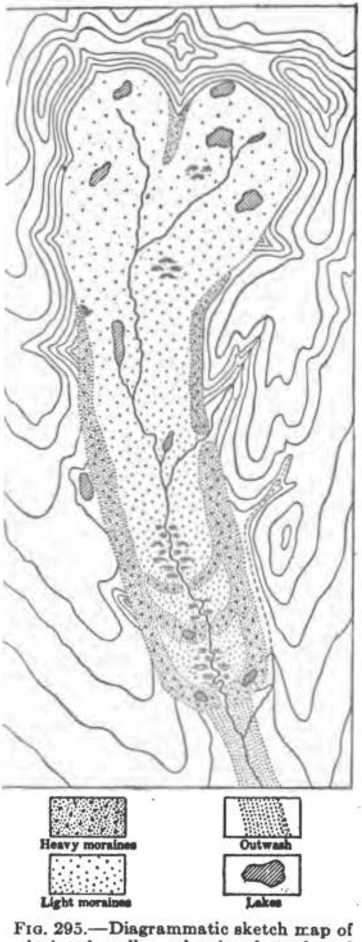


FIG. 295.—Diagrammatic sketch map of glaciated valley, showing lateral and recessional moraines, several blocked tributary streams, and the head of a valley train. (After W. W. Atwood.)

When two ice streams coalesce, the inner lateral moraines of the two unite to form a *medial moraine* downstream from the point of junction. Medial moraines are left on the floor of the valley after the disappearance of the ice. They are not so well marked as lateral moraines and they are more apt to be modified or destroyed by subsequent stream erosion.

At the front of the ice, as at its sides, a great deal of detritus is deposited. Provided the ice front remains stationary for a while, some of this débris accumulates in a *marginal* or *terminal moraine*, and the rest becomes aqueoglacial material in so far as it is handled by water derived from the melting of the ice. Terminal moraines, composed of till or of bowlder heaps, are curved with the convex side pointing down the valley. In the retreat of the glacier a distinct marginal moraine may be formed every time the front pauses in its migration.

These are often termed *recessional moraines* (Fig. 295). Many such may be built in a single valley. Terminal moraines often unite with the contemporaneous lateral moraines. Where glaciers deployed upon broad piedmont slopes, terminal and lateral moraines may be finely developed.

Terminal and recessional moraines are also formed by ice sheets, both piedmont and continental. In origin they are similar to the deposits of the same name made by mountain glaciers, but in form they may be more hummocky, and they are of much greater size. They may consist of till or of loose bowlders (bowlder belts). Since an ice sheet, advancing over an uneven topography, migrates farther in the valleys than on the uplands, its front becomes lobate, and as a consequence, its marginal or frontal moraines will be lobate. In North America the southward convex curves in the terminal moraine often indicate relatively low land in a northerly direction.

——**F.** A deposit of landslide débris has a very irregular, hummock-and-hollow topography, and is generally situated at the base of a steep slope on which the original scar of the slide may be seen. In its plan it may show evidence of having spread out at the time of the fall. Landslide deposits may resemble morainal accumulations in their surface features, in the chaotic arrangement of their materials, and in the occasional presence of scratches on some of the rock fragments, but confusion is likely to arise only when they are in valleys that look glaciated. In this event they may often be distinguished by their local and irregular distribution as compared with most moraines, and by the fact that their materials are of the same rock as that on the mountain side *above* them. In unglaciated valleys no other suggestions of ice action will be found. In valleys that were formerly glaciated, the landslide materials have probably slumped down over any morainal débris that happened to be in the way.

——**G.** In mountain regions, also, snow banks lead to the formation of "winter talus ridges" (Fig. 296). Rock fragments slide down the snow surface and accumulate at the foot of the drift. In summer, after the snow has melted away, a curving ridge of rock fragments remains, convex away from the source of the slide. If the snow banks of successive winters are smaller, a series of concentric talus ridges may result.

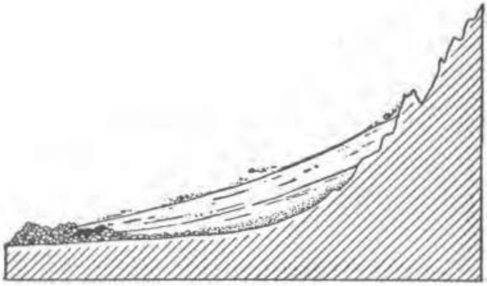


FIG. 296.—Diagram showing mode of formation of a winter talus ridge. (After E. Howe.)

258. Destructional Hills and Ridges.—Destructional hills and ridges are outstanding topographic forms which owe their existence to the deeper erosion of the land that surrounds them. That they have not been worn to a lower level is often due to the superior resistance of the materials of which they are composed, but it may be merely because they are interstream areas or *divides* which have not yet had enough time for their complete erosion. This class of elevations may be regarded as including sharp pinnacles, small rocky knobs only a few hundred square feet in area, and larger peaks and ridges. The following forms will receive consideration: monadnocks, mesas, buttes, mesa-buttes, cuestas, hogbacks, exfoliation domes, roches moutonnées, stacks, and rain pillars. Mention is made of nunataks, baraboos, and steptoes.

——**A.** By long continued erosion a land surface may be reduced to an almost level plain (**242, 261**), but there may still be a few hills, which, having as yet escaped final destruction, rise conspicuously above the plain. These are *monadnocks*. The term connotes nothing in regard to form or structure; it means merely a residual of an old topography standing above a plain of subaerial erosion.

——**B.** A *mesa* is a flat-topped "table mountain" consisting of horizontal or nearly horizontal beds and bounded on all sides by steep erosion scarps (**231, 32**). Mesas sometimes occur as outliers of plateau steps (**237**). When erosion has reduced a mesa so far that there is practically nothing left of the original flat upper surface, the hill is called a *butte* (Fig. 297). It is also called a *mesa-butte* to distinguish it from the somewhat similar

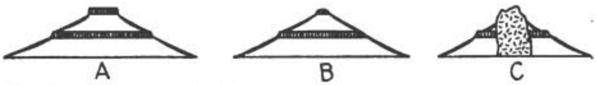


FIG. 297.—Sections of buttes. A and B, mesa-buttes. B is more eroded than A. C, volcanic neck. A thin talus cover lies on the edges of the weaker strata in each of the diagrams.

steep-sided volcanic necks, likewise termed "buttes" (Fig. 297). Many mesas and buttes are monadnocks.

——**C.** If strata of varying hardness are tilted at a low angle, say between 10° and 20°, erosion will develop ridges or *cuestas* on the resistant rock layers. From the crest line of a cuesta there is a steep descent in one direction and a gentle descent in the opposite direction (Fig. 298). The steep slope

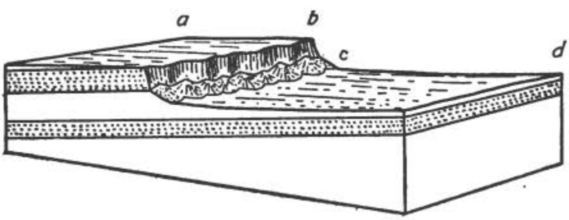


FIG. 298.—A cuesta. *ab*, back slope or "outer lowland," approximately a dip slope; *bc*, escarpment with its base covered by talus; *cd*, "inner lowland." Hard strata are stippled.

is the cuesta face, an erosion escarpment, and the gentle one is the *back slope* of the cuesta. The latter is nearly a dip slope. In beds inclined at angles higher than 20°, the slopes of an erosion ridge developed on a hard rock layer have angles of inclination which are more nearly equal. The side corresponding to the cuesta face (across the stratum) becomes less steep and the back slope, about parallel with the beds, becomes steeper. A ridge of this type is a *hogback* (Fig. 299). Evidently, then, there are all gradations between the plateau step in horizontal strata (Fig. 253), through the cuesta, to the hogback in beds with a relatively steep dip.

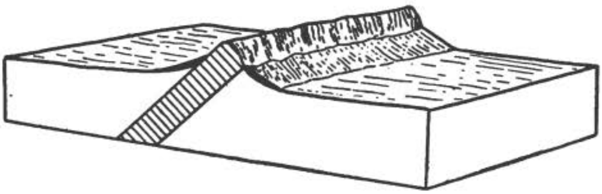


Fig. 299.—A hogback, due to the slower erosion of a resistant stratum (lined).

——**D.** Rounded knobs or *domes* are sometimes produced in the erosion of granitic rocks, conglomerates, etc., by exfoliation (**31**). They may range from a few feet to several hundred feet in height. At the base of a hill of this origin the talus consists largely of great spalls of which some may be seen on the hillside in all stages of separation from the parent rock.

——**E.** In glaciated regions many of the rounded rocky knobs and hills were so made by ice abrasion. Glacial striæ, polish,

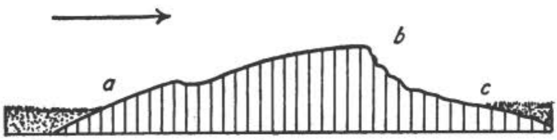


Fig. 300.—Profile section of a roche moutonnée, showing thrust side (*ab*) and lee side (*bc*). Arrow indicates ice motion.

and grooves, on their surfaces bear witness to this fact, but on high hills and rarely in other places, postglacial disintegration may have destroyed these evidences. These rounded rock knobs and hills are called *roches moutonnées* (sing., roche moutonnée). They have a more gentle slope on the side from which the ice thrust came and a steeper, ice-plucked slope on the other side (Fig. 300).

——F. Along rocky coasts there are sometimes outstanding projections of rock, *stacks* or *chimneys*, which have been separated from the sea cliff by the concentrated attack of the waves round and behind them. They are still bedrock in the sense that they are in place. They rise from the wave-cut bench (**237**) from which they will ultimately be razed (Fig. 251).

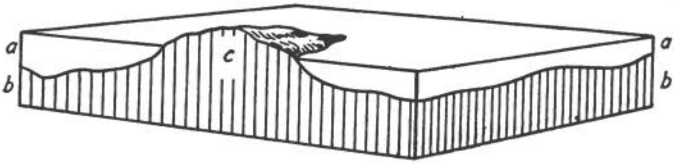


FIG. 301.—A nunatak (*c*). *aa*, ice; *bb*, bedrock.

——G. Relatively soft, fine-grained strata, containing scattered pebbles, or perhaps concretions, may be cut into by the force of falling rain. About any one of these pebbles the matrix may be worn away until the pebble at length rests as a cap on the top of a pillar of the less resistant material. Such *rain pillars* may reach heights of several feet.

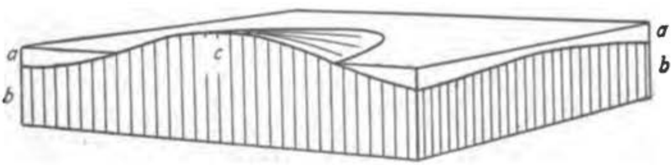


FIG. 302.—A steptoe (*c*). *aa*, lava; *bb*, bedrock and soil which were overflowed by the lava.

——H. Pillars ("hoodoos") may be developed by the erosion of horizontal strata of varying hardness in regions where most of the rainfall is concentrated during a short period of the year. Below hard layers the soft materials may be so far worn away that columns of the latter remain capped by patches of the overlying resistant rock. The height of the pillar depends in part upon the thickness of the weaker stratum.

——I. Three other forms may be mentioned here, although they have no particular relation to destructional or constructional origin. These are the nunatak, the steptoe, and the baraboo. A *nunatak* is an island of bedrock in a glacial field, a hill projecting through, and entirely surrounded by, the ice (Fig. 301). A *steptoe* is a similar island of bedrock in a lava flow. The lava spread out round the hill and froze about it (Fig. 302). Finally, a *baraboo* is a monadnock which has been buried by a series of strata and subsequently reëxposed by the partial erosion of these younger strata.

CHAPTER XII

TOPOGRAPHIC EXPRESSION

Topographic Expression in General

259. Mutual Relationship of Topographic Forms.—The study of topography can not stop at the description and interpretation of land forms as mere isolated phenomena. Not only must we be able to recognize these individual elements, but also we must be able to interpret their meaning as they appear in their mutual relations. The various relief features of a region as a whole are the product of some common cause or interacting causes. Their shape and distribution are dependent partly upon the underlying geologic structure, partly upon the number and kind of geologic agents which have been engaged in their formation, and partly upon the length of time during which they have been under the control of these agents. Using the term *topographic expression* with reference to the general appearance of a land area,[1] we may say, then, that topographic expression is conditioned by three important factors, namely, geologic structure, erosion process, and stage of topographic development. In the succeeding pages topographic expression in its relation to these three factors will receive some consideration, though by no means in an exhaustive way. Topographic development will be treated first; then the association of unlike types or facies of topography, which were produced in successive cycles, and, last, valley pattern, which depends chiefly upon underground structure. In studying a land surface from this broad standpoint, the geologist should never lose sight of the fact that the topographic elements must always be examined individually before they can be explained in their ensemble.

[1] We may speak, likewise, of the topographic expression of a particular kind of rock or type of structure.

Cycles of Topographic Development

260. Definition.—No land forms are strictly permanent. Wind, water, and ice are constantly engaged in modifying the configuration of the ground. In the change successive stages of development are recognized, and these are called youth, maturity, and old age. The sequence, from the beginning of youth to late old age, is known as a *physiographic cycle*. As a matter of fact, old age is seldom attained, for the process of erosion becomes increasingly slow as the cycle advances and various accidents and interruptions interfere with the work (**265**). Since each agent of erosion operates in its own peculiar way, there are several different kinds of physiographic cycle. There are the "normal" or river cycle, the cycle of mountain glaciation, the cycle of marine erosion, and the cycle of arid erosion.

261. Cycle of River Erosion.—No river can cut its channel more than a few feet below sea level because its speed is quickly

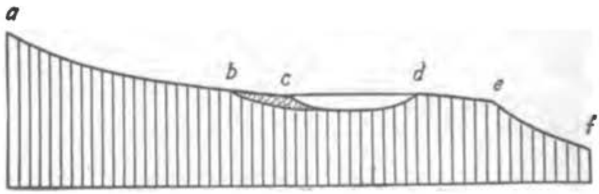


Fig. 303.—A lake as a local base level. *ab*, temporary grade determined by the lake, *cd*; *bc*, delta; *de*, portion of original slope of stream channel; *ef*, upper part of stream profile which is being cut downward to a grade determined by a base level to the right of the diagram. As soon as *e* reaches *d*, by headward cutting, the draining of the lake will begin.

reduced as soon as it empties into the sea. A few hundred feet inland the stream can not cut even as low as sea level, for there must be some slope to enable it to flow. Carrying out this line of reasoning, we find that there must be a slope for the course of every river, below which further erosion is no longer possible. When any stream has cut down to this critical slope it is said to be *at grade*, and the ocean level is termed *base level*. Probably grade has never been attained by any river, for as time goes on a stream must have a constantly diminishing load, and a diminishing load will enable it to cut nearer and nearer to sea level, so that its grade will be a constantly vanishing quantity; but for purposes of general description grade may be regarded as something having a fairly definite value.

Streams that have not yet reached grade are apt to have waterfalls where they cross hard rocks, and lakes where they flow through basins. They are then said to be young and their valleys are in an early stage of erosion. In this condition they are actively cutting downward and headward. For a time a lake may serve as a *local base level* (Fig. 303), reducing the inflowing

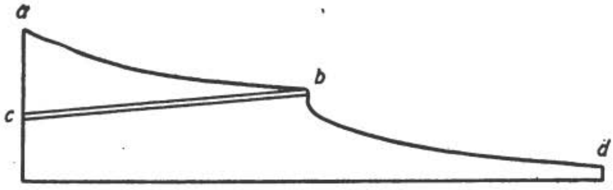


FIG. 304.—Profile of a stream channel, showing how a hard rock layer (*cb*) retards the erosion of the channel upstream from *b*. *b* is a local base level.

streams to *temporary grade*, but at last the lake will be drained and the streams will renew erosion toward a new grade. In like manner, a resistant rock may bring the stream above it to a temporary grade (Fig. 304).

While the stream in its youth is eroding its channel, weathering operates on the valley walls. At first the walls are comparatively steep and the V-section is narrow (Fig. 305). As grade is approached vertical corrasion becomes slower, and with the slackening of this process, weathering relatively gains in speed, so that the V broadens, *i.e.*, its angle becomes more obtuse. When at grade the river is said to be mature. If all the streams in a region are at grade, the topography is mature. The valleys are broad, there is no sharp dividing line between hills and valleys, and there are no waterfalls and lakes.

From the inception of maturity, lateral corrasion becomes more effective than downward cutting. The river builds a flood plain on which it meanders. On the outer curve of each bend the current erodes and on the inner curve it deposits. The beginning of maturity marks the end of the distinct V-section of the valley (Fig. 305, E). During maturity the hills are lowered, the valley grows broader and shallower, the flood plain also broadens until it is much wider than the meander belt,[1] and oxbow lakes result from the coalescence of meanders (**247**). Without any sudden change river and valley pass into old age

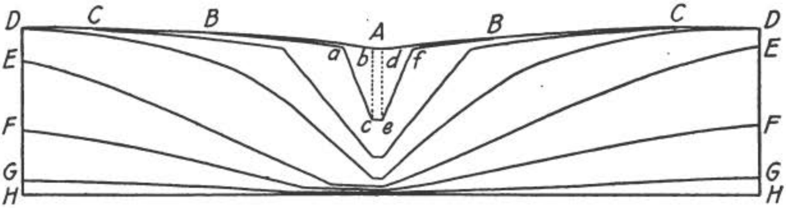


Fig. 305.—Changes in the profile section of a valley from youth to old age. *A*, initial stage. *BB*, youth. *CC*, late youth *DD*, early maturity; here the shoulders once at *a* and *f* have practically disappeared. *EE*, middle maturity; the stream has built a flood plain. *FF*, late maturity. *GG*, old age; the profile is that of a peneplain. *HH*, base level. *bced*, section which was cut by the stream; *abc* and *def*, sections removed by weathering.

and so complete the normal cycle of erosion. When the uplands have all been reduced to low swells and all the streams meander on broad flood plains, the topography as a whole is old (**242**).

Summarizing with reference to the cycle of erosion of streams and valleys: youth is marked by relatively steep valley sides, occasional waterfalls and lakes, and a V-shaped transverse section of the valley; maturity is characterized by a meandering stream, absence of lakes and waterfalls, a flood plain which is not much wider than the meander belt, and a rolling hill-and-valley topography; and, old age is characterized by broad, shallow valleys, broad flood plains, much wider than the meander belts, and the presence of numerous oxbow lakes.

262. Cycle of Mountain Glacier Erosion.—As with rivers, so with mountain glaciers, it is possible to recognize a progressive

[1] The part of a flood plain between two lines tangent to the outer bends of all the meanders is called the *meander belt*.

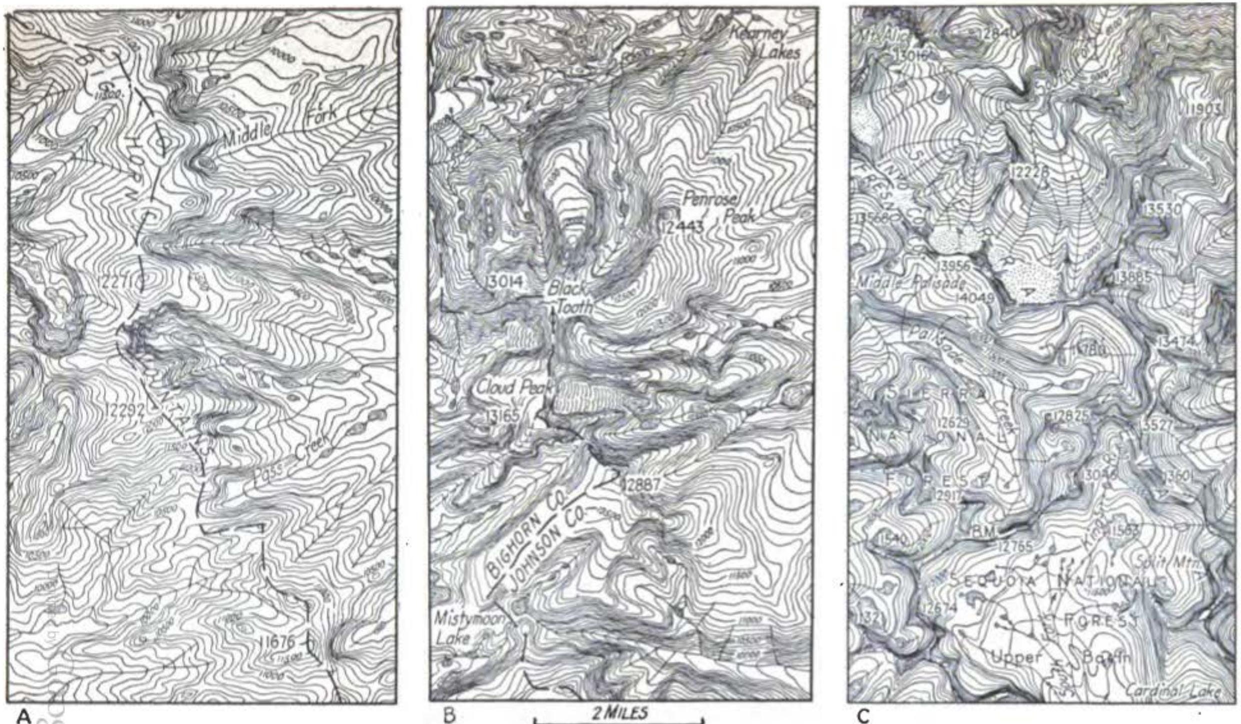


Fig. 306.—Stages of erosion accomplished by mountain glaciation. A, youth; B, early maturity; C, late maturity. In C the stippled areas are snow banks and small glaciers. (A and B from the Cloud Peak quadrangle, Wyo.; C from the Bishop quadrangle, Cal.)

change in the topography according to the amount of erosion to which the region has been subjected. Imagine an upland on which glaciers are beginning to make themselves manifest. The first work of erosion will consist of the carving of drift hollows and then of small cirques. As the process goes on, the cirques will grow larger and will lead out to glacial valleys. That portion of the old upland which has not yet been touched by ice abrasion will constantly diminish in area, for, by headward sapping, cirques on the opposite sides of a divide will approach one another. Thus the upland will become *scalloped* (Fig. 306, A). To a less degree the divides between adjacent valleys that open in the same direction will grow narrower as the valleys are scoured deeper and wider. If glacial erosion continues long enough, adjacent cirques may meet in sharp-edged arrêtes, and the old upland will then remain only in isolated areas (Fig. 306, B). At a still later stage the last remnants of the upland will disappear and all the divides will be knife-edge ridges rising at junction points into abrupt peaks (Fig. 306, C).

263. Cycle of Marine Erosion.—There are two phases of the cycle of marine erosion, that for coasts which have been elevated with respect to sea level and that for coasts which have been depressed. The elevated coast is at first characterized by a coastal plain which slopes gently to the water's edge and then continues with the same inclination beneath the water. The shore line is relatively straight and monotonous. Since the water is very shallow, the waves are forced to break some little distance offshore, and where they break they churn up the bottom sediments and pile them up seaward as a reef (Fig. 307, I and II) (**233**). Between the reef and the mainland is a lagoon of clear salt water. The shore is now in a young stage. Meanwhile the waves cut deeper and they begin to cut into the seaward side of the reef; winds blow the dry sands of the reef over into the lagoon; and streams carry mud and sand into the lagoon from the land side. Thus, two important changes are in progress: the reef is migrating landward and the lagoon is filling up. Gradually plants take root in the shallowing lagoon which eventually becomes a marsh. Over this marsh the reef travels, usually as a body of sand dunes, and at length the edge of the marsh is exposed on the sea side of the reef, that is, on the beach (Fig. 307, III). It is recognizable as a dark band of peat, and very often lumps or "bowlders" of peat, more or less rounded by the waves, may be seen on the beach. Finally, there comes a time when the reef has crossed the entire width of the marsh and has advanced on to what was the land side of the lagoon

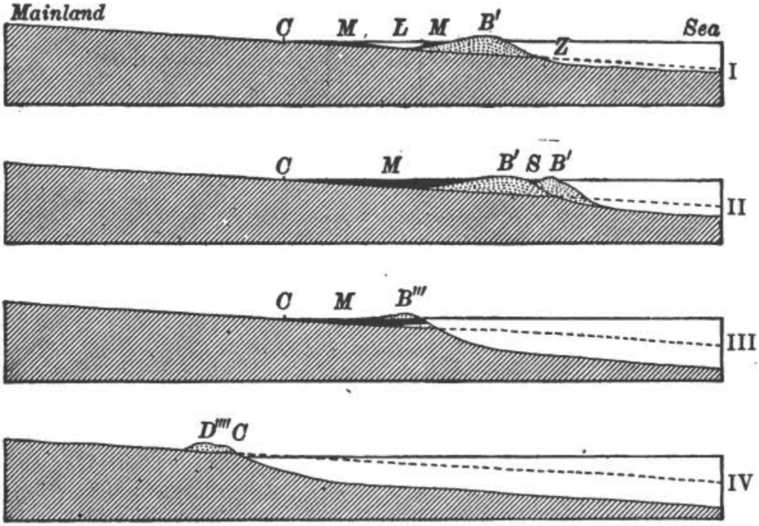


FIG. 307.—Development of a shore line of elevation. *Z*, zone of initial wave attack; *B'*, *B''*, *B'''*, reef; *C*, original shore line, *D''''*, dunes; *L*, lagoon; *M*, marsh. (After W. M. Davis.)

while the latter existed. The shore line is now mature (Fig. 307, IV). It is still nearly straight, but it has a low cliff or "nip" where the waves are cutting into the original coastal plain. The fact is that the waves, by this complicated process, have so far deepened the water that they now break against the shore instead of far out as formerly. They have moved their locus of attack to the land. Henceforth, during maturity, they may cut inland, but the process will slacken and the land will probably suffer elevation or depression and so start a new cycle before the cliff and its accompanying bench have been made large enough to deserve the title, old age.

When a land area is depressed relative to sea level, the sea enters the valleys of the drowned land and the new shore line is irregular in proportion to the unevenness of the topography at the time of submergence. The headlands and islands are more strongly attacked by the waves, and the débris, distributed by currents, finds lodgment here and there in bays or on the

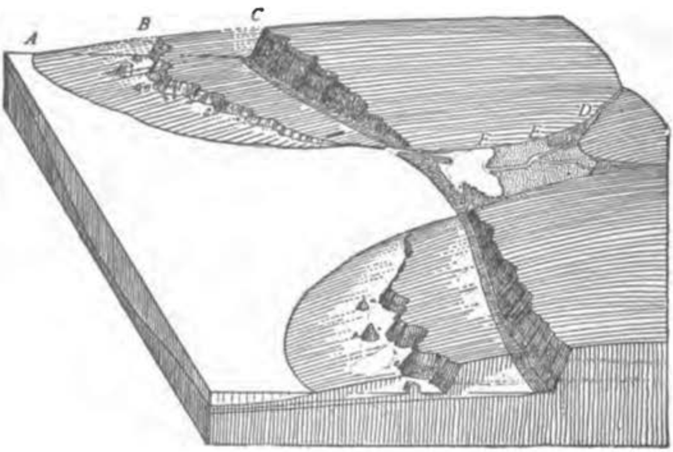


FIG. 308.—Development of a shore line of depression. *A*, initial shore line; *B*, shore line in youth; *C*, same in maturity; *D,E,F*, deposits made by rivers. (After W. M. Davis and W. H. Snyder.)

lee sides of promontories and islands. This is the youthful condition of the depressed coast. Spits, tombolos, bayhead beaches, baymouth bars, etc. (**233**), are abundantly represented. In the lapse of time the islands are demolished, the headlands are cut far back, and the bays are well filled with sediments, partly marine and partly dropped by inflowing rivers, so that the shore line becomes nearly straight (Fig. 308). This is maturity.

Old age is approached, as in the case of the elevated coast, by long continued landward erosion of the coast by the waves.

Lake shores may undergo the same types of erosion as sea shores, but the existence of a lake is generally too short for the complete development of its shore.

264. Cycle of Arid Erosion.—In arid regions wind is the principal agent of erosion. To some extent it is assisted by intermittent streams and sheetfloods. Through the study of present desert conditions in different parts of the world, geologists have deduced a progressive series of changes through which they believe a land mass passes when subjected to erosion by these forces. At the initiation of the arid cycle, the land may be postulated as having any form. If we assume that it consists of a basin and highland topography, whatever drainage exists is centripetal. In each basin the streams flow inward and lay down their waste on the lower slopes and floor of the depression. The relief of the uplands is gradually diminished, partly by their erosion and partly by the accumulation of the basin deposits. . . . "If the climate is very arid, the uplands and slopes . . . are either swept bare, or left thinly veneered with angular stony waste, from which the finer particles are carried away (by wind)[1] almost as soon as they are weathered; if a less arid climate prevails on the uplands and highlands, the plants that they support will cause the retention of a larger proportion of finer waste on the slopes. The areas of deposition are, on the other hand, given a nearly level central floor of fine waste, with the varied phenomena of shallow lakes, playas, and salinas, surrounded with graded slopes of coarser waste."[2]

Under the conditions just described, the region may be said to be in youth. As denudation progresses, the uplands will be cut lower and narrower and adjacent basins may at length coalesce. . . . "Maturity will be reached when the drainage of all the arid region becomes integrated with respect to a single aggraded basin base-level, so that the slopes lead from all parts

[1] The parenthesis has been inserted.

[2] Bibliog., Davis, W. M., 1909, p. 298.

of the surface to a single area for the deposition of the waste." . . . "There will appear. . . large rock-floored plains sloping toward large waste-floored plains; the plains will be interrupted only where parts of the initial highlands and masses of unusually resistant rocks here and there survive as isolated residual mountains. . . . In so far as the plains are rock-floored they will truncate the rocks without regard to their structure"[1] (Cf. **242**).

Wind abrasion, unlike river erosion, can continue below sea level, but the limit to its downward progress is the water table. The upper surface of the ground water is base level for eolian erosion.

Topographic Expression Developed in Two Successive Cycles

265. Topographic Unconformity Defined.—"Topographie unconformity" is a term which has come into wide use in recent

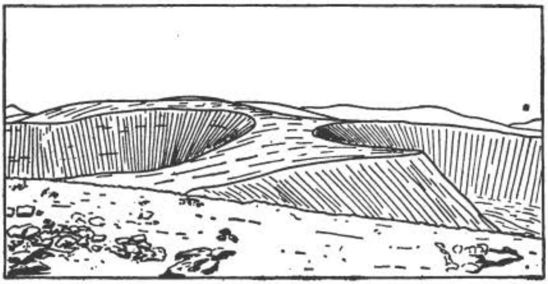


Fig. 309.—Topographic unconformity. A gently rolling preglacial land surface has been invaded by ice which has produced a series of steep-sided cirques. The land is in an early mature stage of glacial erosion. (After W. W. Atwood.)

years. It is applied to land surfaces which consist of two parts that are out of adjustment with one another. This condition is brought about by an interruption or an accident in the ordinary

[1] Bibliog., Davis, W. M., 1909, pp. 303–304.

course of an erosion cycle. For instance, rivers and agents of weathering may have produced a late mature topography which is then uplifted and subjected to mountain glaciation. If the invading glaciers disappear before they carry their erosion beyond youth, the area will show two kinds of topography: (1) the mature upland incised by (2) the new glacial valleys, and these two topographic phases will be out of harmony with one another, that is, they will be topographically unconformable. Their relation will be that of *topographic unconformity* (Fig. 309). The same mature upland incised by streams with young valleys of a new cycle would be another case of such unconformity (profile B, Fig. 305). Abandoned shore lines (**266**) are a third illustration. Other examples might be cited.

266. Abandoned Shore Lines.—Shore-line features—beaches, bars, reefs, benches, and the like—originate for the most part at or near the level of the lake or sea where they are formed. If the water level rises a few feet, relative to the land, they will be submerged; but if it suffers relative lowering, they will be left stranded, as it were, some distance above the new shore line. They are then said to be *abandoned.* Such shore lines are too often called "elevated" before substantial evidence has been brought forward to prove that the land rose, rather than that water level was lowered. "Abandoned" is a better epithet for it implies nothing as to the manner in which the change in relative water level was effected. A shore line may be abandoned, in the case of the sea, either by actual uplift of the land or by actual depression of the sea, and, in the case of lakes, either by differential tilting of the land such that at one end the lake floor is more or less exposed, or by lowering of the lake as a whole, through draining or evaporation (Fig. 310). Whatever the real cause may be, the results are essentially the same. These abandoned shore-line features are in topographic unconformity with the adjoining land forms.

If relative depression of water level sets in after a long period of constancy, and continues at a uniform rate until it is succeeded by another long interval of constant water level, there will be

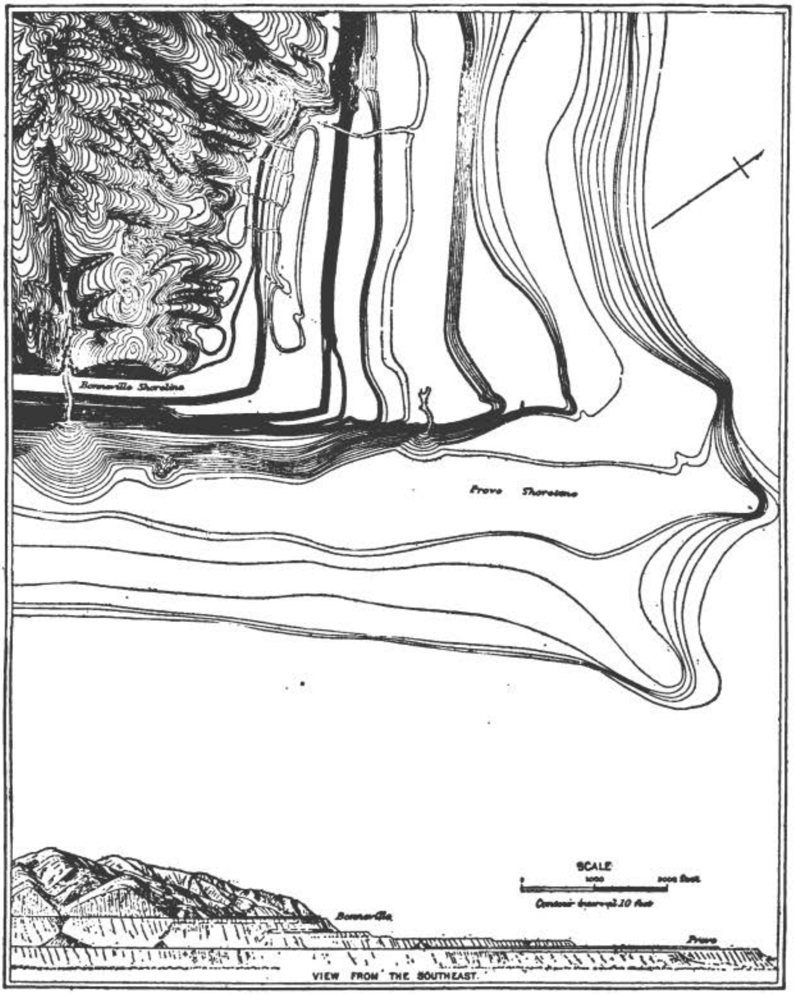


FIG. 310.—Shore terraces exposed by the lowering of an ancient lake. Near Dove Creek, Utah. Map above, view below. (After G. K. Gilbert; drawn by G. Thompson.)

only one belt of abandoned shore-line forms, those of the first period of fixed water level. Probably no other evidence of wave or current action will be seen in the zone between this old shore line and the present one. In other words, for the development of shore-line features there must be a stand of the water level, and the longer this stand, the more pronounced will be the shore-line forms. If a long-enduring great uplift is interrupted by pauses, each pause will be represented by a belt of abandoned shore-line features (Fig. 252). Naturally, the older, higher ones will bear evidence of most subaerial erosion.

Occasionally lakes are impounded on the upstream side of natural barriers which have been built across valleys (**247**). Landslide débris, morainal material, and even ice itself, may temporarily block up a valley in this way. While such a lake is in existence, various shore-line features, both constructional and destructional, may be formed. Beaches may be built; a small "nip" (bench and cliff) may be cut in original unconsolidated deposits of the valley side; and inflowing streams may construct deltas. After the barrier has been cut through, or, in the case of ice, has melted away, the lake will be drained, and small beaches, deltas, wave-cut benches, etc., may be seen on the slopes of the valley through which, perhaps, a stream now flows. If ice served as the dam, the shore-line phenomena end abruptly at the former site of the ice front.

With regard to the field study of abandoned shore lines, the geologist should note that their original characters are usually more or less concealed by vegetation and by erosion. Their recognition depends, first, upon a knowledge of the typical features of shore-line phenomena in their natural position, and likewise upon the ability to distinguish between them and topographic forms of similar appearance (**234**). River terraces are especially apt to be mistaken for abandoned lake beaches. However, river terraces are not associated with abandoned deltas which extend out from their outer margins (see Fig. 310), and river-laid gravels are usually mingled with more sand and fine clastic material than are beach gravels. The latter are relatively "clean." Also, beach materials grade from pebbles and bowlders at the inner margin to finer pebbles and sand toward the outer magin (**74**), whereas river terrace gravels exhibit no such regular gradation.

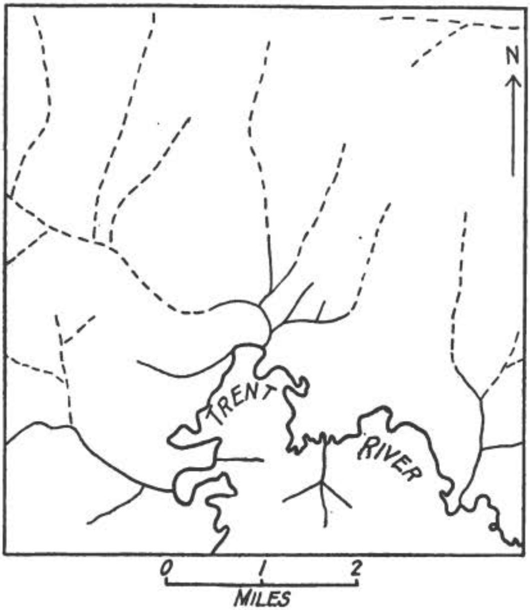


FIG. 311.—Insequent drainage pattern. (Trent River quadrangle, N. C.)

TOPOGRAPHIC EXPRESSION IN ITS RELATION TO GEOLOGIC STRUCTURE

267. Valley Pattern.—Valley pattern, or what commonly amounts to the same thing, drainage pattern, depends on the distribution of bedrock, the attitude of stratiform rocks, the arrangement of surfaces of weakness, such as joints and faults, and on a number of other structural features. Young streams, flowing on a nearly level plain or upon irregular superficial deposits of indefinite form and structure, are likely to wander

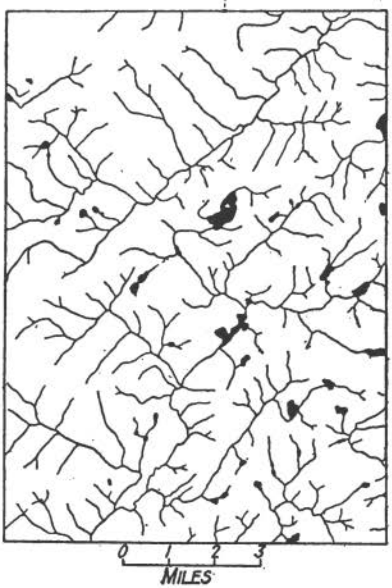


FIG. 312.—Rectangular drainage pattern controlled by joint and fault systems. (Elizabethtown sheet, N. Y.)

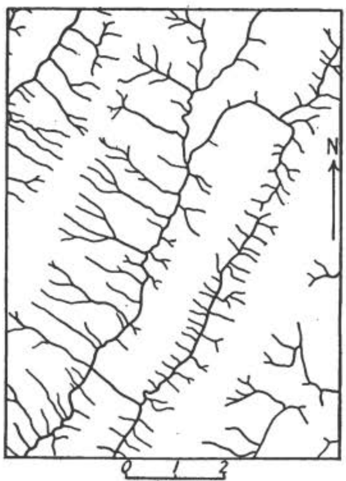


FIG. 313.—Rectangular drainage pattern controlled by folded strata. (Monterey sheet, Va.-W. Va.)

here and there in following the irregularities of the ground. This type of drainage is called *insequent* (Fig. 311). A rectangular, or trellis-like pattern may result from the control of a rectangular joint or fault system (Fig. 312), or from the

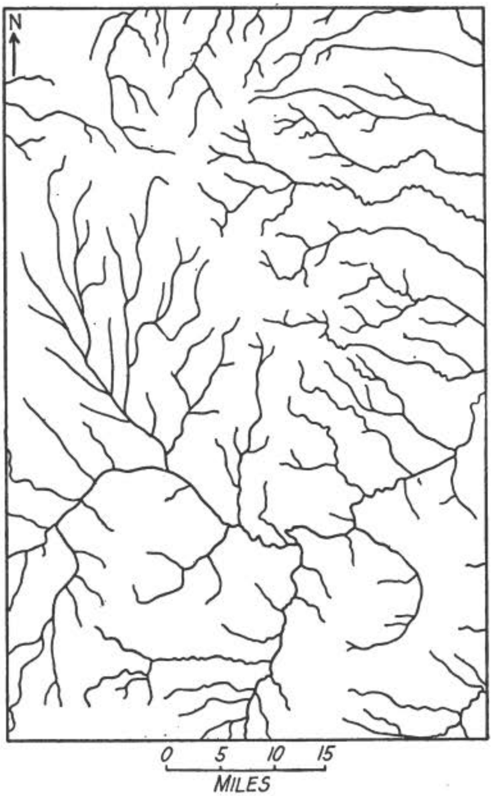


FIG. 314.—Radial drainage pattern of the Black Hills of Wyoming and South Dakota. The range is situated principally in the upper half of the map. (After N. H. Darton.)

influence of tilted or folded, alternating resistant and weak strata (Fig. 313). By the updoming of a relatively flat area, a radial drainage may be induced (Fig. 314). If the radial streams intersect concentric belts of hard and weak rocks, this pattern may be taken as substantial evidence for there having once been such an updoming. The dendritic (treelike) arrangement of rivers and their branches is most common, and is characteristic of regions where structural controls are not exaggerated (Fig. 315).

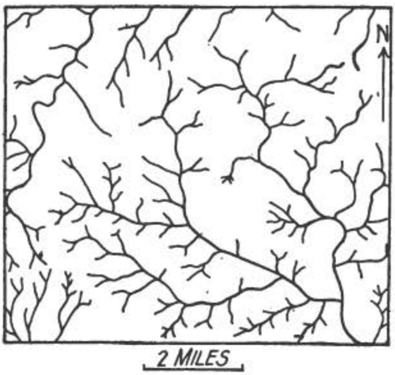


FIG. 315.—Dendritic drainage pattern. (Wartburg sheet, Tenn.)

CHAPTER XIII

TOPOGRAPHIC MAPS AND PROFILE SECTIONS

FEATURES SHOWN ON TOPOGRAPHIC MAPS

268. Classification of Features.—A *topographic map* is one that shows the size, shape, and distribution of features of the earth's surface. On the topographic maps published by the U. S. Geological Survey these features are classified in three groups: (1) *relief*, including hills, valleys, plains, cliffs, and the like; (2) *drainage* or *water*, including seas, lakes, ponds, streams, canals, swamps, etc.; and (3) *culture*, including many of the works of man, such as towns, cities, roads, railroads, boundaries, and names. Relief is printed in brown, drainage in blue, and culture in black. In addition to these, on some recent maps, forests are indicated by a green tint. The significance of the conventional signs employed[1] is often given in a key either on the back of the map or in the right margin. Such a key is called a *legend*. In it the various signs are arranged in a column with those for relief above, those for drainage next, and those for culture at the lower part of the table. Each symbol or line is inclosed in a small rectangle, and all the rectangles are of equal size. If the student has to prepare a topographic map of any kind, he will do well to make the legend for it according to the scheme just outlined. In any case the map must have a legend.

269. Contours.—Relief may be represented on topographic maps by contour lines, by tinting, by hachures, or by shading. In some cases a combination of two or more of these methods is adopted. We shall concern ourselves only with contour maps, since these alone can be used for making satisfactory measurements of height, slope and distance.

[1]See Bibliog., SALISBURY, R. D., and ATWOOD, W. W.

A *contour* is a line drawn through points having the same altitude. The shore line at mean sea level is called the contour of zero elevation, mean sea level being taken as the datum plane from which other contours are measured. A contour representing an elevation of 20 ft. is the line of intersection of the land surface with a horizontal plane 20 ft. vertically above mean sea level. If the sea were to rise 20 ft., the new shore line would

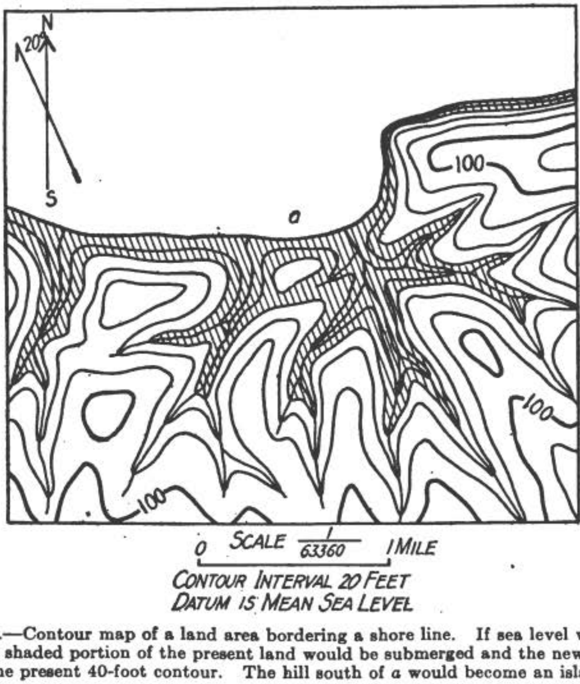


FIG. 316.—Contour map of a land area bordering a shore line. If sea level were to rise 40 feet, the shaded portion of the present land would be submerged and the new shore line would be the present 40-foot contour. The hill south of *a* would become an island.

coincide with this contour. In the same way, if the sea were to rise 40 ft., the new shore line would coincide with the 40-ft. contour (Fig. 316); and so on. When the contours thus indicate differences of level of 20 ft., the vertical distance of 20 ft. is termed the *contour interval*. Other contour intervals, such as 50 ft., 100 ft., 200 ft., and 250 ft., are sometimes chosen instead of 20 ft., but ordinarily only one contour interval is used on a given map.

Certain contours are printed more heavily than others. When the contour interval is 20 ft., the 100-ft. contours are heavy (Fig. 316). A broad contour line of this kind may be called an *index contour*, for it is labelled here and there along its length by a small number which denotes its elevation above mean sea level.

If sea level were to rise, the water would extend up the valleys and so form bays, while the hills and ridges would become headlands. Some hills, having been entirely cut off from the mainland, might become islands. In the present connection the significance of these facts is that (1) contours bend or "loop" upstream in valleys, and (2) the upper contours on hills are relatively short, closed curves. Hollows without outlets are also indicated by closed contours, but they are distinguished from hill contours by having short hachures on the inner (downslope) side of the line (Fig. 265).

270. Scale.—The scale of a topographic map is usually noted in the lower margin. It may be expressed in two ways, either by a ratio or by a measured line (Fig. 316). If, for instance, the ratio is 1 : 125000, this means that the distance between any two points on the map is $\frac{1}{125000}$ of the actual distance between the originals of the two points on the earth's surface; or, to put it in another way, a map 6 in. long on a scale of 1 : 125-000 shows an area 6×125000 in. = 11.8 miles long. The scale of 1 : 63360 is equivalent to the scale of 1 in. to 1 mile. Most of the Geological Survey maps are constructed on one of the following scales:

1 : 62500 , or a little larger than the scale of 1 in. to 1 mile;
1 : 125000, or a little larger than the scale of 1 in. to 2 miles;
1 : 250000, or a little larger than the scale of 1 in. to 4 miles.

Maps on the first scale are "15-minute maps," those on the second are "30-minute maps," and those on the third are "degree maps." On the scale of 1 : 62500, 1 in. on the map represents a distance a little less than 1 mile; on the scale of 1 : 125000, 1 in. represents a little less than 2 miles; and on the scale of 1 : 250000, 1 in. represents somewhat less than 4 miles.

271. Direction.—Compass directions are sufficiently indicated on many maps by meridians and parallels of latitude. On large-scale maps, however, a full arrow is commonly drawn, properly oriented, pointing to true north, and a half arrow, intersecting the full arrow in its center, for magnetic north (Fig. 316). The angle between these two arrows should be marked, and also the date when the observations were made, for the magnetic variation changes from year to year (**294**).

272. Requisite Data on a Completed Contour Map.—The more important features of contour maps have been described above. A contour map is not complete unless it has a name, is accompanied by a legend, and has designated upon it the scale, the contour interval, the datum plane from which the contours were measured, and compass directions.

PROFILE SECTIONS

273. Nature of Profile Sections.—A *profile section* is a diagram showing the shape of the surface of the land as it would appear in vertical cross section. A profile section consists of four lines which completely inclose a space (Fig. 318). They are the profile line, the base line, and the two end lines. The profile line, which is the top line in the diagram, represents the intersection of a vertical plane with the land surface. The base line is drawn horizontal and is chosen at a convenient distance below the lowest point of the profile line. The end lines are perpendicular to the base line.

The position of a profile section should always be indicated by a line, called a *line of section*, on an accompanying map (AB, Fig. 317), for a section has no practical value unless its location is known. The line of section is really the top line of the section as seen in plan.

Every profile section has a horizontal scale, measured in units on the base line, and a vertical scale which is measured in units of elevation perpendicularly above the base line. If these two scales are the same, the section is said to be *drawn to natural scale.* Sometimes the vertical scale is *exaggerated, i.e.,* it is made

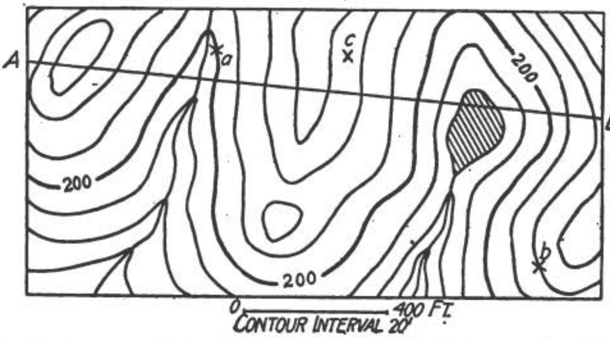


Fig. 317.—Contour map of a land area of moderate relief. Diagonal ruling, lake; *AB*, line of section.

two or more times as great as the horizontal scale (Cf. Figs. 318 and 319). Exaggeration is useful for profile sections of lands of very slight relief merely to emphasize the positions of hills and valleys. Ordinarily natural scale should be employed. Unless accurate measurements are to be made, the vertical scale may be 1 in. to 5000 ft. if the horizontal scale is approximately or actually

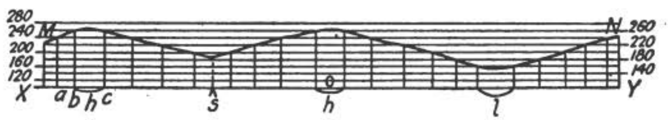


Fig. 318.—Profile section along line *AB* in Fig. 317. Drawn to natural scale.

an inch to a mile (1:62500 or 1:63360). This is so near to natural scale that it is satisfactory for most purposes, and it has the advantage that the contour interval is commensurable with the vertical scale.

274. Construction of a Profile Section.—Let us suppose that a profile section is to be made along line AB, Fig. 317. Lay the straight edge of a sheet of paper along AB and mark a dot on it at each point where a contour is crossed by AB and a small caret at each point where a stream is crossed by AB. Connect the dots for the upper contour on each hill by a curved line (h, Fig. 318), to show where the hills are situated. In the same way connect dots representing the two margins of a lake (l, Fig. 318). It is well also to label some of the index contours by their elevation numbers. Upon a piece of profile paper, ruled with coördinates to $\frac{1}{20}$ in., draw XY = AB for the base line of the section.

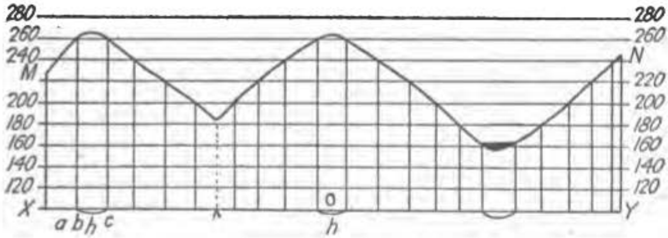


Fig. 319.—Profile section along line *AB* in Fig. 317. Vertical scale three times as great as horizontal scale

Transfer the points, carets, etc., to XY, marking them lightly with a lead pencil. The first three of these points are lettered *a*, *b*, and *c*, the summit contour is *h*, and the stream is at *s* (Fig. 318). Since XY = AB, obviously the horizontal scale of the section is equal to that of the map. If we let $\frac{1}{20}$ in. = 20 ft. for the vertical scale, this section will be drawn to natural scale.

The lowest point crossed by AB happens to be at the lake where the elevation is somewhat less than 180 ft. Therefore 100 ft. above sea level would be a convenient elevation for the base line. Sea level itself may be chosen if preferred. The first contour cut by AB is the 240-ft. line, represented by *a* on XY. Make a dot vertically above *a* on the coördinate for 240 ft Vertically above *b*, the position of the 260-ft. contour, mark a dot on the 260-ft. coördinate. Similarly, mark a dot on the proper coördinate above each point on XY. Connect these points by a curved line, MN, which is the profile line of the section. Note that the hilltops are a little higher than 260 ft., but not as high as 280 ft.; that the stream channel is lower than 200 ft., but not as low as 180 ft.; and that the lake surface is below 180 ft., but above 160 ft.

275. Enlargement of Profile Sections.[1]—Profile sections may be enlarged by multiplying both the vertical and horizontal scales by the same factor. This may be done in two ways. Suppose that the section of Fig. 318 is to be enlarged twice. Draw a base line double the length of AB (Fig. 317) upon a piece of profile paper. As described in the preceding article, mark

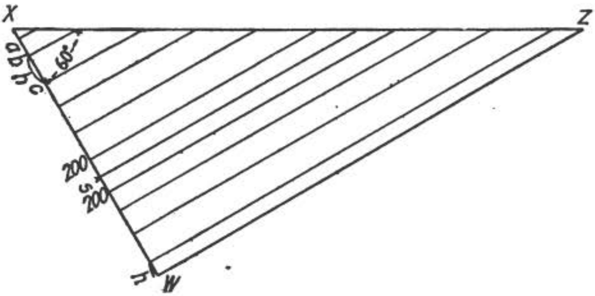


FIG. 320.—Diagram illustrating a method of enlarging a profile section. $XZ = 2XW$. $XW = XY/2$ in Fig. 318.

on the edge of a sheet of paper the positions of the contours and streams intersected by AB. Lay this paper against the base line so that the point, A, will coincide with the left end of the line. Then transfer the contour positions in such a way that the space between each two adjacent points will be doubled, that is, the spaces, beginning at the left, will be equal to $2Xa$, $2ab$, $2bc$, and so on, in order (Cf. Fig. 318). Having set off all these points, continue as in Art. **274**, but with a vertical scale of $\frac{1}{20}$ in. = 10 ft. instead of $\frac{1}{20}$ in. = 20 ft.

The second method is illustrated in Fig. 320. For convenience only half the length, XO, of the section in Fig. 318 is here enlarged. Lay off the base line, $XZ = 2XO = \frac{2AB}{2}$, as in the

[1] A section, and also a map, loses in accuracy in proportion as it is enlarged.

first method. From X draw $XW = \frac{AB}{2}$, making an angle of 60° with XZ. Mark on XW the contour and stream positions, as explained in Art. **274**, from X to W. Draw ZW, and from each of the points on XW draw a line to XZ parallel to ZW. These lines will intercept distances on XZ just double the distances which they intercept on XW.

Interpretation of Contour Maps

276. Direction of Ascent and Descent.—In studying a contour map one may want to ascertain whether one would go up or down hill in crossing contours in a certain direction. This may be done either by noting the elevations of the index contours which are successively crossed or by observing the general arrangement of all the contours without particular reference to those which are numbered. The latter method is often preferable where index contours are not crossed or where the map is so obscured by various features that finding and tracing the index contours is difficult. This second method is simple enough if it is remembered (1) that the contours bend upstream in valleys (Figs. 316, 317), and (2) that the ground must rise away from stream courses. In crossing a valley the last contour met before reaching the stream is the first one to be passed on the other side of this stream. Similarly, the highest contour on a divide between two streams must be crossed twice without meeting any intervening higher or lower contour. Ordinarily divides are characterized by knobs or hills which are shown by closed contours. The innermost of such closed contours is the highest. The divide summit is a little higher, but less than a contour interval higher, than this uppermost contour. Obviously the position of the divide summit between two adjacent valleys must be determined in order to avoid the mistake of estimating too great an ascent in passing up from the valley floor.

277. Elevation of a Given Point.—Suppose that one wants to know the elevation of a certain point on the map. The point may be (1) on an index contour, (2) on a light contour, or (3) between contours. In the first case (*a*, Fig. 317) the elevation of the point may be found by following the index contour along to the nearest number which gives its height above mean sea level. The second case is illustrated by *b* in Fig. 317. To obtain the elevation of this point, first determine the elevation of the nearest index contour, here 200 ft., and whether the point is uphill or downhill from this index contour. In the figure *b* is on the second contour uphill (sea stream) from the 200-ft. line. Since the contour interval is 20 ft., *b* is 2 × 20 ft. above 200 ft.; *i.e.*, its

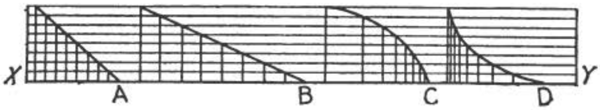


FIG. 321.—Ideal profile sections of slopes.

elevation is 240 ft. above sea level. The third case is left for the student to explain. In Fig. 317, *c* may be taken as the point.

278. Spacing of Contours.—Fig. 321 illustrates the relations of contour spacing to the steepness and form of a sloping surface. A, B, C, and D are profile sections of slopes. A is steep; B is relatively gentle; C is convex upward; and D is concave upward. XY is the base line for all four. The vertical lines are drawn from the intersections of the profile lines with the elevation coördinates. The spaces between the verticals are equal to the distances between the contours on a map representing these slopes. This diagram shows that, with a given contour interval, (1) contours are more closely spaced on steep slopes than on gentle slopes; (2) contours are more closely spaced at the base of a surface which is convex upward, and near the top of a surface which is concave upward. When several contours run together into a single line, this line indicates a cliff, or, if the scale of the map is small, a very steep slope.

279. Distance Between Two Points.—In Fig. 322, *abc* is the profile of a hill. On a contour map the distance from *a* to *c* over the hill would be shown by the length of the straight horizontal line *de*. *abc* may be called the *original* of its projection, *de*. Stated in general, any line that crosses contours on a map represents a distance shorter than the actual distance along the original of that line on the earth's surface. An approximation to the real distance between two given points may be obtained by constructing a natural scale profile section between them and measuring the profile line; but this method can not be quite accurate because contour maps can be approximately correct only at the contours. Within the limits of two adjacent contours the ground may slope uniformly or it may be irregular.

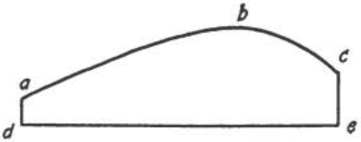


Fig. 322.—Profile section of a hill to show relations between base line and profile line.

280. Inclination of a Slope.—The inclination, grade, or gradient, of a sloping surface or of a sloping line may be expressed as a ratio, as a percentage, or as an angle measured in degrees from the horizontal. Let Fig. 323 be a profile section of a sloping surface, *ac*, and suppose that $ab = 10$, and $bc = 50$, no matter in what units. *i* is the angle of inclination of the surface. In travelling the horizontal distance $cb = 50$, one would ascend a vertical distance $ab = 10$. The ratio ab/bc, or, in this example, 10/50, is an expression for the gradient of the inclined surface. It may be spoken of as a grade of 1 in 5. If the division indicated in the ratio is performed, and the decimal point in the quotient is moved two places to the right, the result will be in percentage. In the present case $10/50 = 0.20$. By moving the decimal point two places to the right, we find that the surface has a 20 per cent. grade.[1]

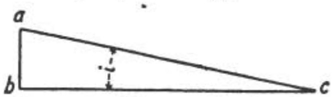


Fig. 323.—Diagram showing the methods of measuring a slope.

[1] Equivalent angles and per cent. grades are tabulated in Appendix VIII.

CHAPTER XIV

GEOLOGIC SURVEYING

NATURE OF GEOLOGIC SURVEYING

281. Definition and Aim.—Geologic surveying is the systematic examination of any region for geologic information. Its purpose may be economic or purely scientific. If economic, the investigation may be somewhat limited in its scope, the object being merely to study the phenomena which bear directly on some particular problem; but it is becoming more and more evident that the broader the range of any field examination, the more accurate and otherwise satisfactory the results are likely to be, for the interrelations of geology are numerous and intricate.

282. Uses of Geologic Surveying.—Geologic surveying is fundamental to all geologic knowledge. Its uses are therefore numberless. It assists the engineer in determining the location and cost of tunnels, bridges, aqueducts, reservoirs, dams, and many other structures. It facilitates the work of the prospector. It shows the farmer what kind of soil he may expect to find in one place or another. In many ways it is of indispensable value to the quarryman and the miner. One of its principal advantages is that it locates for the manufacturer the most accessible sources of his raw materials and so enables him to obtain them at a relatively low cost. Finally, it yields to the scientist facts by which he interprets the structure and history of the earth.

283. Diversity of Surveys.—There are many conditions which regulate the nature of geologic surveys. Work is apt to be difficult in swampy regions, on heavily forested land, and in places where the soil cover is thick and extensive. Marked relief and high altitude increase the physical labor of exploration, and certain climates seriously handicap the geologist. Accessibility to towns and railroads is a significant factor. If the field area is far removed from civilization, a large supply of provisions has to be transported across country and travel is difficult. Where topographic maps have already been published, geologic work can be done more easily and more quickly than where such maps are poor or wanting. Then, again, there are such factors as the time at the disposal of the geologist, the scale on which the geologic mapping is to be done, and, finally, the nature of the problem itself. The consequence is that geologic surveys are very diverse in respect to their needed equipment, their thoroughness, and their manner of execution.

General Field Observations

284. Most Likely Places for Exposures.—The best places in which to look for exposures of bedrock are precipices, hilltops, stream beds, and coasts, along railroads and roads, and in artificial excavations. Cuts in unconsolidated materials may be sought along the banks of streams, along coasts, roads, and railroads, and in artificial excavations.

285. Examination of Outcrops.—The beginner is often at a loss as to the best manner of attacking a rock exposure. The writer has always advised his students to start by quickly walking round and over an outcrop which they have just found, before attempting to take any notes. In this way they soon gain a general idea of the rocks and structures which are exposed, and they are better able to decide what parts of the rock should be examined in more detail. Unless this plan is followed much time may be wasted. For instance, one may spend several minutes trying to determine the attitude of a sedimentary rock where its bedding is obscure, whereas further search on the same outcrop may reveal a place at which the bedding is distinct and easily studied. This method of rapid reconnaissance followed by detailed examination is recommended, on a larger scale, for the geologic investigation of extensive areas (see Art. **305**).

286. Discrimination Between Bowlders and Outcrops.—Care should always be taken not to mistake large, half-buried bowlders, such as are common in glaciated districts, for outcrops of true bedrock. A safe rule to follow is, never accept as bedrock anything that is small enough to be a bowlder, but this is unsatisfactory because there are many places in which large exposures are very scarce and where the small ones are exceedingly useful. It is better to spend some time in studying the questionable rock and correlating it with its surroundings. Bedding, joint systems, cleavage, schistosity, etc., are apt to have similar, though not necessarily exactly the same, character and arrangement in adjoining outcrops of bedrock, whereas in scattered bowlders such structures are usually very variable, especially in trend.

287. Importance of Contacts.—Contacts (**13**) are of the utmost importance in the construction of geologic maps, sections, and diagrams, as well as in the interpretation of underground structure and geologic history. This can not be too strongly impressed. It is therefore obligatory upon the geologist, first, to find the position of contacts in the field, and, second, to map them with as much accuracy as circumstances will allow. These "circumstances" are factors such as the time available and the degree to which a boundary line may be concealed under superficial débris.

288. Discrimination Between Igneous Contacts, Unconformities, and Faults.—Sometimes the relations between two adjoining rock bodies are so obscure that difficulty is experienced in deciding whether their mutual contact is an igneous contact, an unconformity, or a fault. Two specific instances should be noted, in which one of the three possibilities may be discounted: (1) if both bodies are sedimentary, their contact can not be igneous; and, (2) if both bodies are intrusive, they can not meet in a surface of unconformity. In all other cases, including that of an intrusive mass against an extrusive rock, the mutual surface may be any one of the three types of contact. The problem must be approached with a clear understanding of what features are to be looked for in association with faults, unconformities, and igneous contacts, and then the region must be diligently searched for whatever evidence it has to reveal. Several phenomena that may be misinterpreted are mentioned below.

1. The trend of the boundary line can not be accepted as a safe criterion. Igneous contacts, faults, and unconformities, may all outcrop in lines that are straight, undulating, or very irregular, although, generally speaking, igneous contact lines, particularly of subjacent bodies, are more commonly irregular, and fault lines and lines of unconformity are more often broadly undulating.

2. Apophyses of an intrusive may extend into the country rock, but sometimes they are conspicuous for their absence. In any event one should look for them. In the case of unconformities, the younger rock may have filled fissures or chasms in the old land surface. Such a filling, if of sedimentary materials, can hardly be misinterpreted; but one of lava might be mistaken for an apophysis, especially if the flow were overlain by lithified strata (**132**). As for faults, there can be no finger-like projections of the rock of one block into the other unless the displacement occurred close to a preëxisting igneous contact or unconformity (**133**).

3. Angular or subangular fragments of country rock may be contained in an eruptive body near the contact. Likewise angular, subangular, or rounded fragments of the rocks below an unconformity may constitute the lower layers of the overlying formation. However, an intrusive breccia has an igneous matrix, whereas the matrix of a basal conglomerate is sedimentary. For the special case of sills, see Art. **132.** Contrasted with intrusive breccias and basal conglomerates, fault breccia zones are relatively narrow and they are composed of pieces of the rocks from both walls (**204**).

4. An intruded country rock may reveal evidences of more or less contact metamorphism, both by heat and by pneumatolysis, and these effects are usually proportional in their intensity

and kind to their distance from the contact (**118–122**). Also, the eruptive may exhibit textural and other variations which are dependent in character upon the distance from the contact (**111**). Such conditions are not to be expected in association with unconformities. Faults sometimes serve as conduits for volatile substances rising from underlying magmatic bodies, and these gases and vapors may considerably alter the wall rocks on both sides, so that effects in some degree resembling those of contact metamorphism may be produced.

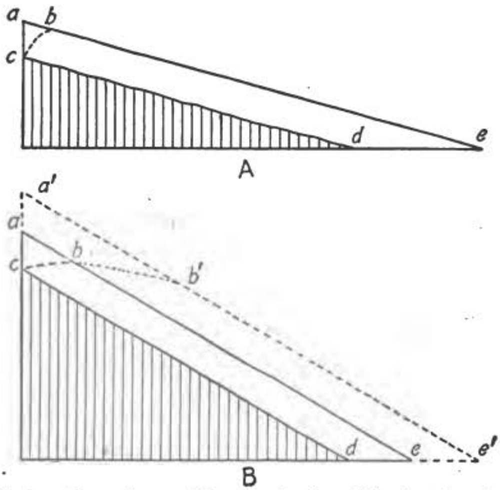


FIG. 324.—Ideal profile sections to illustrate the downhill migration of rock waste in the soil. Shaded, bedrock; blank, soil. Rock fragments reach the surface of the soil (*c* to *b*) a shorter distance downhill where the slope is moderate (*ab* in A) than where the slope is steep (*ab* in B); and, on a given slope, they reach the surface a shorter distance downhill where the soil is thin (*ab* in B) than where it is thick (*a'b'* in B).

289. Location of Contacts Buried Under a Soil Mantle.—A contact hidden under surface débris may be located by observing the distribution of rock chips and fragments in the soil derived from the underlying bedrock. Precision depends upon (1) the inclination of the ground, (2) the thickness of the soil cover, (3) climatic conditions, (4) the trend of the contact line, and (5) the regularity of the contact. The steeper the slope of the ground and the thicker the mantle rock, the farther the loose materials may slide from their source before they work up to the surface where they may be seen (Fig. 324). If the inclination is less than 25°, sliding is usually not great enough to occasion serious error in fixing the location of the contact. Climate has various effects. Of these as important a one as any is the action of frost in facilitating soil creep. When a straight contact line runs directly up a slope, its location may be accurately determined by the soil method. If it is either oblique to the slope or parallel to the contours, allowance must be made for factors (1) and (2), above noted. Its actual position is higher than is indicated in the mantle rock. Bends and angles of an irregular contact line are exaggerated by the distribution of rock fragments in the soil. This method proves useful in locating any kind of concealed contact, provided the rocks on either side are unlike one another.

290. Location of Eruptive Contacts.—The line at which an igneous rock touches its country rock on the surface of an outcrop may be hard to distinguish, even though exposed, either because the two rocks are of like color and texture, or because surface staining due to weathering has impaired an original contrast in hue. There is only one thing to do in this case, and that is to scrutinize the rock surface very carefully. Form the habit of examining one rock inch by inch in a direction toward the other, and then you are not likely to miss the dividing line, provided it is visible. Error is most apt to be made where, by local scaling or exfoliation, relatively fresh surfaces of rock are laid bare next to older surfaces that look different because they have been exposed for a much longer time. Do not let some crack or the edge of a conspicuous stain mislead you into calling this the contact, and, on the other hand, do not be too prone to conclude that a contact is blended and that for this reason no *line* is present (**109**).

Whether or not the boundaries of an igneous body are concealed, they may often be located and traced by the phenomena of contact zones. Thus, if an igneous rock displays a regular diminution in the size of its grains in a definite direction, its contact is likely to be found in this direction. In Art. **200** is explained the value of tension jointing for this purpose. Great abundance of inclusions in an igneous rock may signify proximity to the contact, especially to the roof of a large intrusive body (batholith, etc.). When once the geologist has made out the characteristic variations of the contact zones in a given region, he may use this knowledge in seeking the same contact where exposures are poor or infrequent. By the degree of baking, discoloration, or mineralization observed on outcrops of the country rock, he may be able to tell roughly how far he is from the eruptive body (**138**).

291. Obscure Bedding.—There is hardly need to say that sedimentary rocks should always be examined for their bedding, for if this can not be found, the attitude of the strata and other important facts can not be determined. Stratification may be difficult to see on a rock exposure either because the materials were accumulated under very uniform conditions (**62**), or because the rock was metamorphosed (**211, 212**), or because of surface discoloration. Although, occasionally, sediments are devoid of bedding, perfect uniformity is of rare occurrence. The rock which at first sight appears to be structureless is almost sure to reveal some degree of lamination upon careful scrutiny. When studying an outcrop which is seemingly of even texture, look for sandy streaks in conglomerates, for pebbly or fine sandy streaks in sandstones, for very fine sandy laminæ in mudstones, and for impure streaks in limestones and chemical deposits.

Equipment

292. Articles Used in Geologic Surveying.—For ordinary geologic field work one must be provided with notebook, compass and clinometer, hammer, pocket lens, protractor, a 4-H or 5-H pencil, colored pencils, eraser, ruler, collecting bag, and paper bags for rock specimens. If a good topographic map of the region to be surveyed is available, it should be carried as a *working map* in a convenient manner in the notebook. The working map is used, either with its original scale or photographically enlarged, for marking the locations of outcrops, geologic boundaries, traverses, etc. In many cases one may require a tally register, steel tape, barometer, etc., and for some kinds of field work instruments such as a plane table and a transit may be necessary.

An excellent compass is the "Brunton." It has sights arranged so that directions and slope angles can be read with considerable precision. Strike and dip can also be obtained with it. The hammer is made so that the peen can be employed for splitting and prying and the face for breaking and trimming. It is a good plan to mark inch intervals on the handle. The lens is serviceable for determining the mineral constituents of rocks. With the protractor angles may be measured on the working map to locate the observer's position with reference to known points. The colored pencils are used to indicate different rocks on the working map (**310**). A tally register is an instrument for recording paces. The aneroid barometer is of little advantage in districts of low relief, but where the relief is great, it may be employed for finding the geologist's vertical distance, and from this his position, above or below known localities.

293. The Field Notebook.—The notebook in which data are to be recorded in the field should be of pocket size, about 5 by 7½ in., should open from the shorter edge, and should have its pages ruled with coördinate lines ⅕ in. apart. The pages should be numbered.

Before you begin field work, prepare your notebook in the manner described below. Write your name and address on the inside of the front cover. On the first blank page, facing the front cover, record the name of the region where the investigation is to be made, and the year and date of beginning the work. The magnetic variation of the compass needle (**294**) in the region is noted on the first ruled page. On page 3 you will start your notes unless you can secure a good topographic map of your area for a working map. The scale, contour interval, and name of this working map should be recorded on the first ruled page, as well as the magnetic variation.

Cut the working map into rectangles of equal size and somewhat smaller than a page of the notebook, so that, if mounted, there will be at least ¼ in. margin of the ruled page on all sides. Topographic sheets of the U. S. Geological Survey may be cut into nine rectangles, each bounded by parallels and meridians.[1] These rectangles may be mounted on a piece of linen or they may be pasted in the notebook. When mounted on linen, all parts of the map are together and the whole can be folded and kept in a pocket in the notebook. If they are to be pasted separately in the book, number them as shown in Fig. 325. Glue rectangle 1 on page 3, making its upper and left edges flush with horizontal and vertical coördinates, respectively (looking at the open book with its length up and down). On page 5 mount rectangle 2 in a position exactly analogous to that of rectangle 1, but leave an inch or so near the upper margin of this map free. The lower edge of rectangle 1 can then be bent down to touch the upper edge of rectangle 2, if you wish to see the relations of contours, roads, etc., near this common margin. The other portions of the working map may be mounted like rectangle 2 in proper order on pages 7, 9, 11, 13, etc. Above each rectangle write its number. If you intend to adopt the "coördinate system" in taking your notes (**310**), letter the coördinate spaces (not the lines) above each

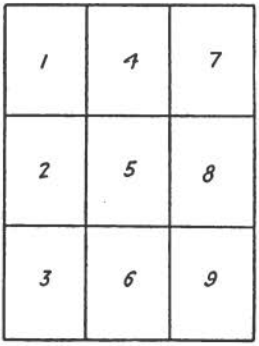


Fig. 325.—Method of numbering the divisions of a working map.

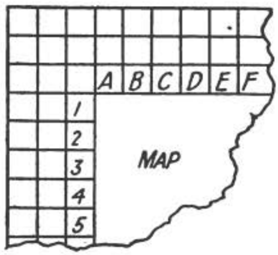


Fig. 326.—Method of mounting a working map.

[1] These are called rectangles although actually the corner angles are not quite 90° on account of the northward convergence of the meridians.

rectangle, and number the spaces on the left of each rectangle, beginning at the top left corner (Fig. 326). In just the same manner letter and number the corresponding spaces on the even-numbered pages facing the maps. All this preliminary writing should be done in waterproof India ink, not in pencil nor in an ink that will wash off.

OBSERVATIONS WITH COMPASS AND CLINOMETER

294. Use of Compass and Clinometer.—Strike (**11**) is measured by means of a compass. Concerning the use of this instrument there are certain rules and facts with which the beginner must familiarize himself at the outset.

1. Degrees are read on the *outer* circular dial.

2. In taking strike, hold the compass so that its face is horizontal and its "length," *i.e.*, the line between the letters "N"

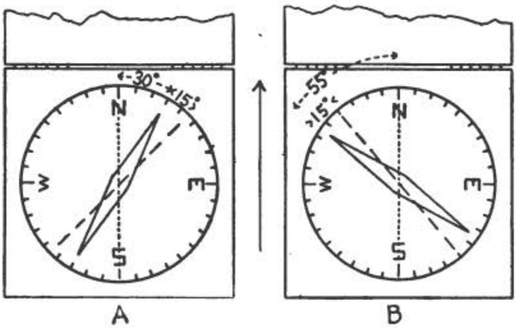


FIG. 327.—Diagrams to illustrate the use of the compass. Dotted line, "length of compass"; dashed line, true north-south line.

and "S" on the dial, lies in the direction of the strike (Fig. 327, A, arrow).

3. When the needle is at rest it points in a constant direction for any given locality. Hence readings should be made from one or the other end of the needle, and not from the letters "N," "E," "S," or "W," printed on the dial. Thus, in Fig. 327, A, the compass length, or line between the letters "N" and "S,"

lies in the NW and SE quadrants and thus indicates a NW–SE direction.

4. Strikes are to be recorded exactly as one reads the compass. If the instrument is in the position shown in Fig. 327, A, and one is looking in the direction of the arrow, the north end of the needle, being the nearest end to this line of sight, should be noted first. Next should appear the angle or number of degrees between the needle and the required direction; and finally is written the direction in which this angle was measured *from the needle end.* If the angle is 30° in this case, the strike is N.30°W.

5. All readings are made from north and south, or sometimes from north only, but never from east or west. Thus, the strike mentioned in the last paragraph would not be recorded W.60°N. A direction 30° east of south may be written S.30°E. or N.150°E., but not E.60°S.

6. A bearing made as just described is spoken of as *magnetic.* There is nearly always a correction which has to be made for this compass reading because the needle seldom points to the *true north.* The compass north (*magnetic north*) may lie a variable number of degrees to the east or west of the true north. Suppose, in Fig. 327, A, that true north is 15° to the east of magnetic north (and therefore that true east is 15° south of magnetic east, etc.); the true bearing is then 30° + 15° to the west of true north, or N.45°W., instead of N.30°W. Similarly a magnetic bearing of S.30°E. would become a true bearing of S.45°E. If the compass reads N.55°E., as in Fig. 327, B, obviously one must subtract the correction of 15° and the true bearing is then N.40°E. Likewise, S.55°W. would be corrected to S.40°W. All cases are covered in the following rules: If true north is to the east of magnetic north, to all magnetic bearings in the NW and SE quadrants add the correction, and from all magnetic bearings in the NE and SW quadrants subtract the correction. If true north is to the west of magnetic north, add the correction to NE and SW readings and subtract it from NW and SE readings. Additions and subtractions are algebraic. (How would you correct a magnetic bearing of N.–S.? of E.–W.?)

Since the magnetic variation is not the same for different localities and since it changes gradually from year to year in any given locality, one must ascertain the proper correction for any place in which geologic field work is to be performed (see Plate I).

7. Be scrupulously careful not to have your hammer or any other steel near the compass while making observations. Magnetic ore, steel nails, electric wires, etc., seriously affect the needle.

Dip is measured by a clinometer. This device is usually constructed in the compass box. It is an attachment so made that it can swing on a pivot and maintain a vertical position while the compass is turned with the plane of the compass in a vertical plane. At its lower end is a point which indicates the dip angle, the degrees being marked on a semicircular dial inside the compass dial.

1. The dip is read directly on the semicircular dial.

2. In taking the dip, hold the compass vertically with its length parallel to the outcropping edge of the stratum and its face in a plane *perpendicular to the strike.* "Care must be taken to have the eye as nearly as possible in the extension of the plane whose inclination is being measured, and to sight on a horizontal line"[1] (the strike line).

3. In recording dip, the vertical angle from the horizontal and the direction of inclination must be noted. Dip is always measured *downward.* If the strike is E.–W., then the dip may be either northward or southward. If the strike is N.50°E., the dip may be northwestward or southeastward. It is necessary to give only the quadrant in which the dip lies, for the exact direction can be determined from the strike, since the *direction* of the dip is always perpendicular to the strike. A record of a strike of N.25°W. and a dip of 45° (downward) toward the NE is written, N.25°W.; 45°NE. Observe that the 45°NE does not mean N.45°E.; it signifies a vertical angle of 45° in a general northeasterly direction.

[1] Bibliog., Hayes, C. W., p. 24.

295. Setting the Compass for True Bearings.—The Brunton compass is made so that the outer dial may be turned by means of a screw. In this way it is possible to set the dial in a position such that, for a given locality, true instead of magnetic bearings may be read directly. In Fig. 328 the dashed line represents the direction of true north, here assumed to be 20° to the east of magnetic north (the north end of the needle). As shown in Fig. 328, A, the magnetic reading is due north and south, and the corrected reading is N.20°W., for the "0" on the dial is 20° to the west of true north. If the dial is turned in the compass

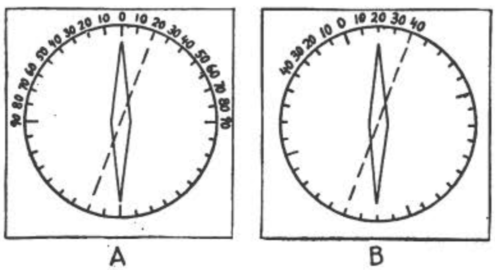


Fig. 328.—Diagrams illustrating the method of setting the compass dial for true readings. Dashed line, true north-south line.

box 20° to the west, and the needle and box are in the same relative position as in Fig. 328, A, the bearing when read directly will be N.20°W. (Fig. 328, B), *i.e.*, the "0" on the dial will now be 20° to the west of the needle. Hence, the rule for setting the compass is this: rotate the dial through an angle equal to the magnetic declination (the angle between magnetic and true north), *westward* if true north is to the *east* of magnetic north, and *eastward* if true north is to the *west* of magnetic north. Do not overlook the fact that magnetic declination is usually different in different regions.

296. Taking Strike and Dip of Strata.—Whenever strata are exposed the attitude of their bedding should be found **(291)**. The actual process of taking strike and dip would be simple enough if it were not for the fact that bedding surfaces are more or less irregular and rarely conform with the surfaces of outcrops. To avoid error the compass should never be placed against the rock. Always stand off a few feet and endeavor to gain a correct notion of the strike and dip by a single observation for a length of several feet of outcrop rather than for only a few inches. Where dipping beds are exposed on a horizontal rock surface, the trend of their edges is their strike; but if they are exposed on an inclined rock surface, as they are ninety-nine times

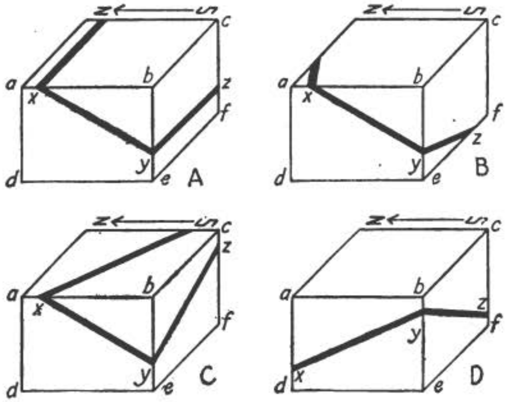


FIG. 329.—Relations of dip and strike of bedding to outcrop surfaces.

out of a hundred, the geologist must appeal to his geometric imagination. The same statement holds for dip, since outcrop surfaces exactly perpendicular to strike are rare. Four possible cases are illustrated in Fig. 329. For convenience the structure is shown in diagrams of rectangular blocks, but it must be remembered that these are unavoidably much more regular than natural outcrops. A, B, and C, in Fig. 329, represent three instances in which the dip might be taken as 30° south and the strike as E.–W. if only the face *abde* were seen; but an examination of another surface (*bcfe*) proves that Fig. 329, A, alone answers to this suggestion. In Fig. 329, B, the eastward inclination of the strata on face *bcfe* indicates that the real dip (steepest inclination) is southeastward and the real strike is northeastward;

and in Fig. 329, C, the westward inclination of the beds as seen on face *bcfe* shows that the real dip must be southwestward and the real strike northwestward. Fig. 329, D, is another case which may arise. It will be noted in all these examples that observation on at least two outcrop surfaces, not parallel to one another, and preferably as nearly perpendicular to one another as possible, is requisite in order to arrive at a correct inference as to strike and dip. The chief aim is to ascertain the position of the plane of stratification. Points *x*, *y*, and *z*, in each diagram, determine this plane. This follows from Plane Geometry. If, on a curved or highly irregular outcrop surface, pebbles be placed at three points, not in the same straight line, on the outcropping edge of a given layer, these pebbles may help to visualize the plane of the bedding.

297. Degree of Accuracy in Taking Strike and Dip of Strata.— The accuracy with which dip and strike should be read depends upon the nature of the problem in hand and upon the character of the folding. In regions where dips are low, averaging, let us say, 5° or 6°, fold axes are apt to be irregular in trend. The strata are warped and strikes vary notably. In such cases dips should be read with an error of less than 1°, and strikes should be taken with care. On the other hand, where high dips point to intense deformation, an error of two or three degrees in dip or strike is unimportant, for the actual variations in the beds themselves amount to this or even more within short distances. In this case pains should be taken to obtain correct averages, rather than to make absolutely accurate local readings.

298. Attitude of Eruptive Contacts.—The position of an igneous body with reference to horizontality and to structure in the adjacent rocks can be ascertained only by studying the attitudes of its contacts. The dip and strike of flows and of uniform dikes and sills may be obtained by clinometer and compass just as in the case of strata (**296**). It is important to remember, however, that even the straightest intrusive sheets, as seen in cross section (vertical, horizontal, or inclined), not uncommonly have jogs or elbow-bends, the effect of which, if the bends are all on the same side, is like that of transverse faults with the offset always in the same direction. One part of the sheet may be far out of line with another part (Figs. 330, 331).

In obtaining the trend or the inclination of very irregular contacts, like those which are typical of many batholiths, chonoliths, etc., the degree of precision necessary must be

FIG. 330.—Apparent offset in two outcrops of a dike of which the strike, where observed, is parallel to the front edge of the block. V-pattern, dike rock in section; stippling, alluvium.

determined by the geologist. Just how much he may generalize the line depends largely upon the scale of the map on which he is plotting. For instance, he may disregard local turns and angles 150 or 200 ft. deep if his map is on a scale of 1 mile to an inch. Nevertheless, observe that this statement does not signify that the details of such a contact are not to be studied. Not only should they be carefully examined, but also their shape

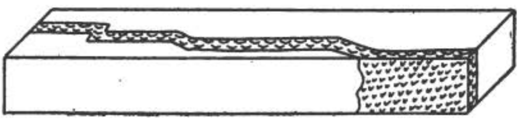


FIG. 331.—Explanation of the apparent offset shown in Fig. 330, the soil having been removed and the top of the block being represented as a horizontal plane.

and other characters should be illustrated by large scale plans and sketches made in the field.

After a contact has been located for a considerable distance and its line of outcrop plotted on a topographic map, its general attitude may often be made out from an inspection of this map, as explained in Art. **343**.

299. Attitude of Contorted Strata.—A word of caution may be given in reference to taking the dip and strike of contorted strata. Fig. 332 is a local vertical section of two layers in a series deformed by minor similar folding. The small folds are from 1 to 5 ft. from crest to trough and the dips of their limbs are approximately 48°W. (*aa*) or 82°E. (*bb*). Yet the general inclination of the strata is neither 48°W. nor 82°E. It is indicated by the double-headed arrow and is about 33°W. Evidently dips which are measured on the limbs of minor folds can not be used for the major structure. The same is true, but to a less degree, of strikes. In dealing with highly crumpled sediments the geologist must be careful to discriminate between principal and subordinate folds, and he must not record angles for the minor folding, which he intends to use in sections and maps of the major structure.

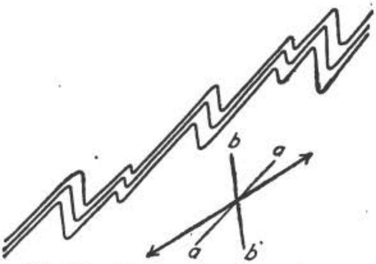


FIG. 332.—Section of two layers in a contorted schist. The section is drawn looking north.

SCHEDULE FOR FIELD OBSERVATIONS

300. General Data to be Observed and Recorded.—Many of those who are engaged in geologic work, particularly in the earlier years of their training, find that a table of the facts which should be looked for in the field is often very helpful. Excellent schedules may be found in Hayes' "Handbook."[1] They refer to the description and interpretation of land forms, to petrology, geologic structure, glaciers, and glacial deposits, ores, building stones, and other materials of economic worth. For general purposes, however, the following outline may be found useful.

SCHEDULE FOR GEOLOGIC SURVEYING

TOPOGRAPHY.—Note: relief; shape and arrangement of uplands and lowlands; relations of topographic forms to rock distribution; effects upon human

[1] Bibliog., HAYES, C. W.

activities; destructional or constructional origin; evidences for agents of erosion and for stage of development in erosion cycle.

ROCKS.—(1) *For any outcrop*, note: color, luster, grain, and irregularities of surface; shape, size, and arrangement; distribution with relation to topographic forms.

(2) *For any rock*, note: its texture, mineral composition, name, kind and degree of weathering, and the color of its fresh fracture; relations to other rocks as regards structure and age.

(*a*) *If an igneous rock*, note further: mode of occurrence; attitude (for dikes, sills, etc.); lithologic structures (flow structure, schliers, primary gneissic structure, segregations, etc.); contact relations; contact metamorphism; and, inclusions (kind, shape, size, arrangement, and source).

(*b*) *If a sedimentary rock*, note further: mode of occurrence (bed, lens, clastic pipe, clastic dike); attitude; breadth of outcrop; degree of consolidation; composition, shape, size, and arrangement of constituents in fragmental rocks; lithologic structures (cross-bedding, ripple-mark, mud cracks, local unconformity, contemporaneous deformation, etc.); kinds, attitude, distribution, and abundance of fossils; and stratigraphic sequence.

(*c*) *If a metamorphic rock*, note further: kind and degree of metamorphism; any preserved original structures (see igneous and sedimentary rocks, above); secondary lithologic structures (slaty cleavage, plane schistosity, linear schistosity, gneissic structure, etc.); attitude of structure; relations of original structures to secondary structures; classification of original rock before metamorphism.

(*d*) *If a vein*, note further: its shape, size, attitude, and relations to the wall rock and to the topography; species, arrangement, and relative amount of mineral constituents.

STRUCTURES.—(1) *For unconformities*, note: kind, extent, and nature of surface; relations of the two unconformable formations; kind and source of basal sediments of the younger formation; age relations.

(2) *For folds*, note: shape; dimensions; classification; major or minor; parallel or similar; with horizontal or pitching axis; relations to topography; relations to rocks; relations of minor to major folds; age relations.

(3) *For faults*, note: extent, attitude, shape, classification as far as can be observed; slickensides, gouge, brecciation, drag, etc.; exposed rocks on each side of fault line; amount and direction of visible displacement; relations to other structures (bedding, folds, joints, etc.); relations to topography; age relations.

(4) *For joints*, note: extent, attitude, shape, spacing, regularity, classification; rocks affected; relations to other structures; relations to topography; age relations.

The foregoing outline will probably not fit all cases, for geologic relations are almost infinite in their variety. The best rule is, search for anything and everything of geologic interest and record all you see. Do not overlook surficial deposits merely because they are unconsolidated. All earth features are but parts of a whole, and you can never tell when seemingly trivial things are going to furnish decisive evidence for the solution of important problems.

METHODS OF GEOLOGIC SURVEYING[1]

301. Traverse Defined.—In studying an area a geologist proceeds along the route which he thinks will show him most in the time at his disposal. His course, known as a *traverse*, is a line, or a system of lines, connecting outcrops or stations where observations were taken. Obviously several traverses have to be made when an area is to be investigated.

302. Kinds of Traverse.—Most traverses are *map traverses*, that is, they are described in terms of compass directions and they are plotted on maps. When emphasis is placed upon changes of elevation and the route is plotted in the form of a profile section (Fig. 333), so that its up-and-down quality is shown, the traverse is a *profile traverse*. Traverses are often designated by the instrument which figures most largely in their making. Thus, there are compass traverses, plane-table traverses, transit traverses, barometer traverses, etc.

303. Compass Traverses.—When there is no map of a region, the geologist generally runs his traverse from outcrop to outcrop by compass. He must make his own map of the route he pursues in studying the area. Even when a good topographic map is available, he must sometimes have recourse to the compass (or plane table, etc.[1]) if the scale of his map is less than the scale on which the work must be done, or if, as is often true, there are comparatively large areas with no satisfactory geographic features to assist in the location of stations.

Let us now briefly consider the manner of conducting a compass traverse. The first thing to do is to "tie up" with some fixed

[1] See p. 477 *et seq.*

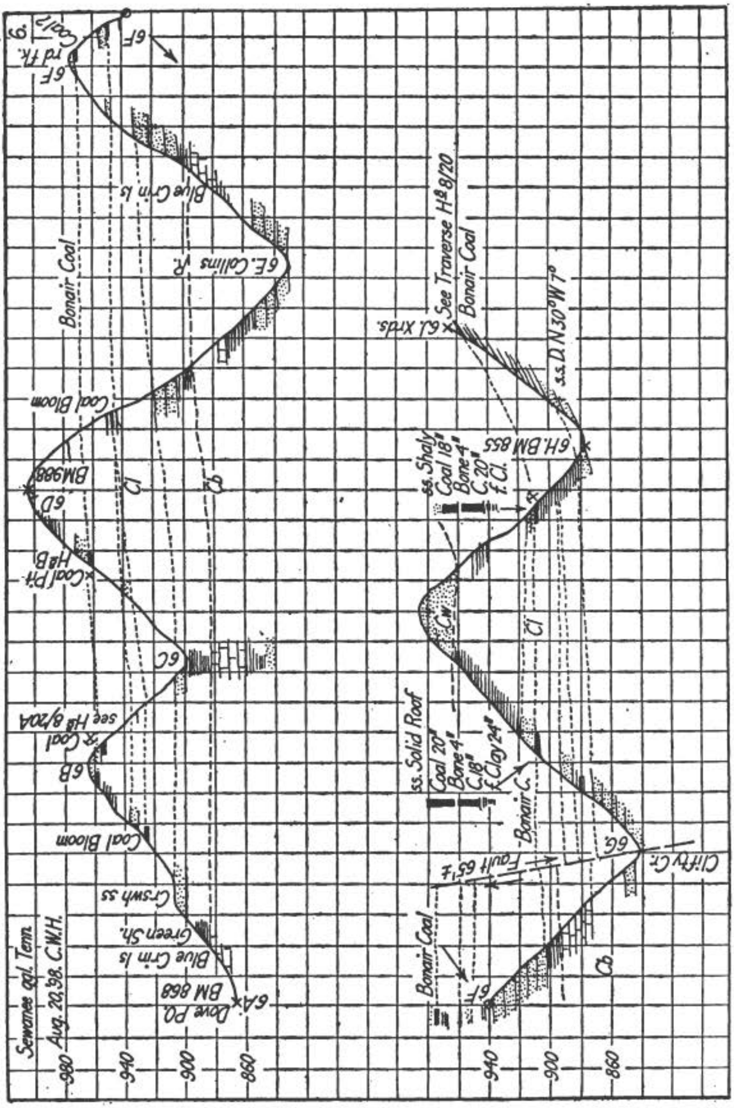


FIG. 333.—A profile traverse record. (After C. W. Hayes.)

point in the field the station at which you intend to begin your traverse. This is done by running a line from the starting point, which may be referred to as Station 1, to the fixed point. The latter may be a triangulation station, a land survey post, a geographic boundary monument, a claim post, etc. It must be something which has been previously located by accurate surveying. If a topographic map is provided, the fixed point may be the intersection of two roads, the confluence of two streams, etc., as shown on this map. That this initial process of tying up must be done with precision is self-evident, for upon its proper execution depends the correctness of all the rest of the work.

Having located Station 1, find the bearing to any conspicuous object, preferably an outcrop, in the general direction in which the traverse is to be run, and pace to this object. Call it Station 2. If it is of geologic interest, record your observations. Proceed in the same way to Stations 3, 4, and so on. In this work it is always a good plan to sight back at the last position whenever possible. For areal surveying traverses should be run as near one another as time will permit and near enough for the geologist to feel reasonably sure that he has seen most of the district.

Observe that distances are measured in paces. Before setting out on a compass traverse, you should ascertain the approximate average length of your stride. This is best done by counting the number of paces in walking half a mile or some other known distance across country of the type you are to investigate, and then dividing this distance in feet by the number of paces. Two circumstances must be allowed for: (1) the length of a pace in going uphill or downhill is not the same as in travelling on level ground; and (2) the map value or horizontal projection of any interval on a slope is less than the actual distance (**279**) (p. 489).

A compass traverse should be tied with a known point at its end as at its beginning. This point may be some new locality not yet visited on this particular route, or it may be Station 1. In the latter case the traverse is said to be *closed*. If the end does not tie up precisely, the gap distance should be measured and this error is subsequently to be divided up proportionally along the whole traverse when the final map is made (**309**).

304. Geologic Surveying with a Working Map.—If you are going to investigate an area of which you have a working map, you must know (1) how to locate outcrops, (2) how to record certain data on the map, and (3) the best methods of note-taking (**310**). The location of stations and, indeed, of the whole traverse is largely a matter of understanding the use of contour maps, it being assumed that the topography is represented by contours. For the starting point of the traverse, whether it be the junction of two roads, the confluence of two streams, the crossing of a stream by a road, a triangulation post, or any other geographic feature, it must be identifiable on the map. From this point you may follow streams, roads, railroads, etc., making detours to one side or the other, but always establishing your course with certainty. A long side trip may be run as a compass traverse (**303**) and the points at which it leaves and returns to the main traverse must then be fixed. If satisfactory landmarks are so few that you can not surely locate your route on the map, you must have recourse to the compass with which you must run a traverse until the map can be used again. Whenever you undertake geologic surveying with a working map, familiarize yourself at the outset with the scale. Find out what distance approximately represents 100 yd., 1000 ft., etc.

305. Beginning a Field Problem.—A few words may be added here in reference to beginning field problems. Some facts concerning the equipment and management of large parties and professional surveys may be found in Hayes' "Handbook."[1] Elementary studies, let us say undergraduate field work, should be approached without any previous knowledge of the locality. In this way the student can be trained to observe on his own initiative. More advanced work, of postgraduate grade, should be preceded by reference to the available geologic literature on the allotted area. It is well to learn all one can of the results of earlier investigations before going into the field.

[1] Bibliog., HAYES, C. W.

Passing over the details of equipment, preparation of the notebook, choice of hotel or camping site, etc., we are brought face to face with the actual field work. What is the best thing to do first? To plunge right in at the outset and make a careful traverse is a rather blind proceeding. It has to be done sometimes, but only when time is very short or when the work is to be restricted to a definite route. Ordinarily several hours or days, depending upon the magnitude of the problem, should be spent in going over the area rapidly, for by such a reconnaissance one can learn enough about the frequency of exposures and about the nature of the rocks and probable underground structure to enable one to plan a systematic mode of carrying out and completing the entire investigation. Several days may be saved in this way. After the preliminary reconnaissance the geologist may continue with the more detailed surveying according to one or the other of the methods outlined in the preceding articles.

Recording Geologic Information

306. Methods of Recording Geologic Information.—The information secured in geologic surveying is always recorded for future reference. This is done by written notes and by maps, sections, photographs, and diagrams of various sorts. Also, specimens of the rocks encountered are collected and classified. Note-taking, mapping, and the collection of specimens, are perhaps the most important duties of the field geologist. Notes should be written, and the rocks and structures should be mapped, by the geologist while he is still in the field (**313**;[1] pp. 477 to 495).

307. Note-taking in General.—Geologic notes should always be full and accurate. Do not rely on your memory. Write down all your observations and impressions. Be careful to distinguish between facts and theories. If you are not quite sure of a statement, punctuate it with a question mark in parentheses. Notes may be abbreviated to save time; but if scientific knowledge is

[1] The principal discussion of maps and other modes of geologic illustration is reserved for Chapter XV.

to be increased by the investigation, abridgment of the field notes should not be of such a character as to impair their lucidity for any geologist who may subsequently read them. Symbols and unintelligible abbreviations should be listed with their meanings near the front of the notebook. Following are a few common abbreviations which may well be learned and put into practice. Others will suggest themselves as occasion demands.

ABBREVIATIONS OF GEOLOGIC TERMS FOR FIELD NOTES

about, ca.
basalt, b.
bedding, stratification, bd.
conglomerate, cg.
diorite, di.
from, fr.
granite, gr, γ.
joint or jointing, jt.
limestone, ls.
metamorphosed, met.
outcrop, otc.
rocks, rx.
sandstone, ss.
shale, sh.
slate, sl.
specimen, sp.
trap, tr.

Strike and dip of bedding may be recorded in short form by always writing them in the same order: N 30 E 40 NW, meaning strike, N 30°E., and dip, 40°NW.

It is good policy to write on only every other page so that plenty of space will be left blank for future additions and corrections. Illustrate all significant geologic structures and other features by sketches and diagrams. These are the briefest and most satisfactory means of recording information (see Chapter XV).

On the last pages of the field notebook the rock specimens and photographs should be separately catalogued (**311, 312**). For each specimen give its number, locality, field name, date of collection, and the page on which it is described, and leave spaces for additional remarks and for the numbers of thin sections if these are to be made. For each photograph give its number, locality, name, the direction in which it was taken, and also remarks on time of day, light value, length of exposure, diaphragm, and focus.

308. Notes for a Compass Traverse.—With regard to recording the data of a compass traverse in the notebook, the student would do well to begin by conforming to a prescribed system. Then, if he prefers, he is at liberty to change his method later. Following is an illustration of a convenient form for field notes:

July 17, 1914.

Up a tributary of ———— River, starting at Sta. 46.

From 46, N10E–60 × N 60 E–35, banks low, evidently of drift × N75E–55 to Sta. 47, a 40′ terraced bank of solid well stratified highly plastic blue clay, showing thin laminæ of fine brown sand ½″–1′ apart. Strata nearly horizontal. If not well sorted Pleistocene, are Tertiary ×

From 47, E–260 (at 160 are otcs[1] of massive ss and sh in S. bank, N 40 E 40 SE (g). At 200 sh seems N 35 E 35 SE) × S70E–80, no rx. Bank slowly rising × N75E–100 to Sta. 48, large blocks of massive ss in stream, ca in place, seems N 10 W 20 NE (o) ×

From 48, N80E–240 (at 60 are large otcs of fine and coarse sandy tuffs and agglomerates (Sp. 268)) . . . . etc.

Observe that each compass bearing for the traverse is followed by a dash and the distance (in paces) of the line along which this bearing was taken; that a large cross (×) indicates a change in direction of the traverse; that notes for stops along a given part of the traverse, between changes in its direction, are put in parentheses; that the number for a hand specimen is given, also in parentheses, after the name of the rock from which it was collected; that strike and dip are recorded thus, N 40 E 40 SE; and, that each such record for attitude is immediately followed by parentheses containing a letter to show how well the bedding was exposed and therefore how reliable the readings are for dip and strike. In the sample notes above, "g" means "good" or "bedding well exposed," and "o" means "bedding obscure."

309. Plotting Compass Traverses.—Compass traverses should be plotted as soon as possible, preferably in the field. This is done on a piece of paper upon which a certain direction has been chosen as north and south, and a certain distance has been

[1] See Art. **307**.

selected as the unit of scale. Beginning at Station 1 the different parts of the traverse, from station to station, are drawn in with proper regard for their true direction and length.

If the last station does not tie up accurately, that is to say, if it is a little out of place, the whole traverse must be corrected. This may be accomplished as follows: Let *abcde*, Fig. 334, represent a traverse of which the last station, *e*, should fall at *f*. Draw a line from *e* to *f* and, parallel to *ef*, rule lines from the other stations (*bx*, *cy* and *dz*). Divide *ef* into as many equal parts as there are stations in the entire traverse, less one. Here there are five stations. Therefore *ef* is divided into 4 equal parts.

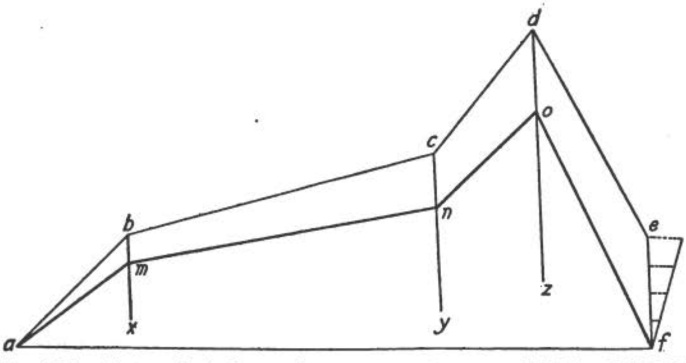


FIG. 334.—First method of correcting a compass traverse. (Cf. Figs. 335, 336.)

On *bx* mark a point, *m*, ¼ *ef* from *b*; on *cy* mark a point, *n*, 2/4 *ef* from *c*; and on *dz* mark a point, *o*, ¾ *ef* from *d*. Draw *amnof*, which is the corrected traverse.

A more exact method is illustrated by Fig. 335. Here *abcde*, again, is the traverse as plotted from the notes, and *f* is the point at which *e* should fall. Determine what percentage of *af* is represented by *ae*. Here *ae* is 101 per cent. of *af*, *i.e.*, *ae* is 1 per cent. too long. Therefore the length of each part of the traverse (*ab*, *bc*, etc.) must be reduced by 1 per cent. of its present length. The angle between *ae* and *af* is 10°, and *af* is to the south of *ae*. Hence the direction of each part of the traverse (*ab*, *bc*, etc.) must be shifted southward 10°. The procedure is as follows: Draw *av* making an angle of 10° with *ab* at *a*. From *a* measure off *ap* = 99 per cent. of *ab*. From *b* draw *bw* making

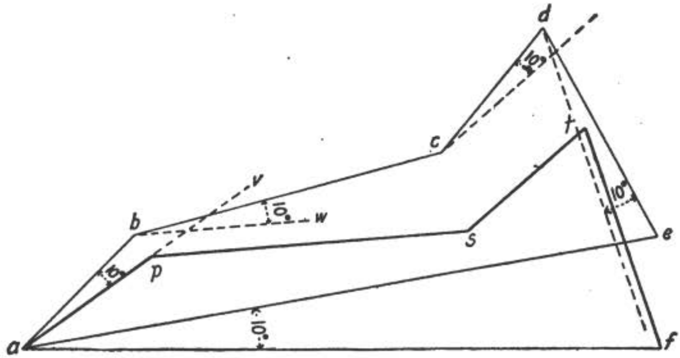


Fig. 335.—Second method of correcting a compass traverse. (Cf. Figs. 334, 336.)

an angle of 10° with *bc*. From *p* draw a line parallel to *bw*, and on this line measure off *ps* = 99 per cent. of *bc*. Proceed in the same way with *cd* and *de*.

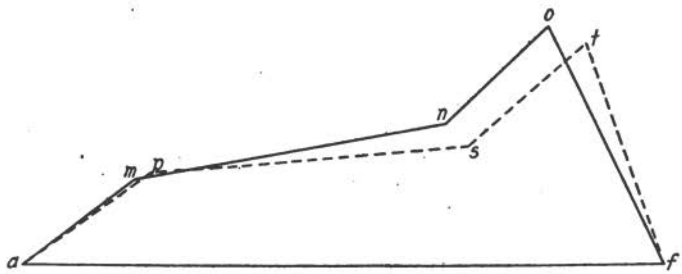


Fig. 336.—Corrected traverses of Figs. 334 and 335 shown together for comparison.

The first method is not accurate because it takes no account of angles, yet it is usually satisfactory for compass traverses. It requires less time than the second method. The difference in the results obtained by both operations is shown in Fig. 336.

310. Taking Notes with a Working Map.—Every outcrop or station at which observations are made is indicated on the working map by a dot or a small cross at the correct place. Where strata are exposed, the dip, strike, and rock type may be recorded by the symbols given in Art. **315**. The different rocks seen, igneous, sedimentary, or metamorphic, may be colored in on the map as far on each side of the traverse as can safely be done without fear of serious error. In this case the distinction must be drawn between alluvium and the several varieties of bedrock.

There are two commonly accepted methods of note-taking, the coördinate system and the point system. For the *coördinate system* the working map is cut into rectangles which are pasted in the notebook, and the pages bearing the maps and those opposite the maps are lettered and numbered as explained in Art. **293**. The dots or crosses, by which outcrops and stations are located on a given map, fall on the coördinate lines or in the intervening spaces. Suppose that the station is in the vertical space "B" and in the horizontal space "5." It is then called B:5. If it is on the vertical line between "A" and "B" and is still in "5," its position is denoted by A–B:5. Similarly, B:5–6 indicates a station in "B" and on the line between spaces "5" and "6;" and A–B:5–6 refers to the intersection of the two lines. If two or three stations are in the same square, they may be called, *e.g.*, B:5W, B:5SE, etc., where the final letters signify compass directions.

The notes are started on the first odd-numbered page after the last map rectangle. In the middle of the page at the top write the date. Just below this, at the extreme left of the page, note the number of the map rectangle on which the traverse starts. On the next line, set in a little from the left margin, record the location of the first station or outcrop, *e.g.*, B:5. Then continue with the notes concerning B:5. Follow the same method for each outcrop. If the traverse runs on to a new rectangle, write the number of this new map in the same way as you did that of the first. Head each day's traverse with the date in the middle of the page. Below is an example:

SAMPLE OF GEOLOGIC NOTES

June 5, 1911

Map 4.

G:26. Small exposure of sandstone. Bedding well shown: N20°W, 30°E.

K:30. Conglomerate with rounded pebbles of quartzite and granite, quartzite predominating. Average, 3 in. in diam. Largest 5 or 6 in. No bedding seen.

Map 5.

H:2. Sandstone like that seen at 4, G:26. Bedding not seen.

The lettered and numbered page opposite each map is to serve as an index to the notes relating to the stations located on that map. For instance, if an outcrop in C:25 is described on page 41, 41 should be written in square C:25 on the page facing the map.

For the point system[1] the map, either with its original scale or photographically enlarged, may be mounted in any way, but preferably on linen. It can then be folded so that any rectangle is face out and can be held thus in the notebook with rubber bands. The stations at which observations are recorded are shown on this map by small crosses. The crosses in any rectangle (or other division of the map) are numbered consecutively from first to last.

The note-taking is essentially like that in the coördinate system except that the remarks on each locality are headed by its station number. When the book is filled a page index ("point index") to the notes may be made in which each group of station numbers is listed in consecutive order, *e.g.*,

Rectangle III

Stations	Pages
1	21–22
2–5	22–23

etc.

With regard to the advantages and disadvantages of the two systems. . . . "locations can be fixed more quickly and more

[1] A more detailed account is given by C. H. CLAPP on pp. 177–181 in "Economic Geology," Vol. VIII. This is one contribution in Bibliog., IRVING, J. D., *et al.*

accurately on the map and can be referred to more quickly by this method than by the system of coördinates more commonly used. It is unlike the coördinate system in that the localities at which notes were made can not be relocated if the map accompanying the notes is lost."[1]

311. Collecting and Trimming Specimens.—In these days of sedulous laboratory study comparatively little can be learned in the field of the true nature of rocks. Hence the necessity of collecting specimens. Judgment must be exercised in doing this. Do not bring in chips from the surface of a weathered exposure. Get as fresh a fragment as possible, for the classification of a rock can not always be made from the products of its decomposition. If time is pressing, irregular fragments may be collected. Otherwise the specimens should be trimmed to a flat rectangular shape, either 4 by 5 by 1 in. or 3 by 4 by 1 in. They are then called *hand specimens*. The width and length should be measured with considerable exactitude, but the thickness may be somewhat variable.

FIG. 337.—Hammer head (b) and rock specimen (a) in proper position for trimming.

In trimming use the *flat* end of the hammer head. Break the fragment down until its dimensions are half an inch or so greater than they are to be in the completed specimen. Finish by striking it on its edges, not on its faces (Fig. 337). In this way chips fly off sideways, and from both faces at the same time, the fragment is trimmed to a thin straight edge, and the strain of the impact is taken up by the width or length of the specimen instead of by its thickness.

If a rock is to be thoroughly studied it must be examined by the petrographic microscope and must be chemically analyzed. For the microscope thin sections have to be cut. Therefore, in order to avoid sawing into the hand specimens, a geologist usually takes, in addition to these, a small chip of every rock that he thinks will need to be sectioned. Of any rock that he

[1] Bibliog., IRVING, J. D., *et al.*, Vol. VIII, p. 181 (CLAPP, C. H.).

considers deserving of chemical analysis he collects several pounds; but chemical analysis is seldom undertaken, unless with some special object, on account of the expense.

Hand specimens and chips *must* be wrapped in paper bags to prevent their scratching and bruising one another. A badly bruised specimen is almost worthless. A label bearing the name, number, and locality of each specimen should be wrapped up with it. Do not mark the specimen itself. *Labelling must be done at the time of collection.*

312. Taking Photographs.—In many respects photographs are the most valuable means of geologic illustration, but they have their limitations depending upon light intensity, light direction, weather conditions, etc. Except for their weight and bulk dry plates are more satisfactory than films.

Do not take a picture merely because it shows something within your area of investigation. Choose only such views as have a definite bearing on the subject in hand. It is best to photograph very irregular rock surfaces on a dull day, for the shadows made by projecting edges and corners on sunny days appear on the print as black patches. Not infrequently contact lines and other rock structures are exposed on granular, pitted, ribbed, or scratched surfaces. If one's aim is to bring out the grain, ribs, etc., take the picture on a bright day when the sun is rather low so that these minor irregularities will cast shadows; but if the structures are to be emphasized, the photograph should be made on a cloudy day.

In spite of the fact that the subject of the picture should be of geologic interest, the view should be taken in such a way as to secure an artistic balance. Experience has demonstrated that the balance is best attained in the following manner: Imagine that the field of the picture is divided by two vertical lines and two horizontal lines into nine equal spaces (see Fig. 338). These lines, and particularly the intersections of these lines, are the strong parts of a picture. One should aim, therefore, to place the camera in a position such that (1) the prominent upright lines or objects (trees, edges of cliffs, etc.) in the view will fall along the vertical division lines (*aa*, *bb*, Fig. 338); (2) the prominent horizontal lines or objects (horizon line, etc.) will come on the horizontal division lines (*cc*, *dd*, Fig. 338); and (3) the principal centers of interest or the conspicuous centers of light or of shadow will be at the intersections of the division lines. It is not necessary that there should be features in the picture

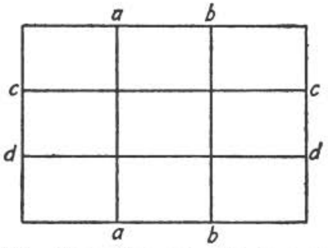


FIG. 338.—Strong lines and points in a picture.

coinciding with all the division lines and their intersections, but merely that those important objects which are present should be arranged as above described.

313. How Much Shall be Undertaken in the Field?—"How much shall be undertaken in the field?" is a question which deserves consideration. An inexperienced geologist is often tempted to do little more than tramp over the ground and record what he sees at the moment, leaving the rest to be done in the office after the field season closes. This is very poor policy. When this man, two or three weeks or months later, sits down to prepare his geologic maps and reason out the geologic structure, he will soon discover that he can not remember just where he saw this thing or just how that one looked. Indeed, either he may have to go back to the district next field season or he may have to write a report that is lacking in certain details, some of which, perhaps, are very important.

The moral of this is that you should accomplish in the field all that is possible. Make your geologic maps and sections, and draw your sketches, plans, and block diagrams. They do not have to be finished for publication. They may be done—

in fact, they should be done in the field—in pencil, black or colored. You will find that this preliminary drawing will be of the greatest assistance in showing you what you have omitted and what you should reëxamine, if possible, before you leave the region. It is a good habit, at night or on rainy days, to copy in full the abbreviated notes recorded during the day. A separate book should be kept for this purpose. Here, too, lists of specimens and of photographs are to be rewritten. Indices arranged according to maps and station numbers, dates, and subjects, may be prepared, so that facts can easily be found when one starts in with the office work.

CHAPTER XV

MODES OF GEOLOGIC ILLUSTRATION

Geologic Maps

314. Definitions.—Any map that shows the distribution of rocks and geologic structures is a *geologic map*. A special type of geologic map is an *outcrop map* which represents only the actual outcrops. In the preparation of a geologic map the geologic features are plotted on a topographic map which, in this connection, is referred to as a *base map*. A good contour map is the best kind of base. The distribution of rocks is indicated on a geologic map by various patterns or colors, and linear features, such as fault lines, igneous contact lines, boundaries, etc., are shown by lines of different kinds and weights. If there are many formations to be represented, a literal abbreviation may be printed at intervals in each color area (see folios published by the U. S. Geological Survey). In the margin of a geologic map is a legend, that is, a key to the meaning of the colors, patterns and lines used on that particular map (**268, 320**).

315. Conventional Patterns, Lines, and Symbols.—The color or pattern to be employed on a geologic map depends largely upon the inclination of the investigator unless he is working for some organization which has already adopted a scheme. On the maps of the U. S. Geological Survey certain colors and patterns have a definite significance. "Patterns composed of parallel straight lines are used to represent sedimentary formations deposited in the sea, in lakes, or in other bodies of standing water. Patterns of dots and circles represent alluvial, glacial, and eolian formations. Patterns of triangles and rhombs are used for igneous formations. Metamorphic rocks of unknown origin are represented by short dashes irregularly placed; if the rock is schist the dashes may be arranged in wavy lines parallel to the structure planes. Suitable combination patterns are used for metamorphic formations known to be of sedimentary or of igneous origin. The patterns of each class are printed in various colors. With the patterns of parallel lines, colors are used to indicate age, a particular color being assigned to each system."[1]

On both colored and black-and-white maps faults may be indicated by heavy black lines and boundaries between adjacent areas of different color or pattern by fine black lines (Fig. 339). These fine boundary lines may stand for conformable contacts

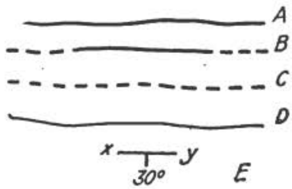


FIG. 339.—Lines and symbols for geologic maps. *A,B,C,* fault lines. *A* is for a fault the position of which is fairly certain. *B* is for a fault of which the continuation in both directions has not been found. *C* is for a fault of which the position is uncertain. *D,* formation boundary line. *E,* dip and strike symbol.

between adjacent strata, lines of unconformity, and igneous contacts. A fault line may be drawn full where its position is reasonably certain, dotted where it is partly buried but where its location, likewise, is reasonably certain, and dashed where its location is less sure (Fig. 339).

On many maps of strata, dip and strike are indicated by a symbol like a broad, low T, which is so placed that the intersection of the two lines is at the part of the outcrop where the reading was made. The upper line of the T (*xy* in Fig. 339, *E*) marks the strike and is therefore plotted accurately in its proper position on the map. The upright of the T is drawn pointing *down* the dip. Since it shows only the direction of dip, the angle of dip must be recorded in figures beside the symbol. In Fig. 340 the symbols indicate anticlinal structure on the west and synclinal structure on the east.

[1] Geologic folios published by the U. S. Geological Survey.

The type of rock, also, may be shown with these symbols for strike and dip (Fig. 341). A second line drawn parallel to the strike line, close to it and just the other side of it from the dip line, stands for shale or slate; a similar line with short cross lines

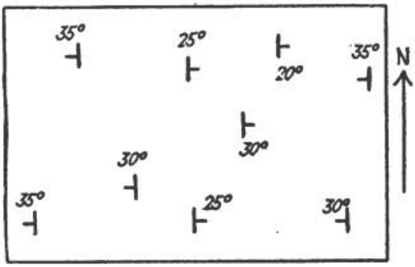


Fig. 340.—Outline map of sedimentary rocks, showing dip and strike symbols.

between it and the strike line means limestone; a row of dots parallel to the strike line, in the same place as the shale line, is for sandstone; and a row of small circles signifies conglomerate.

316. Position of Boundaries between Rock Bodies.—Map-making consists largely of plotting boundaries. When these have been correctly placed, filling in the spaces with arbitrary colors or patterns is a simple matter. Before a line can be properly located on a map, its position must be determined in the field (**289, 290, 291**). Some maps represent only mantle rock with or without the actual outcrops of bedrock; others give the distribution of bedrock only, as if the overlying débris had been entirely removed; and still others, the most common variety, show both bedrock and mantle rock, but the latter is indicated merely where it is comparatively thick.

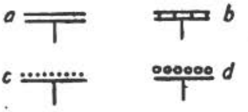


Fig. 341.—Symbols for rock type combined with symbol for dip and strike. *a*, shale or slate; *b*, limestone; *c*, sandstone; *d*, conglomerate.

In field work a good deal of trouble may be experienced in locating boundaries for the second and third types of map. When bedrock only is to be shown (second type), the division lines between rock bodies are often concealed. In this case their position may be suggested by the topography. To take examples from sedimentary rocks, a weak stratum may form a valley between two resistant beds; or a valley may be situated along the junction of two strata which are of nearly equal resistance to erosion (**250, B, D**). Frequently further investiga-

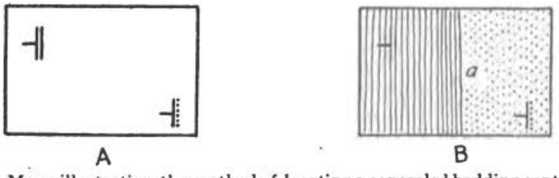


FIG. 342.—Maps illustrating the method of locating a concealed bedding contact between outcrops of different strata. The boundary is drawn through *a*, half way between the outcrops.

tions along the general trend of the line may reveal some substantial key to the relations. Provided the boundary between two outcrops with parallel strikes is neither visible nor can be closely located by the topography, it is usually drawn halfway between these outcrops and parallel to the strikes (Fig. 342). This is on the assumption that the beds in the two outcrops are mutually conformable. Care must always be taken to avoid er-

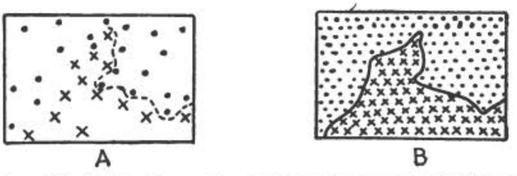


FIG. 343.—Maps illustrating the method of locating a concealed irregular boundary. In A the dots and crosses represent outcrops of two kinds of rock. On the left no boundary is shown; on the right its approximate position is indicated. In B the boundary has been completed and the map filled in with symbols for both rocks.

rors that may be occasioned by unconformity or faulting. For rocks of two kinds, having no definite structure like bedding, the contact line may be put halfway between the nearest outcrops, but its trend must be determined by correlation with exposures over an extensive area (Fig. 343).

When the geologist prepares a map of the third type, he tries to mark out areas where outcrops are numerous and mantle rock is relatively thin and discontinuous from areas in which exposures are rare or absent and the surficial deposits are comparatively thick. Such a boundary is purely arbitrary and is seldom drawn in exactly the same way by different geologists.

317. Relations of Topography to Geologic Mapping.—A map is a projection of lines and areas upon a horizontal plane, lines and areas which, in reality, are usually distributed over an uneven land surface. A line which trends without deviation across hills and valleys is therefore straight on a map; its sinuosities in the vertical plane do not appear. On the other hand, an irregular line which is entirely within a horizontal plane has all its bends and angles represented with their true shape on a map. When a crooked line lies in any plane other than one which is vertical or horizontal, its projection on a map has the same number of bends in the same relative positions, but the arcs of curves are broader

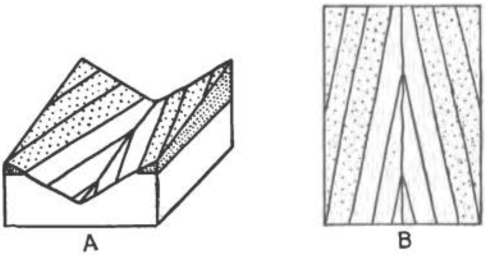


FIG. 344.—Relations of horizontal bedding to contours shown in a block diagram (A) and in a map of the surface of the block (B). Stippled and blank portions represent two rock strata. Figs. 345–348 are drawn in the same way.

and angles are more obtuse. It follows from this that the rules laid down in Arts. **139, 159,** and **187,** with reference to the effects of topography on the distribution of outcrops must be applied in map construction. These rules are repeated below, although in modified form. For the sake of simplicity the relations of a surface only are considered. The surface may be any kind of geologic contact, *i.e.*, the top or bottom of a stratum, the walls of a vein, an igneous contact, a surface of unconformity, or a fault. It is assumed to be flat or nearly so.

(1) If the given surface is horizontal its outcropping edge on a hill-and-valley topography will have all the characters of a contour; in its directions and curves it will closely correspond to

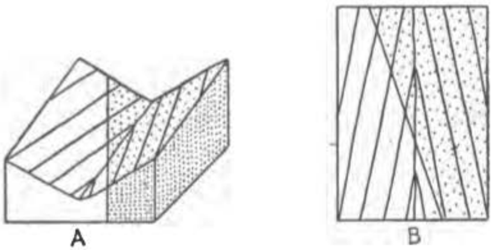


Fig. 345.—Relations of vertical strata to contours. (See Fig. 344.)

the nearest contour lines on the map (Fig. 344). (2) If the surface is vertical its outcropping edge will be a straight line on a map no matter how rugged the topography is (Fig. 345). (3) If the surface is inclined, its outcrop will be an irregular line with elbow-like bends. In valleys these bends will point

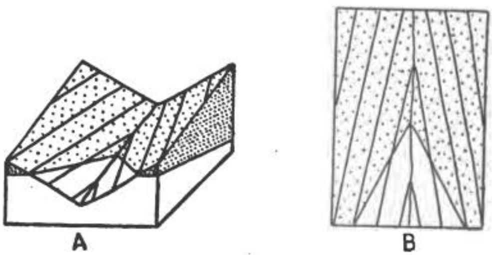
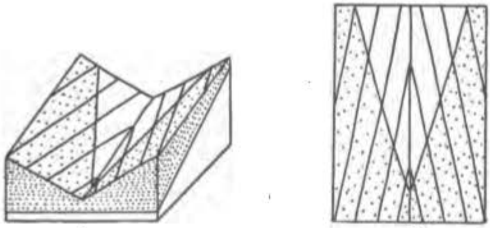


Fig. 346.—Relations of inclined strata to contours. (See Fig. 344.)

upstream if the dip is opposed to the slope of the valley bottom (Fig. 346), and they will point downstream if the dip is in the same direction as the slope of the valley bottom (Fig. 347), unless the dip is less than the slope. In this case, which is rare, the bends point upstream (Fig. 348). Note that the apex of the bend in valleys falls at the stream channel. The more uneven a surface is, the more irregular will be its line of outcrop. Dikes, sills, veins, and strata, when of approximately uniform thickness, may be treated as surfaces if they are thin. Otherwise the top



A B

FIG. 347.—Relations of inclined strata to contours. (See Fig. 344.)

and bottom, or each of the two walls, must be plotted separately, and the distance between the boundary surfaces will then vary according to the slope (**158**).

318. Filling in an Outcrop Map of Stratified Rocks.—The method of filling in an outcrop map of stratified rocks may be described with reference to two cases, according as the land sur-

A B

FIG. 348.—Relations of inclined strata to contours. (See Fig. 344.)

face is level or is uneven. In Art. **318** the ground is assumed to be level. Art. **319** deals with the problem of geologic map construction where the topography is uneven.

Let us suppose that the geology is to be plotted on the outcrop map represented in Fig. 349, A. Presumably the exposed strata are continuous along their strikes beneath the soil mantle. Being along the same line of strike, *d* and *e* are probably outcrops of the same bed of conglomerate. Each of the other outcrops is the visible part of a strip of rock that trends parallel to the *e–d* bed, for all the strikes are here parallel (Fig. 349, B). Now, there is nothing to show that conglomerate does not exist between the *c* strip and the *e–d* strip, and, accordingly, this area may be marked for conglomerate. Similarly, shale probably occupies the space between *g* and *h* along the strike. It will be observed that there are indications of six different belts of rock, as follows: shale on the west, including outcrop *a*; sandstone next east, including outcrop *b*; then conglomerate, including outcrops *c*, *d*, and *e*; then sandstone, *f*, followed eastward by shale, *g* and *h*, and finally sandstone, *i*, at the extreme east. By locating the boundaries between these belts, as directed in Art. **316,** the map is completed (Fig. 349, C).

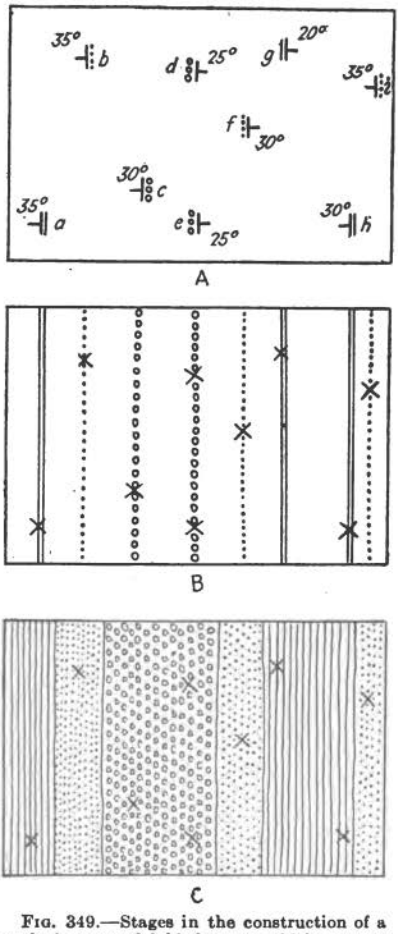


Fig. 349.—Stages in the construction of a geologic map of folded strata which outcrop on a level land surface. The crosses in B and C are in the positions of the outcrops in A.

319. Use of Profile Sections in Geologic Map Construction. —Few regions are flat as in the hypothetical case just described. If the topography is varied, the construction of the geologic map is more complicated. An example is chosen here in which strikes are regarded as trending across valleys, for the relations are better brought out in this way. Let *n* (Fig. 350, A) be an outcrop exposing a contact between two strata and imagine that this

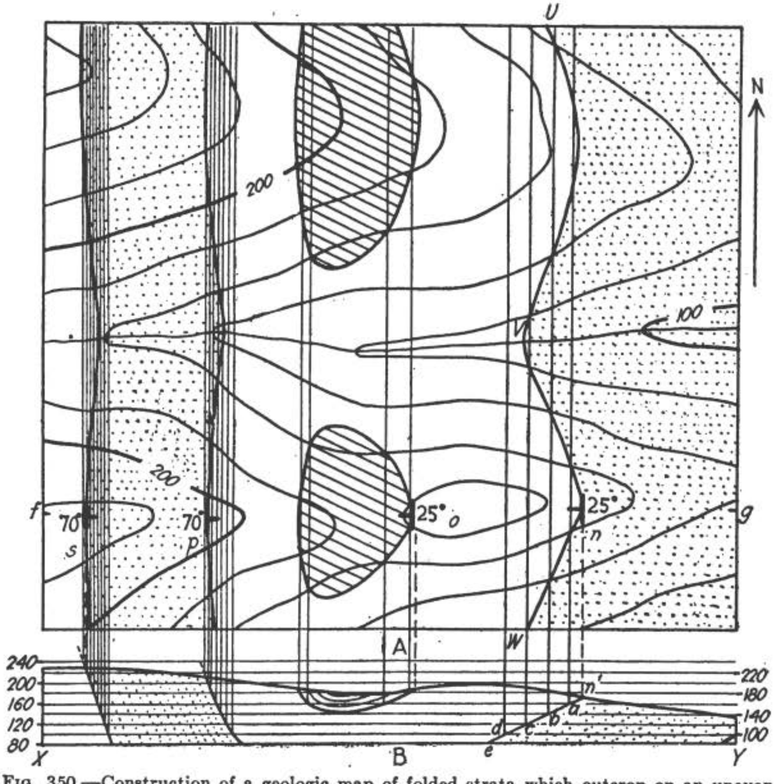


FIG. 350.—Construction of a geologic map of folded strata which outcrop on an uneven land surface. Contour interval, 20 ft.

contact is essentially flat near the surface of the ground. Choose a vertical scale and construct a profile section through *n* perpendicular to the strike (Fig. 350, B) see Art. **274.** The base line X–Y, of this section may be drawn on the same sheet of paper as the map, but it must be drawn actually perpendicular to the strike. Project *n* upon the profile line of the section (*n′*). From *n′* draw a line (*n′–e*) westward and downward at an angle of 25° to the horizontal. *n′–e* is the intersection of the plane of the section with the bedding contact plane through *n*. It cuts the 160-ft. contour level in the section at *a*, the 140-ft. contour level at *b*, the 120-ft. contour level at *c*, and the 100-ft. contour level at *d*. From these four points draw lines perpendicular to X–Y upward and across the map. Wherever the line from *a* crosses the 160-ft. contour on the map, the bedding contact plane comes to the surface at this point; wherever the line from *b* crosses the 140-ft. contour line on the map, the contact plane meets the surface at the level of 140 ft.; and so on. Between these points of intersection on the map a curved line, UVW, is drawn, this line being the position of the continuous outcrop of the contact plane on the surface of the ground. The line from *d* does not meet the 100-ft. contour because the valley in the middle of the map is not deep enough to reach this contact.

Now let *fg*, Fig. 350, A, be a traverse across the strike of a series of strata. Suppose that, at outcrops *o*, *p*, and *s*, contacts between strata have been recorded and that *n* and *p* are at the same horizon. The structure, inferred to be synclinal, may be shown on a profile section along the traverse, as directed in Art. **328**. If one desires to make a geologic map of the rocks and structure represented in this section, each outcrop is to be separately treated as has been explained for *n*. Fig. 350, A, shows the distribution of the contacts exposed in the five outcrops. Between them the different strata are indicated by cross-hatching and stippling. The boundary that runs through *o* is not continuous across the valley, for the stream has cut below this horizon, entirely removing a large part of the overlying bed (diagonally lined in Fig. 350, A).

In ordinary geologic mapping it is not customary to locate contacts with such mathematical precision unless great accuracy is particularly desirable. After one has gained some familiarity with the general effects of topography on the distribution of outcrops, one can sketch the boundaries between strata on a contour map with sufficient precision without the assistance of geometry, provided dips are known and the relief is observed, and provided, also, the different beds in the series have been located along several traverses.

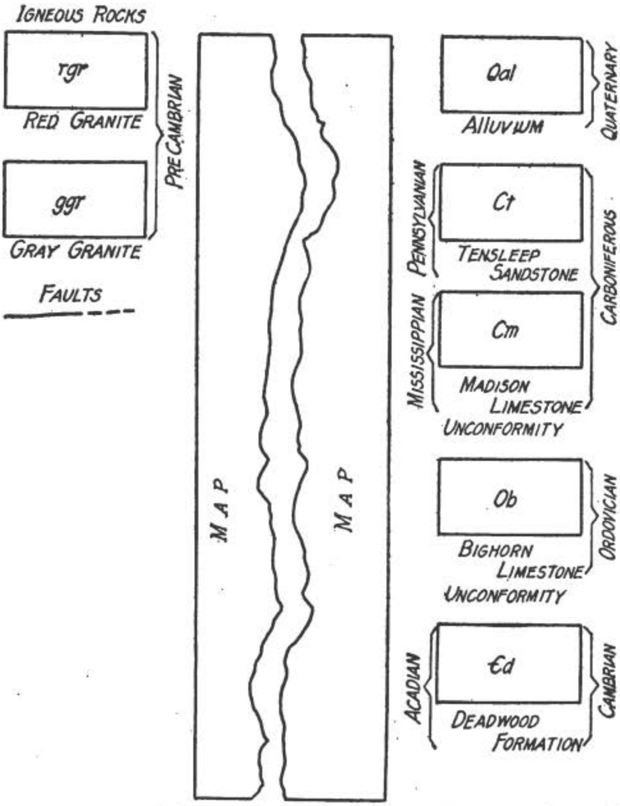


FIG. 351.—Arrangement of the legend for a geologic map. The rectangles would be filled in with the colors or symbols employed on the map.

320. Nature of the Legend.—The nature of the legend of a geologic map is illustrated in Fig. 351. The conventional signs and colors should be tabulated in a column of small rectangles of equal size. On the U. S. Geological Survey maps, the signs for rocks are above those for such features as faults, glacial striæ, lines of section, etc. Igneous and sedimentary rocks, metamorphosed or not, are grouped separately, the sediments being above. For metamorphic rocks whose origin can not be determined, the signs may be placed under the head "unclassified" below those for igneous rocks. In each group the formations are placed in the order of their relative age, youngest being at the top. Unconformities, when present, are often noted between the symbols for the unconformable formations. The geologic ages are printed beside the column. The legend is put in the right margin of the map and, if too long, it is continued in the left margin (Fig. 351). In this case the left portion really belongs below the part in the right margin.

321. Requisite Data for a Completed Geologic Map.—A geologic map is incomplete unless it has a legend, a scale, compass bearings, both magnetic and true, and lines of section (**323**) if any geologic sections have been drawn to accompany this map. It must have a name, and the year in which it was made must appear somewhere upon it. If it was constructed on a contour base map, the contour interval and datum plane must also be recorded. With regard to scale, compass bearings, and contours, what was said in Arts. **269–271** is applicable here.

Joint Diagrams and Maps

322. Methods of Representing the Attitude of Joints.—The field geologist should not neglect to study the joints in his area of investigation. Not until their attitudes and relations to one another are known can deductions be made as to their origin. For the larger fracture systems it is well to prepare special maps or diagrams to show the dips and strikes of the joint sets observed. For each station on a traverse the strikes may be plotted on a map as a radiating group of lines which intersect at the station (Fig. 352). Along each line the strike and also, if it is desired, the amount and direction of dip may be noted.

If one wishes graphically to represent in a single diagram all the joint trends in a region, this may be done by plotting all the strikes about a single center; or the following method may be employed.[1] Tabulate all the joint strikes in groups of 3° each, beginning at the west and passing through north to east. In the first group will be all strikes between N.90°W. (= E.–W) and N.88°W., inclusive; in the next group of three, readings from N.87°W. to N.85° W., inclusive; and so on. Having tabulated the strikes in this way, construct a diagram like that in Fig. 353, in which (1) the radii are drawn at intervals of 3°, beginning at the west, and thus intercepting segments corresponding to the joint groups; (2) the radial distance between the middle and inner circles is measured in any convenient unit and is made proportional to

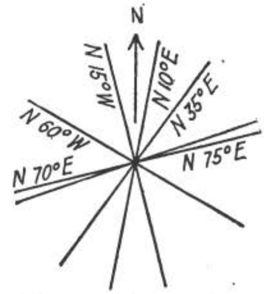


FIG. 352.—Diagram showing the strikes of joints observed on an outcrop.

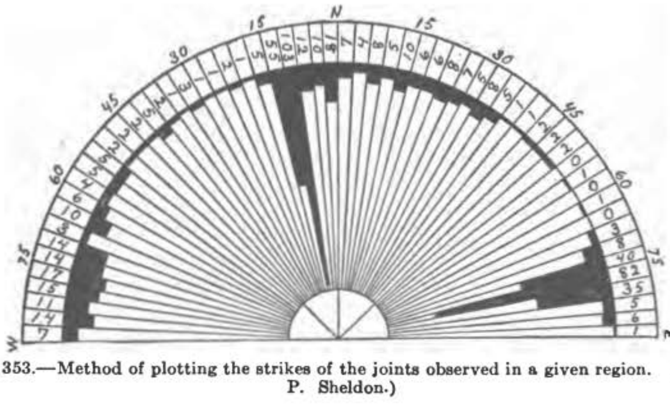


FIG. 353.—Method of plotting the strikes of the joints observed in a given region. (After P. Sheldon.)

the greatest number of joints falling in any one of the groups; (3) the number of joints in each group is recorded between the middle and outer circles; (4) the number of joints in each

[1] See Bibliog., SHALER, N. S., 1889, pp. 583–588; and SHELDON, P.

group is graphically shown by blackening the corresponding segment inward from the middle circle a distance proportional to this number and measured in the chosen unit; and, (5) the compass directions are indicated just outside the outer curve.

Dips may be plotted in like manner; but for this the reader is referred to the reports above cited. Needless to say, the attitudes of veins and dikes may be illustrated by diagrams similar to that above described, if the veins and dikes are comparatively uniform in trend and thickness.

Geologic Sections

323. Definitions and General Nature.—If it were possible to make a deep vertical cut in the ground and then remove all the soil and rocks on one side of the cut, the other side might stand up as a flat vertical wall upon which rock structures and rock relationships could be seen in cross section. While incisions of this kind are impossible, except for very slight depths, the geologist can draw vertical sections of the underground structure as he thinks it exists from data obtained from outcrops, artificial excavations, and drill cores. Such sections, whether actually seen or merely inferred, are called *geologic sections*. They depict geologic structure by means of certain conventional lines and patterns or colors, and therefore, like geologic maps, they must have a legend.

The line of intersection of the land surface with the plane of a geologic section, as shown on a map, is called a *line of section*, exactly as in the case of profile sections (**273**).

For every geologic section one must first make a *base section* upon which the geologic features may be drawn. This may be a profile section, prepared as described in Art. **274**, or a simple rectangle. The simple rectangular base consists of two horizontal lines connected by two vertical end lines. The lower horizontal line corresponds in every way to the base line of a profile section (**273**). The upper horizontal line is intended to represent the intersection of the plane of the section and a horizontal plane which may be taken at any convenient elevation. The advantage of the rectangular base section is that it eliminates the necessity of plotting the topography; but since it does not depict the actual nature of the land surface, it should not be used except where the scale is so small that the relief variations

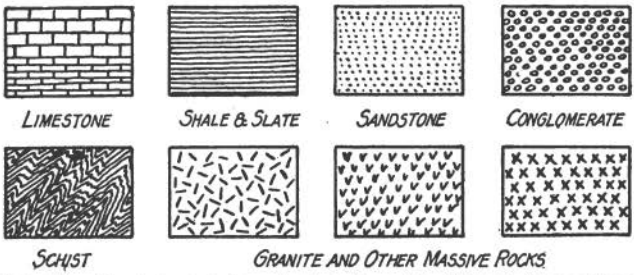


FIG. 354.—Symbols used in geologic sections for different types of rock.

would be negligible in a profile section of the same district on the same scale (**329**).

324. Methods of Indicating Geologic Structure.—Within the closed space of a geologic section all lines for faults, contacts, unconformities, etc., are drawn full, and between these lines, as

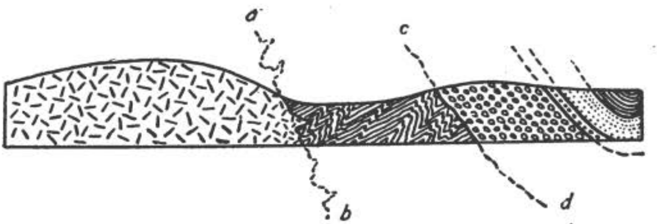


FIG. 355.—Illustration of the nature of a geologic section.

on a geologic map, the rocks or formations are filled in by conventional colors or patterns (Fig. 354). It is a common practice further to indicate the geologic structure by extending the *lines*, now *dotted*, beyond the confines of the base section (Fig. 355); but observe that the colors (or patterns) for the rocks should be restricted to the area of the base section. Above the top line of the base section these dotted lines stand for the inferred structure of the rocks which have been removed by erosion. Below the bottom line such dotted lines represent the structure where it is uncertain on account of its great depth. Note that the general characters indicated by the full line for a particular contact should be similarly represented by the dotted prolongation of the same line (Cf. *ab* and *cd*, Fig. 355).

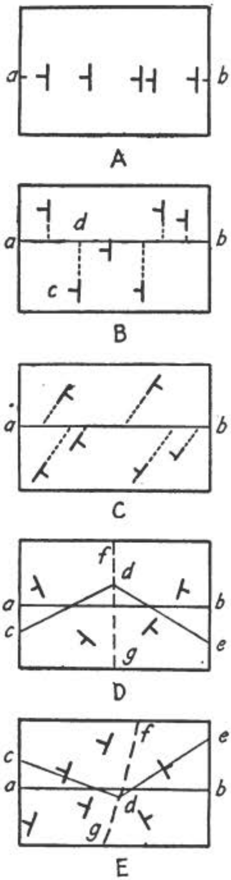


Fig. 356.—Location of a geologic section across stratified rocks.

325. Position of Sections Across Folded Strata.—The location of a geologic section depends upon the exact features which the geologist wishes to emphasize. Ordinarily it is drawn perpendicular to the strike of stratified rocks, so that it will show their true dip. When pitch is to be figured, the section must be drawn parallel to the axis, and it is then called an *axial section.* In districts where the bedrock is abundantly exposed, locating a section is easy; but if outcrops are few and scattered, the rocks and structures which they reveal must be projected along the strike (Fig. 356, B, C). Frequently strikes vary 10° or 15° to one side or the other of their average direction. For a large-scale section, covering a short distance, it may be important to make allowance for these variations; but for a small-scale section they are insignificant if the outcrops are situated relatively near the line of section. Experience will soon teach the student how to deal with these cases. He must not confuse this indiscriminate and slight variation of strikes with a gradual or sudden, pronounced and regular change in direction.

The latter phenomenon may be due to a fault, an unconformity, or some other important cause.

To illustrate the relations between the trend of a geologic section and the position of outcrops and structures, several examples are given below. In all the land surface is assumed to be horizontal.

1. The bedrock is broadly exposed, or the outcrops are situated in a row trending perpendicular to the strike (Fig. 356, A). Draw the section along a line from *a* to *b*.

2. Outcrops are scattered. Strikes are all identical or very nearly so (Fig. 356, B). Project the rocks and dips of the several outcrops along their strikes to points on the line *ab*, which is perpendicular to the strike. Thus, the rock exposed at *c* and the dip of the beds at *c* would be represented in the section at *d*.

3. For some reason, not here stated, the section must be drawn at an acute angle to the strikes, along such a line as *ab* in Fig. 356, C. Project rocks and dips along the strikes of the outcrops to points on the line *ab*, just as in example 2. Since a section perpendicular to the strike shows beds with their maximum inclination or dip, and since, in a section parallel to the strike, the beds would appear to be horizontal, obviously a section located between the dip and strike directions must show the beds inclined at an angle more than 0° and less than their true dip. In other words, in cases like the present one, a correction must be made for the inclination of the beds as this would be seen in the section, and this correction will depend upon the actual dip and upon the angle between the strike and the line of section (see Appendix X).

4. When strikes vary regularly, as in D and E, Fig. 356, the line of section may be straight (*ab*), or it may be drawn with one or more changes in its direction (*cde*), the object in this case being to keep it as nearly as possible perpendicular to the strikes. In Fig. 356, D, the curve in the strikes indicates a pitching fold. Let us assume that the axis of this fold lies along *fg*. The outward dip of the beds shows that the pitch is toward *g*, and, as far as the map reveals, there is every reason to

believe that the strata pitch in this same direction at all points along the axis. Hence, in geologic sections on *ab* and *cde* the beds would appear to be horizontal where *ab* and *cde* cross the axis. (Why?) The sharp change in strikes in Fig. 356, E, suggests a fault or an unconformity (*fg*) between the two sets. In either D or E, Fig. 356, a section along *ab* would need correction for dips as explained for case 3.

326. Operations Necessary in the Construction of Geologic Sections.—The method of constructing geologic sections may be treated under four heads: (1) the transfer of data from a map to a base section; (2) the correlation, in the section, of rocks already correlated in the field; (3) the location of boundaries between adjacent strata or formations; and, (4) filling in the section. The construction of a rectangular geologic section will be discussed first, and then that of a profile geologic section. In both cases we shall consider a region in which all the rocks are folded strata.

327. Construction of a Rectangular Geologic Section Across Folded Strata. A. Transfer of Data Recorded on a Map.—Let Fig. 357 be a map of an area in which the relief is relatively low

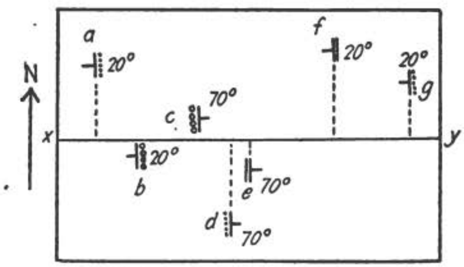


Fig. 357.—Outcrop map of folded strata. A geologic section is to be made along *xy*, the "line of section." (See Fig. 358.)

as compared with the length of the section to be drawn. *xy* is the line along which the section is to be made. Upon *xy* project the rocks and dips of the outcrops as directed in Ex. 2, Art. **325,** and transfer the points of intersection (*a–g*) to *xy* in Fig. 358, A. At point *a,* Fig. 358, A, lay off a row of dots inclined downward and westward and making an angle of 20° with the horizontal line *xy*. This denotes sandstone (**315**) dipping 20°W., and it stands for outcrop *a* in Fig. 357. Follow the same method for each of the other points, always observing the proper rock and dip to be used. Conglomerate is to be represented by a row of small circles parallel to the dip, and shale by a straight line

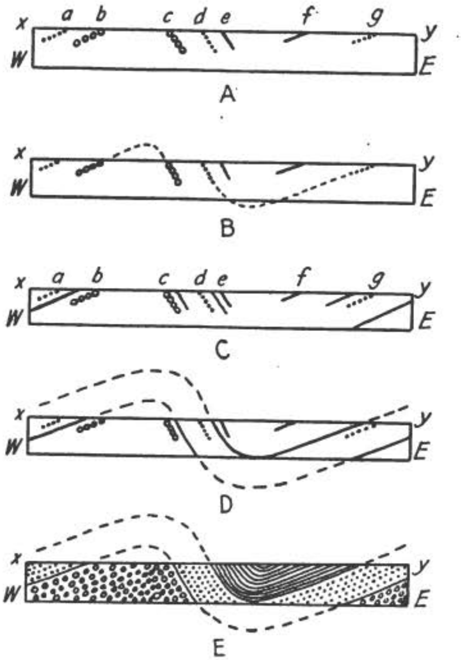


Fig. 358.—Stages in the construction of a rectangular geologic section along line *xy* in Fig. 357.

parallel to the dip. Fig. 358, A, is the result of this work. It is well not to make the symbols, *i.e.*, the rows of dots or circles, or the lines for shale, extend more than a very short distance down from the top of the figure, merely far enough to show the dip.

——**B. Correlation of Rocks.**—In Fig. 358, A, *d* and *g* may be connected in a syncline (Fig. 358, B), since they are parts of the same bed, a fact which we shall assume has been ascertained by one or more of the methods of field correlation mentioned in Art. **162.** For the same reason, the outcrops of conglomerate at *b* and *c* may be drawn as if they had formerly been joined in an anticline. The structure, then, indicates a stratigraphic sequence from conglomerate below, through sandstone, to shale above.

——**C. Location of Boundaries.**—The location of boundaries between strata has been described for maps in Art. **316.** In general the map of a region should be completed before the sections are made; but if a geologic section is to be plotted directly from field notes, location of bedding contacts is determined in the same way as in the case of maps. Stratigraphically, *i.e.*, at right angles to the bedding, outcrops *a* and *b* (Fig. 358), of sandstone and conglomerate, are nearer than *c* and *d*, also of sandstone and conglomerate. Hence, the boundary between these rocks is placed halfway between *a* and *b* (Fig. 358, C). Similarly, the shale-sandstone boundary is located halfway between *d* and *e*. Between *c* and *d* the sandstone-conglomerate contact is placed east of *c* at such a distance that there shall be the same thickness of conglomerate represented between this spot and *c* as there is between *b* and the sandstone-conglomerate contact west of *b*. This is because *b* and *c* have been proved to be at the same stratigraphic horizon (same bed). In like manner the position of the shale-sandstone contact is determined between *f* and *g*.

When locating boundaries between strata, always use the most accurate information available. If a contact is exposed, this contact should be the starting point. From its position other boundaries may be fixed, provided the thickness of each bed is known. If no contact is exposed, determine the position of the boundary between the nearest outcrops of two adjacent strata, and then locate other contacts.

——**D. Filling in the Section.**—It is now possible to complete the section by extending the rock contacts and filling in the inclosed rectangular space with the proper symbols for conglomerate, sandstone, and shale. The boundaries are drawn, as full lines in the section and as dotted lines beyond the confines of the base section, parallel to the structure shown in the anticline between *b* and *c* and in the syncline between *d* and *g* (Fig. 358, D). The last step is the filling in of the section proper (Fig. 358, E).

328. Construction of a Profile Geologic Section Across Folded Strata.—Let Fig. 359, A, be an outcrop contour map of an area and suppose that a section is to be made through the line *xy*

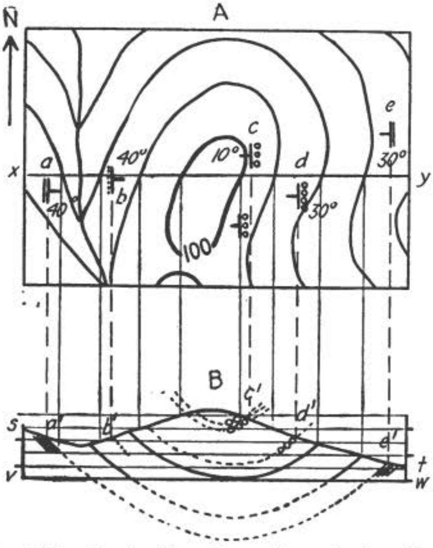


Fig. 359.—Construction of a profile geologic section.

which marks a cross-strike traverse. A profile base section must be constructed (**274**). This is illustrated in Fig. 359, B, where *vw* is the base line which corresponds to *xy* on the map. Here the points of intersection of the line of section (*xy*) with the contours may be transferred to *vw* most conveniently by dropping perpendiculars from these points to *vw*, it being understood that *vw* has been drawn equal in length to *xy* and, like *xy*, perpendicular to the strikes. Just as the intersections of the contours with *xy* are plotted on *vw*, so also the positions of the outcrops (*a*–*e*), projected along their strikes, are located on *vw*. The perpendiculars from the outcrops meet the profile line, *st*, at the proper sites of the outcrops (*a′*–*e′*). At these points on *st* the dip and rock type are to be correctly indicated (**327, A**) and then the section is to be completed in the manner outlined in Art. **327, B–D.**

The vertical and horizontal scales of a geologic section should be the same. Exaggeration of the vertical scale necessitates correction of all the dips and thus not only involves a great deal

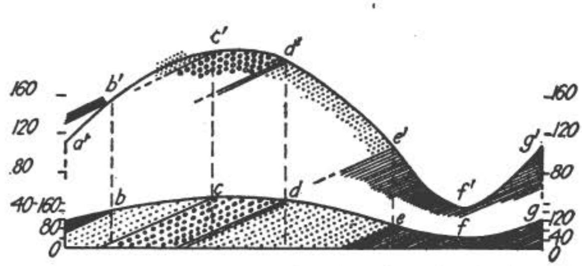


Fig. 360.—Errors resulting from exaggeration of the vertical scale of a geologic section. The lower section is drawn to natural scale; the upper section has a vertical scale exaggerated three times. The effects of this exaggeration are (1) to cause the beds at *b′* to dip out of the hillside instead of into it, as at *b*; (2) to cause the sandstone at *c′* to run into the slate at *b′* (cf. *b* and *c*); and (3) to alter the thickness of beds (cf., especially, the sandstone between *d′* and *e′* with that between *d* and *e*).

of needless labor, but also gives a false notion of the structure. Fig. 360 illustrates three of the absurdities which may result from an exaggerated vertical scale.

329. Comparison of Rectangular and Profile Sections.—The student should observe that rectangular geologic sections are more or less incorrect except when the land surface is flat and horizontal. The profile section, drawn to natural scale, is the most accurate mode of showing geologic structure. Fig. 361 contrasts the results obtained by projecting the same data upon both rectangular and profile sections. Upon a map (not shown) are two stations at each of which the dip is 30°E. The land slopes uniformly 17°W. (Fig. 361, A). The stations, as projected, are at *a* and *b*. From these points the dip is plotted. Measurements indicate that the thickness, *T*, between the beds *a* and *b* is considerably reduced in the rectangular section. It is correct in the profile section. If the beds were projected down their dip to the horizontal level represented by the top line of Fig. 361, B, they would have a breadth of outcrop, *cd* (Fig. 361, A), longer than *ab* in Fig. 361, B. *cd*, however, is the correct horizontal distance between the beds at the level, *cd*. Obviously, then, profile sections are always to be preferred to rectangular sections when actual geologic structure is to be depicted. Rectangular sections are useful for diagrams of general application, such as many used in this book.

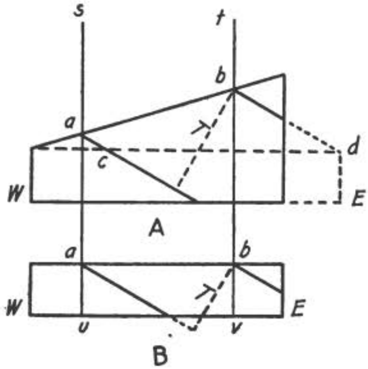


FIG. 361.—Errors introduced by the use of a rectangular section. A, profile section, and B, rectangular section, of a bed whose breadth of outcrop is *ab*, as projected from the map along the lines *su* and *tv*.

330. Interpretation of Dips in the Construction of Geologic Sections.—In many cases after the dips and rock types of folded strata have been plotted, the final interpretation of the structure requires a good deal of thought. Several variations may be suggested by the data. In order to assist the student in completing his sections, a number of relations for dipping strata are noted below, together with their possible interpretations. In these examples it is assumed that field observations on rock type, strike, amount and direction of dip, etc., have been recorded. Simple symmetrical folds, asymmetrical and overturned folds, isoclinal folds, and parallel and similar folds, are considered. Strikes are regarded as parallel in all outcrops unless otherwise stated.

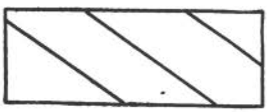


FIG. 362.—Section of beds with monoclinal dip.

——**A. Observations on Monoclinal Dips.**—1. *On a single outcrop or on several adjacent exposures the dip is found to be of* *nearly constant value and in the same direction. There is no duplication of beds.* Let Fig. 362 be a section of the structure beneath the area examined. Beds with this dip may belong in a monocline (Fig. 363, A), or in the limb of an upright anticline or syncline (Fig. 363, B), or in the limb of an overturned fold (Fig. 363, C). To determine which interpretation is correct, the

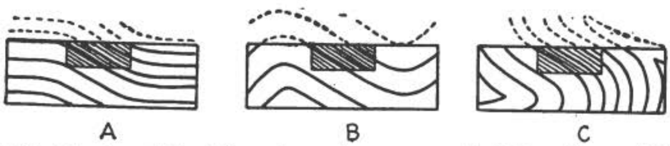


FIG. 363.—Structures inferred from observations on monoclinal dip. The small closely ruled rectangle in each diagram corresponds to Fig. 362.

country must be more extensively investigated across the strike and beyond the limits of the original area. In Fig. 363, C, the strata are overturned, a fact which may perhaps be ascertained by such criteria as have been cited in Art. **151**.

2. *The conditions are similar to those of case* 1, *but beds are repeated in inverse order as seen in a cross-strike traverse.* The

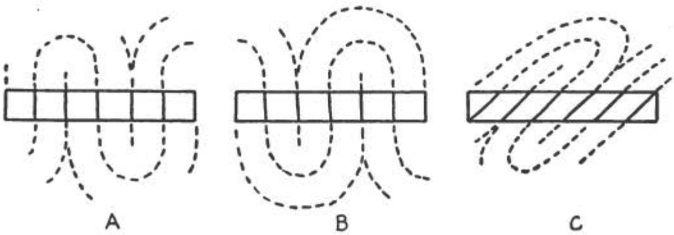


FIG. 364.—Structures inferred from observations on beds which have monoclinal dip and which outcrop alternately in normal and reversed order.

strata have been duplicated once or several times by isoclinal folding (Fig. 364). Obviously, correct interpretation of this kind of structure requires search for the top and bottom of individual strata (**151**) and for stratigraphic sequence (**98**).

——**B. Observations on Dips of Varying Amount and Direction.**—1. *A bed, which is surely identifiable, is exposed in two* *localities where the strikes are alike and the dips, though equal, are in opposite directions.* There are two possibilities: if the dips converge downward, the outcropping stratum is probably continuous underground as a syncline (Fig. 365, A), and if the dips diverge downward, the bed once extended above the ground as an anticline from which erosion has removed the crest (Fig. 365, B). Both folds are symmetrical and the axis is midway between the

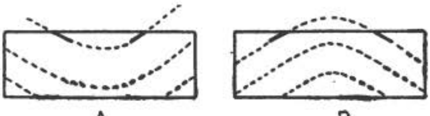


FIG. 365.—Structures inferred from observations on dip. The short black lines indicate the dips as plotted at two outcrops.

outcrops. This rule for converging and diverging equal dips is applicable to all folds except fanfolds. Observe that it is customary to draw the crests and troughs of folds *rounded* unless there is evidence to the contrary.

2. *In two localities two different strata are exposed, one* (*a*) *being older than the other* (*b*). *Dips are about equal in value and are in opposite directions.* As far as any observations reveal, the

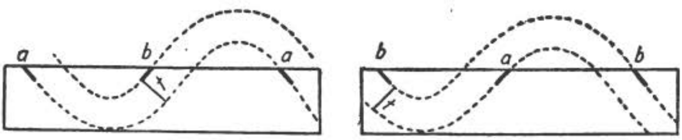


FIG. 366.—Structures inferred from observations on dips recorded at outcrops labelled *a* and *b*.

folding is symmetrical. The dips suggest a syncline on the left and an anticline on the right, in both A and B, Fig. 366. The axis is nearer the younger exposed bed (*b*) in synclines and nearer the older bed (*a*) in anticlines. In order most accurately to determine the position of the axis, the thickness, *t*, of the concealed beds stratigraphically between *a* and *b* should be computed (**353**).

3. *As in case* 1, *under B, above, the same stratum outcrops in two localities, but here the dips are unequal and opposite and one of them is vertical.* The fold is asymmetrical, the axial plane being inclined, and the axis is nearer the steeper limb (Fig. 367). The axis should be placed so that the perpendicular distances (t) from it to the given bed in each of the two limbs are approximately

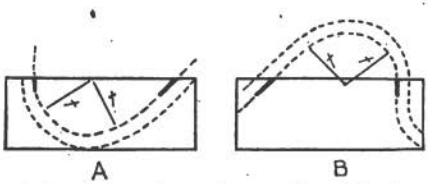


FIG. 367.—Structures inferred from observations on dip. The short black lines indicate the dips as plotted at two outcrops.

equal, unless there is good evidence for actual inequality. As will be explained presently, not all instances of unequal dips are to be attributed to asymmetrical folding (see **C**, below).

4. *The same bed outcrops in two localities, and the dips are unequal and in the same direction.* Great care should be exercised in searching for criteria for overturning in the more steeply dipping rocks (**151**). If proof of overturning is forthcoming, the folds are overturned or recumbent according to the attitude

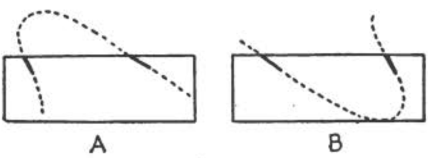


FIG. 368.—Structures inferred from observations on dip. The short black lines indicate the dips as plotted at two outcrops.

of the axial plane, and the axis is nearer the steeper limb (Fig. 368); but if the steeper beds have not been turned beyond 90°, the structure must be that described in **C, 1**.

5. *If available exposures are not of the same bed, but otherwise the conditions are such as were stated in* 3 *and* 4, *above*, the folding may be asymmetrical (see, however, **C**). As in **B, 2**, the thick-

ness, t, of the concealed beds stratigraphically between a and b should be ascertained if possible (**353**). Study the diagrams carefully (Fig. 369).

6. *A succession of strata is exposed, all inclined in the same direction, but with some variation in the angle of dip.* This is a phenomenon of frequent occurrence, chiefly because beds are not

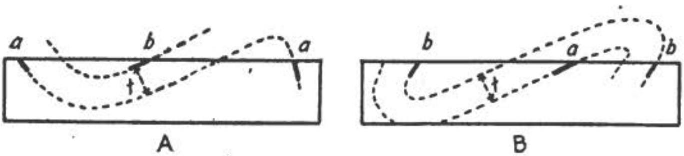


FIG. 369.—Structures inferred from observations on dips recorded at the outcrops labelled a and b.

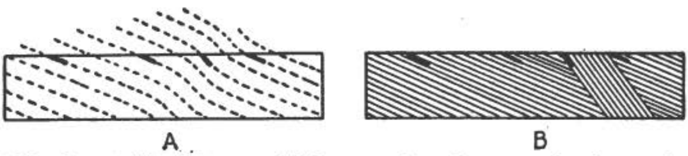


FIG. 370.—Correct (A) and incorrect (B) interpretations of structures based upon observations on varying dips.

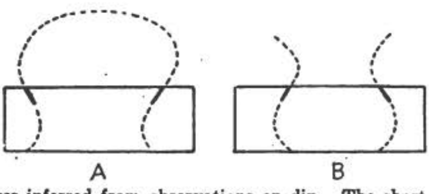


FIG. 371.—Structures inferred from observations on dip. The short black lines indicate the dips as plotted at two outcrops.

likely to undergo exactly the same amount of tilting when subjected to the complex forces of deformation. In this case, unless there is conclusive evidence to the contrary, the beds should be drawn as in Fig. 370, A. A mistake too commonly made by beginners is illustrated in Fig. 370, B, where a curious anomalous structure is given for the interpretation of the dip relations.

7. *The same bed is exposed in two localities. Dips are opposite*

and equal or unequal. The strata are found to be overturned in both localities. The structure is that of a fanfold (Fig. 371).

——**C. Studies Across Axial Regions.**—The student will notice that all the diagrams used for this article are of parallel folding. This is because the major folds in a set of deformed strata are much more apt to be parallel than similar, for similar

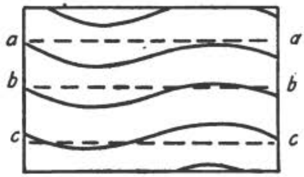


Fig. 372.—Relations of erosion levels (*aa,bb,cc*) to folded strata where deformation has been moderate.

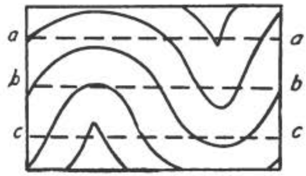


Fig. 373.—Relations of erosion levels (*aa,bb,cc*) to folded strata where deformation has been greater than that shown in Fig. 372.

folding is produced only under extreme compression (**143**). Figs. 364 and 369 would perhaps be more natural if the folds in them were made on the similar pattern. Let us assume, now, that we are dealing only with folds of the parallel type. If the dips on the limbs are moderate, the structure may be like that sketched in Fig. 372, and, on an erosion surface cut down to any level (*aa, bb, cc*), outcrops in the axial region will show low dips or no dip in vertical sections perpendicular to the axis. On the other hand, if the compression has been more intense and the dips on the limbs are relatively steep, synclines will be pinched, or *carinate*, in the upper part of the folded series and anticlines will be carinate in the lower part of the series, whether the axial planes are upright or inclined (Fig. 373).

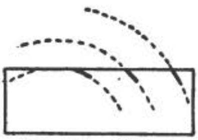


Fig. 374.—Variations in dip (short black lines) due to position of outcrops in a fold.

If agents of erosion cut down to a level, *aa*, outcrops will expose the lowest dips in anticlinal axial regions and the steepest dips in synclinal axial regions. If the land surface has reached a level, *bb*, the steepest dips will be on the limbs, and the lowest dips will be in both synclinal and anticlinal axial regions. And, if erosion has cut down to level *cc*, the steepest dips will be in the anticlinal axial regions and the lowest dips in the synclinal axial regions. In any of these cases the dips recorded on a cross-strike traverse may look like Fig. 374 when they are plotted, but as brought out by the dotted lines, this divergence of dip does not signify actual upward fanning of the strata. The stratification planes may still be parallel.

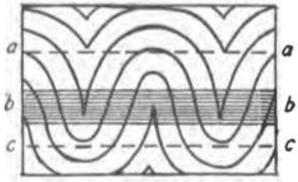


FIG. 375.—Relations of erosion levels (*aa*,*bb*,*cc*) to folded strata where deformation has been more intense than that shown in Fig. 373.

When the folds are even closer, the carinate crests of the anticlines may overlap the carinate troughs of the synclines (Fig. 375). Then, although erosion surfaces at *aa* and *cc* will be the same as in Fig. 373, at any erosion level in the middle belt, *bb*, both anticlines and synclines will be pinched. With the extremely close compression of isoclinal folding there may be no overlap of the carinate axial parts of the folds (Fig. 364).

331. Sections Across Igneous Bodies.—If a dike is to be the principal feature in a section, the latter is drawn perpendicular to the strike of the dike. More commonly, dikes are incidental phenomena in a section of a sedimentary formation or of a larger igneous body, and in this event they may lie in various positions with respect to the trend of the section. Corrections for their inclinations, as represented in the sections, may then be necessary (see Appendix X). Sills are treated like strata. A section through a laccolith or a chonolith is made preferably in the plane of the dip of the basal contact. A section across a rock complex, such as is seen in the case of many of the larger intrusive bodies (batholiths, etc.) and their associated country rocks, may be oriented so that it will cut certain rocks, but generally without fixed relations to their boundaries.

As a rule one may safely infer that the nature of an igneous contact, as, indeed, of any other geologic contacts, is similar in all directions, *i.e.*, that the features to be shown in its section are probably like those exposed in its horizontal, or nearly horizontal, outcrop. Hence, the details observed on rock exposures of contacts may often be drawn in the same general manner, whether on a map or in a vertical section (cf. the different sections shown in Figs. 74 and 77).

332. Vertical Sections of Faults.—A section across a fault should be made as nearly as possible at right angles to the strike of the fault. For a dip-slip fault such a section gives the actual displacement; for all others, any displacement in the diagram is a rectangular component of the net slip. If the section is not perpendicular to the fault strike, the inclination of the fault must be corrected (see Appendix X).

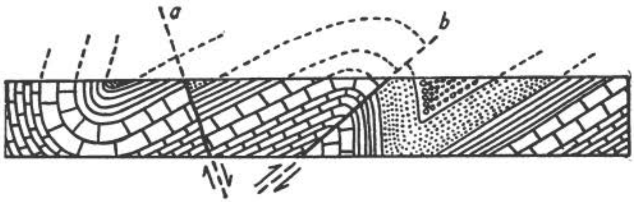


FIG. 376.—Method of representing faults and faulted structures in a geologic section.

In a geologic section a fault is represented by a heavy line, full within the base section and dotted (or dashed) above and below the base section (Fig. 376). On each side of the line, preferably just outside of the base section, a small arrow should be drawn to show the *relative* direction of displacement of the blocks. The structures (bedding, igneous contacts, etc.) in the fault blocks, if indicated above the base section, should be drawn in dotted lines to the positions which they are imagined to have had against the dotted (or dashed) part of the fault line, *after faulting, but before erosion cut them down* to the present level of the land surface (Fig. 376) (Cf. Arts. **164** and **338**).

The construction of difficult fault problems may be simplified by sketching on scrap paper a section of the rocks before the displacement, cutting the paper along the line of the fault, and shifting the pieces along this cut until the rocks and structures are in their present relations.

333. Requisite Data for a Completed Geologic Section.—No geologic section of existing structures is complete which is not accompanied by a legend, vertical and horizontal scales, and some indication of its direction. With reference to scales, see Art. **273.** The direction of a section may be shown by labelling its ends with the proper points of the compass, or by stating that it is drawn looking in such and such a direction, or by labelling its ends by letters or numbers which are also placed at the corresponding ends of its line of section on the map. A common error of beginners is to mark the top and bottom of a section by points of the compass, an impossible condition since all sections are vertical and all compass directions are horizontal.

Structure Contour Maps

334. Nature of Structure Contour Maps.—Most geologic sections of stratified rocks are far from being accurate in the information which they convey of the thickness and depth of the individual layers. They are usually diagrammatic inferences based on such scattered facts as can be assembled from the observation of outcrops and, much less frequently, from drill and mine records. When such sources of information are especially abundant and reliable, the folds may be indicated by structure contour maps better than by geologic sections. A *structure contour map* (Fig. 377), like a topographic contour map, depicts the configuration of a surface by lines of equal elevation, generally referred to mean sea level as the datum plane. These lines are the intersections of the surface with a series of equally spaced horizontal planes, the vertical distance between any two adjacent planes being known as the contour interval. For a structure contour map the surface chosen is that of the top or bottom of some bed which is easily recognized, is persistent over large areas, has not suffered much erosion, and is not too far below the land surface. The elevation of this *key horizon*, as it is called, above mean sea level is obtained in the field at as many points as possible, both at actual outcrops and from the records of drill holes, and

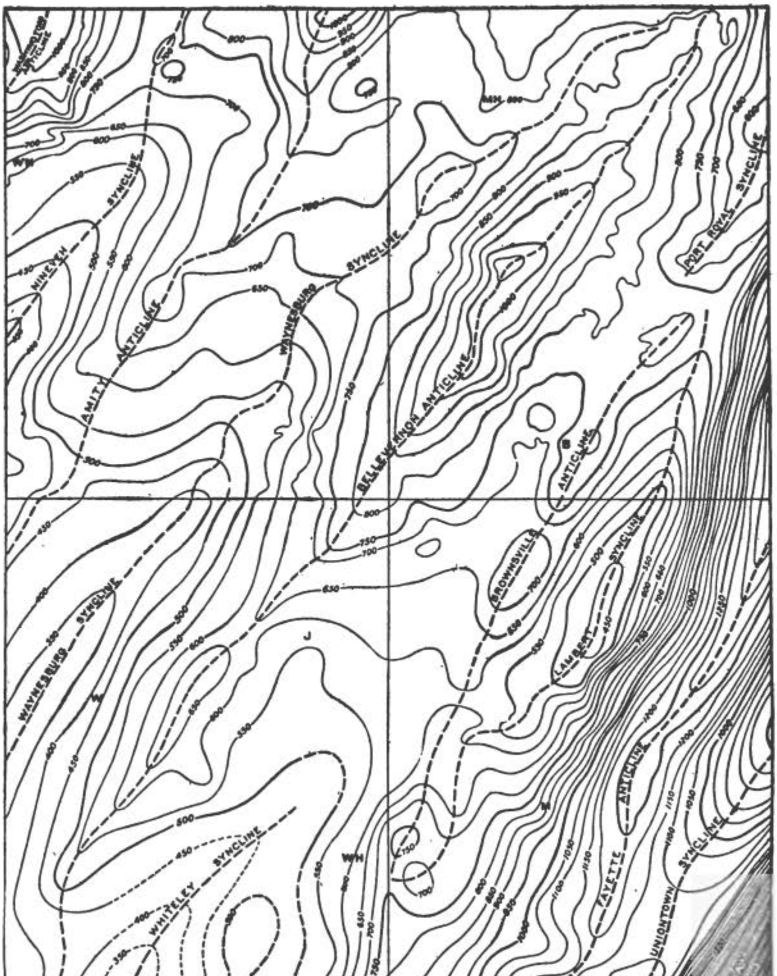


Fig. 377.—Structure contour map of the Amity, Brownsville, Waynesburg, and Masontown quadrangles, Penn. Axes of folds are indicated by dashed lines. The contours are lines of equal elevation of the base of the Pittsburgh coal bed above mean sea level. Contour interval, 50 ft. (After F. G. Clapp.)

the data are plotted at the several stations on a base map. Sometimes it is necessary to secure these elevations by adding to or subtracting from the elevations of outcrops of other known beds, but this method is liable to error on account of the possible variations in thickness of the intervening strata. By drawing lines a contour interval apart, each line connecting points of the same elevation, the contour map of the key horizon is produced.

As regards the accuracy of these maps, the steeper the dip of the strata and the less reliable and less numerous the available data, the greater is the chance for mistake in placing the structure contours. There are often places where generalization is a necessity, simply because the facts are too few. The contour interval is selected with a value such that it is not less than the "limit of error" for the district. "For example, if over a given area the elevation of" the key horizon "was determined to an accuracy of within 50 ft., it would be useless to attempt to draw contours with a 25-ft. interval. Moreover, such a representation would be misleading to the reader, who would be led to believe that the elevation at any given point was accurate within 25 ft., which would not be the case."

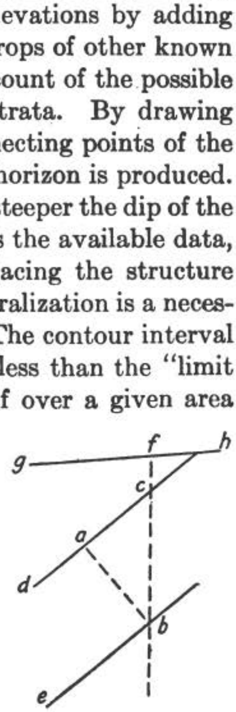


Fig. 378.—Vertical section to illustrate the method of computing the depth of a horizon below the key horizon of a structure contour map.

The intersection of a structure contour with a topographic contour of the same elevation marks a point on the outcrop of the key horizon. Where the land surface is higher than the key horizon, the approximate depth of the latter below the ground surface may be found by subtracting the elevation of the structure contour from that of the topographic contour at that place. When the land is lower than the key horizon, the latter has been eroded away and the structure contours indicate its probable former position. In this case they would better be dotted.

If one wants to ascertain the depth of some horizon other than

[1] Bibliog., Clapp, F. G., pp. 37–38.

that chosen for the "key," one must first know the thickness of the beds between the two horizons. Thus, in Fig. 378, *dc* is the key horizon, parallel to the bedding, *c* is a point of which the depth, *fc*, below the surface of the ground, *gfh*, may be determined on the structure contour map, and *b* is a point vertically below *c* in a horizon, *eb*, with a thickness of intervening beds equal to *ab*. The required quantity, *cb*, can be obtained by solution of the right triangle *abc*, in which *ab* and the angle *acb* are known.

Block Diagrams

335. Definitions.—One of the most successful methods of geologic illustration, both for popular and for scientific demonstration, is the so-called *block diagram*. In brief this is a view of an imaginary rectangular block of the earth's crust. It is as if upon a rectangular block of wood, let us say, two geologic sections had been drawn on two adjoining sides and a map on the top face, and then the block itself had been sketched in a position such that these three faces were visible to the eye (Fig. 77). Frequently the top surface is drawn as if it were a model of the topography, with all the hills and valleys (Figs. 132, 158, 251, 299, etc.). There are, then, two varieties of block diagram. For easy reference the term, *map block*, will be used for the kind with a flat top, and the term, *relief block*, for the kind that shows the topography. The first brings out the relations of geologic structures in normal planes, and the second, the relations between geologic structure and topography. Relief blocks are best constructed in perspective, but map blocks may be made in isometric or cabinet projection or in perspective (**336**). Like geologic sections and maps, a block diagram represents the geology by different lines and patterns, less often by colors, and consequently it must have a legend.

336. Construction of Block Diagrams.—Before the geology can be depicted on a block diagram, the outlines of the block itself must be drawn. This may be done in isometric projection, in cabinet projection, or in perspective. Fig. 379, A, illustrates the isometric projection, and Fig. 379, B, the cabinet projection, of the same rectangular parallelepiped. In each case lines parallel in the block are drawn parallel, vertical lines are drawn vertical, and equal lines (those with the same letter in Fig. 379) are equal in the diagram. In Fig. 379, A, the angles marked x are each of them 120°, and measurements along any of the lines of the diagram are on the same scale. In Fig. 379, B, angle $x = 45°$ and angle $y = 90°$; measurements parallel to a and c are equal, but

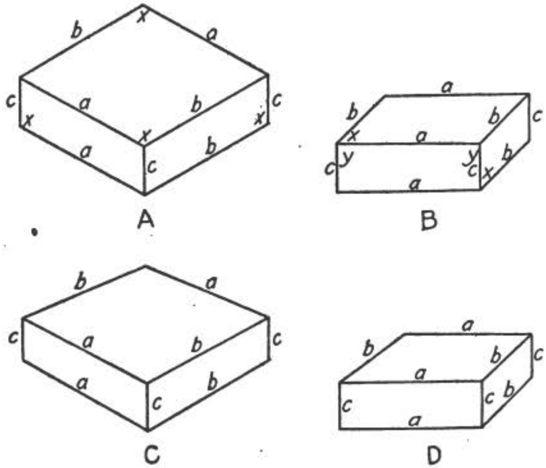


FIG. 379.—A rectangular block drawn in isometric projection (A), cabinet projection (B), angular perspective (C), and parallel perspective (D).

parallel to b the scale is one-half its value parallel to a and c; that is, if an inch or a foot or a mile is measured off as an inch along a and c, the same distance is represented by ½ in. parallel to b. In both isometric and cabinet projections, then, measurements of length can easily be made in directions parallel to the edges of the block.

On the other hand, in a perspective sketch of a rectangular parallelepiped, equal parallel lines are seldom equal or parallel in the figure. Vertical lines are drawn vertical, but horizontal parallel lines generally converge toward the background in such a way that, when produced, they will all meet in a single point, and the several points in which different sets of horizontal lines meet are all on the same straight line, the *horizon line* (*ab* in Figs. 380, 381). If all sets of horizontal lines in the object meet in the horizon line, the perspective is angular (Figs. 379, C, and 380), but if one set of horizontal lines in the object is drawn in

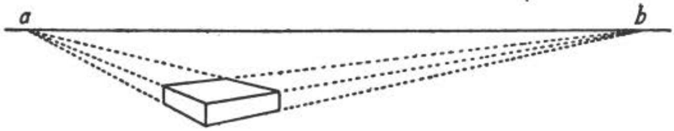


FIG. 380.—Block drawn in angular perspective, showing its relation to the horizon line (*ab*).

the plane of the picture, the perspective is parallel (Figs. 379, D, and 381). Parallel perspective differs from cabinet projection in that the edges marked *b* in D and B, Fig. 379, are parallel in the latter, but converge to a point on the horizon line in the former. Parallel perspective involves a certain amount of dis-

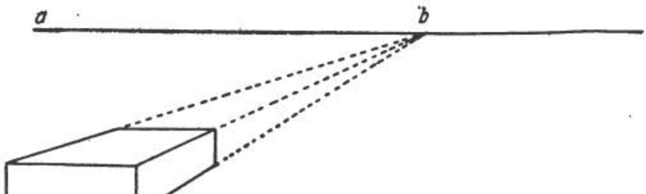


FIG. 381.—Block drawn in parallel perspective, showing its relation to the horizon line (*ab*).

tortion, as may be seen in Fig. 379, D, for if a rectangular block were looked at perpendicular to one of its faces its other sides would not be visible.

Measurements can be made on a block diagram in parallel perspective, but with very much less facility than in cabinet and isometric projections. Let us suppose that, in Fig. 382, *ljkmnop* represents a rectangular block which is 3 ft. thick and 5 ft. square on its top. The construction of this part of the figure may be stated briefly as follows: *abcd* is the square top (or bottom) of the block as viewed from above, drawn to the scale of 1/6 in. = 1 ft. Choose a point, *g*, for the "view point." Produce *dc* a certain distance to the right to *c′*. Draw *ag* and *bg*.

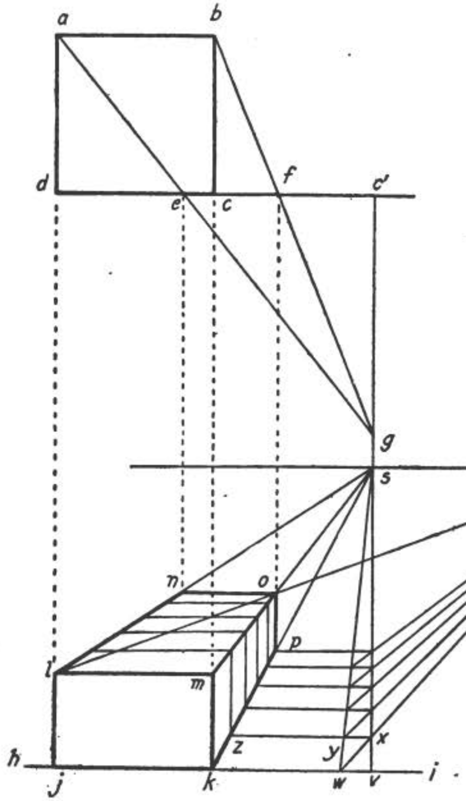


FIG. 382.—Construction used for measurements on a block drawn in parallel perspective.

ag intersects *dc′* at *e*, and *bg* intersects *dc′* at *f*. Next draw *hi* parallel to *dc′* and at a convenient distance below *dc′*. Drop perpendiculars to *hi* from *d* and *c*, meeting *hi* in *j* and *k*, respectively. Mark off *lj* and *mk*, each 3/6 in. long. Draw *lm*.

Then *lmkj* represents the front face of the block constructed on the chosen scale. Through *g* draw a line, *c'v*, perpendicular to *dc'* and *hi*. On this line select a point, *s*, at a convenient distance above *hi*. From *l*, *m*, and *k*, draw lines to *s*. From *e* and *f* draw lines perpendicular to *hi*, intersecting *ls*, *ms*, and *ks*, in *n*, *o*, and *p*, respectively. Draw *no* and *op*. Then *noml* is the top, and *mopk* is the side, of the block, both seen in perspective.

Now, the reader will notice that although, in the block, $jk = lm = no$, and $ln = mo = kp$, and $lj = mk = op$, this is not true in the diagram. Evidently the same scale can not be used for all edges. The front face is here made with both horizontal and vertical scales the same, *i.e.*, 1/6 in. = 1 ft. Because of foreshortening, 1 ft. must be represented by less than 1/6 in. on edges *no* and *op*. To obtain the scale for these two edges, divide *no* into five equal parts and *op* into three equal parts. The divisions of *no* and *op* are equal.

As for edges *ln*, *mo*, and *kp*, each consists of five parts, and each part represents 1 ft. in the block, but in the figure these parts are necessarily smaller toward the background. They are obtained thus: Referring to Fig. 382 again, draw through *s* a line, *su*, parallel to *hi*, and through *l* and *o* draw a line intersecting *su* at *t*. From *v*, on *hi*, mark off a distance, *vw*, equal to 1/6 in. (the unit of the scale) toward *k*, and draw *ws* and *wt*. *wt* intersects *sv* at *x*. From *x* draw a line parallel to *hi* and meeting *kp* in *z*. *kz* represents 1 ft. *xz* intersects *ws* at *y*. Draw *yt*. From the point of intersection of *yt* and *sv* draw a line parallel to *hi* until it meets *kp*. Proceed in this manner until *kp* has been divided into five unequal spaces, each representing a length of 1 ft. in the original block. The divisions of *mo* may be obtained by erecting perpendiculars to *hi* through the points fixed on *kp*, and the divisions of *ln* may be obtained by lines drawn parallel to *hi* from the points on *mo*.

With regard to the advantages and disadvantages of these methods of illustration, perspective drawing looks more natural than either kind of projection, but it greatly increases the difficulty of measuring distances. Therefore, cabinet or isometric projection should be employed when the block diagram is intended to facilitate computations (see Figures in Chapter XVII). Of the two, cabinet is preferable to isometric projection. For geologic illustration parallel perspective has a distinct advantage over angular perspective since it shows the structures in their true relations on at least one face, the front one.

Having completed the outline of the block, the next thing to do is to decide upon its orientation, or, rather, the orientation of the geology to be indicated upon it. A good rule to follow is, let the front of the block be perpendicular or parallel to some important structure. Thus, it is well to make the front face normal to the axis of a fold or normal to the strike of a fault, bed, or dike, on any of which measurements are to be computed.

When you have determined the orientation of the block, you are ready for the third stage. This consists of sketching in the geology and, on a relief block, the topography. The sides or vertical faces of the block are filled in first, and then the top surface. For any block in cabinet projection or in parallel perspective, complete the front face, which is parallel to the plane of the paper, exactly as you would a geologic section. If the finished diagram is to be a map block, this front face is treated as a rectangular base (**327**); if a relief block, it is treated as a profile base (**328**).

In any block diagram, for sides not parallel to the plane of the paper begin by making a preliminary true geologic section on a rectangular base or on a profile base according as the figure is to be a map block or a relief block, respectively. Do not complete this preliminary section; merely carry it far enough to get the locations of important points, and then transfer these points to their correct places on the side of the block diagram. In transferring, remember the rules for measurement in cabinet and isometric projection and in parallel perspective. When the geologist has become proficient in making block diagrams, he seldom needs to construct these preliminary sections unless great accuracy is requisite. He is able to draw the geologic structure directly on the sides of the block in spite of the distortion of projection or perspective.

After the sides of the diagram are finished, the positions of structures and boundaries on its top surface may be obtained from points in the upper edges of the side faces. If it is a map block, this is fairly easy; but if it is a relief block, the topography is difficult to sketch properly. Indeed, good execution requires a true sense of proportions.

337. Requisite Data for a Completed Block Diagram.—A block diagram should have a legend arranged in the same way as for geologic maps and sections. The directions of the block's upper edges must be indicated. This may be done either by lettering the front corners with the appropriate compass points, or, if an edge lies in a north-south position, by drawing an arrow, pointing north, parallel to this edge (Fig. 123). Isometric and cabinet projections should be accompanied by the adopted scales. For blocks in parallel perspective the scale for the front face should be indicated. A general idea of the horizontal scale in perspective may be given by labelling various known localities, such as lakes, towns, hills, etc., on the upper surface.

Serial Diagrams

338. Use and Character.—Geologic sections, maps, or block diagrams are sometimes prepared in series to show the successive stages in the development of a structure or in the geologic history of a region (see Figs. 106, 189, 190). Serial diagrams of this sort are especially useful for illustrating faulting. For example, a rock mass is represented in the first figure before faulting; in the second, after the displacement, but before erosion has reduced the upthrown block; and in the third, after erosion has brought the region to its present aspect. In each of Figs. 160–170, the second and third stages are drawn, but the first is omitted. This method is, of course, quite unnatural since, under ordinary circumstances, denudation more nearly keeps pace with faulting (**164**).

Drill Diagrams and Columnar Sections

339. Definitions and Description.—When a hole is drilled into the ground, a record of the rocks penetrated is usually kept. It

System	Series	Formation	Symbol	Columnar Section	Thickness in Feet	Character and Distribution
Quaternary		Bolson deposits	Qb		700+	Gravel, sand and clay in Salt Flat. Unconsolidated impure gypsum at the surface in lowest part of basin.
		UNCONFORMITY				
Cretaceous	Lower Cretaceous	Comanche series	Kc		400±	Buff sandstone, with subordinate amount of conglomerate, shale, and limestone. Caps the hills 6 miles west of Van Horn and in the vicinity of Plateau station.
		UNCONFORMITY				
Carboniferous	Permian	Rustler limestone	Cr		200±	Fine-grained gray to whitish magnesian limestone in faulted area in eastern part of quadrangle.
		Castile gypsum	Cc		275±	Massive-bedded gypsum in faulted area in eastern part of quadrangle.
		UNCONFORMITY				
		Delaware Mountain formation	Cd		2000+	Interbedded gray limestone and buff sandstone in Delaware Mountains; massive white and gray limestone member in Apache Mountains.
		SECUENCE CONCEALED		SEQUENCE CONCEALED		
	Pennsylvanian	Hueco limestone	Ch		2500+	Massive gray limestone with basal conglomerate. In Sierra, Diablo, Baylor, Beach, Wylie, and Carrizo Mountains.

Fig. 383.—Example of a columnar section. (Van Horn Folio, No. 194, U.S.G.S., 1914). The rocks listed in the column are found in the region mapped for the folio.

may be prepared graphically by showing the different rocks in a vertical rectangular strip, each rock being allowed a space the height of which is proportional to the length occupied by this rock in the drill core. This height and the name of the rock are marked beside it in the column. If beds are horizontal and a drill hole cuts them vertically, the length of any rock strip in the core is the thickness of the bed from which it came; but if a vertical hole passes through inclined layers, the drill record does not give thicknesses. These can be calculated from the record if the dip is known (see Appendix IX).

A *columnar section* or *geologic column* may look very much like a graphic drill diagram. It is made in the same way (Fig. 383), but the height of each bed in the column always represents thickness. If the strata are inclined, the thickness of each member must be computed for the columnar section (Art. **353**). As illustrated in Fig. 383, geologic columns are not drawn to an exact scale because they show formations which vary in thickness from place to place.

Plans, Sketches, and Photographs

340. Requisite Data for Plans, Sketches, and Photographs.— Every plan, sketch, and photograph, which illustrates geologic phenomena should be accompanied by a scale and compass directions. The latter are most readily noted by stating the direction in which the observer was looking in making the picture. Scale, in photographs, is often given by including within the view a ruler, hammer, or some other article of known dimensions. Plans and sketches may be treated like maps and sections. Locality should also be mentioned, and if any conventional signs are employed these are to be tabulated in a legend.

CHAPTER XVI

INTERPRETATION OF GEOLOGIC MAPS

341. Significant Features on Geologic Maps.—From an examination of a geologic map a great deal may often be learned of the geologic structure, provided the topography is shown by contours. In general three things must be considered, namely, the contours, the outcrop areas marked with different colors or patterns to represent different rocks, and the boundary lines between these areas. Contours have been discussed in Chapter XIII. Outcrop areas and boundary lines will be treated in the following paragraphs.

342. Outcrop Areas.—For the interpretation of a geologic map one should begin by ascertaining the meaning of the colors or patterns of the different outcrop areas. From the legend one should find out which colors or patterns are for igneous rocks, which for sedimentary rocks, and which for metamorphic rocks, and wherever the map shows that two rock bodies are in contact, their relative ages should be determined, also from the legend. For this purpose the geologic time scale must be known (Appendix I). The forms of the outcrop areas, being consequent upon the trends of the inclosing lines, may be described under the head of boundaries.

343. Boundaries of Outcrop Areas. Geologic boundary lines on maps represent the exposed edges of contacts, such as surfaces between conformable strata, surfaces of unconformity, igneous contacts, and faults. Rules pertaining to the nature of these lines, as controlled by topography, have been stated in Arts. **159** and **317.** In the present connection the rules may be reversed: (1) if the outcrop of a surface does not cross contours, the surface is horizontal (Fig. 344); (2) if this outcrop line is straight and has no fixed relation to the contours, the surface is vertical (Fig. 345); (3) if the outcrop line has a sinuous course and intersects the contours, the surface is inclined. In the latter case the line has elbow-like bends which point down the dip in the valleys (Figs. 346, 347), unless the inclination of the given surface is in the same direction as, but is less than, the slope of the valley floor (Fig. 348). The longer and more acute the bends are, the lower is the dip of the inclined surface. These statements are based on the assumption that the given surface is essentially flat. If it is undulating or otherwise irregular its outcrop is likewise irregular, but with a little experience one can distinguish the disorderly bends and angles of a line of this sort from the more uniform curves due to the topographic intersection of a flat surface.

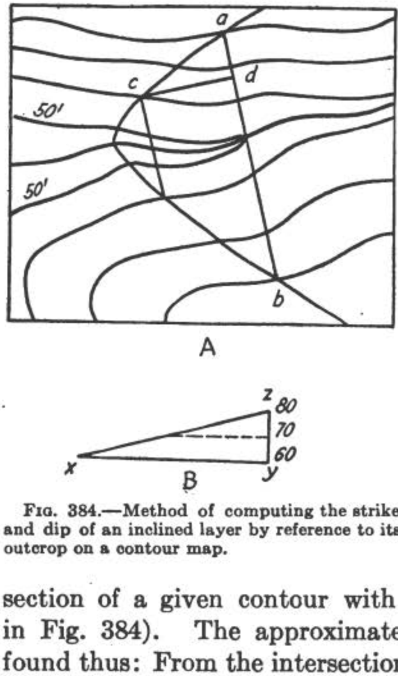


Fig. 384.—Method of computing the strike and dip of an inclined layer by reference to its outcrop on a contour map.

The strike of an inclined flat surface may be obtained by drawing a straight line between two points of intersection of a given contour with the outcrop of the surface (*ab* in Fig. 384). The approximate dip of such a surface may be found thus: From the intersection, *c* (Fig. 384, A), of the outcrop of the surface with any contour except that containing points *a* and *b*, draw a line, *cd*, perpendicular to *ab*. In Fig. 384, A, the second contour below *a* is used. Lay off a horizontal line, *xy* (Fig. 384, B) equal to 2*cd*[1] and at the end for the higher contour (*y*, corresponding to *d* in Fig. 384, A) erect *yz* perpendicular to *xy*, making the length of *yz* equal to twice the contour

[1] For convenience, here, Fig. 384, B, is enlarged twice.

interval. These lines, *xy* and *yz*, must be drawn to natural scale. Complete the right triangle *xyz*. Angle *zxy* will then be the dip of the inclined surface, and this angle may be calculated since *xy* can be measured on the map and *zy* is known. It is hardly necessary to remark that accuracy in the result depends not only upon the flatness of the surface, but also upon the care with which the map was made.

344. Strike Symbols.—On outcrop maps of folded strata the general trend of the strikes may give one an idea of the structure. Three varieties of strike arrangement are noted below. If several possible interpretations are mentioned, the correct one can be determined by a knowledge of the dip directions at the several outcrops.

1. Strikes are straight and parallel. The folding may be monoclinal, synclinal, or anticlinal. If anticlinal or synclinal, the fold axes are horizontal (Fig. 356, A, B, C).

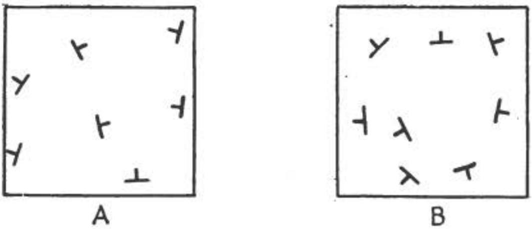


Fig. 385.—Strike and dip symbols on outcrop maps, indicating pitching folds in A and a dome fold in B.

2. Strikes converge alternately, first in one direction and then in the opposite direction, and at the angles of convergence they swing round sharply or broadly (Fig. 385, A). The structure consists of pitching anticlines and synclines.

3. Strikes run round in a complete curve which may be rudely circular or oval. The structure is a dome fold (Fig. 385, B) or a basin fold.

345. Conformable Strata.—Unless the dip of a stratified series exactly coincides with the slope of the ground—an exceedingly rare condition—the beds are exposed in belts. The two edges of any belt on the map are the outcrops of the upper and lower surfaces of a stratum, and for each belt these lines, in their relations to the contours, conform with the rules given in Art. **343**. When the top and bottom surfaces of a given bed are approximately parallel, as they often are, the trend of the outcrop belt as a whole is naturally governed by these same rules. The breadth of the belt varies according to the dip of the stratum and the slope of the land (**158**). To facilitate the interpretation of geologic maps of conformable strata, the following key is given.

Key for the Interpretation of Maps of Conformable Strata

1. The color or pattern used on the map indicates that only one stratum outcrops over a broad area.
   a. The topographic relief is low and the land surface is essentially horizontal.
      The beds are probably horizontal.
   b. The relief is low and the land surface as a whole has a definite slope.
      The beds dip with the surface of the ground.
   c. There is considerable relief.
      The exposed stratum is essentially horizontal and is at least as thick as the measure of the relief (Fig. 386).

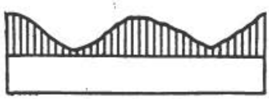


Fig. 386.—Profile section showing the relation between the thickness of a stratum (lined) and the topographic relief.

2. Different strata outcrop in relatively straight, parallel belts.
   A. The beds are exposed in regular sequence across the strike.
      a. The land surface is a nearly flat, horizontal plain.
         The beds are inclined or vertical.
      b. The land surface is a nearly even plain which has a definite inclination.
         The beds are horizontal, inclined, or vertical. If they are inclined, their dip is not parallel to the slope of the ground.
      c. The relief is marked and may be rugged (Fig. 387). In case the topography consists of parallel ridges and valleys, the outcrop belts show no deviation in transverse valleys that may interrupt the continuity of the ridges.
         The strata are vertical.
      d. The relief is marked and the topography consists of parallel ridges and valleys. In transverse valleys the outcrop belts make sharp elbow-like bends.
         The beds are inclined (Cf. Art. **343**).

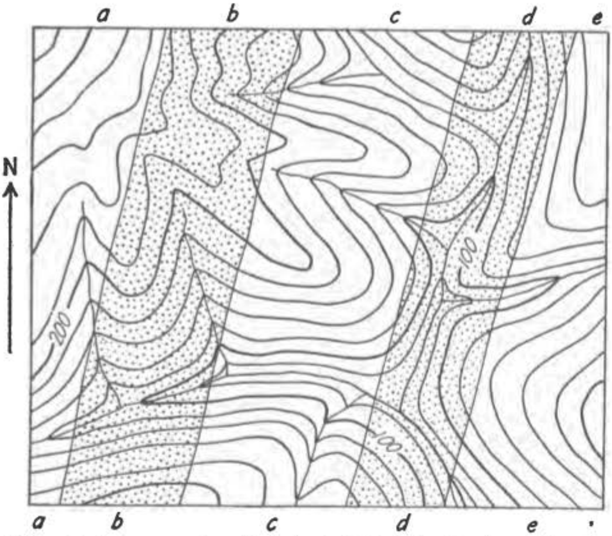


FIG. 387.—Geologic map of vertical strata (*a,b,c,d,e*). Contour interval, 20 ft.

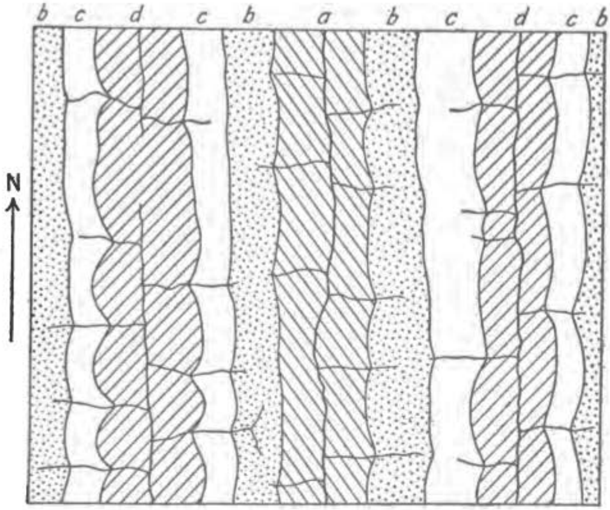


FIG. 388.—Geologic map of folded strata (*a,b,c,d*). *a* outcrops in an anticline, and *d* in synclines. Which is the oldest bed shown? the youngest bed? Note how the contacts between strata bend in the direction of the dip in the valleys (see streams). Contours not shown.

B. Across the strike the stratigraphic succession is alternately normal and then reversed. Thus, if the digits, 1, 2, 3, and 4, stand for the beds in the sequence of their deposition, the order of exposure may be, 1, 2, 3, 4, 4, 3, 2, 1, or it may be, 4, 3, 2, 1, 1, 2, 3, 4.

a. The relief may be low, or the topography may consist of parallel ridges and valleys which coincide pretty closely with the outcrop belts (Fig. 388).

The structure is anticlinal if older beds are flanked on both sides by younger beds, and it is synclinal if younger beds lie between older ones. Variations in the width of these belts may point (1) to symmetrical folds in which opposite limbs are exposed on a uniform slope or on slopes of different inclinations, or (2) to asymmetrical folds outcropping on a surface of low relief and of no or uniform inclination (**158**).

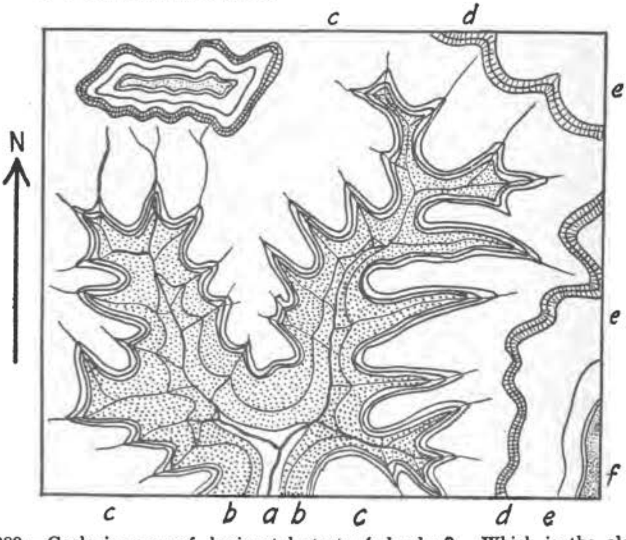


FIG. 389.—Geologic map of horizontal strata (*a,b,c,d,e,f*). Which is the oldest bed shown? which the youngest? In the northwest corner of the map is a mesa. Contour interval, 100 ft.

3. Different strata appear in sinuous or zigzag belts.

a. The relief is considerable. The boundaries between strata are roughly parallel to the contours, following these up valleys and thus giving a treelike, branching, or *dendritic* pattern to the rock distribution on the map (Fig. 389). When traced up the valleys, the belts are seen to make elbow-like turns which point upstream. Followed down the valleys, the same belts bend round projecting spurs of the uplands, here pointing down the slope.

The beds are horizontal or very nearly so.

b. The topography is strongly rolling or rugged. The boundaries between adjacent strata cross the contours. The turns of the belts are situated on the valley floors and on the upland spurs. In the valleys the bends are convex toward younger beds, and on the spurs, toward older beds, but whether on spurs or in valleys, the convexity may point up the slope or down the slope.

The beds are inclined. The turns in the belts are convex down the dip in the valleys and up the dip on the spurs, provided always that the dip is greater than the inclination of the ground (Cf. Fig. 388).

c. The relief may be low or considerable. In the latter case the hills are generally long ridges which trend parallel to the outcrop belts. The boundaries between adjacent strata are roughly parallel to the contours in the valleys which are parallel to the ridges (longitudinal valleys), but they cross the contours in the valleys that are transverse to the ridges (transverse valleys).

The strata are folded in pitching anticlines and synclines. Older beds outcrop between younger beds in anticlines; *vice versa* in synclines. In anticlines the bends are convex down the pitch; in synclines, up the pitch. At the sharp bends the ridges usually have a gentle slope in the direction of the pitch and a steep slope on the opposite side of the crest.

4. Different strata appear in roughly concentric closed belts.

a. The relief is considerable. The boundaries between strata are parallel to the contours. The closed belts appear only in isolated hills. Elsewhere on the map, in valleys and on spurs, the dendritic pattern prevails (Fig. 389).

The strata are nearly or quite horizontal (Cf. 3, *a*).

b. The relief is low or considerable. If the latter, the uplands are concentric ridges parallel to the outcrop belts. The boundaries between adjacent strata are about parallel to the contours in longitudinal valleys, but they cross the contours in transverse valleys.

The structure is that of a basin fold if the strata are successively older outward in all directions from the center of the curving belts and if the boundary lines bend inward in the transverse valleys; and the structure is that of a dome fold if the strata are successively younger outward and if the boundary lines bend outward in the transverse valleys.

5. An outcrop belt, whether continuous or interrupted, becomes gradually narrower and finally disappears.

This signifies that the bed represented by this belt has thinned out to an edge. Do not confuse this phenomenon with the narrowing of a belt which passes on to the face of a steep slope or a cliff, nor with the abrupt termination of an outcrop belt at a fault, an igneous contact, or a line of unconformity.

346. Igneous Rocks.—Since sills and flows are like strata in their field relations, they also look like strata on geologic maps. They may be distinguished by their colors or patterns by referring to the legend. Most of the cases cited for stratified rocks in the preceding article are applicable to eruptive sheets. Dikes, too, have their outcrop belts controlled by the topography in the same manner as sills, flows, and strata. They usually dip pretty steeply. They are readily distinguished by their cross-cutting relations to the adjacent rock bodies, and by reference to the legend.

Necks are comparatively small oval or circular areas, as indicated on maps, and it is not uncommon to see dikes radiating from them and also to find the remnants of flows somewhere in the neighborhood. Volcanic cones are recognized by the fact that they consist of pyroclastic débris or of lava (see legend) and, when fresh, they often have craters. Laccoliths appear as larger closed areas surrounded by sediments which have an outward dip if the intrusive body is essentially horizontal. If the laccolith is inclined, its outcrop may be lenticular. Exposures of batholiths are usually of still greater extent and of very irregular form. The edges of the map area of a batholith commonly truncate the outcrop belts of adjacent older sedimentary rocks. Isolated patches of these older rocks within the confines of the batholithic area are roof pendants or large inclusions (**128**), and isolated areas of the batholithic rock in the older sediments outside the main boundary are cupolas or pipes (Fig. 390) (see Art. **137**).

Fig. 390.—Geologic map of a batholithic rock (blank) and its country rock (lined). *p*, roof pendant or large inclusion; *c*, cupola.

347. Unconformities.—Unconformities are noted in their proper places in the legend. Of the types described in Arts. **71** and **72**, disconformity is the hardest to detect on geologic maps. Its presence is indicated in the legend by the fact that formations which should come between the disconformable strata are wanting. Angular unconformity between two groups of stratified rocks appears on a geologic map as a line, regular or irregular, against which abut the beds of one or both formations. Lines of unconformity of this sort may separate older bedrock from younger overlying surface deposits or lava sheets. Unconformity between an *intrusive* igneous rock and a body of any kind of igneous, sedimentary, or metamorphic rocks, may be mistaken for an intrusive contact. If the intrusive (A, Fig. 391) is older than the rocks on the other side of the doubtful line, this line (*no*, Fig. 391) is one of unconformity; but if the intrusive is younger, the line is an igneous contact. The relative ages can be obtained from the legend.

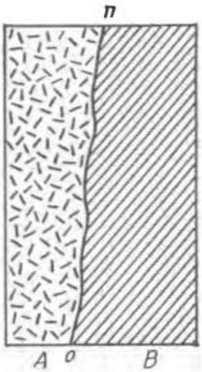


FIG. 391.—Geologic map of a regular contact (*no*) between an intrusive rock (*A*) and a body of sedimentary rocks (*B*). If *A* is younger than *B*, *A* is intrusive into *B* and *no* is an igneous contact; but if *A* is older than *B*, *B* was laid down unconformably on *A* and *no* is a line of unconformity.

Unconformities and faults can not be confused on a map because they are represented by lines of different weight (**315**).

348. Faults.—Before one can interpret the relations of a fault which is shown on a geologic map, one must secure all possible information on the characters, structures, and relative ages of the rocks in the two contiguous fault blocks. These facts are to be sought by aid of the statements made in Arts. **343** and **345–347.** The next step is to ascertain the attitude of the fault. For this, see Art. **343.** Ordinarily a fault with a low dip, and therefore a highly sinuous exposure where the relief is marked, is an overthrust (Fig. 392). In this case there may be associated isolated areas, each entirely inclosed within a fault line. Such an area is

FIG. 392.—Geologic map of a region where an overthrust fault is exposed. Older rocks, stippled; younger rocks, blank. All the boundaries between these two formations are fault lines. *a*, fault outlier; *b*, fault inlier. The main NE.—SW. fault line dips southeastward. How may this fact be ascertained from the map?

a *fault inlier* if the rocks within the closed fault line are younger than the rocks outside, and it is a *fault outlier* if the opposite condition holds (**188**) (Fig. 392).

Having determined the general attitude of a fault and the relations of the rocks on either side of it, we may proceed to classify it. If the fault is vertical, younger rocks are exposed at a given elevation near the fault line in the downthrown block. If the fault is inclined, younger rocks are exposed in the block toward which the fault dips in the case of a normal fault, and in the block away from which the fault dips in the case of a reverse fault. These statements refer to dip-slip and oblique-slip faults. Strike faults, dip faults, and diagonal faults which dislocate stratified rocks can be recognized at a glance.

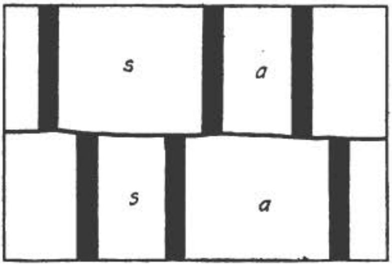


FIG. 393.—Geologic map of folded beds dislocated by a transverse dip fault. *s*, syncline; *a*, anticline.

With regard to offset, repetition and omission, the reader is referred to Arts. **169, 175, 177,** and **178,** where many of the rules laid down for the field interpretation of faults will be found to be applicable to the interpretation of mapped faults.

A word may be said of the appearance of faulted synclines and anticlines which have been truncated by erosion. The effect of dip faults and diagonal faults upon such folds is to increase the perpendicular distance between the outcropping edges of a stratum on opposite limbs of an open syncline (*s*, Fig. 393), and to decrease this distance in an open anticline (*a*, Fig. 393), always on the side of the downthrown block. From the map it is possible to tell which is the downthrown block if the nature of the folding is known, or, on the other hand, to ascertain the nature of the folding if the relative displacement is known.

CHAPTER XVII

GEOLOGIC COMPUTATIONS

COMPUTATIONS IN GENERAL

349. Measurements and Computations Previously Discussed.—Certain problems of measurement and construction have been discussed in the preceding chapters. The more important of these may be listed here for reference, as follows: distance, on the surface of the ground, between two points on a contour map (**279**); inclination of a slope (**280**); correction of a compass traverse (**309**); depth of a horizon below the "key horizon" on a structure contour map (**334**); dip and strike of an inclined surface as determined from the outcrop line of the surface on a contour map (**343**).

350. Application of Computations Explained in the Present Chapter.—In geologic computations it is sometimes necessary to ascertain the direction and angle of inclination of the intersection of two planes which are not parallel, or the position of the point of intersection of a line and a plane. The intersecting planes may be two faults, a fault and the contact between two conformable beds, a bedding surface and the wall of a dike, etc. Accuracy in the results requires that such surfaces be as nearly plane as possible and that the lines be essentially straight. The methods of solving these two problems are outlined in Arts. **351** and **352.** Computations for thickness (**353**) are applicable to any inclined layers of uniform, or nearly uniform, thickness, such as strata, dikes, sills, veins, etc. Variations in thickness introduce errors into the results. Computations for the depth of a point in an inclined surface (**354**) may refer to the top or bottom surface of a bed, dike, sill, or vein, or to a fault or any comparatively flat surface. Measurements of slip and shift (**355**) pertain only to faults.

Solution of Particular Problems

351. Line of Intersection of Two Planes, Not Parallel.—
Given: The dips and strikes of two intersecting planes.

Required: The angle of inclination and the direction of inclination of the intersection of these planes.

Solution:[1] Since strikes and compass directions are horizontal, the construction for this problem is assumed to be in a horizontal plane. Draw MN and OP (Fig. 394), the intersections (strike

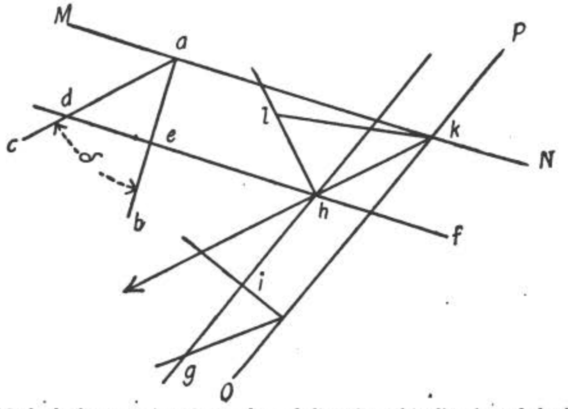


Fig. 394.—Method of computing the angle and direction of inclination of the intersection of two planes. (After H. F. Reid.)

directions) of the given planes with any horizontal plane. MN and OP will be called *lines* when reference is made to the intersections, and *planes* when reference is made to the inclined planes passing through these intersections. From any point, *a*, on line MN erect a perpendicular, *ab*, in the direction of the dip of the plane MN. From *a*, also, draw a line, *ac*, making with *ab* an angle δ, equal to the dip of the plane MN. Through *e*, on *ab* at a convenient distance from line MN draw *df* through

[1] This problem and the next are modifications of those presented by Dr. Reid. See Bibliog., Reid, H. F., 1909, pp. 173–176.

ac parallel to the line MN. The triangle *ead* may be regarded as a vertical triangle rotated about *ae* into a horizontal position. In its vertical position, *ad* would be in the plane MN and *de* would be vertical. *df* is the intersection of the plane MN and a horizontal plane which is at a depth, *de*, below the horizontal plane in which lines MN and OP are situated.

Use the same method of construction for OP, but draw the line *gh*, corresponding to *df*, parallel to line OP, and at such a distance from line OP that *gi* shall be equal to *de*. Then *df* and *gh* are, respectively, the intersections of planes MN and OP with a horizontal plane at a depth equal to *de* (= *gi*) below the plane of the figure; and *h*, the point of intersection of these lines, is also a point in the intersection of the given inclined planes. Therefore, a straight line through *h* and *k* will be the projection of the inclined planes upon any horizontal plane. The direction of inclination of this line of intersection will be downward in the semicircle that contains the dip directions of the given planes. The amount of this inclination may be found thus: From *h* erect a line, *hl*, perpendicular to *hk* and equal to *de*. Draw *lk*. In right triangle *hlk*, $\angle lkh$ is the dip of the intersection of the inclined planes. $\angle lkh$ may be obtained from the equation, $\tan \angle lkh = \frac{lh}{hk}$, in which *lh* and *hk* are known.

352. Point of Intersection Between a Line and a Plane.—

Given: The dip and strike of a plane and the angle and direction of inclination of a line not parallel to the plane.

Required: The point of intersection of the line and the plane.

Solution: Two cases are figured (Figs. 395, 396). The letters apply to both diagrams. MN is the trace of the given plane on a horizontal reference plane. MN will be used likewise to designate this plane. ST is the projection of the given line upon the reference plane. Through any point, *a*, on ST draw OP parallel to line MN. Let OP represent the trace of a plane containing the given line of which ST is the horizontal projection. From *a* draw *ac* making an angle with ST equal to the inclination of the given line. From any point, *b*, on ST

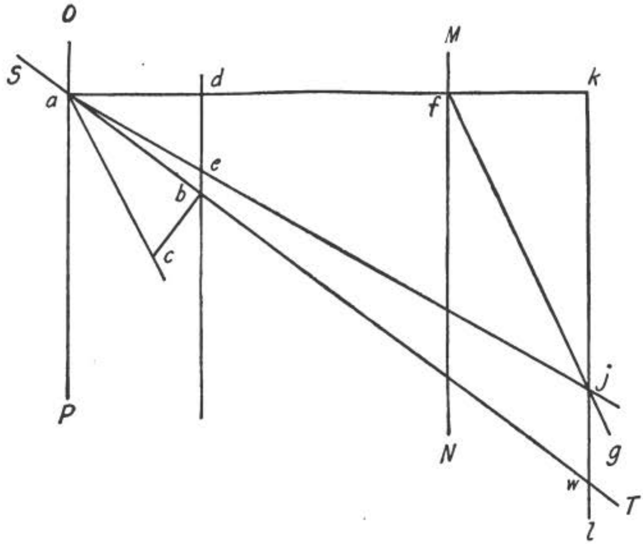


FIG. 395.—Method of computing the point of intersection of a line and a plane when the line and the plane are inclined in the same direction, the plane more steeply than the line.

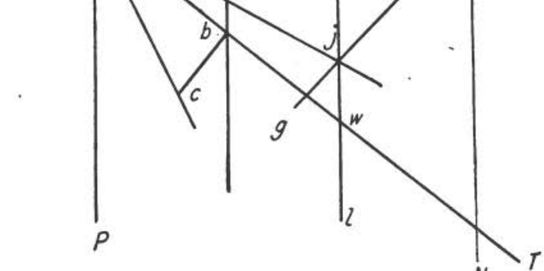


FIG. 396.—Method of computing the point of intersection of a line and a plane when the plane and the line are inclined toward one another.

draw *bc* perpendicular to ST. *bc* is the depth of the given line below its horizontal projection, ST, at *b*. Draw *af* perpendicular to OP and MN, through *a*. Through *b* draw *bd* parallel to OP, intersecting *af* at *d*. From *d* lay off *de* = *bc*. Draw *ae*. Then ∠*dae* is the inclination of the plane OP.

From *f* draw *fg*, making an angle with *af* (produced in Fig. 395) equal to the dip of the plane MN. *fg* must be drawn on the side of line MN *toward the dip* of plane MN. In Fig. 395 the dip is on the right, and in Fig. 396 on the left, of MN. Produce *ae* until it meets *fg* at *j*. Through *j* draw *kl* parallel to line MN. Then *kl* is the projection, upon the horizontal reference plane, of the line of intersection of planes OP and MN at the depth, *kj*, below *k*. The intersection of ST and *kl*, at *w*, is the projection, on the reference plane, of the intersection of the given line and the given plane.

353. Thickness of a Layer.—When an estimate is made of the thickness of a stratum, dike, vein, etc., the calculation is usually based upon a distance measured along a traverse perpendicular to the strike of the layer; that is to say, the breadth of outcrop must first be known. For folded beds, if the deformation is complex, the breadth of outcrop should be measured if possible along the axis of the fold rather than across the axis, for in this direction of least compression there is less likelihood of contortion and of other disturbing factors, and the results are less liable to error.

Thickness can be measured directly only when the surface of the ground or of an artificial excavation is perpendicular to the beds. In all other cases right angle computations must be made. Thus, in Fig. 397, *ab* is the breadth of outcrop and *bc* is the required thickness. Let the dip (here angle *bac*) be represented by δ. In triangle *abc*, $\sin\ \delta = \frac{bc}{ab}$, and therefore $bc = ab \cdot \sin\ \delta$.

Two other cases are illustrated in Figs. 398 and 399. In Fig. 398 the strata dip 20°E. (δ) and the surface of the ground slopes 10°W. Call the latter "*i*." We want to find the thickness, bc. For the solution of right triangle abc we must determine the angle bac. $\angle dac = 20° = \delta$. $\angle bad = 10° = i$. Therefore, $\delta + i = 20° + 10° = 30°$. Then, as in the first example, $bc = ab \cdot \sin(\delta + i)$. In Fig. 399 the beds dip 40°E. and the ground slopes 10° in the same direction. The thickness,

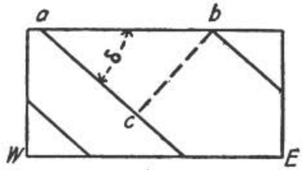


Fig. 397.—Thickness of a dipping layer, the land surface being level.

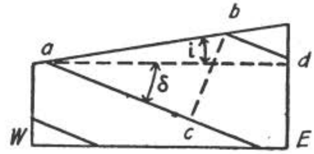


Fig. 398.—Thickness of a dipping layer, the land surface sloping in a direction opposite to the dip of the layer.

bc, is required. $\angle dab = i = 10°$, the inclination of the ground, and $\angle dac = \delta = 40°$, the dip. $\angle bac$ in right triangle abc $= \delta - i = 40° - 10° = 30°$. Therefore, $bc = ab \cdot \sin(\delta - i)$.

354. Depth of a Point in an Inclined Surface.—Another problem that must be solved by right triangles concerns the depth, below the surface of the ground, of a point in an inclined

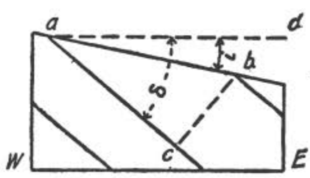


Fig. 399.—Thickness of a dipping layer, the land surface sloping in the same direction as the dip.

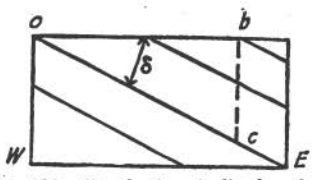


Fig. 400.—Depth of an inclined surface, the land surface being level.

surface. Again, the calculation is based upon the breadth of outcrop. The problem may be illustrated by three cases. In Fig. 400 the beds dip east at an angle of 25° ($\angle bac$). We wish to know the depth, bc, of the bedding surface outcropping at a below some point, b, on the ground surface. In right triangle *abc*, *ab* is known and $\tan \delta = \tan 25° = \frac{bc}{ab}$. Therefore, $bc = ab \cdot \tan 25°$.

In Fig. 401 the strata dip 25°E. and the ground slopes 15°W. *ab* is known. In triangle *abd*, $ad = ab \cdot \cos 15°$. Also, $bd = ab \cdot \sin 15°$. In triangle *adc*, $dc = ad \cdot \tan 25°$. Therefore, $bc = (ab \cdot \sin i) + (ad \cdot \tan \delta)$, where i is the inclination of the ground and δ is the dip.

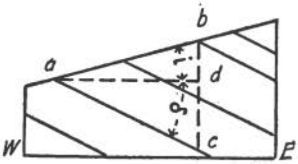


Fig. 401.—Depth of an inclined surface where the ground slopes in the opposite direction.

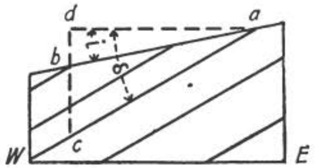


Fig. 402.—Depth of an inclined surface where the land slopes in the same direction.

In Fig. 402 the ground slopes 10°W. and the beds dip 30°W. The depth of the bedding surface, *ac*, below a point, *b*, is required. *ab* is known. In triangle *adb*, $db = ab \cdot \sin 10° = ab \cdot \sin i$, and $da = ab \cdot \cos 10°$. In triangle *adc*, $dc = ad \cdot \tan 30° = ad \cdot \tan \delta$. Therefore, $bc = dc - db = (ad \cdot \tan \delta) - (ab \cdot \sin i)$.

In Appendix IX will be found a table for computing depth and thickness.

355. Slip and Shift of Faults.—A visible displacement between corresponding points in the broken sides of a faulted dike, vein, or other recognizable structure, is almost never the true displacement (net slip) of the fault, for there is small chance that a surface of erosion or an artificial section will coincide with the direction of the net slip which, as we have seen, may lie in any position in the fault surface. Consequently, direct measurement of net slip is seldom possible. Likewise, estimates of shift, when based merely upon superficial evidence of dislocation, are apt to be incorrect. Yet in nearly all cases where fault measurements are to be made—and they must often be made—the net slip or the net shift is the quantity which must be obtained. This is done by the solution of right triangles, as will be explained below.

All fault computations depend upon facts observed and recorded in the field. When, for one reason or another, a geologist suspects the presence of a fault, he should search for the following: (1) the attitude of the faulted dike, bed, vein, igneous contact, etc.; (2) the measure of the visible displacement along an exposed portion of the fault; (3) the amount of gap, overlap, repetition of strata, or omission of strata, if such relations exist (**175, 177, 178**); (4) the strike and dip of the fault; (5) the attitude of the fault with respect to the dislocated structures; (6) the direction of slipping of the blocks as indicated on the fault surface (**171**); (7) the direction of relative displacement of the blocks, *i.e.*, which seems to have moved in a certain direction with respect to the other.

With reference to the first two factors, dislocated structures may change their attitude in the immediate vicinity of the fault (**174**), and consequently, if displacement is visible *at the fault* it may be related to slip and not to shift; but shift is the quantity most desired and the one which will probably be obtained when the displacement is not visible along an exposed fault. This last remark applies especially to gap, overlap, repetition, and omission.

Since a majority of large important faults are more or less concealed, their attitudes with respect both to a horizontal plane and to the structures which they intersect must often be found in the field by indirect observations. If a fault can be approximately located at several points in a hill-and-valley topography, its line of outcrop can be plotted on a contour map and its attitude can be determined from its trace (**343**).

The sixth factor, the direction of slipping, is best ascertained by slickensides and other features on the fault surface (**171**), but these can not always be seen. The same information can be secured in another way if two intersecting structures are cut by the fault. For example, let the structures be a dike and a bed. The attitudes of dike, bed, and fault, must have been recorded in the field. Construct a diagram as described in Art. **351,** and so determine the position of the line of intersection of any chosen surfaces in the dike and the bed. Then find the two points at which the separated portions of this line—one in each block—meet the plane of the fault (**352**). These points, formerly in contact, will show by their mutual relation the direction and amount of the slip (or shift).

This method is not practicable when the fault is parallel to the line of intersection of the dislocated structures. Furthermore, while it may give essentially correct results for slip or shift, as these have been defined, it is subject to misinterpretation as regards the true direction of slipping, just as are slickensides, if there was any change in this direction before the faulting ceased (**171**). It indicates merely the resultant of the combined movements.

We shall now suppose that enough data have been secured in the field to make possible the necessary computations. If the required quantities can be obtained by reference to but one right triangle, the figure should be drawn to scale; but if, as is usually the case, the problem demands the solution of two or more right triangles in different planes, these are best constructed in block diagrams made in cabinet or isometric projection (**336**). This is the most satisfactory method of visualizing the complex relations of faulted structures. This warning, however, must be heeded: in block diagrams *you can not construct all angles and lines to scale on account of the unavoidable distortion due to projection.*

Below are outlined a few examples to illustrate the use of right triangles in solving fault problems. Although the first one might just as well be represented in a plane figure, it is shown in a block diagram so that it may be compared with the more involved cases that follow. In all these examples the surface of the ground (upper surface of the block) is regarded as horizontal and the fault surface is assumed to be flat.

1. *Given:* A vertical strike fault intersecting a series of beds which dip 40° due east. The displacement was vertical. A

knowledge of the stratigraphic sequence in the region proves that a certain thickness of beds is missing.

Required: The net slip (or net shift).

Solution: Construct a block diagram in cabinet projection, having its front face in the plane of the dip of the beds (Fig. 403). Draw lines for the stratification and the fault. Field observations prove that the east block dropped with respect to the west block, for beds are missing on the east side of the fault trace. Draw a right triangle, *abc*, in which one leg, *bc*, meets the point *c*, which was formerly in contact with *a*, in the west block. *bc* is the thickness of the missing beds and the hypotenuse, *ac*, is the required displacement. Since *bc* is known, and $\angle\ bac = \angle\ dac - \angle\ dab = 90° - 40° = 50°$, *ac* may be found by the equation, $\sin \angle\ bac = \sin 50° = \frac{bc}{ac}$.

2. *Given:* The same conditions as those stated for Problem 1, with the exception that the direction of slipping is inclined southward (forward in the block) at an angle of 30° to the horizon.

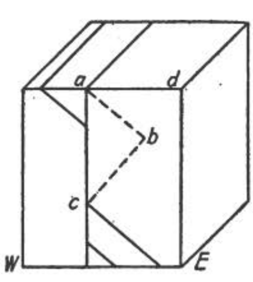


FIG. 403.—Diagram for finding the slip of a vertical dip-slip strike fault.

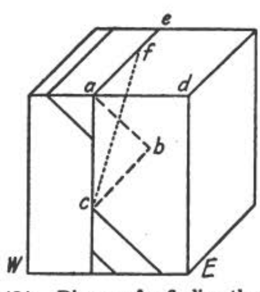


Fig. 404.—Diagram for finding the slip of a vertical oblique-slip strike fault.

Required: The net slip (or net shift).

Solution: Construct triangle *abc* (Fig. 404) as in Problem 1, and determine the length of *ac*. *ae* is the outcrop of the fault. Let *f*, in the west block, be the point which was once in contact with *c* in the east block. Draw *cf*. Then *cf* is the amount of actual displacement. Triangle *afc* is a right triangle seen in projection, and $\angle afc = 30°$. *fc* may be obtained from the equation, $\sin \angle afc = \sin 30° = \frac{ac}{fc}$, for *ac* has been found already.

3. *Given:* A strike fault dipping 70°E. and intersecting a series of beds dipping 35°E. Field observations demonstrate repetition of beds in a strip having a breadth, B. Movement along the fault was in a direction inclined 20°S.

Required: The net slip (or net shift).

Solution: Having constructed, in cabinet projection, a block diagram showing the relations given (Fig. 405), first determine *ac*, the dip component of the net slip (or net shift), as follows: *a*,

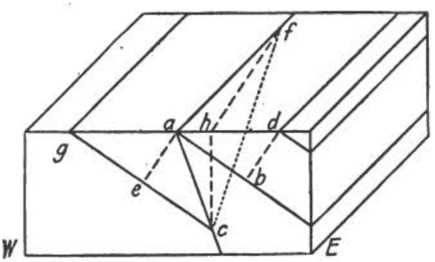


FIG. 405.—Diagram for finding the slip of an inclined oblique-slip strike fault.

in the west block, and *d*, in the east block, are two points at the same horizon in the bedding. The distance between them, *ad*, is the breadth of outcrop, B, of the repeated strata. *db*, the thickness of the repeated beds, may be found from the equation, $\sin \angle dab = \sin 35° = \frac{bd}{ad}$. Draw *ae* from *a* perpendicular to *gc*, the stratigraphic horizon in the west block that corresponds to *ab* in the east block. In triangles *gae* and *abd*, $ae = bd$. Therefore, in triangle *aec*, *ae* is known and $\angle ace = \angle bac = \angle dac - \angle dab = 70° - 35° = 35°$. *ac* may be found from the equation, $\sin \angle ace = \sin 35° = \frac{ae}{ac}$.

Now let *f* be a point in the west block that was formerly in contact with *c* in the east block. Then *cf* lies in the fault and is equal to the net slip (or net shift). Erect the line *ch* from *c* perpendicular to *ad* and draw *hf*. Triangle *hfc* is a right triangle seen in projection and $\angle hfc = 20°$, the inclination of the direction of movement of the faulting. Likewise, triangle *ahc* is a right triangle in the plane of the front face of the block diagram. In triangle *ahc*, $\angle hac = 70°$ and *ac* has been determined. *hc* may be found from the equation, $\sin \angle hac = \sin 70° = \frac{hc}{ac}$. In triangle *hfc*, *fc* may be obtained from the equation, $\sin \angle hfc = \sin 20° = \frac{hc}{fc}$.

4. *Given:* A dip fault dipping 37°E. and intersecting a series of strata which dip 23°S. The fault is a dip-slip fault.

Required: The net slip (or net shift).

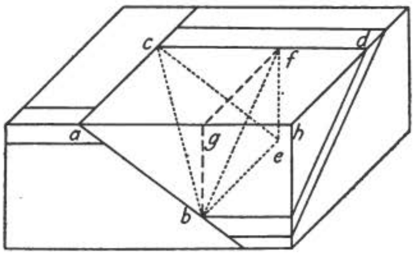


FIG. 406.—Diagram for finding the slip of an inclined dip-slip dip fault.

Solution: Construct a block (Fig. 406) in cabinet projection as in the previous cases. Let *ab* be the net slip (or net shift), and let *ac* be the measurable offset. Draw *bc*, the trace of the bedding plane, *bcd*, on the fault plane, *abc*. Draw *ce* parallel to *ab* and draw *be* parallel to *ac*. From *e* draw *ef* perpendicular to *cd*, and from *b* draw *bg* perpendicular to *ah*. Draw *gf* and *bf*. In triangle *bef*, $be = ac$, which is known, and $\angle ebf = \angle gfb = 23°$, the dip of the beds. $ef = be \cdot \tan \angle ebf$. In triangle *cef*, $\angle ecf = 37°$, the dip of the fault. Therefore, *ce*, the net slip (or net shift) $= \frac{ef}{\sin \angle ecf}$.

CHAPTER XVIII

PREPARATION OF GEOLOGIC REPORTS

The Report as a Whole

356. General Instructions.—Not only must the professional geologist be conversant with methods of research, but also he must be able to set forth the results of his work in good, concise English. The practice obtained in writing geologic reports in college courses is seldom long enough to be thorough. The student should therefore make the most of his opportunities while they last. He should plan his theses as if they were intended for publication, for although some professional papers are finished in manuscript for individuals or private concerns, a majority are written to be printed. The unavoidable differences between course theses and manuscripts for publication are very few indeed. They will be pointed out in the later pages of this chapter where detailed instructions are given for the preparation of reports.

Certain directions of general application may be noted in this place. Endeavor to use clear, idiomatic English. Avoid colloquial and slang phrases. Be heedful of punctuation and spelling. Avoid repetition of words or phrases, but never at the expense of perspicuity. There are many students who seem to have an idea that these are matters of small moment, and who object to criticism which they think should be confined, in a geologic thesis, to geologic matters. They should realize that slovenly writing is as detrimental to their profession as is careless field or laboratory work.[1]

The question is frequently asked, How long shall I make my

[1] Geologists are strongly recommended to peruse pp. 6–22 in Wood's "Suggestions to Authors." See Bibliog., Wood, G. M.

report? This can not be answered in terms of pages. Treat the theme from all points of view; omit nothing which will serve to elucidate the subject; but be concise. Aim to be brief and thorough. Let there be no mistake in your reader's mind between what is fact and what is theory. Also, be conscientious in acknowledging outside sources of important information, whether these were conversations or published works.

After you have completed your paper, number the pages and see that all page citations in the text are correctly filled in. Never submit the final copy of a thesis or of an article for publication until you have examined it critically for mistakes.

As for the paper, use sheets about 8½ by 11 in. Write on one side only. Leave a margin at least 1 in. wide on all sides. Double space the lines if you typewrite, and use a typewriter whenever possible.

357. Parts of a Manuscript Report.—A finished geologic report, in manuscript form, has a title page, a table of contents, a list of illustrations, the text, the illustrations themselves, and, if the paper is very long, an index, and a bibliography. These may be called the "parts" of the report. First, the text is written; then, usually, the illustrations are drawn; and the remaining parts are prepared last.

THE TEXT OF A GEOLOGIC REPORT

358. Order of Topics.—Before beginning to write a paper, one should consider the order of presentation of the subject matter. The topics should be arranged in the sequence of their dependence, that is to say, in a sequence such that each chapter is as little as possible contingent, for intelligibility, upon the chapters that succeed it. This is difficult to carry out for there is always more or less interdependence of subjects.

Different reports, of course, must be drawn up in different ways. Papers of a specific character, usually those with a purely economic motive, may need individual planning. Papers of a general scientific nature, both course theses and articles for publication, may often be arranged in accordance with a set outline like that given below:

OUTLINE FOR A PAPER OF GENERAL CHARACTER

Introduction.
Summary.
Topography.
Descriptive geology.
  Petrography.
  Structural geology.
Historical geology.
Economic geology.

These headings will now be discussed in order.

359. Introduction.[1]—In the introduction of a geologic essay briefly outline the location of the region to be described and the best ways of reaching it from the nearest cities. State its shape and area, and mention in what manner and to what extent, if at all, the district has been put under culture by man. Add a short explanation of the method in which the field work was conducted.

360. Summary.—The usual place for a summary is at the end of a paper, but in scientific literature clearness is gained and time is saved for the reader by putting this section immediately after the introduction. Notwithstanding its position, however, the summary should not be *written* until after the main text is finished. It is in no sense introductory. It should be a very concise review, in outline form, of the principal facts and inferences of the report. The reader should be able to acquire a true perspective of the scope and conclusions of a paper by looking over merely the introduction and the summary.

361. Topography.—Under the head of topography are discussed the relief and drainage of the field area, the nature of the topography, the abundance, shape, and size of outcrops, the

[1] Bibliog., WOOD, G. M., p. 30.

relations of outcrops to topography, and the general distribution of surface deposits. Unless these subjects have an important bearing upon the geology proper, they should be briefly treated. In some reports the topography may be taken up with advantage in the introduction.

362. Petrography.—The subject of descriptive geology is conveniently divided into petrography and structural geology. Petrography is the description of rocks. It is placed first because a knowledge of the rocks of a given region is fundamental to an understanding of the geologic structure. In writing the petrography, name the different rock species found in the area and state their distribution. Group these species in some definite order, *e.g.*, in sequence of age or according to their natural classification, and describe them by topics as suggested in the outline below. If you possess any hand specimens, as you should for each type, refer to these in parentheses.

Outline for the Description of Rocks

1. Name of rock.
2. Constituents; a list of the visible mineral species; then, for each, a statement of its approximate percentage in the rock, and the shape, size, color, luster, degree of freshness, and arrangement of its grains.
3. Lithologic characters, as color, texture, lithologic structures (flow structure, banding, ripple-mark, cleavage, crumpling, etc.), and the weathering of the rock as a whole.
4. Areal distribution.
5. Nature of outcrops.
6. Topographic expression.

No part of a geologic paper is more easily made tedious and inflated with detail than the petrography. This is a defect which should be guarded against with studious attention. Ask yourself, while writing, Is this or that fact necessary for furthering the purpose of my report? If it is not, omit it. If it is, express it in the briefest terms consistent with clearness.

363. Structural Geology.—This is the section in which the geologic structure and the mutual field relations of the different rocks are to be described and explained. Consider here the mode of occurrence of the rocks; the contact phenomena of igneous rocks; the spacial relations of magmatic differentiates in an intrusive body; the attitude of dikes, veins, beds, etc.; the characters of bedding in sediments; the succession of strata; the nature of folding; unconformities; joints; faults; cleavage; schistosity; and other like features. In this section, too, measurements of breadth of outcrop, etc., should be recorded and computations for strata, faults, etc., should be made. Discuss the several topics which relate to your particular problem in some rational order. Whenever appropriate, refer to the geologic maps and sections to illustrate your statements.

364. Historical Geology.—For some reason students seem to find it hard to understand just what they should write under the caption, historical geology. There is really no great difficulty in the matter, provided the facts are at hand, if this one important rule is heeded: *describe the events in the natural sequence of their occurrence.* Here is an example: Suppose that a certain region is underlain by a folded sedimentary series which is unconformably related to an older body of schists and injected granitic rocks; and suppose, further, that most of the bedrock in the district is covered by glacial deposits, and that the outcrops show evidence of glacial abrasion succeeded by more or less weathering. In the historical geology of a report dealing with this particular area, one should describe the events in the following order: (1) origin of the schists; (2) intrusion of the granitic rocks; (3) erosion of these schists and igneous rocks (the lower unconformity); (4) accumulation of the stratified series; (5) folding of the strata (and probably of the older rocks and structures); (6) erosion culminating in glacial abrasion; (7) deposition of glacial materials; (8) postglacial weathering. No doubt other phenomena, such as jointing and veins, would be found in a region of this kind, and these should be mentioned in their proper places in the account.

In the historical geology, then, the mode and conditions of origin of the various rock masses and important structures should receive consideration. Likewise the topographic forms should be described with respect to their origin and in relation to physiographic cycles (Chapter XII).

Try to determine the geologic age of each event. For this part of your report you will find that the field notes on the relative ages of the different observed phenomena are indispensable.

365. Economic Geology.—Geologic facts that have a practical bearing are reserved for the chapter on economic geology. In this place should be mentioned the pits, quarries, and mines of the district, the rock products extracted, the values and uses of these products, and the available means for their conveyance to the nearest transportation depot. Something may also be said of resources as yet untouched, of their nature, distribution, and extent, and of the probable cost of handling them.

Parts Other than the Text

366. Quotations and Footnotes.—Direct quotations from the works of other authors must be identical with the original, except that typographic errors may be corrected.

"Before making a footnote an author should carefully consider whether the matter does not belong in the text. Proper footnotes consist chiefly of references to the literature of the subject discussed. For reference marks superior figures ([1], [2], [3]) should be used."[1] . . . In the manuscript each footnote should be written immediately below the line in which the reference mark appears and should be separated from the text above and below it by dotted, dashed, or full lines. Footnotes should be arranged according to a standard pattern, as in the following examples:

Geikie, Archibald, Text-book of geology, 4th ed., vol. 1, 1903, p. 49.

Dana, J. D., Volcanic eruptions of Hawaii, Am. Jour. Sci., 2d ser., vol. 10, 1850, p. 235.

Archibald Geikie, *Text-book of Geology*, 4th ed. (1903), I, 49.

J. D. Dana, "Volcanic Eruptions of Hawaii," *Am. Jour. Sci.*, (2), X (1850), 235.

[1] Bibliog., Wood, G. M., p. 16.

Observe the details of capitalization, abbreviation, punctuation, and order in these examples. Notice, also, the differences between the first two and the last two. Either way is correct and either way may be adopted; but consistency demands that only one be used for all citations in a given manuscript. If you are preparing an article for some particular journal, adapt your footnotes to the method practised by this journal.

367. Illustrations.[1]—Figures are illustrations which are printed with the text and which are usually smaller than a printed page. Full-page illustrations in the published article are usually printed apart from the text and are then known as plates. All illustrations larger than a printed page are plates in the sense that they are made separately.

With regard to manuscripts, the illustrations should be numbered in the sequence in which they are referred to in the text. The number, name, and description of each *figure* should be given at the place where it is to appear in the text when published. The number, name, and description of each *plate* should be written on a separate sheet of paper, and the place where it is to be found in the publication should be clearly indicated. The original figures and plates themselves are not kept with the text; they are put together in an envelope, and each is properly numbered.

Ordinarily maps and sections should be made in black and white, for the reproduction of colors is expensive. All black line work is to be done with India ink. Put shading in, not by a back-and-forth scratching motion, but by repeated strokes in one direction. The outlines of the illustration may be lightly sketched in pencil before finishing in ink.

If possible, when drawing for publication, make the illustrations larger than they are to appear in print, for their details are often brought into sharper contrast by reduction than by copying in the original size. Lettering must be large enough for the reducing process to make it of proper size. Illustrations on paper over 8½ by 11 in. may be folded for course theses, but

[1] Bibliog., Wood, G. M., p. 26.

never so for reports to be published. In the latter case they should be sent rolled or flat. *Always be neat.* Do not submit untidy drawings either for publication or for course theses.

Directions for the construction of geologic maps and sections have been given in Chapter XV. A few more suggestions of

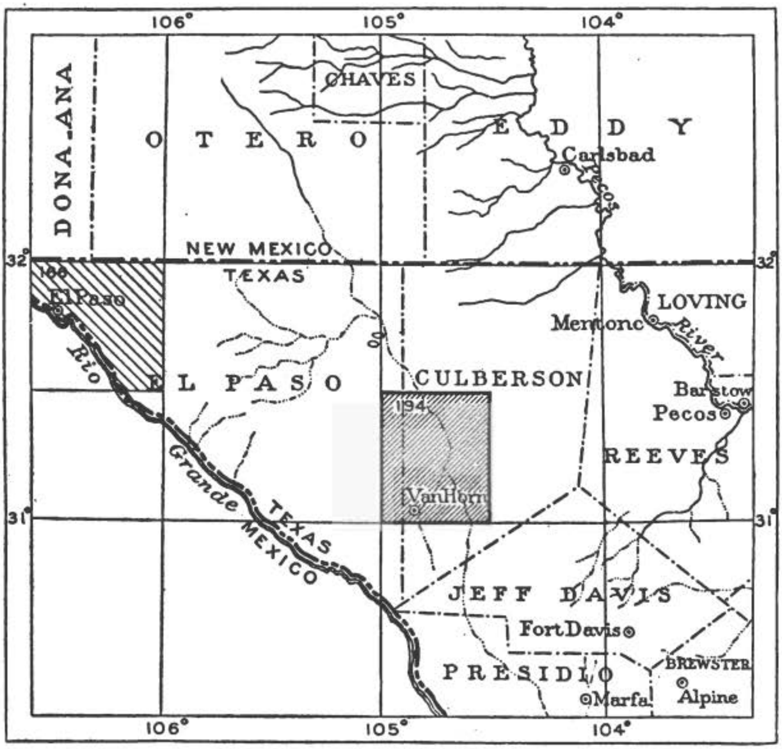


Fig. 407.—An index map. (Van Horn Folio, No. 194, U.S.G.S., 1914). The heavily shaded area is the location of the Van Horn quadrangle of which the geology is discussed in the Van Horn Folio.

practical import may be added here. In preparing a geologic map in black and white, only enough of the details of relief, drainage, and culture, need be shown to enable the reader to ascertain from this map the locations of geologic features in the field. Prominent hill crests, rivers, lakes, railroads, town lines, and a few of the more important roads, may be traced from a topographic map and used as a base for plotting the geology. In more accurate work, a finished topographic base map must be employed. It is often a good plan to make two maps on the same scale, one to represent the bedrock and the other, the superficial deposits and outcrops. You should also furnish a small scale index map of the surrounding country with a small rectangle marked on it to indicate the exact location of the mapped area of investigation (Fig. 407).

Both maps and sections may be drawn on ordinary tracing cloth. Geologic sections should first be sketched on profile paper so that the measurements can be made accurately and quickly for horizontal and vertical scales. Then they may be traced on the cloth. Line drawings for illustrations, if not traced, should be prepared on the thinnest grade of Bristol board. For photographs, which should always be in sharp focus for scientific purposes, glossy prints should be submitted. Do not fail to assure yourself that each of your illustrations has on it all the data necessary to make it serviceable and comprehensible (**321, 333, 337, 340**).

368. Table of Contents, Index, etc.—There remain for consideration the table of contents, list of illustrations, bibliography, index, title page, and the cover. The *table of contents* is a list of headings and subheadings used in the text. Each division, with the page on which it is to be found, is noted on a separate line. The wording is to be literally identical with that employed in the text. Differences of rank are indicated by indentation, the subordinate sections being set in somewhat to the right of those of next higher degree.[1] The *list of illustrations* has only the names of figures and plates, not the accompanying legends. The pages on which figures appear and the pages facing plates are recorded on the right opposite the appropriate illustrations. The *bibliography*, which is best placed at the end or just before the index, is a catalogue of all books and articles referred to in

[1] Bibliog., Wood, G. M., p. 8.

preparing the report. It may be arranged alphabetically by authors, or chronologically. The utility of a lengthy bibliography may be enhanced by grouping the references according to subject.

An *index* is not necessary except for long articles and books. If one is undertaken, it should be comprehensive and thorough, for a deficient index is far worse than none at all.

After the report is complete it should be securely bound in a cover of some kind either by stitching or by metal fasteners. On the front of the cover are the title of the report and the author's name. In college reports the date on which the paper is due is also on the cover The title page bears exactly the same information as the cover. Always strive to make the title brief and to the point.

APPENDIX

APPENDIX I

GEOLOGIC TIME SCALE

Geologic time is subdivided into eras, periods, epochs, etc. The corresponding names for the rock bodies are groups, systems, and series, respectively. Note that the titles under these subdivisions are arranged in the list, with oldest at the bottom of the column and youngest at the top, in the stratigraphic sequence of the formations which they represent.

Era or Group	Period or System	
CENOZOIC	Holocene (Recent)	Quaternary
	Pleistocene	Quaternary
	Pliocene	Tertiary
	Miocene	Tertiary
	Oligocene	Tertiary
	Eocene	Tertiary
MESOZOIC	Cretaceous	
	Comanchean	
	Jurassic	
	Triassic	
PALEOZOIC	Permian	
	Pennsylvanian	Carboniferous
	Mississippian	Carboniferous
	Devonian	
	Silurian	
	Ordovician	
	Cambrian	
PROTEROZOIC	Keweenawan	
	Animikian	
	Huronian	
	Algomian[1]	
	Sudburian	
ARCHEOZOIC	Laurentian[1]	
	Keewatin	

[1] Although "Algomian" and "Laurentian," as now used, refer to periods of mountain building and batholithic intrusion, further investigation of the Pre-Cambrian terrane may reveal stratified formations which were of contemporaneous origin.

APPENDIX II

CLASSIFICATION OF IGNEOUS ROCKS[1]

A. GRANULAR ROCKS, CONSTITUENT GRAINS DISTINCTLY VISIBLE. MOSTLY INTRUSIVE ROCKS

	(a) Feldspathic rocks, usually light in color		(b) Ferromagnesian rocks, usually dark to black	
	With abundant quartz	With little or no quartz	With subordinate feldspar	Without feldspar
Nonporphyritic (even-granular)	Granite	Syenite	Diorite (hornblende or biotite) Gabbro (pyroxene) Dolerite (dark constituent undetermined)	Hornblendite (hornblende) Pyroxenite (pyroxene) Peridotite (olivine)
Porphyritic	Granite Porphyry	Syenite Porphyry	Diorite Porphyry, etc.	

B. DENSE ROCKS, CONSTITUENTS PARTLY OR WHOLLY INDISTINGUISHABLE. INTRUSIVE AND EXTRUSIVE ROCKS

	(a) Light-colored, usually feldspathic	(b) Dark-colored to black, usually ferromagnesian
Nonporphyritic	Felsite	Basalt
Porphyritic	Felsite Porphyry	Basalt Porphyry

C. ROCKS COMPOSED WHOLLY OR IN PART OF GLASS. EXTRUSIVE

Nonporphyritic	Obsidian, Pitchstone, Pumice, etc.
Porphyritic	Vitrophyre (Glass Porphyry)

D. FRAGMENTAL IGNEOUS MATERIAL. EXTRUSIVE

Tuff, Agglomerate, Volcanic Ash, Bombs, etc.

[1] After Pirsson, with slight modification. See Bibliog., Pirsson, L. V.

APPENDIX III

CLASSIFICATION OF SEDIMENTARY ROCKS

A. ROCKS PARTLY OR WHOLLY MECHANICAL IN ORIGIN, CONSISTING OF PARTICLES OR FRAGMENTS OF PREEXISTING ROCKS

(a) Constituent particles or fragments distinctly visible

		Unconsolidated	*Consolidated*
Psephite group	Residual	Residual gravels	Coarse arkose Arkose conglomerate Arkose breccia
	Transported	Talus Landslide débris Till Gravel, pebbles, etc. Volcanic bombs, fragments, etc.	Talus breccia Landslide breccia Tillite Conglomerate Volcanic breccia, agglomerate
Psammite group	Residual	Residual sand	Arkose from feldspathic rocks Graywacke from ferromagnesian rocks
	Transported	Sand (fluviatile, marine, etc.) Volcanic ash	Sandstone Tuff

(b) Constituent particles indistinguishable; rock very fine-grained

		Unconsolidated	*Consolidated*
Pelite group	Residual	Residual clays, laterite, terra rossa, etc.	Residual claystones, etc.
	Transported	Clay Mud Loess, adobe Glacial clay (rock flour)	Claystone, argillite Mudstone, shale, slate

B. ROCKS OF CHEMICAL ORIGIN, SOMETIMES INDIRECTLY DUE TO THE ACTION OF ORGANISMS. MORE OR LESS FIRMLY COMPACTED

Calcareous series	Tufa, travertine, oolitic limestone, dolomite
Siliceous series	Siliceous sinter (geyserite), chert, flint
Iron ores	Ferrous carbonate (siderite), greensand, bog iron ore, hematite
Evaporation products	Gypsum, rock salt, alkali, etc.

C. ROCKS DIRECTLY OF ORGANIC ORIGIN

	Unconsolidated	*Consolidated*
Calcareous series	Shells and shell fragments Ooze	Shell limestone Coral limestone Chalk
Carbonaceous series	Peat, etc.	Coal series
Siliceous series	Diatomaceous earth	Tripolite
Phosphates	Guano, etc.	Phosphate rock

APPENDIX IV

CLASSIFICATION OF METAMORPHIC ROCKS

A. ROCKS WITH A PARALLEL STRUCTURE WHICH IS OFTEN VERY CONSPICUOUS

Constituents principally silicates and quartz	**Gneisses** **Schists (mica schists, chlorite schists, hornblende schists, talc schists, etc.)** **Slates** **Phyllites**
Principal constituents carbonates	**Impure marbles and dolomites**
Principal constituents hematite and quartz	**Itabarite**
Principal constituent carbon	**Graphite**

B. ROCKS COMMONLY MASSIVE; SOMETIMES WITH POORLY DEVELOPED PARALLEL STRUCTURE

Constituents principally quartz or (and) silicates	**Quartzite** **Hornfels** **Serpentine** **Soapstone** **Many diverse products of thermal metamorphism**
Principal constituents carbonates	**Marble** **Dolomite**
Principal constituents magnetite, quartz, etc.	**Magnetite rock**

APPENDIX V

TABLE FOR THE IDENTIFICATION OF CLASTIC SEDIMENTARY ROCKS

This table is applicable to both the unconsolidated and consolidated states. For the sake of brevity, however, a deposit, when referred to, will be given one name and not all the terms which might be applied to it in its different stages of lithification. The primary division of the table is based on texture, for this is perhaps the most striking character of clastic materials. There are three grades, psephites, psammites, and pelites (see Appendix III). In assigning a deposit to one of these groups difficulty may be experienced because there is sometimes great variation in texture even in small exposures. In such a case, if one grade of coarseness predominates (*e.g.*, gravel), look up the material under that grade. If two or three grades are about equally represented, look up the material under the coarser grade. Remember that all the features noted for a particular kind of rock are seldom present; also, that one characteristic feature is not enough to determine the origin or classification of a rock. Study the deposit carefully and suspend judgment until every possibility has been considered.

Under "Sites of Deposition" are mentioned the principal areas where deposition of the sediment may occur. "Structure" refers to the arrangement of the constituent particles and fragments, and to the nature of the bedding in stratified materials. In the column headed, "Surface Features" (omitted under psephites), are remarks on ripple marks, sun cracks, and other phenomena which form on the original surfaces of sands, muds, and clays. The larger constituents of the psephites (pebbles, etc.) and the finer matrix in which these are embedded receive attention in separate columns which together correspond to "General Characters" in the sections on psammites and pelites. Under "Associated Materials" are mentioned only a few significant associations out of many which might be cited. The student will find it advantageous to look back in the earlier chapters of the book for the more complete descriptions of the features listed in this table.

PSEPHITES (GRAVELS, CONGLOM-

	Sites of deposition	Structure	Matrix
Marine and Littoral	Nearly all littoral, high on beach.	Pebbles usually touch one another. Well sorted. Pebbles may have a definite arrangement. Structure may be pell-mell. Larger stratification good; may not be visible. Local unconformity and cross-bedding occasional. There may be sand lenses which are elongate parallel to the shore line. Rarely over 100 feet thick.	Clear sands, fairly well sorted. Grains angular to rounded.
Lacustrine	On lake beaches, principally above the water line.	Similar to marine.	Similar to marine. Less well sorted and less clean.
Fluviatile	Alluvial cones and piedmont plains; along channels of rapid streams; small deltas.	Frequent textural variation. Sand lenses common; these often cross-bedded and showing contemporaneous erosion at their upper surfaces. They are elongate parallel to the course of the stream. Tendency for materials to accumulate in discontinuous layers. Beds vary greatly in thickness. Sorting may be very poor, like some till. Matrix may be so abundant that pebbles do not touch one another. Cross-bedding and local unconformity frequent. Series may be many hundred feet thick.	Poorly sorted. Grains angular to rounded. More apt to be rounded than lake and marine sand grains.
Aqueoglacial	Typically in kames and eskers and upper layers of sand plains; also upstream part of valley trains and outwash aprons.	Very similar to fluviatile alluvial cone gravels as described above. Stratification may be good, poor, or absent. Structure often pell-mell owing to rapid deposition or to slumping after deposition.	Poorly sorted; angular and subangular grains predominate. Many grains may consist of feldspar and other decomposable minerals.

ERATES, BRECCIAS, ETC.)

Larger fragments (pebbles, etc.)	Associated materials	Relations to subjacent materials
Well-rounded, smooth, with a dull polish. Sise pretty uniform.	Sands and sandstones; sometimes limestone which is apt to be of organic origin.	May rest unconformably upon a wave-scoured rock platform. May overlie continental deposits conformably or unconformably. Typically basal.
Similar to marine, but less well rounded and sorted.	Sands and sandstones. Associated limestones apt to be of chemical origin.	May rest unconformably upon an old rock surface or conformably above continental deposits of other kinds.
Of all sizes, up to several tons in weight. Subangular to rounded. Some rounded.	Sands and sandstones, usually cross-bedded. Mudstones may be intimately associated, in thin beds.	Usually lie upon an eroded rock floor. If upon finer sediments in the same formation, local unconformity generally separates the two.
Typically subangular. Large striated bowlders may be found, these having been ice-rafted or having dropped in from adjacent ice walls.	Sand or sandstone. May be till.	May rest upon till, wash, or bedrock. Local or regional unconformity may separate these deposits from the underlying materials. If bedrock underlies, it is apt to bear marks of glacial abrasion.

PSEPHITES (GRAVELS, CONGLOM-

	Sites of deposition	Structure	Matrix
Glacial	In the area originally covered by the ice, or as marginal deposits. Till belongs here.	Till and tillite have no true bedding. They may contain isolated nests and small beds of sand, which are often contorted. They consist of an unstratified mass of miscellaneous unsorted rock material.	If arenaceous, sand grains angular. Fresh feldspar and other decomposeable minerals may be present. If fine, consists of rock flour which may contain scattered sand grains.
Eolian	Chiefly in deserts. Here belong lag gravels. They are usually in thin accumulations.	No definite structure is found in lag gravels because they are merely residual in the sense that they have been left behind by the wind.	Probably of typical wind-worn sand (*q.v.*).
Volcanic	On or near volcanic vents.	Bedding may be lacking or there may be a rude stratification due to sliding of the materials.	Volcanic sand and dust (*q.v.*).
Gravity	Talus at base of cliffs or on steep hill slopes. Rock glaciers in valleys in cool climates.	Bedding is absent. Talus and similar gravity accumulations are heterogeneous and unsorted, although there is a tendency for the heavier fragments to roll farthest.	Grains commonly angular, ranging in texture to the fineness of powder.
Residual	In regions of disintegration. May be the result of differential weathering of a conglomerate or similar rock or the result of spheroidal weathering.	No true bedding is developed in these materials, for there is no process of mechanical sorting to which they are subjected.	May consist of disintegration sand or eolian sand (*q.s.*).

ERATES, BRECCIAS, ETC.)—*Continued*

Larger fragments	Associated materials	Relations to subjacent materials
Angular or subangular, with snubbed ends and striated facets. Of all sizes. Proportion of pebbles to matrix varies. Pebbles may bear concave fracture scars. If not lithified when handled by the ice, fragments may be very angular and may be distorted.	May be associated with aqueoglacial materials.	If basement was not lithified, the underlying materials are apt to be disrupted and contorted. Striæ are wanting. If basement was consolidated rock, it may bear striæ or grooves of glacial origin. Sometimes it is fractured and the upper parts may be thrust over the lower.
Faceted einkanter, dreikanter, etc. Subangular, and with polished and often pitted faces.	Probably eolian sands.	The basement rock may show evidences of wind abrasion.
Angular, sharp-edged. Broken blocks of all sizes. Often consist of volcanic rocks, but may be fragments of country rock through which lava was ejected. Volcanic bombs may be associated.	Volcanic ash, mud flow, or lava.	No necessary relation.
Angular or subangular. Fragments may have had edges dulled by sliding or by weathering while exposed. Surfaces may be somewhat scratched.	No special association.	In case of landslides, basement rock may be scratched. No important relation for talus. Basement beneath rock glaciers may be striated and grooved by the movement of the materials.
If due to spheroidal weathering, well-rounded and with rough surfaces. If due to differential weathering, characters depend upon original source. (May be pebbles or fragments from any kind of a conglomerate, or they may be concretions.)	Associated with the parent rock.	Bowlders of weathering grade down into the unaffected rock. Residual deposits due to differential weathering lie upon the roughened surface of the parent rock.

PSAMMITES (SANDS

	Sites of deposition	Structure
Marine and Littoral	Sea sands are situated chiefly in the littoral belt. Those which are constantly submerged are usually fine and local.	Beach sands (not including dunes) have a gentle seaward dip. Their bedding may be fairly regular, but cross-bedding is not uncommon, especially in bars and reefs. Isolated bowlders and "pockets" or "nests" may be found.
Lacustrine	Lake sands belong to the shore zone surrounding lakes. They may extend a few rods under water.	Similar to marine sands and sandstones.
Fluviatile	Chiefly in relatively small deltas, along river courses, and in the lower parts of alluvial cones.	Bedding is highly irregular. Numerous gravel or conglomerate lenses. Cross-bedding and local unconformity common. Cross-bedding often due to migration of bars downstream. Length of gravel or conglomerate lenses parallel to course of current.
Aqueoglacial	In valley trains, outwash plains, and some eskers and kames.	Typically cross-bedded. Great irregularity of stratification seen particularly in kames and outwash plains. Frequent local unconformities and current ripple marks. Individual beds vary in thickness. Gravel is often interbedded. Isolated bowlders and gravel pockets may be found.
Eolian	Deserts and beaches.	Typically cross-bedded. Curvature of cross-laminæ often flatter than in water-made cross-bedding. May contain clay galls.
Volcanic	Near volcanoes. (Includes ash and small lapilli.)	Bedding may be absent or it may be well developed. If the ash was wind-laid, eolian features may be seen. If it settled in water, lacustrine structure may be seen.
Residual	Chiefly in dry, hot or cold climates. Locally, in temperate humid climates.	Bedding is absent. The materials may contain structures inherited from the parent rock.

AND SANDSTONES)

Surface markings of the deposit	General characters
Ripple marks and wave marks typical. Rill marks, footprints, and current marks may be found.	Well-sorted. Sands are cleaner than lake and river sands.
Wave marks and rill marks rare. Ripple marks, current marks, footprints, etc., may be preserved.	Grains less rounded than in marine sands. Less clean.
Current marks common, but wave ripple marks and other beach features are lacking.	Grains rounded to subangular.
No characteristic features. Current marks and ripple marks may be present.	
Rill marks may be found on the lee sides of isolated pebbles.	Grains well-rounded and with a dull polish. There may be some scattered sharp-edged particles. Mica plates may lie at various angles.

PELITES (MUDS, CLAYS, MUDSTONES,

	Sites of deposition	Structure
Marine and Littoral	Continental shelves, especially in front of river mouths (estuarine). Sometimes littoral.	Typically with uniform bedding. May be thinly banded; or if conditions of accumulation were very uniform, bedding may be absent. Cross-bedding and local unconformity rare; if present, made by submarine currents. Isolated, ice-rafted bowlders possible, but not characteristic.
Lacustrine	Lake floors. May be exposed on lake shores. Playa deposits may be listed here.	Thin, uniform lamination common. Evidences of current action rare. Local deformation by slight settling may occur. Isolated, ice-rafted bowlders possible, but not characteristic.
Fluviatile	Chiefly flood plains and delta flood plains.	Considerable variation. Thin sand layers often interbedded. Local unconformity frequent. Cross-bedding typical, but better developed in sands. Beds not necessarily uniform in thickness.
Aqueoglacial	Principally continental. In glaciated areas. Sometimes many miles beyond extreme limit of ice advance.	Like lake muds and clays, since deposited in standing water. Isolated, ice-rafted pebbles and bowlders, sometimes striated, are not uncommon. Local deformation by the grounding of floating blocks of ice may be observed.
Æolian	Generally far from regions where wind work predominates. Dust accumulates in distant quiet regions.	Bedding often faint or absent. Deposits of loess characteristically homogeneous. Small deposits in the lee of obstructions may show good bedding. Cross-bedding rare.
Volcanic	Usually near volcanoes, but strong winds may blow fine ash far and drop it on land or in water.	Similar to eolian deposits. Particles merely settle down. Cross-bedding rare.
Residual	Regions with a moist climate and with poor drainage facilities.	No bedding. Deposit merely accumulates as a residuum, the soluble constituents being gradually leached out.

ARGILLITES, SHALES, SLATES, ETC.)

Original surface features	General characters	Commonly associated beds
None of importance. Current marks and even true wave ripple marks may be made at depths up to 100 fathoms, but these are uncommon. Ripple marks may be well preserved in littoral muds. Rain prints, sun cracks, etc., seldom preserved in littoral muds and not found in marine muds.	Usually consist of kaolin and fine quartz grains together with organic matter. Common colors are grays, blues, and greenish grays. Fossils marine.	Fine sandstones or limestones. Where bays were shut off from the sea and rainfall was scant, salt, gypsum, saline muds, and other products of arid conditions may overlie the original marine muds.
Surface markings, such as sun cracks, stand a better chance of preservation than in marine muds, because exposure of the muds may be seasonal.	Usually decomposition products of land waste, as marine muds. Fossils of fresh or brackish-water organisms; occasionally terrestrial animals and plants included.	Coarser clastics overlie. If climate was arid, salt, gypsum, etc., may be interbedded. If climate was warm and moist, coal and bog iron ore may be associated.
Current marks, rain prints, sun cracks characteristic especially of flood-plain deposits in arid and semiarid climates. Sheetflood deposition may be listed here.	Colors: blue, gray, green. Red, maroon, and variegated in dry climates, but other types of mud deposit may have these colors.	Coal or peat beds may alternate with sun-cracked mud beds. In dry climates saline deposits may be associated.
Since the water body is generally temporary and sedimentation is rapid, there is little opportunity for the development and preservation of surface markings.	Largely rock flour, *i.e.*, pulverized rock. Hence a greater proportion of soluble salts than in lake and marine muds and clays. Fossils rare on account of coolness of water.	Possibly coarser aqueoglacial stream or lake deposits; till; or soil beds.
None characteristic.	Soluble constituents abundant. Unusual amounts of lime. Fossils terrestrial.	
None characteristic.	Materials largely volcanic glass. Fossils rare. May belong to any habitat according to the site of deposition.	
None characteristic.	The substance of which the deposit is composed would be found thinly disseminated through the underlying parent rock. Plant remains may be found.	

APPENDIX VI

SOLUTION OF TRIANGLES

Right Triangle (Fig. 408):

$$\sin A = \frac{a}{b}. \quad \cos A = \frac{c}{b}. \quad \tan A = \frac{a}{c}.$$

$$\sin C = \frac{c}{b}. \quad \cos C = \frac{a}{b}. \quad \tan C = \frac{c}{a}.$$

$$C = 90° - A. \quad b = \sqrt{a^2 + c^2}. \quad c = \sqrt{(b + a)(b - a)}.$$

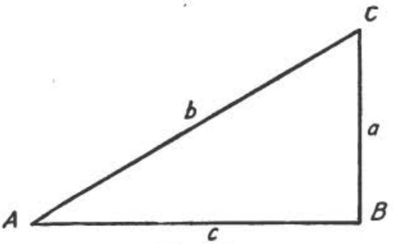


FIG. 408.

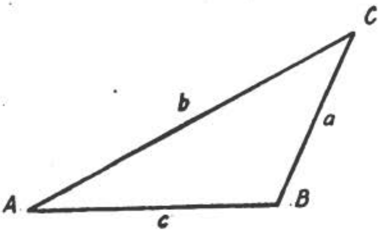


FIG. 409.

Oblique Triangle (Fig. 409):

Given	Required	Formula
A, B, a	b	$b = \frac{a \cdot \sin B}{\sin A}.$
A, a, b	B	$\sin B = \frac{b \cdot \sin A}{a}.$
C, a, b	B	$\tan B = \frac{b \cdot \sin C}{a - b \cdot \cos C}.$
a, b, c	A	If $s = \frac{1}{2}(a + b + c)$, $\sin \frac{1}{2}A = \frac{\sqrt{(s - b)(s - c)}}{bc}$; or $\cos \frac{1}{2}A = \frac{\sqrt{s(s - a)}}{bc}.$
a, b, c	Area	$\text{Area} = \sqrt{s(s - a)(s - b)(s - c)}$
A, B, c	Area	$\text{Area} = \frac{1}{2}\, bc \cdot \sin A.$

APPENDIX VII

NATURAL CIRCULAR FUNCTIONS[1]

°	Sine	Tang.	Cosine	Cotang.	°
0	0.0000	0.0000	1.0000	Infin.	90
1	0.0175	0.0175	0.9999	57.2900	89
2	0.0349	0.0349	0.9994	28.6363	88
3	0.0523	0.0524	0.9986	19.0811	87
4	0.0698	0.0699	0.9976	14.3007	86
5	0.0872	0.0875	0.9962	11.4301	85
6	0.1045	0.1051	0.9945	9.5144	84
7	0.1219	0.1228	0.9926	8.1444	83
8	0.1392	0.1405	0.9903	7.1154	82
9	0.1564	0.1584	0.9877	6.3138	81
10	0.1737	0.1763	0.9848	5.6713	80
11	0.1908	0.1944	0.9816	5.1446	79
12	0.2079	0.2126	0.9782	4.7046	78
13	0.2250	0.2309	0.9744	4.3315	77
14	0.2419	0.2493	0.9703	4.0108	76
15	0.2588	0.2680	0.9659	3.7321	75
16	0.2756	0.2868	0.9613	3.4874	74
17	0.2924	0.3057	0.9563	3.2709	73
18	0.3090	0.3249	0.9511	3.0777	72
19	0.3256	0.3443	0.9455	2.9042	71
20	0.3420	0.3640	0.9397	2.7475	70
21	0.3584	0.3839	0.9336	2.6051	69
22	0.3746	0.4040	0.9272	2.4751	68
23	0.3907	0.4245	0.9205	2.3559	67
24	0.4067	0.4452	0.9136	2.2460	66
25	0.4226	0.4663	0.9063	2.1445	65
26	0.4384	0.4877	0.8988	2.0503	64
27	0.4540	0.5095	0.8910	1.9626	63
28	0.4695	0.5317	0.8830	1.8807	62
29	0.4848	0.5543	0.8746	1.8041	61
30	0.5000	0.5774	0.8660	1.7321	60
31	0.5150	0.6009	0.8572	1.6643	59
32	0.5300	0.6249	0.8480	1.6003	58
33	0.5446	0.6494	0.8387	1.5399	57
34	0.5592	0.6745	0.8290	1.4826	56
35	0.5736	0.7002	0.8192	1.4282	55
36	0.5878	0.7265	0.8090	1.3764	54
37	0.6018	0.7536	0.7986	1.3270	53
38	0.6157	0.7813	0.7880	1.2799	52
39	0.6293	0.8098	0.7772	1.2349	51
40	0.6428	0.8391	0.7660	1.1918	50
41	0.6560	0.8693	0.7547	1.1504	49
42	0.6691	0.9004	0.7431	1.1106	48
43	0.6820	0.9325	0.7314	1.0724	47
44	0.6947	0.9657	0.7193	1.0355	46
45	0.7071	1.0000	0.7071	1.0000	45
°	Cosine	Cotang.	Sine	Tang.	°

[1] This table has been copied from Dr. C. W. Hayes' "Handbook of Field Geology," 1909, p. 42.

APPENDIX VIII

EQUIVALENT ANGLES OF SLOPE AND PER CENT. GRADES

Angle of slope	Per cent. grade	Angle of slope	Per cent. grade	Angle of slope	Per cent. grade	Angle of slope	Per cent. grade
35′	1.0	11°	19.4	20° 3′	36.5	33° 49′	67.0
52′	1.5	11° 2′	19.5	20° 18′	37.0	34°	67.4
1° 9′	2.0	11° 19′	20.0	20° 48′	38.0	34° 13′	68.0
1° 26′	2.5	11° 35′	20.5	21°	38.4	34° 36′	69.0
1° 43′	3.0	11° 52′	21.0	21° 18′	39.0	35°	70.0
2°	3.5	12°	21.3	21° 48′	40.0	35° 23′	71.0
2° 17′	4.0	12° 8′	21.5	22°	40.4	35° 45′	72.0
2° 35′	4.5	12° 24′	22.0	22° 18′	41.0	36°	72.6
2° 52′	5.0	12° 41′	22.5	22° 47′	42.0	36° 8′	73.0
3°	5.2	13°	23.0	23°	42.5	36° 30′	74.0
3°	5.5	13° 13′	23.5	23° 16′	43.0	36° 52′	75.0
3° 26′	6.0	13° 30′	24.0	23° 45′	44.0	37°	75.4
3° 43′	6.5	13° 46′	24.5	24°	44.5	37° 14′	76.0
4°	7.0	14°	24.9	24° 14′	45.0	37° 36′	77.0
4° 17′	7.5	14° 2′	25.0	24° 42′	46.0	38°	78.0
4° 34′	8.0	14° 18′	25.5	25°	46.6	38° 19′	79.0
4° 52′	8.5	14° 34′	26.0	25° 10′	47.0	38° 40′	80.0
5°	8.8	14° 51′	26.5	25° 39′	48.0	39°	81.0
5° 9′	9.0	15°	26.8	26°	48.8	39° 21′	82.0
5° 26′	9.5	15° 7′	27.0	26° 6′	49.0	39° 42′	83.0
5° 43′	10.0	15° 23′	27.5	26° 34′	50.0	40°	84.0
6°	10.5	15° 39′	28.0	27°	50.9	40° 22′	85.0
6° 17′	11.0	15° 54′	28.5	27° 1′	51.0	40° 42′	86.0
6° 34′	11.5	16°	28.7	27° 29′	52.0	41°	87.0
6° 51′	12.0	16° 10′	29.0	27° 56′	53.0	41° 21′	88.0
7°	12.3	16° 26′	29.5	28°	53.2	41° 40′	89.0
7° 8′	12.5	16° 42′	30.0	28° 22′	54.0	42°	90.0
7° 24′	13.0	16° 58′	30.5	28° 49′	55.0	42° 18′	91.0
7° 41′	13.5	17°	30.6	29°	55.4	42° 37′	92.0
7° 58′	14.0	17° 13′	31.0	29° 15′	56.0	43°	93.0
8° 15′	14.5	17° 29′	31.5	29° 41′	57.0	43° 14′	94.0
8° 32′	15.0	17° 45′	32.0	30°	57.7	43° 32′	95.0
8° 49′	15.5	18°	32.5	30° 7′	58.0	43° 50′	96.0
9°	15.8	18° 16′	33.0	30° 33′	59.0	44°	96.5
9° 5′	16.0	18° 31′	33.5	31°	60.0	44° 8′	97.0
9° 22′	16.5	18° 47′	34.0	31° 23′	61.0	44° 25′	98.0
9° 39′	17.0	19°	34.4	31° 48′	62.0	44° 43′	99.0
9° 56′	17.5	19° 2′	34.5	32°	62.5	45°	100.0
10°	17.6	19° 17′	35.0	32° 13′	63.0		
10° 12′	18.0	19° 33′	35.5	32° 37′	64.0		
10° 29′	18.5	19° 48′	36.0	33°	65.0		
10° 44′	19.0	20°	36.4	33° 26′	66.0		

APPENDIX IX

DIP, DEPTH, AND THICKNESS OF INCLINED STRATA

This table may be used for determining the thickness of inclined strata or the depth of a point in an inclined stratum provided the dip and the breadth of outcrop on a horizontal surface are known. Divide the breadth of outcrop by 100 and multiply the result by the constant for thickness (or depth) for the given dip.

Dip	Thickness	Depth	Dip	Thickness	Depth	Dip	Thickness	Depth
1°	1.75	1.75	31°	51.50	60.09	61°	87.46	180.40
2°	3.49	3.49	32°	52.99	62.49	62°	88.29	188.07
3°	5.23	5.24	33°	54.46	64.94	63°	89.10	196.26
4°	6.98	6.99	34°	55.92	67.45	64°	89.88	205.03
5°	8.72	8.75	35°	57.36	70.02	65°	90.63	214.45
6°	10.45	10.51	36°	58.78	72.65	66°	91.35	224.60
7°	12.19	12.28	37°	60.18	75.36	67°	92.05	235.59
8°	13.92	14.05	38°	61.57	78.13	68°	92.72	247.51
9°	15.64	15.84	39°	62.93	80.98	69°	93.36	260.51
10°	17.36	17.63	40°	64.28	83.91	70°	93.97	274.75
11°	19.08	19.44	41°	65.61	86.93	71°	94.55	290.42
12°	20.79	21.26	42°	66.91	90.04	72°	95.11	307.77
13°	22.50	23.09	43°	68.20	93.25	73°	95.63	327.09
14°	24.19	24.93	44°	69.47	96.57	74°	96.13	348.74
15°	25.88	26.79	45°	70.71	100.00	75°	96.59	373.21
16°	27.56	28.67	46°	71.93	103.55	76°	97.03	401.08
17°	29.24	30.57	47°	73.14	107.24	77°	97.44	433.15
18°	30.90	32.49	48°	74.31	111.06	78°	97.81	470.46
19°	32.56	34.43	49°	75.47	115.04	79°	98.16	514.46
20°	34.20	36.40	50°	76.60	119.18	80°	98.48	567.13
21°	35.84	38.39	51°	77.71	123.49	81°	98.77	631.38
22°	37.46	40.40	52°	78.80	127.99	82°	99.03	711.54
23°	39.07	42.45	53°	79.86	132.70	83°	99.25	814.43
24°	40.67	44.52	54°	80.90	137.64	84°	99.45	951.44
25°	42.26	46.63	55°	81.92	142.81	85°	99.62	1143.01
26°	43.84	48.77	56°	82.90	148.26	86°	99.76	1430.07
27°	45.40	50.95	57°	83.87	153.99	87°	99.86	1908.11
28°	46.95	53.17	58°	84.80	160.03	88°	99.94	2863.63
29°	48.48	55.43	59°	85.72	166.43	89°	99.98	5729.00
30°	50.00	57.74	60°	86.60	173.21			

APPENDIX X

CORRECTION FOR DIP IN DIRECTIONS NOT PERPENDICULAR TO STRIKE[1]

Angle of full dip	Angle between strike and direction of section							
	80°	75°	70°	65°	60°	55°	50°	45°
10°	9° 51′	9° 40′	9° 24′	9° 5′	8° 41′	8° 13′	7° 41′	7° 6′
15°	14° 47′	14° 31′	14° 8′	13° 39′	13° 34′	12° 28′	11° 36′	10° 4′
20°	19° 43′	19° 23′	18° 53′	18° 15′	17° 30′	16° 36′	15° 35′	14° 25′
25°	24° 48′	24° 15′	23° 39′	22° 55′	22° 0′	20° 54′	19° 39′	18° 15′
30°	29° 37′	29° 9′	28° 29′	27° 37′	26° 34′	25° 18′	23° 51′	22° 12′
35°	34° 36′	34° 4′	33° 21′	32° 24′	31° 13′	29° 50′	28° 12′	26° 20′
40°	39° 34′	39° 2′	38° 15′	37° 15′	36° 0′	34° 30′	32° 44′	30° 41′
45°	44° 34′	44° 1′	43° 13′	42° 11′	40° 54′	39° 19′	37° 27′	35° 16′
50°	49° 34′	49° 1′	48° 14′	47° 12′	45° 54′	44° 17′	42° 23′	40° 7′
55°	54° 35′	54° 4′	53° 19′	52° 18′	51° 3′	49° 29′	47° 35′	45° 17′
60°	59° 37′	59° 8′	58° 26′	57° 30′	56° 19′	54° 49′	53° 0′	50° 46′
65°	64° 40′	64° 14′	63° 36′	62° 46′	61° 42′	60° 21′	58° 40′	56° 36′
70°	69° 43′	69° 21′	68° 49′	68° 7′	67° 12′	66° 8′	64° 35′	62° 46′
75°	74° 47′	74° 30′	74° 5′	73° 32′	72° 48′	71° 53′	70° 43′	69° 14′
80°	79° 51′	79° 39′	79° 22′	78° 59′	78° 29′	77° 51′	77° 2′	76° 0′
85°	84° 56′	84° 50′	84° 41′	84° 29′	84° 14′	83° 54′	83° 29′	82° 57′
89°	88° 59′	88° 58′	88° 56′	88° 54′	88° 51′	88° 47′	88° 42′	88° 35′

Angle of full dip	Angle between strike and direction of section								
	40°	35°	30°	25°	20°	15°	10°	5°	1°
10°	6° 28′	5° 46′	5° 2′	4° 15′	3° 27′	2° 37′	1° 45′	0° 53′	0° 10′
15°	9° 46′	8° 44′	7° 38′	6° 28′	5° 14′	3° 33′	2° 40′	1° 20′	0° 16′
20°	13° 10′	11° 48′	10° 19′	8° 45′	7° 6′	5° 23′	3° 37′	1° 49′	0° 22′
25°	16° 41′	14° 58′	13° 7′	11° 9′	9° 3′	6° 53′	4° 37′	2° 20′	0° 28′
30°	20° 21′	18° 19′	16° 6′	13° 43′	11° 10′	8° 30′	5° 44′	2° 53′	0° 35′
35°	24° 14′	21° 53′	19° 18′	16° 29′	13° 28′	10° 16′	6° 56′	3° 30′	0° 42′
40°	28° 20′	25° 42′	22° 45′	19° 31′	16° 0′	12° 15′	8° 17′	4° 11′	0° 50′
45°	32° 44′	29° 50′	26° 33′	22° 55′	18° 53′	14° 30′	9° 51′	4° 59′	1° 0′
50°	37° 27′	34° 21′	30° 47′	26° 44′	22° 11′	17° 9′	11° 41′	5° 56′	1° 11′
55°	42° 33′	39° 20′	35° 32′	31° 7′	26° 2′	20° 17′	13° 55′	7° 6′	1° 26′
60°	48° 4′	44° 47′	40° 54′	36° 14′	30° 29′	24° 8′	16° 44′	8° 35′	1° 44′
65°	54° 2′	50° 53′	46° 59′	42° 11′	36° 15′	29° 2′	20° 25′	10° 35′	2° 9′
70°	60° 29′	57° 36′	53° 57′	49° 16′	43° 13′	35° 25′	25° 30′	13° 28′	2° 45′
75°	67° 22′	64° 58′	61° 49′	57° 37′	51° 55′	44° 1′	32° 57′	18° 1′	3° 44′
80°	74° 40′	72° 75′	70° 34′	67° 21′	62° 43′	55° 44′	44° 33′	26° 18′	5° 31′
85°	82° 15′	81° 20′	80° 5′	78° 19′	75° 39′	71° 20′	63° 15′	44° 54′	11° 17′
89°	88° 27′	88° 15′	88° 0′	87° 38′	87° 5′	86° 9′	84° 15′	78° 41′	44° 15′

[1] This table has been adapted from Appendix I, on p. 128, in Dr. A. R. Dwerryhouse's "Geological and Topographical Maps," published by Messrs. Edward Arnold, London.

APPENDIX XI

GEOLOGIC MAPPING

Advantages of Field Mapping.—A most important function of geologic surveying is the mapping of the geologic data observed in the field. The various types of contacts and rock bodies should be charted in their proper relations to one another. Although such mapping can be done as office work by referring to the notebook, provided the notes are adequate, nevertheless it is accomplished with more satisfactory results if actually done in the field. The latter method has two decided advantages: as the plotting proceeds, errors are likely to be detected by the eye so that they can be corrected on the spot, and the features mapped may suggest further significant lines of observation which might otherwise have been overlooked.

Controls.—Geologic mapping, like all kinds of mapping, is done by determining and plotting the locations of certain chosen points or stations and then sketching in the details with reference to these points. Gannett has well defined a map as "a sketch, corrected by locations." These selected points may be said to *control* the map. Their horizontal directions and distances from one another are termed the *horizontal control*, and their elevations the *vertical control*, of the map. Occasionally, in regions which have not yet been surveyed, the geologist has to establish the entire system of control points for his map; but generally he finds that a control of the district to be investigated has already been plotted, perhaps by the U. S. Geological Survey, or the Coast and Geodetic Survey, or by a survey conducted by state or township, by a railroad or mining company, or by some other interest.[1] Yet, even in this case, because the fixed control points are too far apart or because, as is usual, they have been chosen with little regard for geologic structure, he will have to locate a secondary group of stations whose horizontal and vertical positions will be determined in relation to the original or primary control points. In brief, then, the geologist should be familiar with certain methods of measuring and plotting directions and horizontal and vertical distances.

Paper for the Map.—Field mapping of geologic data is usually done on a page of the notebook or on a sheet of paper fastened to a plane table (see below). The plane table is commonly preferred. If a good contour map of the district can be procured, it may be mounted in the notebook or on the plane table to serve as a base upon which the geology may be plotted; or a

[1] The control points may be triangulation stations, U. S. G. S. bench marks, township corner posts or quarter posts, claim corner posts, etc.

photographic copy[1] of it may be employed in the same way. When there is available a plat that shows only the positions of previously established control stations, or a topographic map with poorly drawn contours, but with a satisfactory control, the control points should be transferred to the sheet of paper on which the geology is to be mapped, great care being taken to make this transfer accurate on the scale adopted for the work. Under all circumstances the paper for the geologic map should be divided into squares by coördinate lines with their spacing commensurate with the scale. These lines should run true north-south and east-west.

The Notebook for Mapping.—If a notebook is used for the mapping, one 8 by 10 in. is often better than the smaller varieties. In it directions, which have been determined by compass, are plotted by a protractor with reference to the north-south and east-west coördinates.

The Plane Table.—A plane table may be described as a drawing board adjusted to a tripod in such a way that the board may be turned horizontally, when the table is set up, without moving the tripod. Geologists ordinarily prefer a table 15 by 15 in. or 18 by 18 in.[2] The paper for the map may be attached to the board by thumb tacks or thumb screws.

The plane table may be used either oriented or unoriented. (See p. 481.) A compass needle for orienting is sometimes sunk into the board at one edge. When *unoriented* the table is set up at a given locality without reference to directions. It serves merely as a page in the notebook, but is a more convenient support for the map. Lines between stations are plotted by protractor with respect to the north-south and east-west coördinates. An *oriented* plane table is set up at every station in exactly the same position relative to true or astronomic bearings, and lines between stations are plotted by sight alidade (p. 479) or telescopic alidade (p. 480).

Other Instruments for Geologic Mapping.—Other instruments that may be included in outfits for various types of geologic mapping are, a steel tape, a sight alidade, a hand level, a clinometer, a Gurley compass, a Brunton compass, a stadia rod, a small telescopic alidade, a protractor, a plotting scale, and a barometer (see also **Art. 292**). Not all of these are needed for any one survey.

The *steel tape* is of especial importance in the measurement of base lines for triangulation systems. It is also useful for determining pace lengths and for measuring short distances where considerable accuracy is required. For geologic mapping there is practically never any necessity for correcting taped distances for tension, temperature, sag, or standardization of the tape.

[1] For accurate work copies should be made by photolithography upon double mounted paragon paper. Ordinary prints are apt to shrink unequally and so distort the original scale.

[2] A simple plane table may be made with a drawing board and a firm wooden camera tripod, if a brass plate, threaded for the tripod screw, is fastened centrally on one side of the board.

A *sight alidade* consists of a flat rectangular metal base with one edge bevelled, about 10 in. long, provided with a folding sight at each end. It is used in conjunction with the plane table. In practice the sights are turned up. They should be at least 4 or 5 in. long. The observer, having set up his plane table at a station (p. 481), places the fiducial (bevelled) edge of the alidade against the point that represents this station on the map, and rotates the alidade about this point until he brings some distant object, which he has selected as the next station, into line with the cross hair and the slit of the two sights. He then draws a line on the map along the fiducial edge from the point for his present location toward the distant object. The distance to this object is found by one of the methods described below. (See also p. 487.)

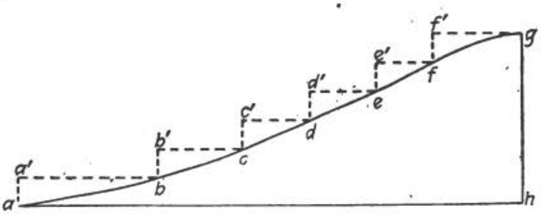


FIG. 410.—Profile section of a slope, illustrating the method of finding difference of elevations by hand level.

The *hand level* may be of either the Locke or the Abney pattern. The Locke level is a tube with a spirit level. It is used as illustrated in Fig. 410. *ag* is a hill slope. Standing at *a*, and being careful to hold the level so that the bubble is centered, the observer looks through the tube at some point, *b*, at the same elevation as the instrument; *i.e.*, *a'b* is horizontal. He then proceeds to *b*, noting the distance *ab*, and repeats the process at *b*, looking toward *c*. The height of the instrument, *aa'* is known. Hence the elevation of *g* above *a* is, in this case, 6*aa'*.

The Abney level has a graduated vertical arc in addition to the tube and spirit level. With the arc set at 0° it can be employed just like the Locke. The Abney can also be used as a clinometer. In Fig. 411, *abcd* is a slope with a change at *b* and another at *c*. The observer stands at *a* with the instrument at *a'*, and, sighting through the tube at *b'*, at the elevation $bb' = aa'$ above the ground, he simultaneously rotates the spirit level until the bubble is centered. The angle of the slope, $\angle b'a'f$, may then be read directly from the graduated arc. The height of *b'* above *b* is generally estimated from *a* by eye. It may be obtained with greater precision if an assistant at *b* holds a rod, known as a "grade rod," having the proper length, *aa'*, indicated upon it. At *b* the observer sights at *c'* and reads the slope angle, $\angle c'b'g$. Notice that these readings are always made at changes of slope.

At *c* he would sight forward to a position on another change of slope; and so on.

The *Gurley compass* is provided with a pendulum clinometer, folding sights, rectangular spirit levels, and a square base with bevelled edges, two of which are graduated in degrees of arc. The sights and the straight edge of the base may be employed as a sight alidade. The two edges, graduated in degrees, may serve as a protractor. The pendulum clinometer is useful for reading dips, but is unsatisfactory for determining slope angles. For compass bearings the dial should always be corrected for magnetic declination (**295**).

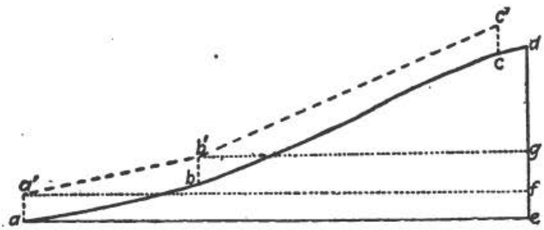


FIG. 411.—Profile section of a slope, illustrating the method of finding slope angles by clinometer.

The *Brunton compass* is comprised of an ordinary compass, folding sights, a mirror, and a spirit level clinometer. The mirror greatly facilitates making readings for direction and for slope when the observer holds the instrument in his hands. In taking bearings, the compass box should be essentially level. By virtue of the spirit level clinometer the Brunton may serve as a hand level. Although this kind of clinometer can be used for taking dips, the pendulum type, like that in the Gurley, is better for this purpose. The Brunton can not be employed as a protractor and it is unsatisfactory as a direct sight alidade. Always set the compass dial for true bearings (**295**).

A *stadia rod* is a stiff rod graduated in feet and tenths of feet, or in meters. It is used in conjunction with the telescopic alidade or the transit.

A *telescopic alidade* differs from a sight alidade chiefly in having a small telescope instead of folding sights. It is used with the plane table and stadia rod. The telescope is mounted on a horizontal axis supported by a post and fork at the middle of the flat metal base in such a way that it may be rotated in a vertical plane parallel to the long edges of the base. A vertical arc registers the angle of inclination of the telescope. The latter is also provided with stadia hairs which are generally placed so that the distance between them will exactly cover a length of 1 ft. on an object 100 ft. away from the center of the instrument. If the object is 200 ft. away, they will include a length of 2 ft.; and so on. Evidently, then, if the plane table has been set up and oriented at a given station, *A*, and the alidade has been properly oriented with respect to *A* and the next station, *B*,[1] the observer at *A* can determine the distance, *AB*, by looking through the telescope at a stadia rod held by a rodman at *B*. The slope angle from *A* to *B* is read on the vertical arc. The elevation of *B* above or below *A* is computed from the slope angle and the horizontal distance.

A *protractor* is needed for plotting directions on the map if the mapping is done with a compass and notebook or unoriented plane table.

A *plotting scale* is a straight-edge graduated in intervals representing feet, yards, meters, or paces, on the scale adopted for the mapping.

An *aneroid barometer* is a metal vacuum box which responds to differences of atmospheric pressure. In view of the fact that atmospheric pressure diminishes with increasing altitude above sea level, this instrument is made with two circular scales, one representing inches of barometric pressure and the other corresponding feet of elevation. The latter scale is movable so that any point of elevation upon it may be brought opposite the index needle which is controlled by the expansion and contraction of the box. Errors being adjusted, the elevation of one station above another is the difference in altitudes recorded by the instrument at the two stations.

Various precautions are necessary in using the aneroid on account of the delicacy of its mechanism and its ready response to changing weather conditions. It should always be handled with care. To keep its temperature as constant as possible it should be carried in a pocket close to the body. In reading, hold it vertically opposite the eye and tap it gently to prevent the needle's sticking. Read it frequently and for small differences of elevation. After making an abrupt ascent or descent, wait a few minutes for the needle to "catch up" before recording the elevation. When possible choose calm, bright, dry days for barometric work. Thunderstorms and sudden meteorologic variations sometimes produce pressure changes which correspond to 1000 ft. or more of altitude. Under these circumstances aneroid observations should be postponed until weather conditions are more satisfactory. Aneroid barometers are made with different ranges for altitude. An instrument graduated to 3000 ft. should be used where elevations do not exceed 2000 ft., and one for 5000 ft. for elevations up to 3000 or 4000 ft. Do not use an aneroid for elevations near the limit of its range. The barometer should always be set at the altitude of the camp before departure in the morning.

Setting up the Plane Table; Orientation.—If mapping is being done with oriented plane table, three operations are performed when a station is occupied. The plane table is levelled, the point for the station on the map is brought above the proper point on the ground, and the board is oriented. For careful work levelling is usually done with rectangular spirit levels, and centering by a plumbing arm; but for ordinary plane table surveying with

[1] Orientation should be performed as described above for the sight alidade.

sight alidade, when the sight lines average 400 or 500 ft. in length and the error is about 1 in 500 (see p. 491), the first two operations may be done by eye.

The plane table may be oriented by compass, backsight, or resection. (1) For orientation by compass, set up the table over the new station, lay a Gurley compass, previously corrected for magnetic declination (**295**), with its north-south edge against a north-south coördinate on the map, and turn the board until the needle points to north on the dial. If the compass has not been set for true bearings, or can not be so set, the coördinates on the map should be drawn as magnetic north-south and east-west lines. Orientation by compass is subject to error on account of local attraction. Hence set-ups should be checked by backsight or resection. (2) To orient by backsight, set up the table over the new station and roughly orient it by eye, lay the alidade with its fiducial edge against the line which has already been drawn on the map from the last station to the one now occupied, and turn the board until the last station is brought into the line of sight of the alidade. (3) Orientation by resection is explained in the next article. Both backsight and resection can be accomplished only by reference to points which have been previously established.

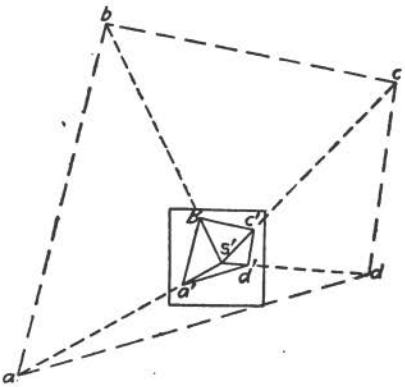


FIG. 412.—Mapping by the method of radiation. The square represents the plane table board.

Methods of Location.—There are four methods of locating points for map construction. They are radiation, intersection, resection, and progression or traversing. Intersection and resection are the two principal modes of triangulation. Each of these four methods, except resection, may be used with notebook, unoriented plane table, or oriented plane table, and each may be used with any suitable combination of instruments (see p. 490), but they will be described here only for oriented plane table and alidade.

1. The *method of radiation* is illustrated by Fig. 412. *a, b, c,* and *d* are stations to be located. Set up the plane table above any point, *s*, from which the stations are visible and accessible. Orient if necessary. Let *s'* be the position of this point on the map. *s* is vertically below *s'*. Place the fiducial edge of the alidade against *s'*, sight at *a*, and draw a line from *s'* toward *a*. Measure *sa*. Lay off *s'a'* on the scale adopted for the map. In like manner plot *s'b'*, *s'c'*, and *s'd'*. This method is practicable for small areas, quarries, etc. It has the disadvantage of giving no check upon the accurracy of the work.

2. The *method of intersection* is the most rapid of the four methods. In Fig. 413, *a, b, c, d, e,* and *f* are points to be plotted. Set up the plane table

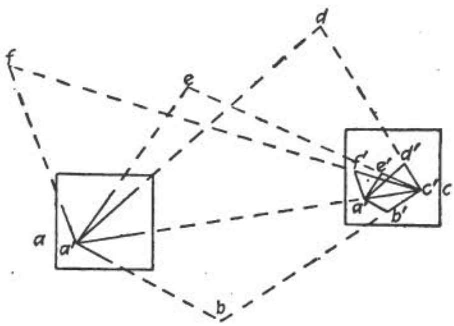


Fig. 413.—Mapping by the method of intersection. The squares represent different positions of the plane table.

at a given station, *a*. Let *a'* on the map represent *a* on the ground. Sight with the alidade at *b, c, d, e,* and *f*, and draw lines from *a'* toward these points. From *a* measure the distance to one of these stations, *c*, and lay off *a'c'* on the scale adopted for the map. Set up at *c* by backsight on *a*. From *c* sight at *b, d, e,* and *f*, and draw lines toward these points from *c'*. The intersection of the two lines of sight from *a'* and *c'* to each point will determine the position of this point on the map. The angle made by these two lines at each point (*e.g., a'e'c'*) should not be less than 30° nor more than 120°. Whenever possible it should approximate 60°. To check the work the observer should always sight from a third station at all points previously located by two-line intersections (Fig. 414). If the line from the third station does not pass through the intersection point for any other station, there has been an error in the plotting and the mapper must go back and repeat until this error has been discovered and corrected. By advancing from station to station, always locating points by intersection in the manner just described, any number of stations may be plotted. The lines joining stations will form a network of triangles or *triangulation net*. The process of developing this net is called *expansion*. Expansion may be accom-

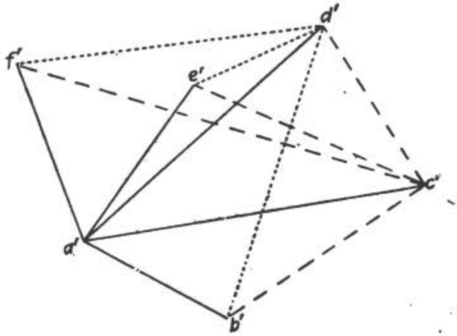


FIG. 414.—Enlargement of the plot shown in Fig. 413. All points are fixed by the intersection of at least three lines. Full lines were sighted from *a*, dashed lines from *c*, and dotted lines from *d*; *a*, *c*, and *d*, being the stations represented by *a'*, *c'*, and *d'*.

plished by building up a series of triangles, quadrilaterals, or polygons (Fig. 415). The method of intersection is the only one by which inaccessible points may be located. It requires measurement of the length of but one line, termed the *base line* (*ac* in Fig. 413). In most cases, however, the system should be tied to a check base line at the other end of the net (Fig.

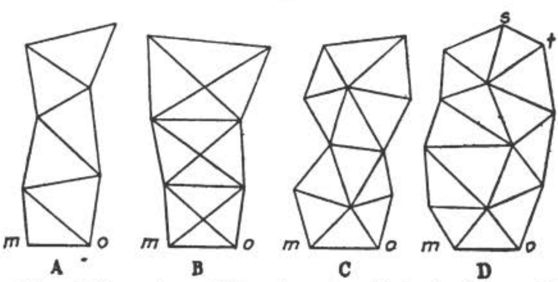


FIG. 415.—Triangulation nets consisting of a series of triangles (A), quadrilaterals (B), polygons (C), and intersecting polygons (D). In each figure *mo* is the base line. *st* is a check base line. A is the least accurate method. B and D are most satisfactory.

415, D). The accuracy of the whole net is proportional to the degree of precision with which the base line is measured. Nevertheless, it is impracticable to measure this line with greater accuracy than can be attained in the rest of the work. The position for the base line should be chosen on as open and as level ground as possible. It should be of such a length in the field that it will be at least 2 in. long when plotted to scale on a plane table map of any scale.[1]

3. The *method of resection*, or "cutting in," is virtually intersection backward. It is frequently employed for finding one's position by observation on a number of known stations which have already been located on the map. It is of great value for the geologist who is generally provided with a base map and who wants to locate outcrops with reference to visible fixed control points. Let *a*, *b*, and *c*, in Fig. 416, be three stations previously determined, and let *a′*, *b′*, and *c′* represent these stations on the map. The observer is at *d* and wishes to ascertain his exact location with respect to *a*, *b*, and *c*, which are visible from *d*. Set up the table at *d* and orient it by compass. Lay the fiducial edge of the alidade at *a′* and turn it until *a* is in line with the sights. Draw a line from *a′* away from *a*. Place the alidade against *b′*, turn it until its sights are in line with *b*, and draw a line from *b′* away from *b*. This line intersects the line from *a′* at *d′*. Check by repeating this operation for a third station, *c*. If the line from *c′* intersects *a′d′* and *b′d′* at *d′*, *d′* is the correct location of the point. If it does not, the three lines will form a "triangle of error," which may lie inside or outside the triangle made by the three fixed points (*a′*, *b′*, and *c′*) on the map, and inside or outside a circle which passes through these three fixed points.[2] In this case the correct position of the observer can be found through a series of approximations by the application of the following rules: (1) The desired point will be on the same side of each of the three lines, when looking from the triangle of error toward the respective stations; *e.g.*, in Fig. 417, the point is on the *right* of each line (arrow). (2) If the triangle of error is inside the triangle made by the three points (*a′*, *b′*, and *c′* in Fig. 416), the observer's position is inside the triangle of error, and *vice versa*. (3) The distance of the observer's position from the three lines is proportional to the lengths of these lines from the fixed points to the triangle of error. Having chosen a point, *d′* (Fig. 416), for the approximate position of the observer, draw a line from *d′* to *b′*, the most distant of the three fixed points, lay the alidade against *d′b′*, and turn the *table* until the sights are in line with *b*. Check by sighting along

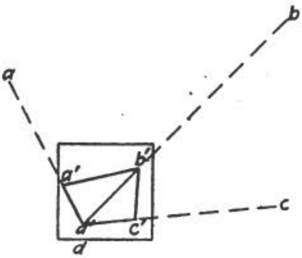


Fig. 416.—Mapping by the method of resection. The square represents the plane table.

[1] This does not mean that the line on the map should not be drawn 6 or 8 in. long, when its *direction* is plotted, in order to facilitate laying the alidade along it.

[2] If the triangle of error falls about on this circle, it is well to substitute another station for one of the three fixed points.

$d'a'$ at a and along $d'c'$ at c. If there is still a triangle of error, repeat the procedure.

The solution of this "three-point problem," as it is called, may be performed graphically as follows: If a triangle of error is obtained by drawing lines from the three fixed points, as described above, rotate the table a little and, in just the same way, draw three more lines from the same three points, making another like triangle of error. Now draw lines through the similar angles of the two triangles. These lines will intersect in a point which will

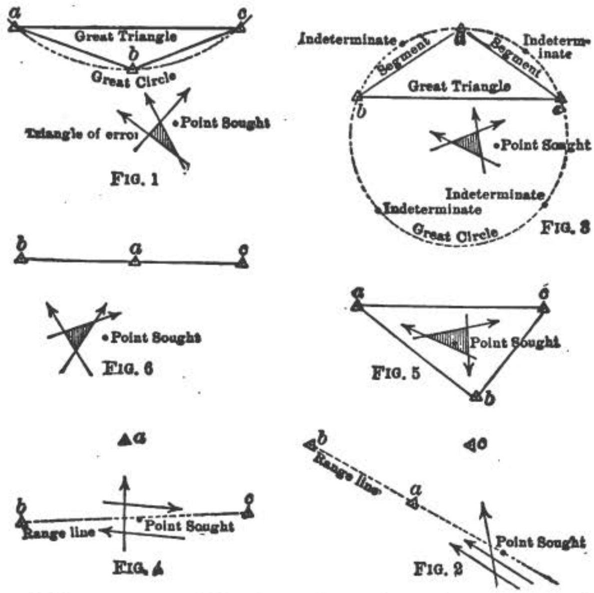


FIG. 417.—Different aspects of the three-point problem. The "point sought," in each case, is the correct position, on the map, of the station occupied. The arrows are the lines drawn toward the three stations in the field. (Reproduced by permission of John Wiley & Sons, Inc.)

be the observer's correct position on the map. Lay the alidade against this point and the most distant fixed point, rotate the table until the alidade sights are in line with the station represented by this fixed point on the map, and then check by sighting at the other two stations.

A third useful, but less accurate, solution is accomplished by means of tracing paper. Fasten the tracing paper to the board, orient the table by compass, let a point near the center of the paper be the observer's position, lay the alidade against this point, and sight successively at three distant stations already determined, each time drawing a line from the station of the set-up. Unfasten the tracing paper and shift it on the board until the three lines fall over the plotted points for the three distant stations. Prick through the observer's position. Test the correctness of the location in the way described for the preceding methods.

4. The *method of progression*, commonly termed *traversing*, is illustrated by Fig. 418. *a*, *b*, *c*, and *d* are points to be plotted. Let *a'* on the paper represent *a* on the ground. Set up the plane table at *a* and orient it by compass or, preferably, by backsight or resection from some fixed points. Place the fiducial edge of the alidade against *a'* and sight at *b*. Draw a line from *a'* toward *b*. Measure *ab* and lay off this distance, on the scale adopted for the map, along the line just drawn. This will locate *b'*. Set up at *b* and orient by backsight on *a*. Place the fiducial edge of the alidade at *b'*

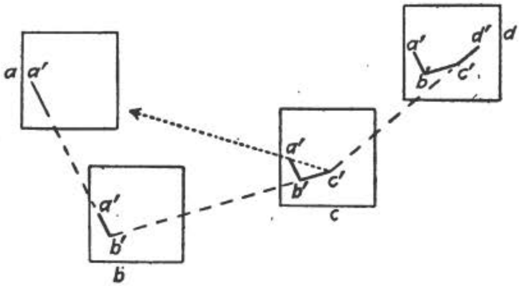


FIG. 418.—Mapping by the method of progression or traversing. The dotted line is a check sight line made by the observer at *c* looking toward *a*. The squares represent different positions of the plane table.

and sight toward *c*. Draw a line from *b'* toward *c*. Measure *bc* and lay off *b'c'*. Set up at *c*, orient by backsight on *b*, and continue as before. When possible sight back from a given station, such as *c* (Fig. 418), to an earlier station, such as *a*, and note whether the direction from *c* to *a* coincides with the line *c'a'*. This will serve as a check on the work. In passing, always tie the traverse to fixed points, previously located, and if there is an error of closure, correct that part of the traverse, which has not yet been corrected, as explained in **Art. 309**. At its end, too, the traverse line should be tied to a fixed point, and any error of closure should be corrected. The method of progression is useful for route maps along roads, streams, or across country. Features on one or the other side of the course are plotted in by eye estimate, by perpendicular offset with measured distance (*s* and *t* in Fig. 419), by radiation (*w*, *x*, *y*, in Fig. 419), or by intersection from two or more of the stations of the traverse (*m* in Fig. 419). Such intersection often helps as a check on the traverse.

Methods of Measurement.—As was stated above, mapping usually necessitates the measurement of directions and horizontal and vertical distances. By these three quantities each station is located with respect to other stations, *i.e.*, its three coördinates are determined. In most cases the initial station of a plot should be carefully located from ("tied to") a control point which has been previously established by precise methods, or, better, such a control point may itself serve as the initial station. A base line for a triangulation net may often be run with advantage between two fixed control points. In geologic surveying the choice of stations is governed by geologic features. Frequently they are outcrops. Contacts in particular should be traced and plotted.

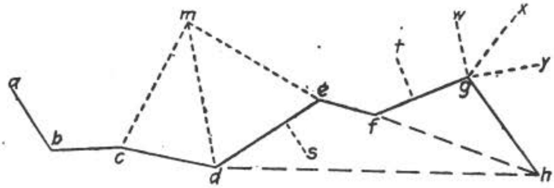


FIG. 419.—A plotted traverse, showing side points located by intersection (*m*), perpendicular offset (*s*, *t*), and radiation (*w*, *x*, *y*). *hf* and *hd* are check sight lines from *h*.

In the process of location, directions may be ascertained by observations with compass, sight alidade, or telescopic alidade, or by triangulation.[1] Distances are generally found by estimates of time consumed in travelling, provided the rate is essentially uniform; by counting paces of man or horse; by counting wheel revolutions; by observations with stadia rod and telescopic alidade; by triangulation; or by taping. Elevations may be obtained by eye estimates, or by barometer, clinometer (Abney or Brunton), hand level (Locke, Abney, or Brunton), or telescopic alidade and stadia rod.

A few words may be said here regarding the measurement of elevations and of distances on slopes. The elevation of each station is determined as the mapping proceeds. Wherever distances and directions are checked, elevations should likewise be checked. . If an error is discovered, it should be adjusted before continuing. In general it should be divided up, in proportion to intervening distances, between the stations occupied since the last similar correction was made. Elevations obtained by reading slope angles with clinometer or telescopic alidade may be checked by backsight. Any method of finding elevations may be checked by tying to control points approached in the course of the survey. In traversing it is a good plan occasionally to close on earlier stations of the course. An aneroid should always be reset at the proper altitude at such tie-points. It is often neces-

[1] The transit, although employed by geologists for certain special kinds of work, is not commonly used, and is therefore omitted in the present discussion. For plotting in mines it is often very convenient in combination with the stadia rod. The geologist then acts as · and chooses points of the traverse and points to which to radiate.

sary to have an assistant make readings, at regular intervals during the day, of a barometer which is kept in camp and which was set at the altitude of the camp at the same time that the field barometer was so set (see p. 481). A barograph, or self-recording barometer, left at headquarters may be a convenient substitute for the camp barometer. In the evening the field readings may be corrected with reference to the barometric records made in camp.

Distances which are measured on slopes must be reduced to their horizontal equivalents before they can be plotted. For slopes of 5° or less such correction is unnecessary. If, in Fig. 420, *ab* is the slope distance, *bc* the

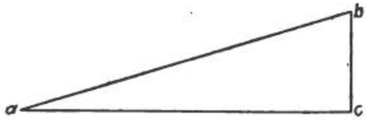


FIG. 420.—Section of a slope to illustrate slope distance (*ab*), horizontal or map distance (*ac*), and difference of elevation (*bc*).

elevation of the point *b* above *a*, *ac* the horizontal or map equivalent of *ab*, and $\angle\, bac$ the slope angle, then *ac* may be obtained by the equation, $ac = ab \cdot \cos \angle\, bac$, or by the equation, $ac = \sqrt{ab^2 - bc^2}$, according to whether the slope angle, $\angle\, bac$, or the difference of elevations, *bc*, has been determined. The slope angle may have been found by clinometer or by stadia rod and telescopic alidade, or the difference of elevations may have been obtained by hand level or barometer.

In pacing a special correction may be necessary because paces are shorter going uphill or downhill than they are on level ground. The following table may be used for finding the value, in terms of horizontal paces, of any number of paces on a slope of 30° or less.[1] Multiply the number of

TABLE FOR REDUCING PACES ON SLOPES TO THEIR EQUIVALENTS IN TERMS OF HORIZONTAL PACES

Angle of slope	0°	5°	10°	15°	20°	25°	30°
Gradient of slope	....	1/11.4	1/5.7	1/3.7	1/2.7	1/2.1	1/1.7
Factor for paces going uphill	1.000	0.907	0.799	0.717	0.625	0.542	0.413
Factor for paces going downhill	1.000	0.959	0.929	0.905	0.860	0.753	0.591

[1] Before using this table each individual should test it for his own paces measured on different slopes. He will do well to make a similar table for himself. As a matter of fact however, many geologists standardize their paces by walking several miles uphill and downhill over the kind of country to be mapped and computing an average pace length for the whole distance. This average pace is then adopted for all measurements of distance without reference to slope.

paces recorded on the slope by the factor in the table for that slope, thus: if a distance on a slope of 20°, going uphill, is 300 paces, the actual distance on the slope is equal to $0.625 \times 300 = 187.5$ horizontal paces. If the horizontal pace is equal to 2.5 ft., the distance *on the slope* is 2.5×187.5 ft. $= 468.75$ ft. After making this correction for the slope value of the paces, the slope distance obtained, here 468.75 ft., must be reduced to the horizontal by one of the equations given in the preceding paragraph. In using the table for slope factors, interpolate for slope angles not multiples of 5.

Methods of Instrumental Combination.—Some of the methods employed for locating points are less precise than others. For any given area to be mapped, the methods adopted for measuring the three quantities of direction, horizontal distance, and vertical distance, should be approximately of the same degree of accuracy. Ordinarily the plotting is done by one of the combinations listed below. In general these combinations are tabulated in the order of increasing possible accuracy of results.

METHODS USED IN COMBINATION FOR LOCATION OF STATIONS

	Directions measured by	Horizontal distances measured by	Vertical distances measured by	Mapping with
Traversing and radiation	Brunton compass	Pacing	Estimates by eye	Notebook or unoriented plane table
	Brunton compass	Pacing	Barometer	Notebook or unoriented plane table
	Brunton compass	Pacing	Brunton clinometer	Notebook or unoriented plane table
	Gurley compass or sight alidade	Pacing or wheel revolutions	Barometer or hand level	Oriented plane table
	Brunton compass	Tape	Brunton clinometer	Notebook or unoriented plane table
	Gurley compass	Tape	Hand level	Oriented plane table
	Telescopic alidade	Tape, stadia rod, and telescopic alidade		Oriented plane table
Triangulation and radiation	Gurley or sight alidade	Tape and alidade	Barometer or hand level	Oriented plane table
	Telescopic alidade	Tape and alidade	Stadia rod and alidade or vertical angulation	Oriented plane table

Limits of Error.—Distances obtained by pacing may be correct to 3 per cent. or less. The error may be reduced to 1 per cent. if the paces are frequently standardized. Taping, with ordinary precautions, is much more accurate, being correct to at least 1 in 3000. Compass traverses in which distances are measured by tape should be correct to 1 in 300. Triangulation performed with sight alidade and oriented plane table should be correct to 1 in 500, and with telescopic alidade and oriented plane table to 1 in 1000 or 1200. It should be noted that the error in location is equal to the error of the least precise method of measurement employed for the three quantities of direction, horizontal distance, and vertical distance. For instance, a compass traverse or a traverse with plane table and sight alidade is correct only to about 1 per cent. if the distances are measured by careful pacing. In any mapping the error permissible for elevations should be equal to that allowed for the horizontal control. For this reason, on the basis of the limits of error cited above, reduction of slope distances to their horizontal equivalents is unnecessary on slopes of 1 in 7 (about 8°), or less, for work in which distances are paced; on slopes of 1 in 12 (a little under 5°), or less, for compass traverses in which distances are measured by tape; on slopes of 1 in 15 (about 3° 30′), or less, for triangulation with sight alidade; and on slopes of 1 in 25 (a little under 2°), or less, for ordinary triangulation with telescopic alidade.

Choice of Method.—The choice of the particular method and combination of instruments to be used for mapping is conditioned by several factors of which the following are important: the character of the topography, the geologic structure, whether or not a control system of the area has been previously established, the nature of the cover (vegetation and culture), the object of the work, the cost, and the time available. In low, flat country and in heavily wooded land where there are no prominent landmarks for triangulation, points are located by traversing. Preliminary surveys of properties containing metalliferous deposits are often conducted by traversing with compass or clinometer, or with clinometer, sight alidade, and oriented plane table. For highly folded strata and for rocks of complex structure, the probable variations in strike and dip and the difficulty of finding the exact position of contacts render accurate methods of mapping infeasible. Yet, on mine properties, even in complex structure, the mapping may be done by precise methods if expectations justify the cost. In regions of low-dipping or horizontal strata containing coal, phosphate, oil, or other commercial products, mapping is done with telescopic alidade, stadia rod, and oriented plane table. Under all circumstances important features, when too small to map, are measured and recorded in the notebook.

Contour Sketching.—Occasions not infrequently arise when the geologist finds it of advantage to sketch contours. To do this, a contour interval adapted to the relief of the land and to the scale of the map must first be selected. In general a smaller interval will be used for low relief and for large scale. Mean sea level is commonly taken as the datum plane. The position of the first contour drawn on the plot will depend upon the altitude of station 1 above sea level and upon the slope of the ground between stations 1 and 2. As the mapping proceeds, the points where successive contours intersect the lines of sight are interpolated according to the differences of elevation between stations. The spacing of these points will naturally be close on steep slopes and wide on gentle slopes. Observations for relief should always be made at changes of slope. The contours themselves are sketched in by eye, the observer having due regard for the changes of slope, and for valleys, hills, and other topographic forms. Contour sketching is often done in connection with traversing. If the traverse runs across a slope, the geologist stops at any favorable locality, notes the distance from the last station, sights uphill or downhill perpendicular to the contours, and reads the slope angle in this direction. He plots the sight line on the map and marks off the points where the contours intersect this line at intervals which are determined by the slope angle. If the traverse runs up or down the slope, he can sight parallel to the contours and plot their directions adjacent to his course. When a few such lines with the contour intersections have been plotted, the contours themselves can be sketched.

Schedules for Geologic Mapping.—To illustrate certain methods of procedure in geologic mapping, the following schedules have been prepared. They will serve as a partial summary of the subject in hand. In using them, the reader must bear in mind that, since it is impossible to make such schedules applicable to the great variety of conditions which may arise, they may require modification or enlargement.

Schedule I. A Compass Traverse

Method.—Directions by Brunton; distances paced; elevations by barometer; plotting with notebook or unoriented plane table.

Conditions.—A control system established. A base map with a few control stations plotted. Camp (or headquarters) near one of the control stations.

Procedure.—

Preliminary.—(*a*) Rule base map with N.-S. and E.-W. coördinates. (*b*) Set the compass for true bearings. (*c*) Find the elevation of camp with reference to the adjacent control station, which may be called Sta. 1. (*d*) Arrange to have barometric readings recorded in camp. (*e*) Set the field and camp barometers at the elevation of camp.

At Station 1.—(*a*) Check barometer. (*b*) Mark a point on the map for Sta. 1, and record the elevation of Sta. 1. (*c*) Select a suitable point in the field for Sta. 2. (*d*) Find the bearing from 1 to 2 and plot this bearing on the map. (*e*) Observe and plot the bearings of any other objects to be located from Sta. 1.

Between Stations 1 *and* 2.—(*a*) Pace toward Sta. 2. (*b*) If necessary stop to make and plot offsets, or to record useful geologic information. (*c*) Always note and scale off the distance from Sta. 1 to the point of stopping. (*d*) Continue pacing toward 2.

At Station 2.—(*a*) Make a note of the distance, 1–2. (*b*) Check bearing by backsight on 1. (*c*) Scale off distance, 1–2. (*d*) Read barometer, estimate vertical distance of 2 above or below 1, and compute and record elevation of 2. (*e*) Select a suitable point in the field for Sta. 3. (*f*) Find the bearing from 2 to 3; etc., etc. (Continue as before. See (*d*) under Sta. 1.)

Whenever possible tie the traverse to another control station and make any necessary corrections.

Schedule II. A Compass Traverse

Method.—Directions by Brunton; distances paced; differences of elevation estimated by eye; plotting with notebook or unoriented plane table.

Conditions.—No control established; no base map or plat.

Procedure. —

Preliminary.—(*a*) Ascertain by inquiry the approximate elevation of the region above sea level. (*b*) Decide on a scale for the map. (*c*) Rule the map sheet with coördinates. (*d*) Set the compass for true bearings.

At Station 1.—(*a*) Mark a point for Sta. 1 on the sheet of paper for the map. (*b*) Assume a reasonable altitude for Sta. 1 and record this altitude beside the plotted position of Sta. 1. (*c*) Select a point in the field for Sta. 2. (*d*) Find the bearing from 1 to 2 and plot this bearing on the map. (*e*) Observe and plot the bearings of any other objects to be located from 1. (*f*) Estimate the vertical distance of 2 above or below 1, and make a note of this estimate.

Between Stations 1 *and* 2.—(*a*) Pace toward 2; etc., etc. (Same as in Schedule I.)

At Station 2.—(*a*) Make a note of the distance, 1–2. (*b*) Check bearing, 1–2, by backsight on 1. (*c*) Correct paced distance between 1 and 2 for slope, reduce to horizontal equivalent (p. 489), and scale off corrected distance on map, marking point for Sta. 2. (*d*) Record elevation of 2, as figured from its estimated vertical distance above or below 1, at position of 2 on the map. (*e*) Select a point in the field for Sta. 3. (Continue as before. See (*d*) under Sta. 1.)

Schedule III. Traverse with Oriented Plane Table

Method.—Directions by sight alidade; horizontal distances by pacing; vertical distances by clinometer; contours by clinometer; plotting with oriented plane table.

Conditions.—A control system established; a base map with a few control points plotted; one of these control points is taken as Sta. 1; another control point, *X*, is visible from Sta. 1.

Procedure.—

Preliminary.—(*a*) Rule the base map with N.-S. and E.-W. coördinates. (*b*) Select a contour interval.

At Station 1.—(*a*) Set up the plane table at Sta. 1 and orient it by the method of backsight on *X*. (*b*) Select a suitable point in the field for Sta. 2. (*c*) Sight at 2 and draw 1–2. (*d*) Determine the slope angle from 1 to 2 and record it. (*e*) Observe and plot the bearings of any other objects to be located from 1, or of slopes for contouring (see p. 492). (*f*) Fix the position of contours and sketch them in (p. 492).

Between Stations 1 *and* 2.—(*a*) Pace toward Sta. 2. (*b*) If necessary stop to make and plot offsets, or to record useful geologic information, or to take slope directions and slope angles for contouring. (*c*) Always note and scale off the distance from 1 to the point of stopping. (*d*) Continue toward Sta. 2.

At Station 2.—(*a*) Set up the plane table at 2. (*b*) Make a note of the distance, 1–2. (*c*) Correct this distance for paces on slope and reduce to horizontal equivalent. (*d*) Scale off the corrected distance, 1–2, on the map. (*e*) Orient the plane table by backsight on 1. (*f*) Select a suitable point in the field for Sta. 3. (Continue as before. See (*c*) under Sta. 1).

Schedule IV. Triangulation

Method.—Directions by telescopic alidade; base line measured by tape; other horizontal distances plotted by triangulation; vertical distances computed by stadia method; plotting with oriented plane table.

Conditions.—The elevation of Sta. 1 is either known or assumed; no plotted control; no base map.

Procedure.—

Preliminary.—(*a*) Rule the paper for the map with N.-S. and E.-W. coördinates. (*b*) Choose a suitable position for the base line. (*c*) Call one end of the base line Sta. 1 and the other end Sta. 2.

At Station 1.—(*a*) Mark a point on the map for Sta. 1 and record its elevation. (*b*) By observations on the sun or on Polaris[1] determine

[1] See text-books of surveying.

the position of a true north-south line passing through Sta. 1. (*c*) By reference to this north-south line orient the table and set the compass (to be used for any necessary radiation, traversing, strike-reading, etc.) for true bearings. (*d*) With the table oriented, sight at Sta. 2 and draw 1–2. (*e*) Note angle of inclination from 1 to 2.[1] (*f*) Sight at other stations to be located from 1 and draw lines from 1 toward them.[2] (*g*) Note also angles of inclination to these stations.[1]

Between Stations 1 *and* 2.—(*a*) Measure base line by tape.[2]

At Station 2.—(*a*) Scale off 1–2. (*b*) Carefully orient the table by backsight on 1 and check for inclination.[1] (*c*) Sight at all stations located from 1, and at any additional stations; draw lines on the map from 2 toward these stations; and note the angles of inclination[1] from 2 to each of them. (*d*) Call one of these stations 3.

Between Stations 2 *and* 3.—(*a*) Proceed to Sta. 3.

At Station 3.—(*a*) Orient by backsight on 2 and check for inclination. (*b*) Check also by sighting at other stations located from 1 and 2. (*c*) Sight at any additional stations, draw lines toward them, and note the angles of inclination from 3 toward them.

Continue thus from station to station, each time using one of the plotted sides of a triangle as a base for the further expansion of the system.

[1] Elevations of stations will be computed in the office from the scaled horizontal distances on the map and the recorded angles of inclination between stations.

[2] It is often better to measure the base line twice, once in each direction, before locating stations from 1 or 2.

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