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CHARLES D. WALCOTT, DIRECTOR

ROCK CLEAVAGE

BY

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
Washington, D. C., May 17, 1904.

SIR: I have the honor to transmit herewith the manuscript of a paper on rock cleavage, by Charles Kenneth Leith, and to recommend its publication as a bulletin.

The paper embodies the results of a very careful and laborious investigation of facts concerning rock cleavage and a discussion of their theoretical significance. Its publication will place the subject of rock cleavage in a much more satisfactory shape and be of material assistance to all structural geologists.

Very respectfully,
C. W. HAYES,
Geologist in Charge of Geology.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

ROCK CLEAVAGE.

By Charles Kenneth Leith.

INTRODUCTION.

DEFINITION OF CLEAVAGE.

Rock cleavage, as commonly defined in geological text-books, in effect, is a rock structure by virtue of which the rock has the capacity to part along certain parallel surfaces more easily than along others. It is possessed by a considerable proportion of the rocks of the lithosphere. It is usually distinguished from actual partings of a similar nature. The parallel structures may be original or secondary.

(1) Original structures are induced in the rock mainly during its solidification from a magma or deposition in water, though perhaps modified by subsequent static metamorphism. They comprise sedimentary bedding, flow structure of lavas, certain gneissic structures, and pegmatite structures.

(2) Secondary structures are induced by deformation through metamorphic processes subsequent to the formation of the rock. They have been given various names, such as cleavage, slatiness, schistosity, foliation, fissility, etc.

Generally, the secondary structure only has been considered under cleavage, but it is apparent that there is nothing in the definition of the term, rock cleavage, as above given, to prevent its application to any of these structures, whether original or secondary. It was so applied by Le Conte.[a] The writer believes that the facts presented in this paper will justify the conclusion that there is no essential difference between the original and the secondary structures; that in some cases they are not to be discriminated with certainty, and that both should be included under rock cleavage. Therefore, the term cleavage will be used as above defined; it will be confined to structure, and will have no significance as to origin. Where the

[a] Says Le Conte: "This structure is usually treated under metamorphic rocks, as a kind of metamorphism; but it is found in rocks which have not undergone ordinary metamorphic changes, and it is produced by an entirely different cause." Le Conte, J., Elements of Geology, 4th ed., 1896, p. 189.

origin of the structure is clear the term original, or secondary, may be prefixed.

The application of terms pertaining to cleavage, as here used, is summarized in the following table:

- *Rock cleavage.* (Cleavable rock.)
  - *Original cleavage.* (Protoclase or original-cleavage rock.)
    - Bedding.
    - Flow structure in lavas.
    - Parallel structure in certain gneisses.
    - Pegmatitic structure.
    - Parallel structure due to the arrangement of feldspars in certain gabbros, etc.
  - *Secondary cleavage.* (Metaclase or secondary-cleavage rock.)
    - *Flow cleavage.* Including in whole or in part: "Ultimate cleavage" of Sorby, "Cleavage" of most writers, "Slaty cleavage," "Cleavage proper," etc.
      - Schistosity. (Schists.)
      - Slatiness. (Slates.)
      - Parallel structure in certain gneisses. (Comes partly under schistosity.)
    - *Fracture cleavage.* Including in whole or in part:
      - Close joints cleavage.
      - False cleavage.
      - Strain slip cleavage.
      - Slip cleavage.
      - Ausweichungs cleavage.
      - Fissility in part. (The term is retained for closely spaced parallel partings.)
      - Rift.

In this classification several new terms required for the systematic classification of cleavage structures and cleavable rocks have been introduced. *Protoclase* may be defined as a rock possessing a cleavage originally developed during sedimentation under water or cooling from magma, such as bedding, flow structure, etc. *Metaclase* may be defined as a rock possessing a cleavage secondarily developed during rock deformation. Secondary cleavage is considered under the heads of *fracture cleavage* and *flow cleavage*. *Fracture cleavage* is conditioned by the existence of incipient, cemented, or welded parallel fractures, and is independent of a parallel arrangement of the mineral constituents. *Flow cleavage* is conditioned solely by a parallel arrangement of the mineral constituents. Fracture cleavage is a phenomenon of the zone of fracture, and flow cleavage of the zone of rock flowage. The structures are correlative, just as jointing and folding are correlative. The fitness of these terms will not be argued here, but it is hoped that it will appear from the following discussion.

IMPORTANCE OF METACLASIC STRUCTURE OR SECONDARY ROCK CLEAVAGE.

Secondary rock cleavage is found wherever rocks have been much deformed under conditions of rock flowage, and especially in mountainous areas and regions of ancient crystalline rocks. The correct interpretation of the structure throws light on the nature of rock deformation in general and its relation to the stresses producing it, and hence is of fundamental significance in determining the nature of mountain-making movements and stresses. Since so large a proportion of the rocks of the lithosphere develop this peculiar structure in adjusting themselves to the earth's stresses, there is warrant for the attempt to determine the true nature of the structure and the reason for its occurrence.

LITERATURE ON SECONDARY ROCK CLEAVAGE.

The literature on secondary rock cleavage is voluminous, but the conclusions thus far reached are so diverse that the geologist is still in doubt as to the true explanation of the phenomenon. An attempt is made below to outline the well-known hypotheses and to indicate what points are still under controversy.

The English geologists seem to have been the first to seriously attempt the explanation of secondary rock cleavage. Among them Sedgwick[a] should receive the first mention. His theory (proposed in 1829), that cleavage is due to the parallel arrangement of individual particles making up the rock mass, caused by "crystalline or polar" forces acting on the whole mass "simultaneously in given directions" and "with adequate power," was long and widely accepted. In 1838 Fox[b] published an account of the development of cleavage in clay used in the separation of copper and zinc in an electric battery. Because of the work of Sedgwick and Fox, cleavage was usually explained in the first half of the last century as due to "crystalline," "polar," or "magnetic" forces, terms evidently carrying somewhat vague meanings and well illustrating the state of knowledge on the subject at that time.

About the middle of the last century there appeared notable contributions to the subject by Darwin,[c] Dana,[d] Sharpe,[e] Sorby,[f] Tyndall,[g]

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[a] Sedgwick, Adam, Remarks on the structure of large mineral masses, and especially on the chemical changes produced in the aggregation of stratified rocks during different periods after their depositions: Trans. Geol. Soc. London, 2d ser., vol. 3, pt. 1, 1835, pp. 461–486.

[b] Fox, R. W., On the lamination of clay by electricity: Edinburgh New Philos. Jour., old ser., vol. 25, 1838, pp. 196–198.

[c] Darwin, Charles, Geological Observations on South America during Years 1832–1836, pp. 161–168. Published in 1846.

[d] Dana, J. D., Silliman's Am. Jour., 1st ser., vol. 45, 1843, pp. 107–108.

[e] Sharpe, Daniel, On slaty cleavage: Quart. Jour. Geol. Soc., vol. 3, 1847, pp. 74–105, and vol. 5, 1849, pp. 111–129. On the arrangement of the foliation and cleavage of the rocks of the north of Scotland: Philos. Trans. Royal Soc. for 1852, 1852, pp. 445–461. Contains references to early work by De la Beche, Austin, Hunt, Murchison, and others.

[f] Sorby, H. C., Edinburgh New Philos. Jour., old ser., vol. 55, 1853, pp. 137–148; ibid., new ser., vol. 4, 1856, p. 339 et seq.; ibid., vol. 6, 1857, p. 316 et seq.; Philos. Mag., 4th ser., vol. 11, 1856, pp. 20–36; ibid., vol. 12, 1856, pp. 127–128; Quart. Jour. Geol. Soc. for Nov., 1863, pp. 401–406.

[g] Tyndall, John, Comparative view of the cleavage of crystals and slate rocks: Philos. Mag., 4th ser., vol. 12, 1856, pp. 35–47, 129–135.

and Phillips.[a] All subsequent contributions have contained in whole or in part the essential conclusions of these men. Among those who have added to or modified the theories of rock cleavage proposed by the scientists above named, the following should be particularly mentioned: King,[b] Daubrée,[c] Harker,[d] Becker,[e] Van Hise,[f] Hoskins,[g] and Adams and Nicolson.[h] Many other names might well be included, such as Dale,[i] Hutchings,[j] and Reade and Holland,[k] but the men named have suggested, emphasized, or modified some particular feature of the subject, and a discussion of their conclusions will indicate with a fair degree of clearness the present state of knowledge of the subject, and will obviate a tedious bibliographical discussion.

SECONDARY CLEAVAGE IN ITS RELATION TO A PARALLEL ARRANGEMENT OF MINERAL CONSTITUENTS.

All the writers above named, except Tyndall, King, Daubrée, and Becker, have assumed rock cleavage to be for the most part dependent on a parallel arrangement of the greatest, mean, and least dimensions of the mineral particles of unequal dimensions making up the rock mass. Sorby[l] was the first to maintain that the best cleavage exists in rocks which contain minerals "whose length and thickness differ most." Dana[m] and Van Hise[n] have in addition proposed and amplified the idea that the mineral cleavage of the parallel-arranged particles

[a] Phillips, John, Report on cleavage and foliation in rocks, and on the theoretical explanation of these phenomena (pt. 1): Rept. 26th Meeting Brit. Assoc. Adv. Sci., held 1856, pp. 369-396. Published in 1857.

[b] King, W., On the structure of rocks called jointing: Trans. Royal Irish Acad., vol. 25, 1875, pp. 605-662.

[c] Daubrée, A., Géologie expérimentale, vol. 1, 1879, pp. 407-418.

[d] Harker, A., On slaty cleavage and allied rock structures, with special reference to the mechanical theories of their origin: Rept. 55th Meeting Brit. Assoc. Adv. Sci., held 1885, published in 1886, pp. 813-852. Contains bibliography.

[e] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 13-90. Schistosity and slaty cleavage: Jour. Geol., vol. 4, 1896, pp. 429-448. Experiments on schistosity and slaty cleavage: Bull. U. S. Geol. Survey No. 241, 1904, 32 pp.

[f] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 633-668. Deformation of rocks, pt. 3, Cleavage and fissility: Jour. Geol., vol. 4, 1896, pp. 449-483. Metamorphism of rocks and rock flowage: Bull. Geol. Soc. America, vol. 9, 1898, pp. 269-328. A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 748-763.

[g] Hoskins, L. M., Flow and fracture of rocks as related to structure: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845-874.

[h] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flowage of marble: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1900, pp. 363-401.

[i] Dale, T. N., The slate belt of eastern New York and western Vermont: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1899, pp. 163-307. Contains bibliography. Structural details in the Green Mountain region and in eastern New York: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 549-570.

[j] Hutchings, W. M., Clays, shales, and slates: Geol. Mag., new ser., dec. 4, vol. 3, 1896, pp. 309-317, 343-350.

[k] Reade, T. M., and Holland, Philip, The green slates of the Lake district, with a theory of slate structure and slaty cleavage: Proc. Liverpool Geol. Soc., 1900-1901, pp. 101-127. The phyllades of the Ardennes compared with the slates of North Wales: Proc. Liverpool Geol. Soc., pt. 1, 1897-98, pp. 274-293, and pt. 2, 1899-1900, pp. 463-478.

[l] Philos. Mag., vol. 12, 1856, p. 128.

[m] Loc. cit., p. 107.

[n] Jour. Geol., vol. 4, 1896, p. 453.

may aid in giving a secondary rock cleavage. Dana's conclusion is expressed in the words, "Modern igneous rocks are laminated, and in general more or less so according to the quantity and cleavability of the cleavable minerals they contain. Mica, the most perfectly foliated mineral, produces, when abundant and not overruled by other constituents, the most perfectly laminated rock." Van Hise has concluded that "rock cleavage is due to the arrangement of the mineral particles with their longer diameters or readiest cleavage, or both, in a common direction."

On the other hand, Tyndall[a] and Daubrée[b] performed experiments from which they concluded that secondary rock cleavage is independent of any parallel arrangement of the constituent particles. King[c] also maintained that cleavage, while perhaps in part due to a flaky or dimensional arrangement of the mineral constituents, "is essentially the result of pressure exerted against divisional planes, chiefly belonging to jointing, that existed in any given rock prior to its becoming affected by such pressure." Becker,[d] largely from a mathematical and experimental analysis of the relations of cleavage to pressure, later reached the conclusion that cleavage is essentially independent of any parallel arrangement of the mineral constituents, although such parallel arrangement may be present as an incidental result of the development of cleavage.[e]

MANNER IN WHICH A PARALLEL ARRANGEMENT OF MINERAL CONSTITUENTS IS BROUGHT ABOUT.

Those who maintain that the parallel arrangement of minerals is an essential condition for secondary rock cleavage differ among themselves as to the manner in which this arrangement is brought about. Sedgwick and Fox, followed by others, referred the parallel arrange-

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[a] Philos. Mag., vol. 12, 1856, p. 37.

[b] Géologie expérimentale, vol. 1, 1879, p. 413.

[c] Trans. Royal Irish Acad., vol. 25, 1875, p. 657.

[d] Bull. Geol. Soc. America, vol. 4, 1893, pp. 79, 80.

[e] Becker summarizes his view as follows (Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3, p. 206):

"Slaty cleavage is produced when a solid but plastic mass, firmly supported on one side, experiences a pressure on the opposite side which is not perpendicular to the supporting surface. The resulting cleavage has a direction intermediate between that of the applied force and the fixed support. The cleavage itself makes with the deforming force an angle which may vary between a very small value and one equaling or even exceeding 45°. The firm support of the deformed rock required by the theory may be afforded either by a purely material resistance or by any combination of forces which prevents the mass from rotating as a whole while undergoing deformation. Lateral pressures not equal in all directions appear to be of minor importance so long as they do not interfere with the condition that the angle between the resultant force and the fixed support shall differ sensibly from 90°. The origin of the cleavage as conceived in this theory is incipient "solid flow," which is a different thing from liquid flow. The production of cleavage should usually be accompanied by the formation of master joints at angles to the cleavage approaching 90°, and the direction of the pressure is perpendicular to the intersection of the cleavage with such joints, intersecting (but not exactly bisecting) the obtuse angle. The grain of the slate should be parallel to this intersection. In general there should be an elongation in the direction of the grain and a contraction in the plane of cleavage at right angles to the grain."

See also Becker, G. F., Experiments on schistosity and slaty cleavage: Bull. U. S. Geol. Survey No. 241, 1904.

ment to "crystalline," "polar," or "galvanic" forces. Darwin[a] supposed the arrangement to have been induced by "tension," "before the final consolidation of the mass and the total cessation of molecular movement." Sorby[b] assumed the previous existence of flat particles and supposed their arrangement to be due to rotation during the secondary deformation of a rock by shortening of the rock mass in one direction and elongation in a perpendicular direction, but he concluded also that other particles may have been flattened in situ, and that some of the parallel flat particles are secondary developments, particularly in "schists," which he distinguished from "slates." Sharpe[c] supposed every particle in a deformed rock to have taken part in the elongation and shortening which the rock underwent, thus accounting both for the flatness of the particles and for their parallel arrangement. Sharpe[d] concluded also that, while "no connection has been detected between cleavage and crystallization beyond the tendency of mica and talc to arrange themselves along the planes of cleavage," still on these planes "there would be the least resistance to their intrusion or formation" and the development of such minerals "may have been a subsequent operation." Van Hise[e] believes the causes of the parallel arrangement conditioning rock cleavage to be, first and of most importance, the parallel development of new minerals; second, the flattening and parallel rotation of old and new mineral particles; and third and of least importance, the rotation into approximately parallel positions of particles which had originally a random arrangement. Van Hise thus differs from Sorby in maintaining the predominance of the new development of minerals, which was suggested by Sorby only as a minor detail. Adams and Nicolson deformed limestone at temperatures of 300° and 400° C., and obtained a flattening of calcite particles, and thus a parallel structure, through twinning and gliding, a movement which occurs also in the deformation of metals and ice. At ordinary temperatures the flattening produced in this way was associated with actual granulation of the particles. Comparing the results of experiments with the deformation observed in marbles in the field, they concluded that while "recrystallization undoubtedly plays an important, and in many cases probably a chief, part in the great movements which are observed to have taken place in the limestones of contorted districts, this process is by no means the only one by which such movements are brought about."[f] They may be brought about by the development of cataclastic structure and through gliding and twinning of the constit-

[a] Philos. Mag., vol. 12, 1856, p. 168.

[b] Edinburgh New Philos. Jour., vol. 55, 1853, pp. 137-148. Quart. Jour. Geol. Soc., vol. 19, 1863, pp. 401-406.

[c] Quart. Jour. Geol. Soc., vol. 3, 1847, p. 74-105.

[d] Quart. Jour. Geol. Soc., vol. 5, 1849, p. 129.

[e] Jour. Geol., vol. 4, 1896, p. 453. Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 635.

[f] Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1900, p. 398.

uent crystal particles. The latter processes give a parallel arrangement of the particles. They concluded further that the "flowage of the granite and other harder crystalline rocks" (and, presumably, a parallel arrangement of the deformed particles) might be induced in much the same way.[a]

The processes resulting in the deformation of rock masses have been discussed by many other writers,[b] who do not emphasize the development of parallel arrangement of mineral particles, resulting from the deformation.

TWO STRUCTURES INCLUDED UNDER CLEAVAGE, ONE OF THEM NOT DEPENDENT UPON A PARALLEL ARRANGEMENT OF MINERAL CONSTITUENTS.

Sorby,[c] in 1857, showed that cleavage properly included two distinct phenomena, a capacity to part along incipient parallel fractures independent of any parallel arrangement of the minerals, and a capacity to part parallel to, and conditioned by, the parallel arrangement of the mineral constituents. The first he called "close-joints cleavage," and the second "ultimate structure cleavage." A similar view was held in 1878 by Professor Heim,[d] who discriminated an "ausweichungs cleavage" which results from a succession of small displacements or faults, usually in connection with overfolds, and independent of any parallel arrangement of mineral constituents, from another cleavage called in part "micro-cleavage," which is dependent for its existence on the parallel arrangement of the mineral constituents. Harker,[e] in 1886, used the term cleavage "in a sense sufficiently wide to include not only the structure discussed under the name slaty cleavage proper, but also other structures, which though effectively identical with it have been produced in a different manner;" that is, in the manner described by Sorby and Heim for their "close joints" and "ausweichungs" cleavage. Van Hise[f] in 1896 distinguished *cleavage* or capacity to part, dependent on a parallel arrangement of the mineral constituents, from *fissility*, "a structure in some rocks by virtue of which they are already separated in parallel laminae in a state of nature," and do not necessarily require a parallel arrangement of the mineral constituents, although this is usually developed in rocks showing this structure. As thus defined, fissility is a phenomenon quite separate and distinct from cleavage. But Van Hise in a subsequent discussion used the term fissility also for rocks in which the

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flowage of marble: Philos. Trans. Royal Soc. London, ser. A., vol. 195, 1900, p. 399.

[b] See excellent summary by Adams, op. cit.

[c] Rept. 27th Meeting Brit. Assoc. Adv. Sci., held 1857, p. 92. Published in 1858.

[d] Uber den Mechanismus der Gebirgsbildung, vol. 2, 1878, pp. 51–58.

[e] Rept. 55th Meeting Brit. Assoc. Adv. Sci., held 1885, p. 836. Published in 1886. Contains bibliography.

[f] Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 633. Jour. Geol., vol. 4, 1896, pp. 449–450.

parallel fractures are incipient or have been cemented or welded, giving the rock a capacity to part, or cleavage, rather than an actual parting. Other terms which have been used for cleavage developed in this manner are rift, fault-slip cleavage, slip cleavage, and false cleavage.

FALSE CLEAVAGE.

"False cleavage," or "grain," or "bate cleavage," normal to cleavage proper, was noted by several of the early observers, Sedgwick,[a] Phillips,[b] and De la Beche,[c] and by many later investigators. Sharpe and many following him have concluded that the structure is due to breaking along the greater or mean axes of the mineral particles arranged parallel, but others have held that the structure is due to obscure divisional planes developed in the manner of fracture cleavage.

CLEAVAGE IN ITS RELATIONS TO DIRECTION OF APPLICATION OF THE PRESSURE PRODUCING IT.

Concerning the relations of secondary cleavage or parallel arrangement of minerals, or both, to pressure, there is again considerable difference in the views held. Sharpe,[d] Sorby,[e] and Tyndall[f] held that cleavage develops in planes normal to the greatest pressure, the two latter having produced it in such planes experimentally. Sharpe supposed also that heat and "galvanism" may have helped pressure, and Sorby admitted the existence of another cleavage structure, his "close-joints cleavage," presumably developed with inclination to the pressure in the manner of joints. King argued that slaty cleavage is the result of "pressure exerted against divisional planes, chiefly belonging to jointing, that existed in any given rock prior to its becoming affected by such pressure,"[g] the preexisting divisional planes having developed in planes inclined to the greatest compression in a manner common to jointing structures. Daubrée[h] produced cleavage parallel to the direction of flow by forcing plastic clay through a cylinder. Becker,[i] in 1893 and 1904, maintained on mathematical grounds that slaty cleavage is developed along planes inclined to the greatest pressure. In

[a] Synopsis Classification British Paleozoic Rocks, London, 1854, p. xxxv.

[b] Phillips, John, On a group of slate rocks ranging east-southeast between the rivers Lune and Wharfe, from near Kirby Lonsdale to near Malham, and on the attendant phenomena: Trans. Geol. Soc. London, 2d ser., vol. 3, pt. 1, 1829, pp. 1-19.

[c] Geol. Observer, 2d ed., 1853, p. 588, fig. 239.

[d] Quart. Jour. Geol. Soc., vol. 3, 1847, p. 75.

[e] Philos. Mag., vol. 11, 1856, p. 26.

[f] Philos. Mag., vol. 12, 1856, p. 37.

[g] Trans. Royal Irish Acad., vol. 25, 1875, p. 657.

[h] Géologie expérimentale, vol. 1, 1879, p. 413.

[i] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 13-90. Experiments on schistosity and slaty cleavage: Bull. U. S. Geol. Survey No. 241, 1904.

1896 Van Hise and Hoskins[a] held that cleavage, during deformation, develops at any instant in planes normal to the greatest pressure, but that the final direction of cleavage may be inclined to the direction of greatest pressure which has produced the deformation. This conclusion was based on field observations by Van Hise and on mathematical analysis by Hoskins. Their "fissility," corresponding essentially with Sorby's "close-joints cleavage," develops, they maintain, in the manner of fractures in shearing planes inclined to the greatest pressure.

PURPOSE OF PRESENT PAPER.

It will be fundamentally assumed that secondary rock cleavage is of two kinds, which differ widely in their essential causes and conditions. Abundant evidence of the truth of the assumption appears, it is believed, in the facts here recorded. The cleavage developing during rock flowage (or the deformation of rock without conspicuous fracture) will be called *flow cleavage*, and that developing through the deformation of rock by fracture and subsequent cementation will be called *fracture cleavage*.

In distinguishing the two kinds of cleavage the writer is in essential accord with Sorby, Heim, Harker, Van Hise (if his fissility be in part called cleavage), and others. The term fissility is retained for closely spaced parallel partings as defined by Van Hise, but is not extended to include the capacity to part fractures, which is properly a cleavage, and is here called fracture cleavage.

One of the principal causes of confusion in the discussion of cleavage has been the attempt by some authors to make the explanation of one kind of cleavage apply to all cleavage. On the one hand, the parallel arrangement of mineral constituents has been held to be essential to all cleavage, and, on the other, the parallel fractures independent of any arrangement have been strongly urged as sufficient cause for all cleavage.[b] An attempt will be made to show that each of these explanations is adequate for one kind of cleavage, but not for all cleavage. Especial emphasis will be placed on the proof that incipient or cemented parallel fractures, yielding what is here called fracture cleavage, will not explain what is here called flow cleavage, or cleavage dependent upon the parallel arrangement of the mineral constituents. This will require detailed discussion of the internal arrangement of the mineral constituents of rocks with each kind of cleavage, the relations of this arrangement to the observed cleavage, the nature of the processes bringing about the arrangement, and the relations of the arrangement to pressure. Especial attention will be paid to the causes and conditions of flow cleavage, which is the most characteristic structure in rocks ordinarily considered cleavable.

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[a] Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 638. Jour. Geol., vol. 4, 1896, p. 457.

[b] Becker, G. F., Experiments on schistosity and slaty cleavage: Bull. U. S. Geol. Survey No. 241, 1904.

The prevailing differences of opinion concerning the relations of cleavage to the arrangement of mineral particles, the processes bringing about the arrangement, and even the relations of cleavage to pressure, may be traced in part to vague and incomplete knowledge of the intimate nature of cleavage itself. Students of the subject have made numerous careful observations, but with a few exceptions have confined their observations to one aspect of the subject. There is thus a need of systematic microscopical study of cleavage of rocks of all kinds from many localities, with a definite purpose of ascertaining the exact arrangement of the mineral particles, the relations of the observed arrangement to cleavage, and the relations of cleavage to the deformation of rocks. The present investigation has attempted to supply in some degree this observational deficiency. With the basis of observed fact thus obtained it is possible to present with some degree of confidence certain general conclusions as to the origin and conditions of cleavage.

The phenomena of flow cleavage will be treated in Part I. Part II will be devoted to fracture cleavage, and a comparison of fracture cleavage and flow cleavage. Original cleavage of bedding, flow structure, etc., will be treated independently in Part III.

MATERIAL USED IN INVESTIGATION.

The material studied has been drawn from the rock collection of the section of pre-Cambrian and metamorphic geology of the United States Geological Survey, numbering 40,000 specimens and upward of 15,000 thin sections, representative of the principal crystalline schist areas of North America; from the metamorphic rocks belonging to the Wisconsin Geological Survey; and from the University of Wisconsin collection of metamorphic crystalline rocks from various parts of North America and Europe, including specimens of most of the well-known metamorphic cleavable rocks of both continents. From the Survey and university material a large number of typical specimens and slides were selected for special study. Where any feature was especially well exhibited in the slide, or where the slide had been cut in planes indeterminate with reference to the rock cleavage, new sections were cut, usually in three mutually perpendicular directions, with known relations to cleavage. Perhaps 1,000 specimens and slides were selected for close study, and of these 250 slides were specially prepared. In addition to the metamorphic crystalline rocks, a considerable number of semicrystalline and partly consolidated sediments in the same collections were examined. Finally several specimens and slides of typical cleavable rocks from various parts of North America were loaned by men who had collected and studied them. It is believed that the conclusions as to the causes and conditions of rock cleavage, which are based on the study of the great variety of cleavable rocks available from widely separated localities, will apply to cleavable rocks in general. It is inevitable, however, that certain phenomena are more apparent than others in the particular slides examined, and thus that these phenomena will be overemphasized in the following discussion and others will receive less attention than they should. Further work will doubtless show modification of emphasis to be necessary.

Illustrative specimens and slides are cited in the text. Where no letters are attached the numbers refer to the collection of the section of pre-Cambrian and metamorphic geology of the United States Geological Survey. The letter W. with a number signifies Wisconsin Geological Survey, U. W., University of Wisconsin, H., Hobbs, and C., Clements.

EXPERIMENTAL WORK.

This report, in substantially the present form, was submitted for publication in the spring of 1903, and was referred to a committee consisting of Messrs. Whitman Cross and George F. Becker. On the recommendation of Doctor Becker, publication was postponed until he and the writer might jointly perform experiments, which had been planned by Doctor Becker, on the artificial development of cleavage. In December, 1903, a few days were spent on these experiments in the chemical and physical laboratory of the United States Geological Survey at Washington. It was planned to continue the experiments at a subsequent date, but opportunity did not recur. The results, which were not decisive, are referred to on pages 126–130. So far as they were carried, the experiments did not seem to the writer to require a modification of the views here stated. Further, so largely is the present report a record of observed facts of cleavage produced by nature, with only such general conclusions as would obviously follow, that it is not thought likely that further experimental work would require essential modification, although it would doubtless make possible a more definite and mathematical treatment of the subject and aid in the interpretation of the facts observed.[a]

ACKNOWLEDGMENT.

The investigation here reported upon was undertaken at the suggestion of Dr. C. R. Van Hise, was carried on under his supervision, and the results reviewed by him. The paper, as it stands, is in considerable part an expression—amplified, modified, and accompanied by

[a] While the above paragraph was in proof, the writer received a report by Doctor Becker on Experiments on schistosity and slaty cleavage (Bull. U. S. Geol. Survey No. 241, 1904), which covers the experimental work above referred to, as well as work previously and subsequently done by Doctor Becker. The conclusions reached are essentially the same as in Doctor Becker's previous papers (cited p. 14), in which, as it seems to the writer, the attempt has been made to apply one explanation to two distinct cleavage phenomena. Doctor Becker's conclusions are, as he states, "founded on experiment and analysis." He does not attempt to describe the facts as shown by the rocks themselves. His method is deductive. The writer's point of view is almost altogether different. He has attempted, after the inductive method, to study the facts in the field and laboratory and to point out their significance.

detailed proof—of general ideas which he had obtained from his own observations on rock cleavage. For this material aid, as well as for unusual facilities for study, the writer is pleased to acknowledge his indebtedness to Doctor Van Hise.

Thanks are due Prof. L. M. Hoskins, of Leland Stanford Junior University, and Prof. E. R. Maurer, of the University of Wisconsin, for helpful suggestions and criticisms of the parts of this paper dealing with the laws of mechanics.

For the loan of specimens and slides the writer is indebted to Profs. William H. Hobbs and J. Morgan Clements, of the University of Wisconsin; Dr. Samuel Weidman, of the Wisconsin Geological Survey; Prof. Frank D. Adams, of McGill University, Montreal, and Messrs. Whitman Cross and Ernest Howe, of the United States Geological Survey, Washington; and for a large number of measurements of the dimensions of parallel arranged minerals, to Mr. Sydney H. Ball, of the University of Wisconsin.

PART I.

FLOW CLEAVAGE.

By flow cleavage is meant the cleavage dependent on the parallel arrangement of the mineral constituents of the rock, an arrangement which will be shown to be developed during rock flowage.

In studying flow cleavage the following queries have been kept in mind:

Do the particles of the same mineral species in a cleavable rock show variation in shape, or are they uniform throughout? If they vary, do their dimensions show variations proportional to the amount of deformation which the rock shows? Are the greatest and mean axes of the mineral particles always parallel to the rock cleavage? Do the particles of the same mineral species show a parallelism of their vector or directional properties—i. e., properties related to direction in crystals, such as cohesion, elasticity, optical, thermal, electrical and magnetic properties, and crystalline form? Do the minerals ever exhibit a parallelism of vector properties and not a dimensional parallelism, or vice versa? Are they arranged dimensionally parallel and with no parallelism of their vector properties? Are both dimensional and vector properties parallel; and if so, to what extent? To what extent is cleavage independent of any parallel arrangement of the mineral constituents?

CHAPTER I.

MINERAL ARRANGEMENT IN ROCKS WITH FLOW CLEAVAGE.

Comparatively few minerals make up the great bulk of the rocks possessing secondary flow cleavage. The micas, including muscovite and biotite, chlorite, hornblende, quartz, and feldspar, are in greatest abundance, making up perhaps nine-tenths of them. Other minerals, characteristic though less abundant, are calcite, tremolite, actinolite, garnet, tourmaline, staurolite, chloritoid, sillimanite, etc. Olivine and the pyroxenes are rare in the typical rocks showing flow cleavage, for the most part having been altered to one or more of the minerals above named. In the following discussion the first-named group of minerals will receive the most attention. Discussion of the remaining minerals on the same scale would unduly extend the paper and complicate the conclusions. Many of the features of arrangement of the constituents of cleavable rocks below described are well known, indeed almost axiomatic, to petrographers, but it is necessary again to present them in order to secure a firm basis for generalizations.

MICA.

Of the minerals in rocks with flow cleavage the micas are by far the most characteristic. Muscovite, sericite, and biotite are the common micas of these rocks, and these alone are considered; statements concerning them will apply nearly as well to the rarer micas. The common association of the micas is with quartz and feldspar, making up rocks which are called, because of the relative abundance of the constituent minerals or because of their texture, micaceous schists, micaceous gneisses, quartzose schists, slates, phyllites, etc. It is preferred in this paper to use the mineral prefix as an adjective, as in the term micaceous schist.

The micas are monoclinic but pseudo-hexagonal in symmetry. The basal plane has a hexagonal or rectangular outline. The characteristic physical feature is the perfect cleavage parallel to the base.

As is well known, mica in cleavable rocks is arranged in plates parallel to its own perfect basal cleavage. The plates are observed to be parallel or nearly parallel to an observed plane of cleavage in the micaceous cleavable rocks. In sections cut normal to the plane of cleavage the mica cleavage plates appear as narrow laths with parallel extinction, usually crowded into layers. Sections cut parallel to the plane of rock cleavage show basal planes of the micas, the biotites nearly isotropic and the muscovites highly refracting. Study of the micas in slides in these two directions yields interesting results.

Mica plates looked at normal to their flat surface do not show any great uniform difference in dimensions. They are commonly of rather irregular shape, sometimes hexagonal and sometimes rectangular, but in any case with slightly unequal dimensions as shown by average measurements. So far as there is any difference in the dimensions of the plates, they may show a small degree of parallelism of their greatest and mean diameters in the plane in which they lie. In some slides a parallelism somewhat similar to that indicated in fig. 1 is to be seen. This in most cases would probably be overlooked if the other minerals in the slide did not usually show a better parallel arrangement of the same kind, and thus indicate where the parallelism of the micas is to be looked for. It will be seen that the mica plates are not strictly parallel to a plane, and hence a section cut parallel to the plane most nearly common to all plates is likely to show oblique sections of many plates, and any faint tendency to parallelism of the greatest and mean diameters of the plates in this plane may not appear in the slide.

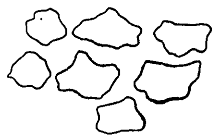

FIG. 1.—Rough parallel arrangement sometimes shown by the greatest and mean diameters of mica plates lying in the plane of rock cleavage.

Slides cut across the plane of cleavage of rock containing biotite or muscovite show roughly parallel aggregates of mica plates, bounded by their excellent basal cleavage planes. In cross section they look like laths. The laths are commonly concentrated into layers, with other minerals, such as quartz, intervening (Pl. X). Each mica crystal shows several cleavage laminæ, perhaps due to incipient movement, but the crystal is still evidently a unit.

While there is a characteristic parallelism of mica plates, the deviations from this arrangement are numerous and marked. These irregularities may be seen to be in the neighborhood of harder minerals which have been relatively rigid during deformation, but are present also where the harder minerals are evenly arranged in bands or are very subordinate in quantity. Irregularities are also occasionally due to the development of micas in cracks or along the cleavage of minerals, such as feldspar. The irregularities in the parallel arrangement are of two kinds: (1) They may be due to actual bending or breaking of the mica plates themselves (Pl. II, *B*), in which cases there may be considerable gliding or slipping between the mica laminæ. These bendings are sometimes so great as to make the cleavage more nearly parallel to an axis than to a plane, giving it an approach to linear or "pencil" cleavage (Pl. I). The minute folds so formed may also give a capacity to part parallel to one of the limbs of the fold (Pl. XIV, *B*), thus yielding a structure to which in part the term false cleavage has been applied. (2) Irregularities are formed by unbroken or unbent plates abutting against each other at low angles, producing a characteristic feathering out of one set of laminæ diagonally against another set, as shown in fig. 2 and Pl. II, *A*. A hasty examination of such separate groups of plates gives the impression of bending and breaking, particularly where the micas are about a core of some harder mineral. The angles which these contiguous plates make with one another average less than 15°. Not infrequently this change in direction is accompanied by a change in substance; one mica may be a muscovite and the other a biotite. This curious feathering out of the laminæ of the mica against one another is exceedingly characteristic, and is usually present where there has been no contortion of the mica plates. For its explanation see page 114. It is to be noted that while the irregularities about hard particles give a structure with a mesh appearance, where the micas come together at the ends of a hard particle they do not cross each other, but change their direction in either of the ways above described until they run nearly parallel.

The above description applies to both biotite and muscovite. The two micas, however, show these general features in different degrees, and biotite shows certain features which have not yet been mentioned. It may sometimes be seen in cross section in stumpy porphyritic crystals whose cleavage lies at any angle to the rock cleavage (Pl. III).[a] The other constituents of the rock may bend around them, may stop at their peripheries, or may pass through them without change of direction; in other words, in the last-named case the biotites have the same characteristics of occurrence as have certain of the chloritoids, garnets, etc., described on pages 43–45. Rarely, when the cleavage of porphyritic biotite is uniformly normal to the main rock cleavage, it is found to be parallel to a later developed "false" cleavage (Pl. XIV, *B*). The porphyritic biotites show a characteristic stumpy habit as compared with the biotites developed in plates parallel to the plane of rock cleavage. There may be occasionally observed a breaking down of the porphyritic biotites along their cleavage, the resulting slices having a tendency toward parallelism with one another and with the plane of rock cleavage. Where the process has gone far the porphyritic micas have given way entirely to aggregates of parallel mica plates. The greater diameters of the porphyritic biotites may be parallel or transverse to their cleavage, and thus may form any angle with the rock cleavage.

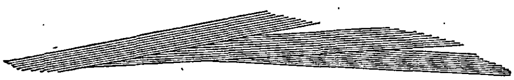

FIG. 2.—Sketch showing the manner in which mica plates feather out, one against the other, in rocks with flow cleavage.

[a] Sp. 1106 H., Williamstown, Mass., slight arrangement; sp. 14930, sl. 7672; sp. 14971, sl. 7709, Black Hills, S. Dak; sp. 4662 H., southern Connecticut.

Occasionally the biotites occur in flattened lenses with muscovites passing around them, as shown in fig. 3. In this case the cleavage of the biotite is seldom parallel to that of the muscovite and of the rock, but usually makes a considerable angle with the plane of rock cleavage.

Again, the biotite may be associated with quartz, and the two have very much the same relation to the adjacent muscovite. The sketch in fig. 4 shows the biotite and quartz in the same band with muscovite passing around them.

In spite of these differences and irregularities in the biotite and muscovite, commonly the greater diameters of the cleavage plates are parallel, as first described.

As the shapes and dimensions of the micas are commonly those of cleavage pieces of mica crystals, the shapes and dimensions must have uniform relations to other physical properties of the crystals. Hence so far as there is uniformity of arrangement of the dimensional axes of mica plates, there is also uniformity of arrangement of the crystallographic or vector properties. Only one dimensional axis of the mica plates, the shortest, has a tendency toward uniform parallelism in the particles of a cleavable rock. Hence only the physical properties parallel to the shortest diameter of the mica particles are parallel. These are the properties represented by the crystallographic axis *c* and the elastic axis $\mathfrak{a}$.

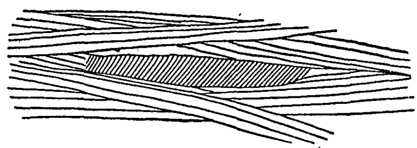

FIG. 3.—Biotite with its own cleavage inclined to rock cleavage, as marked by the adjacent muscovite plates. (Sp. 14901, sl. 7651, Black Hills, South Dakota.)

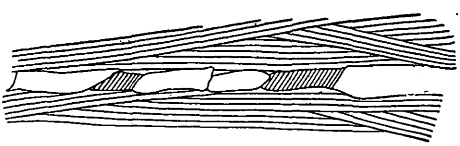

FIG. 4.—Biotite and quartz in a band with parallel muscovite plates adjacent. (Sp. 14901, sl. 7651, Black Hills, South Dakota.)

The elastic axes $\mathfrak{c}$ and $\mathfrak{b}$ in the micas lie in the plane of cleavage. Do these axes in the different mica plates in a secondary cleavable rock lie parallel? In the case of the biotites it was hoped that the determination, by the use of con-convergent polarized light, of the direction of the plane of the optic axis, indicated by the slightly opening cross, would give some information bearing on this subject. However, the optic angle is so small and the basal plane so nearly isotropic that the determinations of the direction of the plane of the optic axes were uncertain and unsatisfactory. A number of such determinations were made in various slides, and such as they were seemed to indicate no parallelism whatever. It is to be noted that the physical differences in the directions of the crystallographic axes in this plane are very slight, and if such characters ever affect the orientation of a mineral they would be little likely to do so here.

In the muscovites, while there are no uniform dimensional differences in the diameters of the plates, the behavior with reference to light, represented by axes 𝔠 and 𝔟, varies somewhat widely. A quartz wedge used with basal sections of muscovite indicates clearly the positions of these axes. About 100 determinations of the position of the optic axes in parallel muscovite plates were made from a dozen selected slides, and no certain parallelism was found in the arrangement of the axes of elasticity. One slide seemed to show a predominance of basal sections with the 𝔟 axis corresponding to the greater dimensional axes of the parallel arranged particles, and the 𝔠 axis in the direction of the mean dimensional axes, but other basal sections in the same slide and in many other slides showed no such arrangement.

Dimensions.—There is little or no difference between the length and breadth of mica plates, as noted in the discussion of basal sections. Between thickness and either length or breadth there is, of course, a marked difference. The ratio of the least to the greatest diameters of the mica plates is generally uniform. Four hundred measurements of both biotite and muscovite from selected slides give an average ratio of greatest to least dimensions of 100 : 16. From this common figure, however, there are many variations. The biotites and muscovites show a uniform difference; the average for biotite is 100 : 20, and that for muscovite is 100 : 14. The various porphyritic and semiporphyritic forms which the biotites sometimes show have an average ratio of greatest to least diameter of 100 : 40, while in the same slides[a] the mica cleavage plates parallel to the plane of rock cleavage, mainly muscovite, have ratios running from 100 : 20 to 100 : 10. In one case[b] the ratio of length or breadth to the thickness of the porphyritic biotites averages 100 : 65, while the muscovites parallel to the plane of rock cleavage average 100 : 13. The measurements of porphyritic biotite above noted are of the greatest and least diameters regardless of the mineral cleavage.

HORNBLENDE.

Common hornblende is a characteristic constituent of a large number of metaclasic rocks. Hornblendic schists are common resultants of the metamorphism under dynamic conditions of intermediate and basic rocks, particularly of igneous origin, such as diorite, basalt, or diabase. They also result from the metamorphism of the sedimentary rocks, such as feldspathic and ferruginous graywackes and slates.

Common hornblende is monoclinic in symmetry, with columnar habit

[a] Sp. 12480, sl. 14846, Wissahickon Creek, Pennsylvania; sp. 14884, sl. 9448; sp. 14901, sl. 7651, Black Hills, South Dakota.

[b] Sp. 14930, sl. 7672, Black Hills, South Dakota.

and prismatic cleavage (fig. 5). Basal sections show the prismatic cleavage in planes intersecting at an angle of 124°.

Examination of the specimens and slides of the hornblendic schists shows the hornblende to occur in characteristic columnar crystal form with linear parallelism or fascicular arrangement (Pl. V). In many cases the crystals are aggregated into indefinite layers. In individual instances there is wide variation from the general parallelism. This variation is likely to be in a plane, and not at angles to this plane—that is, the hornblende crystals, while not parallel to one another, are parallel to a plane.[a] Where the hornblende crystals are best arranged parallel to one another, a section cut parallel to their long dimensions shows the prism faces of the hornblende with only an occasional basal section (Pl. V). Sections cut across the plane of rock cleavage show mainly basal sections with prism faces less conspicuous (Pl. VI). In many cases the longer axes of the cross sections of the hornblende have a tendency (perhaps scarcely noticeable) to lie approximately in the plane of rock cleavage, which thus bisects the acute angles of the hornblende cleavage (fig. 6, and Pl. VI).[b] In slides showing the best arrangement, however, there are numerous wide variations from such parallelism of the axes of the cross sections of the crystals.

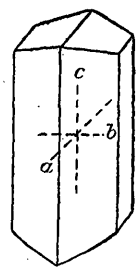

FIG. 5.—Habit of common hornblende crystal.

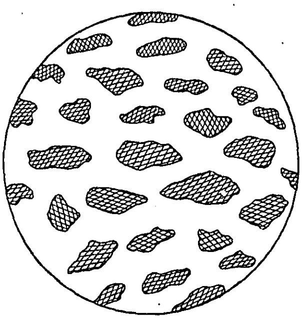

FIG. 6.—Sketch showing tendency toward parallelism of dimensional axes and cleavage of hornblende as viewed in basal section.

In addition to parallel columnar crystals of hornblende, porphyritic hornblende crystals may frequently be observed having considerable variety of shape and arrangement. They are usually short and broad, and their cleavage and greater diameters make almost all angles with the plane of rock cleavage. All stages of the breaking down of such hornblendes may be observed. This breaking down occurs usually, though not always, along the crystallographic cleavage planes and in some cases results in a fairly good parallelism of the slices (fig. 7). In other cases hornblende crystals of different color and evidently of secondary origin are seen to be developing with parallel arrangement out of the porphyritic hornblende.

The hornblende particles in a rock with secondary cleavage being crystals with characteristic habit, and such crystals being arranged

[a] Sp. 1101 H. Croatia.

[b] Sp. 28501, sl. 14854, sp. 28504, sl. 14854, sp. 27750, sl. 13308, Black Hills, South Dakota.

with their greatest, mean, and least diameters respectively parallel, or more commonly with their greatest dimensions parallel, it follows that the vector properties of these diameters must have a proportional degree of parallelism in all crystals. These physical properties, represented by the crystallographic axes, *a*, *b*, and *c* (fig. 8), and the elastic axes, 𝔞, 𝔟, and 𝔠, bear the following relations to the diameters of the particles in the common hornblende. The axis of least elasticity, 𝔠, lies in the acute angle β at an inclination of not more than 20° to the crystallographic axis, *c*, of the hornblende, and hence to the axis of greatest development. The axis of mean elasticity, 𝔟, corresponds to the crystallographic axis *b*, or direction of mean development of the crystal. The axis of greatest elasticity, 𝔞, lies in the obtuse angle *B* at an inclination of not more than 30° to the crystallographic axis, *a*, the direction of least dimensional development. Where all the dimensional axes are parallel, the vector properties represented by these axes are also parallel. Where the mean and least diameters of the hornblende have no uniform parallelism, the only vector properties that are parallel to one another are those parallel to the greatest dimension—the crystallographic axis *c* and the axis of elasticity 𝔠—while the properties represented by *a* or *b* are parallel to a plane and not to each other. Where all the hornblende crystals are not parallel to one another, but are parallel to a plane, the shortest diameters of the particles may be uniformly at right angles to this plane, and hence the axes *a* and 𝔞 in different crystals may be also parallel. However, observation shows that when the greatest dimensions of the hornblende crystals are not parallel to one another, but only to a plane, the mean and least diameters are not likely to be parallel to one another.

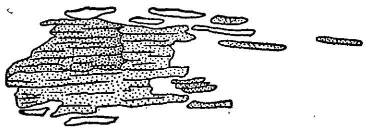

FIG. 7.—Slicing of hornblende. (Sp. 40685, sl. 15360, sp. 40690, sl. 15363, hornblende schist, Mesabi district of Minnesota.)

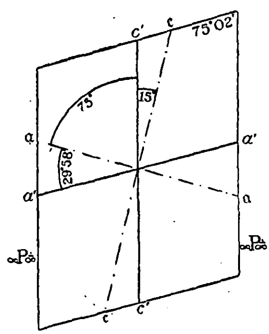

FIG. 8.—Cross section of hornblende crystal parallel to clinopinacoid (parallel to axes *a* and *c* in fig. 5), showing positions of crystallographic and elastic axes.

Dimensions.—One hundred and fifty measurements were taken of the dimensions of the hornblende crystals in prismatic section from 15 selected slides. A striking uniformity was found in the ratio of the length of the longest diameters—i. e., the dimensional axes corresponding to the columnar development—to the length of the shorter ones at right angles to them. This ratio varies between 100 : 25 and 100 : 20. The ratio between the mean and the least diameters of the crystals, as seen in basal sections, averages about 100:60, and corresponds well with the ratio calculated for the crystal form.

There appears to be a difference between the dimensions of hornblende crystals in secondary cleavage rocks and the dimensions of hornblende crystals in original igneous rocks which have not been deformed since their solidification. Measurements (125) of original hornblende crystals in a number of selected hornblendic granites and diorites and more basic hornblendic rocks showed that the ratio of length to breadth or thickness ranged from 100:30 to 100:75, with 100:40 common.

QUARTZ.

Quartz is a common and abundant constituent of the more acidic cleavable rocks. Its common associates are mica and feldspar in rocks which are named quartzose schists, micaceous schists, micaceous gneisses, slates, phyllites, etc., according to the relative abundance or the cleavage-making importance of the minerals composing them.

The quartz crystal is hexagonal, commonly of short, columnar, habit, and lacks good cleavage. The quartz observed in rocks with secondary cleavage is described below according to its characteristic shape. Later it will be shown that the shape is dependent on the manner of development.

(1) Quartz occurs in particles that have more or less modified crystal outlines and grade into irregular, rounded to subangular forms; the crystal outlines are rare, while the irregular, rounded to subangular forms which grade into the forms described under (3) are common. The crystal forms when present rarely show any tendency toward parallelism, dimensional or crystallographic. The irregular forms sometimes have a dimensional arrangement and sometimes not. In no case do they have a uniform crystallographic arrangement. The ratio of the greatest to the least diameters of this group varies from 100:100 to 100:50 or less. A common ratio is not far from 100:75.

(2) Quartz occurs in angular fragments, which apparently owe their shape mainly to the fracturing of larger particles, and in forms that grade from angular fragments to the grains described under (1). Gradations in the fracturing of the larger particles are to be observed, beginning with undulatory extinction and ending with granulation of every original particle. The fine lines of undulatory extinction perhaps associated with lines of inclusions that represent the intersection of a plane with the slide not infrequently occur in sets crossing each other at angles approaching 90° and making an angle of 45° to the plane of rock cleavage. Not infrequently, in intermediate stages, the residual material left in grains which have been subjected to granulation may be seen to have roughly lenticular shapes (augen), the long direction being parallel to the plane of rock cleavage. This lenticular appearance is emphasized by the occurrence of granulated quartz in tails at the ends of the nongranulated

material. Parallel quartz particles developed by the parallel fracturing or slicing of a large quartz individual are also not uncommon. The fractures may be mainly in one set of planes and are either parallel to or inclined at a low angle to the plane of rock cleavage as conditioned by the other constituents of the rock (fig. 9). Close to the point where the slicing occurred the length of such slices may be from two to six times their breadth, but a short distance away particles of apparently the same shape have been broken into small pieces. In advanced stages of granulation the quartz particles have been strewn out and left in nearly even layers.

As soon as any of the micaceous minerals begin to be in evidence the quartz is likely to show undulatory extinction. The advanced stage of the granulation of the quartz is usually reached before the feldspar begins to show signs of pressure. Early stages of granulation of the quartz, with the mica well developed and the feldspar still

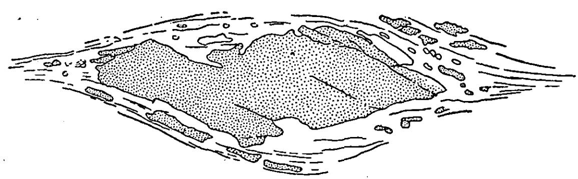

FIG. 9.—Slicing of quartz grain in schistose conglomerate (Metropolitan, Mich., large slide No. 1).

unaffected, are well exhibited in some of the Black Hills schists. A schist[a] from the Medicine Bow Mountains, Wyoming, shows well-advanced granulation of the quartz, while the feldspars show only peripheral granulation.

The granulated quartz particles are usually unequidimensional and in 100 fractured particles the ratio of the greatest to the least dimensions ranged from 100:50 to 100:100, with an average of 100:75. The most angular pieces are in many cases the small ones, although it can hardly be said that, on the average, the smaller the particles the more angular they are. The longer diameters of the particles[b] in the earlier stages of the granulation are commonly in random positions. In later stages they show a very slight tendency to parallelism to the observed cleavage in the rock, as above noted. This is due to rotation, as will be seen below.[c]

The dimensional arrangement of the quartz particles, formed by fracturing in advanced stages of the granulation, carries with it, as shown by the varying extinction, no crystallographic or vector arrangement whatever. In early stages of fracturing the angular

[a] Sp. 15570, Medicine-Bow Mountains, Wyoming.
[b] Sp. 14815, sl. 7577, sp. 14817, sl. 14849, Black Hills, South Dakota; sp. 923 U. W., Dittersdorf, Saxony.
[c] Sp. 15665, sl. 8084, Medicine Bow Mountains, Wyoming.

pieces derived from the breaking down of a single large particle may have similar crystallographic arrangement, but the particles derived from different crystals show no such parallelism.

(3) Quartz appears in a variety of elongated lens-shaped, ribbon-shaped, and spindle-shaped forms, with their longer axes parallel or inclined to the plane of cleavage. Lenticular or augen forms composed of single individuals developed by peripheral granulation have already been described in connection with the granulated forms discussed under (2), p. 31. Other flattened lenses, with outlines curved and even, made up usually of several individuals, give no evidence of development by granulation and slicing. They lie with their longer axes in the plane of rock cleavage, and are usually a little more elongated in one direction than in another. In some cases this elongation is very marked and the cross section is a flattened lens.[a] Whether or not the lenses show a difference of dimensions in the plane of rock cleavage, they commonly have considerable length or breadth as compared with their thickness (Pls. VII, VIII, IX, X). It is not uncommon to see a lens extending the length of a hand specimen, and to have a thickness of only 0.25 mm. Each lens may be made up of a number of crystal individuals lying side by side. The individuals themselves usually, though not always, have their greater dimensions in the plane of rock cleavage, the ratio of the greatest dimension in the plane of rock cleavage to the thickness of the crystal averaging perhaps 100:50, but varying from 100:20 to 100:100. These figures were determined by 200 measurements from 20 selected slides.

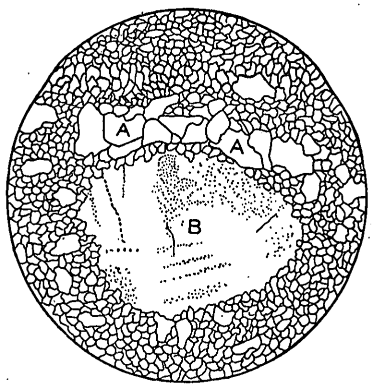

FIG. 10.—Sketch showing granulation of quartz (A) where feldspar (B) is comparatively unaffected by deformation.

The lenses above described, consisting of several individuals lying side by side, grade into shorter lens-shaped forms, consisting mainly of a single individual, although the "tails" may be formed of smaller separate particles. These forms are really phenocrysts (Pl. XI, *A*). These single crystals in flattened lenses in turn grade into spindle-shaped forms which are elongated in one direction and shortened in all directions normal to this. The ratio of the length to the thickness of the individual crystals varies widely. In the quartz-porphyry from the Thüringer Wald described by Futterer,[b] it varies from 10:1 to 2:1.

[a] Sp. 18845, sl. 10185, Laurentide Mountains, Canada.

[b] Futterer, Karl, Ganggranite von Grosssachsen und die Quartzporphyre von Thal im Thüringer Wald: A thesis presented to the University of Heidelberg for the degree of Ph. D., 1890, p. 48. Sp. 88.

The arrangement of the quartzes in parallel lenses and spindles may be observed in slides in which the feldspars have not been at all deformed. In the quartz-porphyry from the Thüringer Wald (Pl. XI), all stages of deformation of the quartzes into these forms may be observed, while the feldspars in many cases at least are relatively undeformed or deformed only by fracture.

In the forms described under (3) dimensional arrangement usually does not carry with it a crystallographic arrangement of the individuals. The crystallographic arrangement is entirely random, as shown by the extinction of different particles at different times when revolved under crossed nicols. In the slides which have been examined during this investigation the quartz-porphyry from the Thüringer Wald shows a parallelism of the crystallographic *c* axes to each other, to the greatest development of the crystals, and to the plane of rock cleavage. This may be an original orientation retained during deformation.

In the above lens- and spindle-shaped forms, both in layers and in separate individuals, one feature of the crystallographic arrangement is of special interest. Not infrequently, where the particles lie in such a position that their *c* axes are in the plane of rock cleavage, and particularly where the crystals show strain effects, such as undulatory extinction, sections cut normal to the *c* axis show the quartz not to be optically uniaxial, but to be slightly biaxial, and the plane of the optic axes to lie normal to the plane of rock cleavage. This position of the plane of the optic axes is what would be expected from the flattening of a uniaxial ellipsoid of elasticity in the plane of rock cleavage. Futterer[a] describes this feature in the Ganggrànite von Grosssachsen, and in the quartz-porphyry of the Thüringer Wald. Other similar crystals lying with their *c* axes in the plane of rock cleavage are optically uniaxial, but in such cases strain effects are usually lacking. The biaxial nature of the quartz appears itself to be a strain phenomenon.

The relative abundance of the forms of quartz particles above described of course varies widely in different cleavable rocks. Probably, however, in the quartzose cleavable rocks as a group the forms described under (1) and (2) occur in greatest abundance. The flattened lens-shaped forms described under (3) are less abundant, but are very characteristic of cleavable rocks which have undergone severe metamorphism. The spindle forms described under (3) are of rare occurrence.

It appears from the above account that the occurrence of quartz in

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[a] Ibid., pp. 20, 34.

cleavable rocks is essentially different from that of mica or hornblende. Mica and hornblende are usually in crystals with characteristic habit, with good dimensional arrangement, and for the most part with a good crystallographic arrangement. Quartz, on the contrary, is characteristically without crystal habit; the shape of the particles varies somewhat with the nature and amount of the deformation which the rock has undergone, and, except in rare instances, there is no crystallographic parallelism.

FELDSPAR.

Feldspar is present in considerable quantity in the gneisses, micaceous schists, hornblendic schists, chloritic schists and slates, and, in fact, in all of the metaclasic rocks, with the exception of certain ultrabasic and quartzose schists.

In the following discussion the various feldspars are not discriminated except in descriptions of individual specimens. The differences in arrangement between the varieties are numerous, but for the purposes of this paper a general statement covering the feldspars as a group is sufficient.

The feldspars occur (1) in forms that have more or less modified crystal outlines, (2) in small, nearly equidimensional particles, with irregular angular outlines, and (3) in ellipsoidal or lenticular forms with curved or angular outlines. Between these all intermediate shapes are to be observed. In each of these classes the feldspars show minor differences of occurrence, the description of which would involve the discussion of the processes by which they are arranged. These differences will be ignored here as far as possible and will be described in connection with the processes of arrangement on pages 87–89.

(1) The feldspars that have more or less modified crystal outlines may have their longer diameters arranged (*a*) at random or (*b*) parallel to the plane of rock cleavage.

(*a*) The crystals with random arrangements in many cases crowd the other parallel constituents of the rock, which bend around them. In other cases the parallel constituents are not crowded, but about against the feldspars without any bending and even pass through them without change of direction.[a]

(*b*) Where the crystals lie with their greater diameters parallel to the plane of rock cleavage, there is a tendency toward uniformity of arrangement of the crystallographic axes and of the feldspar cleavage which requires special description. Several good cases of this arrangement have been observed and two of these will be described in detail.

[a] Sps. H. 1060, 1068, Greylock, Mass.

The first is that of the Hoosac schist[a] of Massachusetts, representing an extreme case of metamorphism. It is a micaceous quartzose schist with large albite phenocrysts. The mica and quartz are arranged in bands. The porphyritic albites include parallel particles of quartz and biotite (Pl. XIII, *A*). The micas abut against the albites frequently without the slightest change of direction; they are not crowded, and do not bend around the albites. The feldspars themselves lack evidence of mechanical deformation. Their greater dimensions lie in the plane of rock cleavage. The ratio of the greatest to the least dimensional axes of the feldspar particles, determined by 100 measurements from 10 selected slides, varies from 100 : 50 to 100 : 75.

An examination of these feldspars in sections cut across the plane of rock cleavage shows that the elongated feldspars have a marked tendency toward parallel extinction. The angle of extinction with the long side of the crystal and with the rock cleavage varies from 0 to 19°. Many crystals also show simple twins; the twinning plane cuts across the short direction of the crystal, and frequently lies normal to the plane of rock cleavage (Pl. XIII, *A*). Other crystals show a twinning plane parallel to the longer dimensions of the crystal—that is, parallel to the rock cleavage. Albite with a simple twinning has two habits, a common tabular development parallel to the brachypinacoid, and a less common tabular development parallel to the macropinacoid (figs. 11, 12). The relation of the twinning lines to the shape of the feldspar sections in this rock shows that crystals of both habits evidently are present. The greatest diameters of the feldspar particles lie in the plane of rock cleavage but are not parallel.

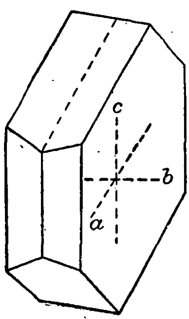

FIG. 11.—Twinned albite crystal with brachypinacoidal development.

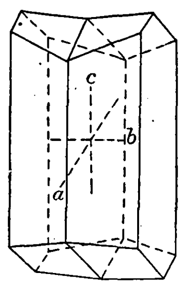

FIG. 12.—Twinned albite crystal with macropinacoidal development.

Another case of parallel arrangement of feldspar crystals is in a mashed feldspar rock from the Wausau district of Wisconsin, described by Weidman.[b] This rock has been subjected to severe metamorphism, acquiring thereby a parallel arrangement of its mineral constituents.[c] The feldspars are in separate parallel tabular crystals, and also in the parallel flattened lenses described in a subsequent paragraph. Where they are in crystals (albite), the tabular brachypinacoidal faces are parallel to each other and to the rock cleavage. The longest diameters are parallel to the plane of rock cleavage, but not necessarily to each other.

[a] Sp. 18062, sls. 14972, 14973, 14974, Hoosac tunnel, North Adams, Mass.

[b] Bull. Wisconsin Geol. Nat. Hist. Survey, in preparation.

[c] A considerable portion of the rock shows an original parallel arrangement of different origin, which will not be here discussed, but which is not confused with the particular phenomenon described.

This is the arrangement shown by part of the albite crystals of the Hoosac schist. The average ratio of the greatest to the least diameter is 100:20.

In albite the axis of elasticity, 𝔠, is approximately normal to the brachypinacoid, while the axis of elasticity, 𝔞, is nearly normal to the macropinacoid. In the parallel arranged albites above described, therefore, these axes have different positions, depending upon which of the two tabular developments is present and controls the arrangement. Where the tabular development is parallel to the brachypinacoid, the common case, the axis 𝔠 is normal to the cleavage of the rock. The axes 𝔞 and 𝔟 are not parallel, but lie in the same plane. Where the tabular development is macropinacoidal and the feldspar is arranged parallel to this plane, the axis of greatest elasticity 𝔞 always stands normal to the plane of rock cleavage determined by the dimensions of the crystals. The axes 𝔠 and 𝔟 in this case are not parallel to each other, but are parallel to the plane of rock cleavage.

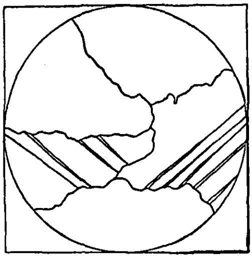

FIG. 13.—Microscopic view of fresh anorthosite. (Cf. Adams, Geol. Survey, Canada: vol. 7, 1894, pt. J.

(2) The angular particles clearly owe their shape principally to the granulation of larger particles, although they may be partly original and partly due to other causes. The first effects noticeable in the mechanical deformation of a feldspar crystal are twinning lamellæ and peripheral granulation. With increasing deformation there is gradation from these phenomena to complete granulation of the particles. At an intermediate stage of deformation the feldspar crystal may have a lenticular form. Where the small particles ground off from a large particle lie close at hand, forming a "tail," the group forms a conspicuous lenticule, or "augen." At later stages of granulation the minute particles not infrequently lie in a layer of uniform thickness.

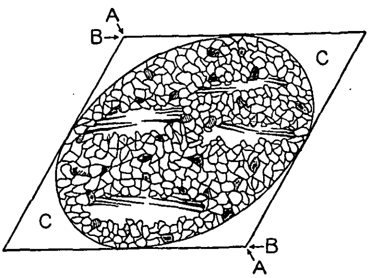

FIG. 14.—Microscopic view of anorthosite after granulation. The residual feldspars may lie with their longer axes parallel or inclined to the elongation of the rock as a whole.

In the sheared anorthosite from north of Montreal, described by Adams,[a] feldspar particles in parallel, elongated, sometimes ribbon-like forms, with irregular angular borders may be seen lying in a matrix of finely granulated material (figs. 13 and 14; also Pl. XII, *B*). Measurements show that the larger feldspars have been granulated into nearly 70,000 small particles. The residual feldspars show strain

[a] Adams, F. D., Report on the geology of a portion of the Laurentian area lying north of the island of Montreal: Geol. Survey of Canada, vol. 8, pt. 1, 1896, Pl. VII.

shadows grading into minute fractures. Granulation of feldspars is well exhibited in the Berlin rhyolite-gneiss of Wisconsin (Pl. XII, *A*).

Occasionally the fracturing of feldspar particles has resulted in their division into parallel slices, either parallel or inclined to the plane of rock cleavage as conditioned by the other constituents of the rock mass (figs. 15, 16, 17; Pl. XI, *B*). Usually the fractures producing such slices are in one set of planes at a low angle with the plane of elongation of the rock mass as a whole, but sometimes also in intersecting planes.

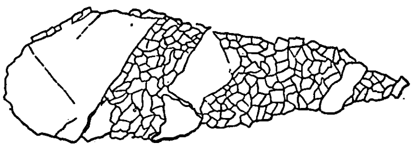

FIG. 15.—"Sliced" feldspar in rhyolite-gneiss. (Berlin, sp. 3813, Wis. Survey.)

In the early stages of mechanical deformation there is practically no parallel arrangement of the greater diameters of the minute granules developed by granulation. In subsequent stages the angular particles, through rotation, have a very slight tendency to lie with their longer diameters parallel to the plane of rock cleavage. In many thin sections of rocks with fair secondary cleavage, the mica and hornblende, and even the quartz, have their longer diameters parallel, while the angular feldspar particles show no tendency to such arrangement. Where best developed the dimensional parallelism is hardly noticeable on a cursory examination. A reason for this appears in the fact that the angular particles as observed in the cleavable rocks have such slight differences in dimension. The ratio of the greatest dimensional diameters to the least, obtained from 100 measurements from 10 selected slides, is in extreme cases 100:40, while the average is more nearly 100:60.

FIG. 16.—Feldspar showing incipient "slicing" in schist-conglomerate. (Metropolitan, Mich., large slide, No. 1.)

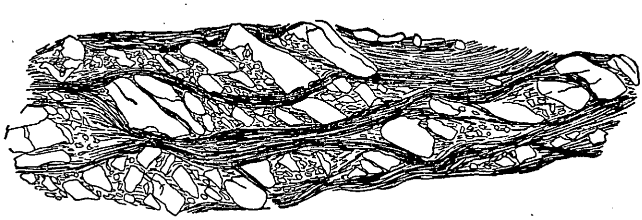

FIG. 17.—"Sliced" feldspars in micaceous and chloritic schist from southern Appalachians.

The slight dimensional arrangement of the minute feldspar granules carries with it no tendency toward a parallel crystallographic arrangement, so far as the observations made in this study have gone, except in the infrequent cases of the slightly moved slices of individual feldspar particles. Diligent search has failed to reveal even a faint tendency toward parallelism; if present at all it must be in exceptional cases. This comes from the fact that the relations of the dimensions of the granulated feldspar particles to the crystallographic properties are ordinarily not uniform, and even where they are partially uniform, the tendency toward dimensional arrangement due to difference in dimensions is so slight that uniformity in crystallographic arrangement is not evident.

It is to be noted that most of the fragments formed from a single sliced individual have close approach to crystallographic parallelism, although there is no parallelism between the pieces formed from the slicing of different feldspar particles; also that there has frequently been rotation of these slices toward a common plane inclined to the planes of fracture and parallel to the longer diameters of other constituents which have developed in a parallel position by another process shown later to be recrystallization.[a]

(3) The remaining occurrences of feldspar to be described have lenticular or ribbon forms with their flat surface in the plane of rock cleavage. These forms show all gradations into both the angular feldspar particles and the feldspar crystals above described. In the nepheline-syenite of the Wausau district and in a hornblendic schist from the Mesabi district of Minnesota[b] the lenses of albite either occur as separate individuals or lie end to end and form lens-shaped layers of considerable extent (fig. 18). Many of the feldspars in the lenses or layers show no uniform relations of their dimensions to the crystallographic properties.[c] The feldspars extinguish at various angles, like the quartz lenses of similar shape described in the preceding section. The ratio of the greatest to the least axes of the individuals is 100:30. In other cases the greater dimensions of the albites of the lenses or layers correspond roughly with the tabular developments parallel to the brachypinacoid, in which case there is a tendency to extinguish parallel to the longer diameters of the lenses, although the extinction varies from 0 to 20° or 30°.[d] There is a characteristic lack of strain effects, although the rock gives evidence of deformation. The axis of elasticity $\mathfrak{c}$ is parallel to the shorter diameters of the lenses and thus transverse to the cleavage of the rock.

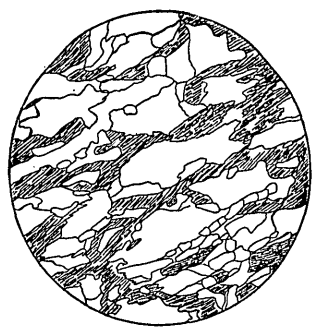

FIG. 18.—Feldspar in parallel lenses with crystallographic parallelism. The longer axes of the lenses are approximately in the brachypinacoid. From hornblendic schist of Mesabi district of Minnesota.

In general the feldspar particles in rocks with secondary flow cleav-

[a] Cf. Lehmann, Atlas, Pl. XXI, fig. 3.
[b] Sp. 45492, sl. 15759, Mesabi district of Minnesota.
[c] Sp. 6022A, Wausau, Wis. Cf. Weidman.
[d] Sp. 6024C, Wausau, Wis. Cf. Weidman.

age are present in quantity in the order in which they are described above. The common parallel arrangement of feldspars is thus dimensional, although, even where the dimensional arrangement is best, the approach to parallelism of the longer diameters of the particles is not close. Rarely the parallel arrangement is also crystallographic, in which case the good basal cleavage of the feldspar is normal to the plane of the greatest and mean dimensional axes, and hence to the plane of rock cleavage with which the longer axes are parallel. The poorer brachypinacoidal cleavage or clinopinacoidal cleavage is in most cases parallel to the plane of tabular development and the rock cleavage, but in a few cases is normal to it.

CHLORITE.

Chlorite is characteristic of chloritic schists or slates. The development of such cleavable rocks may be in part under conditions somewhat different from those under which metaclasic rocks containing mica or hornblende are developed.[a]

Not infrequently chloritic schists result from the alteration of biotitic schists, and in such cases the chlorite is essentially pseudomorphic.

Chlorite is monoclinic, but pseudo-hexagonal, with prismatic habit, and with excellent basal cleavage.

In cleavable rocks the mineral occurs in cleavage plates that have their flat surfaces parallel to the rock cleavage in a manner similar to that of the micas. It appears also in irregular and ill-defined aggregates. Because of its tendency to hexagonal development, the greater diameters of the cleavage plates are not markedly unequal in length, and thus no parallelism of greatest and mean diameters in the plane of rock cleavage can be looked for. The ratio of the thickness of the plates to the diameter is about the same as in the micas, in average cases perhaps 16:100. As in biotite, the axis of greatest elasticity $\mathfrak{a}$ is normal to the cleavage plane. The axes $\mathfrak{b}$ and $\mathfrak{c}$ lie in the plane of rock cleavage, but are not parallel in different cleavage plates. Chlorite has the same manner of aggregation into layers etc., as the micas.

CALCITE.

Cleavable marbles are not abundant, notwithstanding the great number of limestone formations which have been subjected to extreme metamorphism. Neither is calcite an abundant secondary constituent in cleavable rocks in which other constituents, such as mica and hornblende, are predominant. The conditions favorable for the development of such constituents apparently do not favor the development of secondary calcite. Indeed, under such conditions there is a marked tendency toward the replacement of calcite by silicates. The

[a] See discussion of development of chlorite in Van Hise's Treatise on Metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904.

arrangement of the calcite in cleavable marbles is of principal interest, and to this the description below is mainly restricted.

Calcite has hexagonal rhombohedral form, with, in general, a tendency to columnar development parallel to *c* when crystal outlines are present. Its cleavage parallel to the rhombic faces is excellent, and polysynthetic twinning parallel to $-\frac{1}{2}R$ is a common feature.

Calcite in marbles with flow cleavage appears in two ways—(1) in small nearly oval grains, and (2) in small angular pieces. Another occurrence is discussed under fracture cleavage on pp. 119–121.

(1) Some of the most cleavable marbles examined, especially those from Talledega Mountain, Georgia,[a] were seen to have a distinctly granular aspect and to be made up of oval grains of calcite of somewhat uniform size, arranged with their dimensional diameters in a common direction parallel to the observed rock cleavage (fig. 19). Between these grains may be a considerable amount of finely granulated material. Few strain effects, such as fractures or close polysynthetic twinning, are to be observed. The dimensional parallelism is well marked. No crystallographic parallelism accompanies the dimensional parallelism. The grains extinguish at different angles, and their cleavage lies at all angles with the greatest dimensions of the particles.

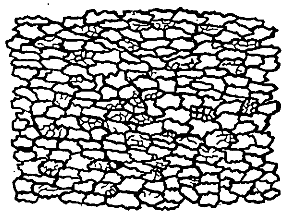

FIG. 19.—Parallel grains of calcite in schistose marble. (Special slides I, III, Talledega Mountain, Georgia.)

In the cleavable marbles the ratio of length of these parallel grains to breadth, as determined by 100 measurements from 10 selected slides, is from 100:32 to 100:60. This ratio is not far different from that obtained in marbles showing no cleavage, in which a number of measurements give an average of 100:73.

(2) The calcite particles may sometimes be seen in irregular angular pieces. Commonly their greatest and least diameters are not far different from those described under (1), and gradational phases into (1) are noted. There is a slight tendency to parallel arrangement, which is dimensional and not crystallographic. In those rocks examined the angular particles are not so common as the ellipsoidal grains described under (1).

While the accessory calcite occasionally found in micaceous schists, quartzose schists, or hornblendic schists, is perhaps partly original, it is in many cases a secondary replacement of other minerals after the cleavage of the rock has been produced. It may fill irregular elongated areas left by the solution of other minerals, although, in general, in rocks of this sort there is little tendency for parallel dimensional arrangement of the calcite. In no case is crystallographic arrangement observed.

[a] Sp. 18083, sl. 9626, Green Mountain Range, Vermont; sp. 18192; sls. I, II, III, IV, Talledega Mountain, Georgia; near Comstock, N. Y.; Cambro-Silurian marbles of western Massachusetts described in Mon. U. S. Geol. Survey, vol. 23, 1894, Laurentian marbles.

TREMOLITE, ACTINOLITE, GRÜNERITE, AND OTHER AMPHIBOLES.

These minerals are especially characteristic of cleavable rocks formed by the metamorphism of calcareous and sideritic rocks and known as tremolitic schists, actinolitic schists, and grüneritic schists. They are characteristically developed by contact metamorphism, but are formed also at considerable depths under conditions of high temperature and pressure. They are all monoclinic, with a marked prismatic or acicular development. They occur either in single crystals, or, characteristically, in sheaf-like or radial aggregates.

In cleavable rocks the undoubted characteristic occurrence of these minerals is in radial and fascicular aggregates with entirely random arrangements. Occasionally the individual crystals are arranged with their longer dimensions in the plane of rock cleavage, though rarely parallel to each other in this plane. The arrangement is not conspicuous and might be overlooked, but on examination in a slide the crystals, especially those of actinolite or grünerite, are seen to cross each other at acute angles, perhaps 40°, and lines bisecting these angles are seen to have a common direction. The best cases of parallelism are observed where the crystals are in single individuals. Where the crystals are in the sheaf-like and radial aggregates, the rays lying in the plane of rock cleavage are likely to have a greater development than those crossing it. Between random arrangement and this tendency to parallelism there is complete gradation; but the former is believed to be by far the more common. Where the parallel arrangement is best developed, no data are at hand to determine whether or not the amphiboles of this group have their shorter axes parallel, like hornblende. From analogy to the hornblende it is reasonable to suppose that this is sometimes the case. So far as this may occur, the crystallographic and elastic axes would have the same relations to the plane of rock cleavage as in common hornblende.

KAOLIN AND TALC.

Talc is largely the result of weathering, but in places it forms cleavable rocks. It is similar to mica and chlorite in habit and arrangement.

GARNET.

Garnet is probably the most common of the porphyritic minerals of the "crystalline schists." In extremely metamorphosed cleavable rocks, and especially in the micaceous schists and in phyllites, porphyritic garnets may be seen.

The garnets are isometric, and thus show no dimensional or crystallographic variations along their different axes. In the rocks examined their diameter is commonly not less than 1 mm., and is occasionally 4 cm. Being equidimensional, the individual crystals can be said to have no dimensional arrangement with reference to the plane of rock cleavage. However, an examination of secondary cleavable rocks shows that, in many cases at least, the garnets are more numerous in certain planes of cleavage than in others. They are likely to occur along planes where mica has been abundantly developed, and are not so numerous in the quartz and feldspar layers.

TOURMALINE.

Tourmaline is characteristic of the micaceous schists and certain feldspathic schists. Its development is commonly supposed to be largely due to the contact action of the magma and the introduction of extraneous material into the metamorphosed rock.

The mineral is hexagonal (trigonal), with a marked columnar habit. In the rocks with secondary cleavage the columnar crystals of tourmaline have a marked tendency to lie parallel to the plane of rock cleavage, but not to one another.[a] In a few cases they are parallel to one another as well as to the plane of rock cleavage.[b] There is no parallelism of the shorter axes, except to a plane, when the longer axes are parallel.

So far as the crystals have dimensional arrangement the crystallographic properties also are parallel. The crystallographic axes, *c*, or the principal optic axes (negative) in the different particles thus lie in the plane of cleavage and rarely are also parallel to one another in this plane. The crystals vary considerably in the ratio of their greatest to their smallest diameters; 100 : 60 and 100 : 20 are extremes from 25 measurements in 5 selected slides and specimens.

STAUROLITE.

Staurolite is characteristic of micaceous schists. It is orthorhombic, and characteristically in short tabular crystals and cross twins, in each case with a well-marked development parallel to the macropinacoid. The arrangement of the staurolite in the secondary cleavable rocks may be observed macroscopically, and especially well on a weathered surface. An examination of numerous specimens shows that the staurolites have a strong tendency to lie with their flat surface parallel to the plane of cleavage,[c] although many exceptions to this rule are noted. The greater axes of the crystals in this plane are not parallel.

As the staurolites in crystal form have uniform relations of their

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[a] Sp. H. 1049.1, Hoosac Mountain, Massachusetts; sp. H. 4154B, near Seymour, Conn.; sp. H. 4151, Beacon Falls, Conn.; sp. H. 4083, A, near Danbury, Conn.

[b] Sp. 14889, Black Hills, South Dakota; sp. 29633, Laramie, Wyo.

[c] Sp. H. 1105, west side Conanicut Island, Narragansett Bay; sp. H. 1084, Conn., sp. 14919, Black Hills, South Dakota.

crystallographic axes to the dimensional axes, it follows that the crystallographic properties of the crystals are arranged to the same degree as the dimensional axes. The crystallographic axis c and the axis of greatest elasticity $\mathfrak{a}$ thus lie in the plane of cleavage.

OTTRELITE (AND CHLORITOID).

Ottrelite and chloritoid are found principally in the micaceous schists or phyllites. They are closely related in their properties and occurrence, and are commonly not discriminated, although they seem to differ in chemical composition. The minerals are monoclinic and the basal cleavage is good, although it is not so perfect as in mica.

They occur in the micaceous schists or phyllites in a variety of ways—in radial or sheaf-like aggregates, in thin scales or plates, and in simple crystals. In the rocks examined the ottrelite has predominantly crystal form. The crystals are more or less hexagonal, tabular plates, with a good basal cleavage parallel to their longer dimensions. "Hourglass" twins are not uncommon.

In the typical ottrelite-schist from Ottrez, Belgium,[a] the ottrelites have no parallel arrangement whatever, dimensional or crystallographic. In rocks from other localities, however, there is a tendency for the dimensions of the plates to control the arrangement of the crystals, causing the greater dimensions to lie more nearly in the plane of cleavage than normal to it. Within this plane the greater dimensions of the crystals make all angles with one another. The mica-schists of the Black Hills, South Dakota,[b] show this arrangement. The tendency toward parallelism is slight, even where most marked, and in rocks showing such arrangement many ottrelite crystals lie squarely across the rock cleavage and at all angles to it. The result is that any rock with secondary cleavage containing ottrelite is likely to show ottrelite cleavage faces on any surface, but more conspicuously in the zone normal to the plane of rock cleavage, for in the plane of rock cleavage the mica cleavage (the ottrelite is commonly associated with mica) is likely to obscure the cleavage of the ottrelites.

The average ratio of the length of the crystals to the breadth, taken from 100 measurements from 10 selected slides, is 100:40.

ANDALUSITE (CHIASTOLITE).

Chiastolite is not important as a cleavage-giving mineral, but it is characteristic of certain dense cleavable hornfels in which long, prismatic, chiastolite crystals stand out conspicuously against a fine-grained, dark-colored background. The mineral is orthorhombic with columnar habit. In most of the rocks with secondary cleavage that were examined the chiastolite crystals were either inclined or perpen-

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[a] Sp. H. 1104, Ottrez, Belgium.

[b] Sp. 14874, Black Hills, South Dakota.

dicular to the plane of rock cleavage,[a] but in certain of the rocks there is a tendency for the long directions of the crystals to lie roughly in the plane of rock cleavage.[b] The greatest and mean axes have no parallelism in this plane. The average ratio of length to breadth, measured in 30 crystals from 3 slides, is 100:10.

As chiastolite occurs in crystals whose dimensional and crystallographic properties are uniformly related, it follows that the crystallographic properties are parallel so far as the dimensional axes are parallel. The properties represented by the *c* axis are thus parallel to a plane and not to a line.

SILLIMANITE (FIBROLITE).

This is a rare constituent of the cleavable rocks as a whole, and even where most abundant makes up but a small portion of the rock. It is orthorhombic, with a very strong columnar habit.

In the cleavable rocks sillimanite is seen to occur in single, slender, rod-like forms, with characteristic cross fractures, and also in sheaf-like aggregates and parallel bunches. The individuals and the crystals in aggregates have a strong tendency toward a parallelism of their longer axes.[c] They furthermore have a tendency toward concentration into definite layers.[d] The individuals are always slender, frequently almost hair-like, and their length as compared with their thickness is very great. On account of the fineness and cross fracture average measurements are not practicable. The crystallographic axis *c* and the axis of least elasticity, $\mathfrak{c}$, lie in the plane of rock cleavage.

SUMMARY STATEMENT CONCERNING FACTS OF ARRANGEMENT IN ROCKS WITH FLOW CLEAVAGE.

The above facts are believed to afford a basis for the following generalizations:

Rocks with flow cleavage are made up principally of flat or elongated particles with a variety of shapes and dimensions. Particles of a particular mineral have characteristic shapes and dimensions and are easily distinguished from particles of other minerals. Occasionally, however, they show minor variations of form due to differences in origin and behavior during deformation. To illustrate: Mica is in thin plates; hornblende is columnar; quartz is seldom in crystal form, but is in angular or lenticular grains; feldspar is sometimes in crystal or lenticular form, but usually in angular to subangular grains. The ratio of the greatest to the least diameter varies in mica from 100:20 to 100:10; in hornblende, from 100:20 to 100:25; in quartz from

[a] Sp. H. 71.1, Yaqui Gulch, California.
[b] Sp. H. 1112.1, H. 71, Gefrees, Fichtelgebirge, Germany.
[c] Sp. 14 Bayley, sp. 504 Bayley, sp. 906 W., Saxony, sp. 14901, sl. 7651 Black Hills, South Dakota.
[d] Sp. 504 Bayley.

100:50 in common cases to 100:15 in exceptional cases; in feldspar it is about 100:60. The uniformity of this ratio for a given mineral species disproves the idea sometimes held that the degree of flatness or elongation of particles in a rock with secondary cleavage is proportional to the amount of deformation which the rock has undergone.

The unequiaxial particles of the rocks with flow cleavage have a tendency to lie with their greater, mean, and least diameters parallel to one another, although this tendency varies with the nature of the mineral, with the processes which have been effective in bringing about the arrangement (as will be shown in a subsequent chapter), and with the amount of deformation which the rock has undergone. There is also a tendency for minerals of the same kind to be aggregated into layers. It is obvious that there must be complete gradation from the random arrangement of minerals of undeformed rocks to the parallel arrangement of minerals of a very cleavable rock. A parallel arrangement is reached at different stages in the development of rock cleavage by different minerals. In the same rock it may be reached by mica, chlorite, and hornblende and not by feldspar and quartz. In a further stage of deformation it may be possessed by mica, chlorite, hornblende, and quartz and not by feldspar. In still more advanced stages of deformation it is acquired by tourmaline, actinolite, grünerite, tremolite, staurolite, sillimanite, andalusite, chloritoid, etc., so far as they receive it at all. Calcite has not been compared directly with these minerals, but unquestionably takes on a parallel arrangement early in the deformation.

The crystallographic or vector properties of the particles of any mineral are parallel only when they have uniform relations with the parallel dimensional axes. This is commonly the case where the particles are either crystals or cleavage plates from crystals that have the characteristic shape and habit of the mineral species represented. In arranging themselves dimensionally such crystals or cleavage plates must necessarily arrange their crystallographic axes. The relations of dimensions to vector properties are uniform in most mica, chlorite, and quartz particles, and in only a small portion of the feldspar particles, while in calcite they show no uniformity whatever. While in a particular mineral these relations may be uniform, in different minerals they may vary. A vector property may be parallel to the greatest dimensional axis in one mineral and to the least dimensional axis in another. Thus the degree of parallelism of vector properties in the rocks with flow cleavage as a whole may be ascertained by listing under each mineral the vector properties corresponding to the parallel-arranged greatest, mean, and least dimensional axes, and seeing how far these properties correspond in all the minerals in the rocks.

While the arrangement of the vector properties of the particles of a cleavable rock is thus subordinate to, and entirely dependent upon, the dimensional arrangement, and while the arrangement of the physical properties with reference to the dimensional axes varies with different minerals, in some of the more common cleavable rocks the net effect of the parallel arrangement of the vector properties of the mineral particles, incidental to and resulting from the dimensional arrangement, may be such as to give the cleavable rock as a whole a definite polarity with reference to these properties—i. e., to give the cleavable rock certain properties for certain directions and other properties for other directions. Experiments on heat, electric properties, cleavage, and hardness of cleavable rocks seem to show some such condition, although it is probably due more to the dimensional than to the crystallographic arrangement of the individual particles. A discussion of these properties in cleavable rocks is outside the scope of this paper. However, attention will be called to one property, the behavior of the cleavable rocks with reference to light, which has been noted in this investigation.

The axis of greatest elasticity $\mathfrak{a}$—the axis affording the easiest vibration of light for rays propagated normal to it—has a position normal to the plane of rock cleavage in the micas, in chlorite, and in talc; within a few degrees of the normal to the plane of rock cleavage in the crystals of hornblende showing triaxial parallelism and in the smaller number of feldspar crystals showing parallel arrangement of their crystallographic properties. In most of the feldspar crystals the axis $\mathfrak{a}$ lies in the plane of the greatest dimensions, while the axis $\mathfrak{c}$ is normal to the plane of rock cleavage. The arrangement of the mean and least elastic axes in some parallel minerals is known, and in others is not known; in the rocks showing flow cleavage as a whole, sufficient data are not yet at hand to warrant any definite statement concerning the uniformity or nonuniformity of arrangement of the mean and least axes. These minerals include the most abundant minerals appearing in the cleavable rocks with uniform crystallographic arrangement. The minerals not mentioned are the porphyritic minerals which are commonly supposed to crystallize either after movement has entirely ceased or near the close of the deformation, such as tourmaline, garnet, staurolite, sillimanite, etc.

In other words the above facts show that so far as the common cleavable rocks have any uniform effect on the transmission of light, due to the optical orientation of the individual particles, they allow the light ray to travel faster normal to the plane of rock cleavage (but vibrating parallel to this plane) than the rays traveling parallel to the plane of rock cleavage. The possible significance of this in its bearing on molecular structure is discussed on pages 97–99.

Repeating the main conclusion, then, the mineral particles in a rock with flow cleavage, so far as they are arranged, have their respective dimensional axes parallel, but only incidentally and partially are their vector properties parallel. The mineral particles have been arranged with their dimensional axes parallel regardless of any influence which the vector properties may have had, except in so far as they modified the dimensions. Even in minerals such as quartz and calcite, in which the physical properties along the principal and lateral axes are strongly differentiated, these vector properties show no tendency to parallelism because they have no uniform relations to the parallel-arranged dimensional axes of the particles. Moreover, the vector properties have no influence in arranging the crystal, where there are no dimensional differences in the principal axes. When two of the three principal dimensional axes of a particle are of the same length, so that there can be said to be no parallel dimensional arrangement of such axes, the vector properties show no parallelism, although in the absence of dimensional control they would have an opportunity to show any influence they might have. For instance, the vector properties lying in the plane of the mica cleavage are not parallel, in spite of the fact that the length and breadth of these plates are not so far different, but that the vector properties, had they had any influence, could have succeeded in arranging themselves without violating the principles of dimensional control.

CHAPTER II.

THE OBSERVED RELATION OF SECONDARY ROCK CLEAVAGE TO THE PARALLEL ARRANGEMENT OF MINERAL PARTICLES.

In the rocks with secondary flow cleavage examined during this investigation, which are believed to be fairly representative of such rocks in general, a plane, or surface, of cleavage has been observed to be uniformly parallel to the greatest and mean, or greatest and least dimensions, or both, or even to the greatest alone, of the parallel constituent mineral particles. This has been observed macroscopically in thousands of specimens, and microscopically in several hundred specially prepared slides. Not only has a cleavage been observed to coincide with the longer diameters of the parallel particles, but it has been apparent that the excellence of such cleavage is proportional to the degree of the arrangement and to the inequality of the dimensions of the particles. In addition to this essential condition of parallel arrangement, another condition, dependent on the first, has been observed to be of great importance—the parallel arrangement of mineral cleavages. This has usually aided the dimensional arrangement, but has rarely tended to cause a cleavage in a plane different from that caused by the dimensional arrangement of the mineral constituents. The characteristic segregation of particles of the same mineral species into layers may develop also planes of weakness that are due to intrinsic strength of the minerals, quite independent of any dimensional arrangement. Minute foldings of parallel-arranged constituents, as in micaceous slates, may yield a plane of weakness parallel to the limbs of the folds (Pl. XIV, *B*), causing a cleavage which has been called in part "false cleavage."

It is needless to say that the agreement of secondary flow cleavage with parallel mineral arrangement, above emphasized, is not a newly observed relation. It has been described and noted by so many geologists that the coincidence of the two structures has been accepted as almost self-evident. Yet, as will be shown in Part II, there is a cleavage, here called fracture cleavage, which is independent of such a parallel structure, and largely because of this certain geologists have concluded that all cleavage may be independent of a parallel arrangement of minerals. A comparison of cleavage independent of a parallel arrangement and cleavage dependent upon such an arrangement—in other words a comparison of fracture cleavage and flow cleavage—is made in Part II.

RELATIVE IMPORTANCE OF MINERALS IN PRODUCING FLOW CLEAVAGE.

If the dimensional arrangement of the particles in the secondary cleavage rocks, and the attitude of the mineral cleavage of the particles are known, there are at hand the facts of occurrence necessary to an intelligent discussion of the relative cleavage-producing capacities of the minerals occurring in rocks with secondary cleavage.

Before taking up the detailed discussion, however, it may be well to explain what is meant when it is said that one rock has a better cleavage than another, or that one mineral affords a better rock cleavage than another. In the following discussion excellence of secondary rock cleavage, parallel either to a plane or a line, will be considered as determined by (1) the facility of parting, (2) the evenness of the parting, (3) the number of planes or lines of parting in a given thickness of rock. The extent to which a given mineral contributes these properties to a rock determines its cleavage-producing capacity.

By observation it is known that secondary flow cleavage in rocks occurs parallel to the greater diameters of the constituent particles, or parallel to the mineral cleavages or both. Usually, but not always, they are in the same plane. It is further a matter of direct observation that the perfection of cleavage depends upon the following factors:

Shape and arrangement.—The degree of flatness or elongation of the particles, and their degree of parallelism, is here meant. The greater the difference between the length or breadth and thickness of parallel particles and the better the parallelism the better the cleavage. The shape and arrangement must be considered together, because particles having shapes favorable to the development of cleavage can produce no cleavage unless they have parallel arrangement, and vice versa, particles well arranged produce poor cleavage unless they show marked differences in dimensions.

According to the relative differences between the dimensional axes, the parallel particles may tend to produce cleavage parallel to a plane, to two intersecting planes, or to a line. Where two of the dimensions are not far different and are both greater than the third, the cleavage produced by the parallel arrangement is in a plane; where two are much smaller than the third the cleavage may be parallel to a line; where the three diameters are of different lengths there may be cleavage parallel to the plane of the greatest and mean diameters, and a poorer cleavage in the plane of the greatest and least diameters; that is, normal to the first one. This less perfect cleavage conditioned by the greatest and least dimensions of the particles is what has been called grain, particularly in descriptions of slates.

Thickness.—The thinner the cleavage-making particles the greater the number of planes or lines of parting between or through the minerals possible in a given thickness of rock.

Cohesion, principally mineral.—The cohesion of the particles is the bond by which molecules of like character are held together. Mineral cleavage is a property of cohesion. The cleavage of the particles themselves and its attitude with reference to the plane of the greatest and mean dimensional axes help to determine the perfection of rock cleavage. The more nearly parallel to the greater dimensions of the particle, and the better the mineral cleavage, the better the rock cleavage produced. Usually, but not always, the mineral cleavage is parallel to one or both of the greater dimensions.

Adhesion.—The adhesion of the particles is the bond by which molecules of unlike character are held together. Where adhesion is less than cohesion, the less the adhesion the better the parting. Where adhesion is greater than cohesion, parting occurs within the particles by overcoming cohesion, and variation in adhesion has no effect on cleavage.

Abundance.—The more abundant a good cleavage-producing mineral is and the more area it occupies in the plane of its greater diameters the better the rock cleavage produced. Aggregation of good cleavage-giving particles into layers may give a good cleavage in such layers, but may leave intermediate layers with a poor cleavage or with none at all. This applies especially to the coarser rocks (schists). It is well known that fine-grained slates, yielding the easiest and most even planes of parting, show no marked concentration of their different cleavage-giving minerals into layers.

Below an attempt is made to indicate the extent to which these factors are applicable to individual minerals, and to determine the relative importance of the minerals as cleavage producers. The cleavage-producing factors are discussed in the same order as above.

MICA.

Shape and arrangement.—The particles have a ratio of greatest or mean diameter to thickness averaging perhaps 100:16, which is the greatest difference found in any of the cleavage-making minerals. They have a strong tendency to parallelism. The greatest and mean diameters do not show any uniform differences in dimensions, and hence the only cleavage produced by the parallel arrangement is parallel to the plane of the mean and greatest diameters.

Thickness.—The thickness of the particles in the rocks examined varies from about 0.01 to 0.40 mm., but averages perhaps 0.15 mm., giving a great number of mica plates and of possible planes of parting in a given thickness of rock.

Cohesion.—Mica has perfect mineral cleavage strictly parallel to its greater dimensions. It is the only important cleavage-giving mineral in which this relation holds, unless chlorite and talc be here included. The cohesion of the cleavage laminae is probably less than in any other mineral with which the mica is commonly associated in a cleavable rock, and usually less also than its adhesion with other minerals. As a result the parting in a rock containing mica is likely to be caused by the separation of the mica plates along their cleavage.

Adhesion.—As stated above, the adhesion of the micas to other particles is usually greater than its cohesion along its own cleavage planes, so that parting seldom occurs between micas and adjacent minerals. When concentrated into the layers the adhesion of the separate crystals of mica may be less than the cohesion of their cleavage, but as the shape of the separate crystals is that of cleavage plates the adhesion in this case might as well be called cohesion. Whether the parting be through the individual micas or between them the parting planes of rocks with secondary rock cleavage containing mica show mica as a dominant constituent.

Abundance.—Mica is very abundant and widespread in the rocks with secondary cleavage. In the rocks with coarser cleavage it has a tendency to be concentrated into layers, which are usually continuous and large in area. In the slates this tendency is slight.

When considered with reference to all of these factors mica is found to be a good producer of rock cleavage, affording great facility of parting parallel to a plane, and causing even planes of parting and a large number of possible planes of parting in a given thickness of rock. Indeed, as will be seen later, mica is probably more important as a cleavage producer than all other associated minerals combined.

HORNBLENDE.

Shape and arrangement.—The ratio of the length to the shortest diameter varies between 100 : 20 and 100 : 25. The ratio of the two shorter diameters is about 100 : 60. The long axes are commonly parallel to one another, and in these cases it is not uncommon to find a tendency for the least and mean axes also to be parallel. In other instances the longer axes are not parallel, but lie in the same plane, and the mean and least axes may not be parallel. In the first case the rock cleavage is almost anywhere in the zone parallel to the long axes, although when the least and mean axes are arranged, probably it is a little better in the plane of the greatest and mean axes than in the plane of the greatest and least axes. If the effect of their concentration into layers is disregarded the parallel hornblendes themselves tend to produce a linear parallel type of cleavage rather than a plane parallel type. There is an axis of cleavage rather than a plane of cleavage. Where the hornblendes have their longer diameters parallel to a plane and not to each other the tendency to parting may be only parallel to this plane.

Thickness.—The smallest diameter in the rocks examined varied from about 0.03 to 0.20 mm.

Cohesion and adhesion.—Hornblende has good prismatic cleavage in two planes inclined at about 28° to the plane of the greatest and mean dimensional development. Where the hornblende particles lie with all three dimensional axes respectively parallel, the prismatic cleavages are inclined 28° to the plane of cleavage produced by the dimensional arrangement. The hornblende cleavage therefore assists but little in producing a parting parallel to this plane. It may, however, and probably does, have an effect in producing the linear parallel type of cleavage, just as do the normal crystal dimensions. The cleavage is parallel to the unit prism faces and produces forms identical with the normal crystal outlines. It is hard to determine whether the parting is more easy around the particles than through their cleavage. The resulting forms are practically the same. The glistening cleavage surface shown on fresh fracture would seem to indicate that the fracture has been through the mineral cleavage planes to some extent at least, and when examined with a lens of high power the hornblende crystals are seen to have a grooved and irregular surface. Whether the parting is through or around the hornblendes, the fractured surface has irregularities which probably correspond roughly to the cleavage surface or to the prismatic shape of the hornblende.

Abundance.—Where hornblende occurs at all in a secondary cleavable rock it is ordinarily in considerable abundance, not infrequently making up much the greater bulk of the rock. There is also a tendency for the hornblendes to lie in layers. However, even where abundant and in layers, they do not occupy all of the area of the potential plane of parting. An average case would be one in which the hornblendes occupy two-thirds of the area, and from this proportion there is gradation to disappearance. While individual hornblendes tend to produce a linear-parallel parting by their shape and cleavage, the effect of their concentration into layers is to make the parting approach the plane-parallel type. In general, therefore, so far as the hornblendes are not concentrated into layers they tend to give a linear-parallel parting; so far as they are in layers they tend to give the plane-parallel type of parting. The common case is perhaps intermediate between these two extremes. [a]

In shape and aggregation, the hornblendes are not so well adapted to give the plane-parallel type of rock cleavage as the micas. They are better adapted by their shape, cleavage, and aggregation to give a linear-parallel type of parting. In either case their effect is much greater than that of quartz or feldspar.

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[a] Sp. 40686, sl. 15361, Mesabi district of Minnesota.

QUARTZ.

Shape and arrangement.—The quartz particles described under (1) and (2) on pp. 31–33, that is, the angular and subangular particles due to fracturing, showing all gradations in shape into original, angular, subangular, rounded or crystal-shaped grains, to the slight extent that they are arranged, exhibit a tridimensional parallelism. They may help to produce a rock cleavage in the plane of their greatest and mean diameters, or the plane of their greatest and least diameters (grain or side), or even in the plane of the least and mean diameters, depending upon the relative differences between the dimensional axes. The ratio of the greatest to the least dimensional axes in the rocks measured varied from 100 : 50 to 100 : 100. The lengths of the mean axes varied from almost that of the greatest to almost that of the least. When in slices inclined to the prevailing plane of elongation of the rock mass, the effect of the quartz on cleavage is small. The inclination of the slices to the prevailing cleavage is usually slight and causes only local variations from the prevailing surface of cleavage.

The quartz individuals in the layers and lenses described under (3), on page 33 have a good tridimensional arrangement which may again yield cleavage in the plane of the greatest and mean diameters and in the plane of the greatest and least diameters. But the layers are so thin compared with their length that the cleavage is mainly parallel to their flatness.

In the exceptional spindle-shaped forms described under (3), on page 33 the ratio of length to thickness varies widely. In the slides examined, it averages 100 : 50. The least and mean diameters of these forms are practically the same, so that any tendency to parting which these minerals might condition would be anywhere in a zone parallel to the greatest diameter. However, these grains are phenocrysts and in themselves probably have little effect.

In general, the dimensional inequality of the quartz individuals is so slight, and their arrangement so poor, that their effect as individuals in the production of rock cleavage is small. When aggregated into layers, as described on page 33, their effect may be considerable.

Thickness.—In thickness the quartz particles, of course, vary widely, ranging from large conspicuous phenocrysts to submicroscopic size. A common thickness for the lenses or layers of quartzes described on page 33 is from 0.06 to 0.40 mm.

Cohesion.—The cleavage of quartz is so poor that it probably has no effect on the parting. The cohesion is so great that parting seldom occurs across or within the grains. It is a fact of observation that cleavage surfaces of schists or slates seldom show fracture surfaces of quartz.

Adhesion.—The adhesion with other minerals is usually great. It is again a matter of observation that cleavage surfaces of schists or slates containing quartz seldom show quartz on such surfaces. When associated with feldspar in the "leaf gneisses" it may sometimes appear, but in its common occurrence with mica in the mica-quartz-schists, mica alone appears.

Abundance.—Quartz is one of the most abundant minerals of the rocks with secondary cleavage as a whole, but varies in individual cases from nearly 100 per cent to disappearance. In the coarser schists it has a tendency to aggregation into layers. The layers may be continuous, large in area, and relatively thin and even. The effect on the parting due to the abundance of the particles and to the aggregation of the particles into layers is considerable, notwithstanding the fact that the individual particles are so poorly adapted by their dimensions and arrangement to induce a good parting.

The total effect of the quartz in the production of cleavage is much less than that of either the mica or the hornblende. The parting is less easy. The plane of cleavage is as a rule less smooth, although probably, when the quartz is in the recrystallized layers, it is nearly as smooth as that due to hornblende. The planes of parting are much less numerous for a given thickness. When compared with the feldspars, as will be seen further on, quartz probably has the greater effect on rock cleavage.

FELDSPAR.

Shape and arrangement.—The feldspar with crystal and lenticular outlines, (1) page 35, has in part its longer diameters in the plane of rock cleavage. The diameters in this plane are not respectively parallel. The ratio between the greatest and least diameters varies from 100 : 50 to 100 : 75. So far as any rock cleavage is produced by the shape and arrangement it is parallel to a plane. The angular feldspar particles described under (2), on pages 37–39, have a very slight tendency to parallel arrangement. Such as it is, it is probably usually tridimensional. The difference between the greatest and least diameters is not large, 100 : 40 being an extreme and 100 : 60 to 100 : 75 being common ratios. The parting may be parallel to the plane of the greatest and mean axes and also to the plane of the greatest and least axes (grain and side). But in either case, owing to the poor arrangement and the small inequality in the axes, this tendency to parting is very slight. The residual feldspars left after granules have been rubbed off may themselves lie in irregular parallel lenticules (fig. 14). Where the feldspar has been sliced (see p. 38) the longer axes of the slices usually lie at low angles to the plane of rock cleavage (figs. 15, 16, 17). The ellipsoidal and lenticular forms described on page 39 usually have their longer diameters in the plane of rock cleavage. The individuals show a ratio of greatest to least axes of 100 : 30.

In the cleavable rocks feldspar with random arrangement is probably as abundant if not more abundant than feldspar with parallel arrangement, so that even were the effect of the arranged feldspar considerable, the total effect of feldspar on cleavage due to its dimensional arrangement would be very slight.

Thickness.—The thickness, of course, varies widely, from the largest phenocrysts to submicroscopic size. In the slides examined the arranged feldspars were not thicker than 3 mm.

Cohesion.—As the parallel arrangement of feldspar particles is mainly dimensional and not crystallographic, it follows that the cleavages of the different feldspar particles in general are not parallel and therefore have no uniform effect on the rock cleavage. In exceptional instances the feldspar particles exhibit both dimensional and crystallographic parallelism, and the feldspar cleavages have an effect on the rock cleavage. The good basal cleavage stands at right angles to the greater dimensions of the crystal, and hence to the plane of rock cleavage, to which the greater dimensions of the crystals are parallel. As the greater diameters of the crystals are parallel only to the plane of rock cleavage and not to each other, the basal cleavages of the different crystals, while always at right angles to the plane of the greatest and mean diameters, may be at any angle to one another. The poor macropinacoidal or brachypinacoidal cleavage may stand either normal or parallel to the rock cleavage determined by the dimensional arrangement of the constituent particles, depending upon the nature of the tabular development of the feldspar, whether brachypinacoidal or macropinacoidal. In the former case it is parallel to it; in the latter case it is at any azimuth normal to the plane of the dimensional cleavage, but of course always at right angles to the basal cleavage.

The characteristic arrangement of the basal feldspar cleavage normal to the plane of dimensional cleavage, to which the greater axes of the feldspars lie parallel, has a tendency to produce another rock cleavage at right angles to the rock cleavage conditioned by the dimensional arrangement of the constituent minerals of the rock. The cross cleavage may be well seen in the examination of hand specimens. On the ragged edges of parting normal to the best rock cleavage anywhere in a zone about the specimen, there may be seen numerous glistening cleavage faces of feldspars, many of them undoubtedly basal and some of them pinacoidal; while on the cleavage surfaces of the rock the feldspar cleavages usually do not appear. The basal cleavage of the feldspar would tend to make a better rock cleavage than a rock cleavage produced by the arrangement of the pinacoidal cleavage of the feldspar alone, or by the arrangement of the greater and mean dimensional axes, or both; but the total cleavage-producing effect of the feldspar in any plane is very small compared with that of the other minerals usually present, and thus the cross cleavage produced by the feldspar is usually insignificant compared with the cleavage formed by the dimensional arrangement of the other constituents.

Adhesion.—The adhesion of the feldspar particles to adjacent particles is usually great, probably greater than its own cohesion or the cohesion or adhesion of the particles with which it is associated, with the exception of quartz. As a result feldspars do not appear uniformly on the cleavage face of the schist except where the feldspar is associated with quartz, as in the case of leaf gneisses. In the case of uniform crystallographic arrangement, the feldspar cleavage surfaces may appear as indicated in the preceding paragraph.

Abundance.—Feldspar is one of the most abundant of the minerals of the cleavable rocks. It shows a slight tendency to aggregation into layers, particularly where granulated and in the coarser schists. Where the feldspars have crystal outlines they are usually porphyritic and not concentrated into the planes of rock cleavage; where in layers the effect on cleavage is probably greater than where not so aggregated.

In general, feldspar exerts its effect on rock cleavage in two ways: (1) By its shape, dimensional arrangement, and aggregation it gives a little assistance to other minerals in producing rock cleavage parallel to the greater dimensions of the particles; (2) in the rare cases where feldspar has crystallographic as well as dimensional arrangement the mineral cleavages of the feldspar condition a poor rock cleavage, both parallel and normal to the greater diameters of the particles.

Feldspar and quartz have less effect on the production of rock cleavage than any of the other principal cleavable rock constituents. With respect to the effects of the mineral cleavages on rock cleavage feldspar is more important than quartz. If the effect of an arrangement parallel to their flatness is compared, it seems that feldspar is far less important than quartz. As the arrangement parallel to the flatness is more common than parallelism of mineral cleavage in both quartz and feldspar, it is seen that the general effect of quartz on cleavage is probably more important than that of feldspar. For this reason feldspar has been placed last in the group of principal cleavage-making minerals. In its cleavage-producing capacity it is, however, unique among the minerals in affording rock cleavage in two directions at right angles to each other.

The comparatively slight effect which feldspar has in the production of cleavage is well illustrated in certain feldspathic rocks of the Wausau district of Wisconsin. Here in a number of places the feldspars may be observed to have tridimensional parallelism, yet in breaking out a hand specimen only a very poor rock cleavage, parallel to the basal cleavages of the feldspars, or parallel to the greater dimensions of the parallel crystals may be observed.[a] The same lack of cleavage when the feldspar is well arranged appears in certain of the Archean feldspathic schists of the Mesabi district of Minnesota.

CALCITE.

Shape and arrangement.—The shape of the calcite particles varies in different slides. Where in angular and ellipsoidal grains (p. 41) the ratio of the longest to the shortest axes of the particles varies widely, but 100 : 50 was found to be an average for several slides. The parallelism of the longer axes is not marked, but still a distinct tendency toward it can be detected. The rock cleavage produced depends on the differences in the three dimensional axes and the degree of arrangement, and is (1) parallel to the plane of the greatest and mean diameters—this may be fairly good—and (2), parallel to the plane of the least and greatest diameters—a very poor cleavage.

Thickness.—The thickness varies from submicroscopical to, perhaps, several centimeters.

Cohesion.—The calcite cleavage is rhombohedral. In practically all cases this cleavage is at random angles to the plane of the greatest development of the particles. In one instance the acute angles of the cleavage faces were observed to show a slight and doubtful tendency to lie in the plane of rock cleavage, giving the rhombohedral cleavages an inclination of $37\frac{1}{2}°$ to the plane of the greatest dimensional axes and to the rock cleavage.

Adhesion.—Adhesion of the particles to one another and to other particles is not far different from the cohesion of the mineral along cleavage planes. In the most cleavable marbles the plane of parting is a smooth one and shows but few calcite faces, which indicates that the rock cleavage follows the greater diameters of the constituent particles. Cleavable marbles with a poor cleavage commonly show the calcite cleavage faces on the rock cleavage surface.

Abundance.—Calcite, when present at all, is likely to make up a considerable proportion of a rock, where in subordinate amount there is a strong tendency to be concentrated into layers.

The total effect of calcite in producing rock cleavage measured by the importance of the above factors may be considerable in the cleavable marbles (see Pl. XVI). So far as observed the effect is due entirely to the shape and parallel arrangement. It must be remembered, however, that cleavable marbles are rare when compared with the abundance of noncleavable marbles, which have undoubtedly been under conditions of rock flowage.

[a] Sp. 5678, Wausau, Wis., cf. Weidman.

CHLORITE.

In general the same statements can be made concerning chlorite that were made above for mica. It has much the same shape. The parallel structure is not so common as in mica, but locally it is quite as good. Chlorite is not classed with the micas because in the typical rocks with secondary cleavage it is certainly far less abundant.

KAOLIN AND TALC.

Talc has essentially the same effect on cleavage as chlorite, but is a rare constituent in the rocks with secondary cleavage as a whole.

TREMOLITE, ACTINOLITE, GRÜNERITE, AND OTHER AMPHIBOLES.

Shape and arrangement.—The particles are commonly greatly elongated. The ratio of the length to the breadth is great. The crystals lie for the most part in random directions, but in some cases are parallel to a plane, and perhaps to a line. Rosettes or sheaf-like aggregates also are common, and the individuals of these aggregates may have a greater development in the plane of rock cleavage than normal to it.

Thickness.—The rosettes are sometimes a foot in diameter, while there is every gradation from this to submicroscopic size. Commonly the crystals are very thin.

Cohesion.—Where the particles are at all definitely arranged, the inclination of the planes of the prismatic cleavages to the plane of the greater diameters is not known; the particles are for the most part too fine to determine this. From the general arrangement of the individual particles it may be stated that it is probable that in general there is no uniformity in this inclination, but that in certain cases, from analogy with the hornblendes, the acute angles of the prismatic cleavage lie in the plane of rock cleavage, in which cases the planes of prismatic cleavages lie at angles of 27° to the plane of rock cleavage. The effect of this factor in the production of the rock cleavage must, however, be practicably negligible because of the imperfect dimensional arrangement of the particles.

Adhesion.—Concerning the adhesion of the particles, it can be said that cleavage surfaces of rocks containing them commonly show the particles on the surface. It is presumable that most of them appear with the normal outlines of the particles, but some of them undoubtedly present the cleavage surfaces of the minerals.

Abundance.—The minerals are not abundant in the rocks with secondary cleavage as a whole. They are, however, often found in the derivatives of calcareous and sideritic rocks. In such rocks they show a tendency toward segregation into layers. This is shown in some cases by the greater development of the rays of a rosette or sheaf-like aggregate in certain planes. Their concentration into layers affords a poor parting.

The total effect of these minerals in the production of cleavage is relatively slight. In some comparatively few instances their parallelism and aggregation are such that a poor parting is produced; but their common occurrence is in blades which interlock to such an extent that parallel planes of parting are not possible, and indeed in places the minerals by their interlocking prevent the parting which the other constituents of a rock have a tendency to condition.

TOURMALINE.

Shape and arrangement.—The crystals are elongated in the prism zone. The ratio between the longer and the shorter diameters varies considerably, a number of measurements of different specimens showing a maximum of 100:20 and a minimum of 100:60. The elongated particles have a marked tendency to lie parallel to the plane of rock cleavage. In this plane there is also to be observed at times a tendency for the crystals to lie with their longer dimensions parallel.

Thickness.—The absolute thickness, of course, varies greatly. The crystals measured vary from 0.1 to 1 cm. in thickness.

Cohesion.—The particles themselves have practically no cleavage.

Adhesion.—In breaking a cleavable rock containing tourmaline, the parting commonly occurs around the tourmaline individuals. The adhesion with the other particles with which it is associated is thus slight.

Abundance.—Tourmaline, even where most abundant, does not form any considerable proportion of a rock with secondary cleavage, and occupies no large area in the plane of possible parting. It also shows little or no tendency toward concentration into layers.

The total effect of the tourmaline on the production of cleavage is slight. Such as it is, it is due to its shape and arrangement and weak adhesion to the adjacent particles. It can produce but few planes of parting, and these planes are very uneven. It may aid other minerals in producing cleavage by preventing fracturing across its longer dimensions.

STAUROLITE.

Shape and arrangement.—Staurolite occurs as tabular individuals, frequently with cross twins. The crystals have a strong tendency to lie with their tabular development approximately parallel to the plane of rock cleavage, although there are many exceptions to this.

Thickness.—The absolute thickness varies widely, from submicroscopic to 2 cm. or more.

Cohesion.—The staurolite cleavage is so poor that parting is seldom or never observed to occur parallel to it.

Adhesion.—The adhesion of the particles to the adjacent minerals is slight, although probably greater than that of garnet or tourmaline. On cleavage surfaces of rocks the staurolites are likely to appear with their natural crystal surfaces.

Abundance.—Staurolite crystals, even where most abundant, occupy but a small proportion of the area of possible parting. They are seldom or never concentrated into layers.

Staurolite has practically no effect in the production of cleavage. Such as it has is due to its tabular development and low adhesion and its tendency to lie with its tabular development in the plane of rock cleavage.

OTTRELITE.

Shape and arrangement.—As shown on pp. 44–45, ottrelite occurs in a variety of forms, but only one shows any parallel arrangement in rocks with secondary cleavage. This appears in flat crystals with a ratio of the greatest to the least diameters varying from 100:50 to 100:35.

Thickness.—The absolute thickness of the crystals measured varies from 0.24 to 0.90 mm.—averaging perhaps 0.45 mm.

Cohesion.—The cleavage of the particles is basal, and corresponds with the longer diameters of the particles. Hence, so far as the crystals have any arrangement, the mineral cleavage is parallel to the plane of rock cleavage.

Adhesion.—The adhesion of the particles to other particles is greater than its own interior cohesion or the cohesion of any of the other minerals with which it is associated except, perhaps, mica. The brilliant basal cleavage is all that usually appears on a surface of rock cleavage.

Abundance.—Ottrelite crystals are not abundant, and show no concentration into layers.

The total effect of the ottrelite in the production of cleavage is practically nothing.

ANDALUSITE.

Shape and arrangement.—These crystals are greatly elongated in the prism zone. The ratio of length to thickness was found from a number of measurements to average about 100:10. The crystals run in every direction through the rock, but there is a greater tendency for them to lie parallel to the plane of rock cleavage than transverse to it.

Thickness.—The absolute thickness in the specimens measured is small, 0.15 mm. being, perhaps, an average.

Cohesion.—The cleavage of the particles themselves is poor, and the rock cleavage is seldom seen to follow the mineral cleavage.

Adhesion.—The adhesion of the particles to the other minerals with which they are associated is usually slight, as shown by the fact that the crystals commonly appear on the cleavage surfaces of the rock containing them.

Abundance.—When most abundant andalusite makes up but a small proportion of the rock, and shows but a slight tendency toward concentration into layers.

Compared with the other subordinate cleavage-producing minerals andalusite may have considerable effect in the production of cleavage on account of its shape, parallelism to a plane, and low adhesion. It has also a negative effect in preventing cross fracture. Its importance is indicated by the number of crystals usually appearing on a cleavage surface of the rock containing this mineral.

SILLIMANITE.

Shape and arrangement.—This mineral occurs as slender acicular crystals, which are sometimes almost hairlike. Average measurements are difficult to obtain as the crystals are characteristically broken across, and it is not possible to determine the limits of the individuals. There is a strong tendency to parallelism of their longer dimensions, either in individuals or in sheaf-like bunches or aggregates.

Thickness.—The absolute thickness is very small, as is indicated above.

Cohesion.—The mineral cleavage parallel to the brachypinacoid is perfect; but the crystals are not flat, and this cleavage probably does not have any uniform relation to the plane of rock cleavage. The crystals are so fine that no direct observations of this relation have been made.

Adhesion.—The adhesion of the particles to other particles is small, as is shown by the fact that the sillimanite commonly appears on the fracture surface of the rock with secondary cleavage in which it occurs.

Abundance.—Sillimanite is not abundant, and forms no considerable proportion of the rocks in which it is present. It is, however, concentrated into layers to a considerable extent.

When the mineral is present in a rock with secondary cleavage, its effect on the parting may be considerable. The effect comes from its shape, parallelism, poor adhesion, and its concentration into layers.

GARNET.

Garnet is isotropic, has no cleavage, and has but a slight tendency to concentration into layers; hence the effect on the production of cleavage is practically nothing.

SUMMARY STATEMENT OF EFFECT OF PRINCIPAL CLEAVAGE-GIVING MINERALS (MICA, HORNBLENDE, QUARTZ, FELDSPAR) ON FLOW CLEAVAGE.

Shape and arrangement.—With reference to the inequality of the dimensions of the fragments the micas stand easily first, hornblende second, quartz third, and the feldspars last. Between the micas and hornblendes the difference is wide; between hornblende and quartz it is still greater; between quartz and feldspar it is little.

The degree of parallel arrangement varies with the inequality of the axes of the fragments; the micas have the best arrangement, while the feldspars have the poorest.

The parallel unequiaxial particles of cleavable rocks tend to cause the best cleavage parallel to the plane of the greatest and mean diameters. In mica there is no uniform difference between the mean and greatest diameters, and hence the mineral affords no other cleavage. In hornblende there is but little disparity between the least and mean diameters, and hence the greatest and least diameters give a cleavage almost as good as that afforded by the greatest and mean diameters. There is an axis rather than a plane of cleavage. In quartz and feldspar the difference between the greatest and mean diameters is usually slight, but when arranged there may be a tendency to produce other cleavages parallel to the plane of the greatest and least diameters (side)[a] and rarely and doubtfully even parallel to the plane of the least and mean diameters (end).

It is to be remembered that all of these minerals may exceptionally occur as porphyritic constituents in rocks with secondary cleavage, in which case there may be no dimensional arrangement.

Thickness.—With reference to the absolute thickness, and hence the number of possible planes of parting in a given thickness of rock, the order on the average is mica, hornblende, quartz, and feldspar, although local conditions may change this order.

Cohesion.—In the effect of its own mineral cleavage one group of minerals—the micas (and chlorite, kaolin, and talc)—stands preeminent. Not only is the cleavage of the micas exceedingly good along one plane, but this plane corresponds exactly with the plane of the greatest dimensional development of the crystals. The mineral cleavage and the dimensional arrangement work together. Next in importance is the hornblende cleavage. The hornblende cleavage aids the dimensional arrangement of this mineral in producing the linear-parallel type of parting. The influence exerted by the feldspar cleavage is relatively slight. Of the two feldspar cleavages one is commonly parallel to the plane of the greatest dimensions, and the other, the best, normal to it. This latter is a conspicuous feature. Feldspar is there-

[a] Such cleavage has been called "false cleavage" by Sharpe.

fore unique among cleavage-producing minerals in affording two cleavages at right angles to each other.

Adhesion.—In general there is great adhesion between the mineral particles, as evidenced by the fact that the minerals appearing on the rock cleavage surface are likely to exhibit their mineral cleavage planes, indicating that parting has occurred within the micas, the hornblende, or the feldspars. Less commonly it occurs between the hornblende and adjacent minerals, or between the quartz and feldspar and adjacent minerals.

Abundance.—As to abundance, no comparative statement can be made. The minerals vary widely in proportion in different rocks. Quartz and the feldspars, however, in general probably make up a greater bulk of the rocks with secondary cleavage than do the hornblendes or the micas. As to aggregation into layers, particularly in the coarser cleavable rocks, the micas are again far in the lead, with hornblende and quartz next, and the feldspars probably last. This gives a better parting but fewer planes of parting in a given thickness of rock. The tendency of all minerals toward concentration into layers rather than toward even distribution is the characteristic feature for the coarser cleavable rocks. For the slates the grain is so fine that this concentration can not be observed.

Mica, then, stands easily first as a cleavage producer. It is more important probably than all the other minerals together, because of the parallelism of its perfect mineral cleavage with the rock cleavage afforded by its greater dimensional arrangement, a condition found in no other mineral. Its cleavage is parallel to a plane. Hornblende stands next in importance, and locally may produce a cleavage nearly as good as that made by the micas. Its effect is to produce either a plane-parallel or a linear-parallel type of cleavage, or some combination of these. Quartz and the feldspars are relatively unimportant compared with the first two minerals. Quartz probably has a greater effect than feldspar, due to its better dimensional arrangement. Feldspar, however, when arranged by recrystallization, exerts through its own cleavage a unique influence in producing cross rock cleavage.

CHAPTER III.

THE PROCESSES THROUGH WHICH THE SECONDARY PARALLEL ARRANGEMENT OF MINERALS IS BROUGHT ABOUT.

The production of secondary parallel structures has been observed to be associated with the deformation of rocks. A consideration of the factors of rock deformation in general will enable us to see more clearly the nature of the particular kind of deformation which is accompanied by the production of parallel structures.

As has been shown by observation and experiment the principal factor in the deformation of rocks is differential pressure. The statement is almost axiomatic. For the present purpose, it is immaterial whether the pressure[1] be produced vertically by the superincumbent weight of strata, horizontally by the lateral thrust due to the crustal shortening of the earth, by the intrusion of igneous rocks, by increase of temperature, or by any combination of these or other causes. Other factors affecting the manner of rock deformation are the physical and chemical properties of the constituent minerals, the original arrangement of the minerals, and the conditions of temperature, moisture, and time under which rocks are deformed. According to the relative importance of these factors, rocks yield to pressure in different ways. The adjustment may be accomplished by coarse fracturing and differential movement; by minute slicing; by fine fracturing extending only through the individual mineral particles of the rock, called granulation; by chemical change or redistribution, called crystallization or recrystallization; by the molecular-mechanical change of gliding along crystal planes; by parallel rotation of its constituent parts, without either molecular change or fracturing; or by any combination of these methods. Where the rock has permanently changed its form without losing its integrity, the molecular attraction being strong enough to hold the particles together, it is said to have flowed. All of the processes through which the rock may change its form may be effective in rock flowage, the essential limitation being that fracturing must not be so extensive or so preponderate over the other processes as to disintegrate the rock.

One of the common results of "rock flowage" is a parallel arrangement of the mineral constituents of the rock, giving it a "flow" cleavage. So common is such an arrangement in rocks which have been deformed by "flowage" that the existence of a parallel arrangement is commonly accepted as proof that a rock has flowed. For those not accepting this as proof, however, there is other evidence as is noted on pp. 102–108.

Where rock deformation occurs by slicing a "fracture cleavage" may be developed independent of any parallelism of mineral constituents. This occurs through the development of incipient fractures or the welding or cementation of parallel fractures, yielding parallel planes of weakness.

The conditions under which fractures are prominent may be observed near the outer part of the lithosphere. The conditions under which fractures are less extensive or subordinate to other processes of deformation are believed to exist at greater depth. Hence for convenience in discussion, the outer part of the lithosphere has been designated by Van Hise[a] the zone of fracture, while the deeper zone where rocks are deformed without fracture more extensive than granulation, has been designated the zone of rock flowage. It is readily understood that there is no sharp and regular plane of demarcation between these zones, but everywhere gradation and irregularity. For some rocks the zone of fracture extends to great depth; for others the zone of flowage extends to the surface. Local physical conditions may also cause these variations for the same rock. An attempt has been made by Van Hise to determine, on a basis of observed fact and mathematical deduction, the approximate depth to which the zone of fracture may extend, the result obtained being about 12,000 meters for the hardest rocks. Below this depth fractures probably do not exist; the rock flows when deformed. Thus flow cleavage, as a result of rock flowage, is essentially a phenomenon of the deep-seated zone of flowage. It appears at the surface through the removal of the overlying rock by erosion.

In this chapter flow cleavage will be discussed. The consideration of fracture cleavage is deferred to Part II.

SECTION I. GENERAL ACCOUNT OF POSSIBLE PROCESSES OF ROCK FLOWAGE YIELDING PARALLEL ARRANGEMENT.

It follows from the foregoing that the processes resulting in the change of form in the rock during flowage must also be the ones which in some way result in bringing about the parallel arrangement of the mineral constituents. These processes in their relation to parallel arrangement are:

(1) Crystallization and recrystallization, resulting in flattening of

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 589-603.

old mineral particles and growth of new ones in planes of easiest relief. These processes might conceivably also result in segregation of minerals of the same kind into bands, with or without parallel arrangement of the constituent particles, and might thus afford a parallel parting due to differing tenacity in or between different bands.

(2) Gliding along definite planes in minerals, resulting in flattening of the mineral particles. Gliding, crystallization, and recrystallization are the only processes which have been suggested to explain the flattening of mineral particles without fracture.

(3) Rotation of particles, of whatever origin, toward a parallel dimensional arrangement.

(4) Granulation without rotation may produce a parallel arrangement of the mineral constituents by leaving residual parallel grains and by breaking the particles into slices which have a rude parallelism. Through the crystallization of other constituents, or through the cementing of such fractures by infiltration of mineral material, or through the uniting of the parts due to molecular attraction under pressure, the rock may retain its integrity.

The nature of each of these possible processes will be considered, after which will be taken up their relative importance in the arrangement of individual minerals and in the arrangement of the particles of the metaclasic rocks as a group.

CRYSTALLIZATION AND RECRYSTALLIZATION.

Crystallization and recrystallization include the growth of old crystals, fortunately orientated, in the plane of easiest relief, and the production of entirely new crystals with their greater dimensions in the same plane.

Attention has been paid to this subject by many investigators, but the latest and fullest discussion, especially in application to the development of secondary rock cleavage, has been made by Van Hise,[a] whose work is briefly summarized below.

Crystallization and recrystallization are brought about by solution and deposition of minerals principally through the agency of water.

Water has long been known to have the power of taking minute quantities of mineral matter, including silicates, into solution. At ordinary temperature this process is exceedingly slow, yet it occurs to an appreciable extent; at higher temperatures it takes place much more rapidly. Barus has shown 180° C. to be the critical temperature for glass. At higher temperatures glass is dissolved in water very rapidly—from 180° to 220° C. it remains in a colloidal state, and beyond 220° it is in clear solution. In lowering the temperature the glass goes through a reverse series of changes. Temperatures as high

[a] Van Hise, C. R., Bull. Geol. Soc. America, vol. 9, 1898, pp. 269-328; Mon. U. S. Geol. Survey, vol. 47, 1904.

as 180° C. exist in the crust of the earth at a depth of about 5,000 meters, with the normal temperature gradient, though in regions of volcanic or dynamic action this temperature may exist near or at the surface. Barus has shown the solution of glass to be accompanied by a diminution of the volume of the glass-water system, and probably also by the development of heat. Vice versa, the deposition of glass from the glass-water system is accompanied by increase in volume of the glass-water system and by absorption of heat. Pressure and temperature therefore have an important influence on the solution and deposition of the glass. If refractory glass behaves in this way, minerals in rocks are likely to yield to similar changes even more readily.

All rocks contain water, in supercapillary, capillary, and subcapillary openings. Under varying conditions of high temperature and pressure of the lower zone of flowage now under discussion this water must be active in taking mineral material into solution and depositing it. The water takes the material from the mineral particles and deposits it in an unstrained crystal form, either on the parts of the same particle or elsewhere. There is probably no extensive migration of material, for the openings are minute. If an entirely new mineral or crystal is developed the process is called crystallization; if an old particle is regenerated or changed in form the process is called recrystallization. However, there is no sharp line between the two. The material for crystallization may come from minerals close at hand, and thus, so far as the rock as a whole is concerned, the process is really recrystallization. In the following the two terms are separated when practicable, but in many cases it seems advisable to use the term recrystallization to cover the general process of molecular change for the rock as a whole.

Pressure is the dominant factor. If the pressure on a solution near the solubility temperature of the solute increases, solution takes place; if it decreases, deposition occurs. In a rock undergoing deformation, pressure on capillary and subcapillary filaments of water probably varies from time to time and from place to place. It must vary in different-sized openings. This may result in crowding the water out of the places of great pressure and concentrating it in places of less pressure. If near the critical temperature, deposition may be supposed to take place wherever the lessening pressure, causing supersaturation, allows it.

On the other hand, with the pressure near the critical point, changes of temperature will cause solution and deposition. A rise of temperature may enable the water to take more material into solution, while a fall of temperature may cause supersaturation of the solution and consequent deposition. Different parts of the same rock mass may be at different temperatures, and solutions moving from place to place almost certainly find conditions of temperature favorable for depositing their load; also, the temperature at the same point may vary from time to time.

A third factor in influencing deposition is the selective influence of the solid mineral particles with which a solution comes in contact. There is a tendency for minerals to select from solution material like that of which they are composed and add it to themselves in crystallographic continuity. Of course, some minerals, under given conditions, have much greater power in this way than others; such are those favored by possessing a mineral habit, cleavage, or density best adapted to the conditions of existing pressure. Certain particles fortunately oriented may grow or survive, while adjacent particles, not so oriented, may be destroyed.

Another factor affecting the solution and deposition of mineral material is the physical condition of the mineral particles. If the minerals with which water is in contact are in a state of strain, and thus have energy potentialized in them, solution is known to be greatly accelerated. As the mineral material after deposition is not in a state of strain the process of recrystallization obliterates evidences of strain. If a strained condition of the minerals accelerates solution a condition of no strain in the mineral in contact with the solution does not accelerate solution, and thus may be of negative assistance to deposition. The strain effects present in a mineral are probably dependent largely on the position of the mineral crystal with reference to pressure, minerals unfavorably situated being most strained and hence likely to be the first to go into solution.

With the proper combination of the above factors old mineral particles grow and new particles develop with their greater diameters in the directions of relief from pressure. The relations of these directions of relief to pressure are discussed on pages 109–118.

The process of molecular change by crystallization or recrystallization is thus one of solution and deposition of mineral material by the water contained in rocks. In its accomplishment much or little water may be used, but an extremely small amount only is necessary. Also the amount of material in solution may be much or little, but it is usually so small compared with the adjacent solid minerals that the rock throughout the process of its change of form by recrystallization is essentially a solid. Indeed, there is evidence that changes between solid particles may occur, to a yet unknown extent, without the intervention of water, but the important process is believed to be as above described.

Crystallization or recrystallization under rock deformation tends to result in the condensation of chemical systems—that is, the minerals so developed during rock flowage usually have a higher specific gravity than the average of the minerals from which they are derived.

Thus far Van Hise's discussion has been followed in the main. Below are discussed certain additional features of the subject which have appeared during the investigation here reported.

Criteria for determining crystallization or recrystallization.—Criteria for determining the probability of crystallization or recrystallization of a given mineral during rock flowage may in part be deduced from what has been said on the principles of recrystallization, but in large part they have been brought to mind by a study of individual minerals during this and other investigations. They are as follows:

(1) The conditions of depth, temperature, moisture, or time under which the rock is deformed. Often important evidence can be obtained which will show this, and thus determine the presumptive importance of recrystallization. The presence of water is usually an essential condition.

(2) The nature of the rock itself as showing the probability of its yielding by recrystallization, rotation, or fracture.

(3) The mineral associations and the character of the mineral itself. Not infrequently the mineral is known to be of a secondary nature from its characteristics of color, zonal growth, etc.

(4) Presence of minerals in a metaclasic rock which were not present in the rock from which the metaclasic rock can be shown to have been derived.

(5) The occurrence of minerals with their greater diameters at right angles to an original structure—such as bedding—which does not show sufficient deformation to warrant the assumption that the minerals at right angles to the bedding reached their position through rotation. Such minerals could not have been deposited in this position; they could not have been rotated to this position; development in situ is the only alternative.

(6) The shape of mineral particles in the rocks with secondary cleavage, as compared with the shape of those in original igneous rocks.

(7) The manner of contact of the minerals. In the micas, for instance, the laminæ of one crystal feather out diagonally against those of another, giving close diagonal contact, which could be produced only by molecular adjustment.

(8) The size of the particles. Crystallization or recrystallization has a tendency to increase the size of the grain (see pp. 76–78). If the grain is coarser than seems necessary for the amount of deformation the rock has undergone, or coarser than in the original rock, crystallization or recrystallization, the only constructive processes known, must be the cause. This evidence is decisive in many cases, as for instance, in a coarse schist derived from a mud stone.

(9) Better than the size of grain is the evenness of grain. It is shown (pp. 71–78) that recrystallization combined with granulation has a marked tendency to produce an even grain.

(10) The lack of strain effects commensurate with the deformation shown by the rock as a whole or by adjacent minerals. When strain effects are present in most minerals they are conspicuous; when absent or slight this is easily determined.

(11) The complete parallelism of minerals, or, what amounts to the same thing, the lack of bending or breaking due to interference of particles, which would necessarily be in evidence if the particles had been much rotated.

(12) Recrystallization has a tendency to segregate minerals of the same kind into bands, in this showing great similarity to original flow structure.

Crystallization or recrystallization accompanied by rotation.—Crystallization or recrystallization is usually accompanied by rotation of the particles, as will be shown in the discussion of the relations of parallel structure to pressure (pp. 109–118).

So-called flattening of particles in situ largely a process of recrystallization.—It is believed that the so-called "flattening of particles in situ," so frequently cited, occurs in most cases through the process of recrystallization above described. But gliding along mineral cleavage planes may be partially responsible in some cases.

ROTATION.

The part which rotation plays in producing a parallel arrangement of mineral constituents during deformation is most difficult to determine.

Effectiveness of rotation in bringing about an approach to parallelism of mineral constituents in rocks with secondary cleavage may depend upon the conditions of temperature, moisture, pressure, and speed under which the rock is deformed and upon the characteristics of the particles themselves—their size, shape, and manner of aggregation. The interrelations of these two factors, determining the rotation of a mineral particle, are exceedingly complex.

When differential pressure is applied to the complex mass of particles forming a rock, and the rock flows, there is a tendency to a rotation of all particles which are not already arranged with the best possible attitude toward the pressure there acting—i. e., on all particles on which couples are effective under the given stress conditions. This applies to all particles, whether original, recrystallized, or recrystallizing.

If there is freedom of movement of the particles, sufficient rotation is likely to cause approach to parallelism. In a soft, plastic clay which is deformed at the surface under conditions where recrystallization is not possible the particles have such freedom of movement that approximate parallelism of the particles may be reached, but this requires a very considerable amount of shortening of the rock mass. Also in the deep-seated zone where rock deformation is brought about mainly by recrystallization, considerable freedom of movement may be allowed certain particles by the process of recrystallization affecting the particles of the rock unevenly. In an ideal case where the particles have no interference the degree of parallelism reached by a certain amount of rotation may be indicated in figs. 20 and 21, taken from Harker. If a circle with a definite number of radii representing the greater diameters of original particles be compressed into an ellipsoid with its shorter diameter one-fourth the length of the diameter of the circle, the radii making an angle of less than, say, 10°, with the plane of greatest elongation will be twelve times the number within the same angle in the undistorted form.

The shape of the minerals also is likely to have some effect on the freedom of movement. One would suppose that in a complex of long narrow crystals there would be more interference in rotation than in a complex of short, stumpy crystals. If this is the case the crystal best adapted to a parallel arrangement under differential pressure—that is, one with great differences in dimensions—is not adapted for rotation into such parallel arrangement. Suppose, for instance, that the long, slender hornblende crystals in a rock had random arrangement, and the attempt were made to rotate them toward a common plane or line. It may be clearly seen that long before approximate parallelism is reached the crystals will mutually interfere, and then because of unequal transverse support they are likely to be broken in their further movement. This fact of necessary interference is dwelt upon here because later it will be shown that many long, slender crystals which now lie parallel in schists could not have been rotated to this position because they do not show such interference effects. Where the slender crystals are few, or are so arranged that they will not interfere, rotation may be effective in bringing about their parallelism, as has been shown during this investigation.

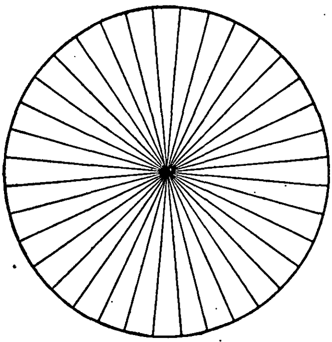

Fig. 20.

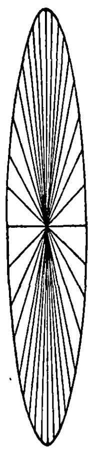

Fig. 21.

Figs. 20 and 21.—Diagrams showing the rotation accompanying a given amount of shortening. After Harker, Rept. 55th Meeting Brit. Assoc. Adv. Sci., 1885, p. 822.

The size of the particles may also have an effect on the degree of parallelism reached by rotation. With a given amount of deformation under certain conditions the smaller the particles affected the more will they be rotated. Figs. 22, 23, 24, and 25 illustrate this.

If a particle with the diameter X Y is rolled between two plates P P′, until the one plate is past the other to a distance S S′, the diameter X Y, which was originally normal to the plates, as shown in fig. 22, will have the position shown in fig. 23. Now roll a particle of smaller size with the diameter X′ Y′ (fig. 24) between two plates until the upper plate is past the lower plate the same amount as in fig. 23. In this case the diameter X′ Y′ of the smaller particle will rotate to a much greater angle with its original position than did the diameter of the larger particle. If the circumference of the first particle is 2 inches and that of the second 1 inch, a movement of one-fourth of an inch

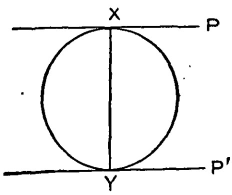

Fig. 22.

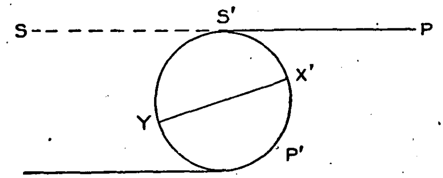

Fig. 23.

FIGS. 22 and 23.—Diagrams showing angle of rotation of large particle under differential movement amounting to SS′.

will revolve the axis of the large particle 45°. A similar movement will revolve the axis of the smaller particle 90°. Therefore the amount of revolution which a particle undergoes in a given amount of movement is inversely as its circumference. This has been shown experimentally in clay mixed with particles of mica. With a given amount of movement it has been shown that the finer the particles of mica so mixed the more nearly parallel they are. Granulation produces smaller particles and hence may aid rotation in bringing particles into parallelism.

It is thus seen that rotation is likely to be effective so far as there is freedom of movement, so far as the particles are equidimensional,

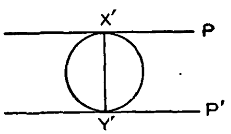

Fig. 24.

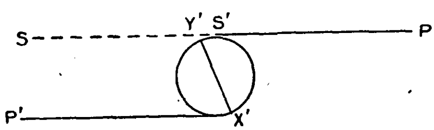

Fig. 25.

FIGS. 24 and 25.—Diagrams showing angle of rotation of small particle under differential movement amounting to SS′.

and so far as they are small. It will be shown (pp. 109–118) that rotatory stresses are always present in the strains commonly occurring in rocks, and that all particles, whatever be their origin, so far as they are not already in the best possible attitude toward pressure, or normal to this position, are likely to feel the effects of these strains.

For rotation the obvious criteria are as follows:

(1) The presence of strain effects, which are certainly more characteristic of rotation than of recrystallization. One of the most characteristic of these is angular outlines, indicating that the shape is due to

granulation. Where the particles are angular and clearly due to the granulation of larger particles it is certain that any parallelism of their longer diameters that is observed in the rocks with secondary cleavage is due to rotation, as no other process is possible in such a case. In such rocks the granulation of larger particles can be observed in all its stages, and accompanying the granulation may be seen all stages of rotation of the fractured particles. These granulated particles are not markedly unequidimensional, and hence there is usually little interference. The occurrence of angular particles apparently due to granulation is one of the best criteria observed for determining that rotation has occurred. The lack of angular character, however, is not evidence that rotation has not occurred.

(2) The absence of positive evidence of recrystallization. The reverse condition, the presence of evidence of recrystallization, does not show that rotation has not occurred.

GLIDING.

Certain crystals may change their form under pressure by differential movements along "glide" planes without open fractures.[a] The glide planes frequently follow the mineral cleavage. After the movement the glide planes may be planes of secondary twinning. Movements with minute fracturing along twinning or cleavage planes of minerals have also been called gliding by some writers. They are considered in this paper under "slicing." Gliding is accompanied by a minute change of form. For only a few minerals has this change of form been shown to have any considerable value. The best gliding observed is found in calcite, and the process will be described in connection with that mineral (pp. 88–90).

The principal and almost the only criterion for the detection of gliding is the presence of repeated twinning and slip planes, sometimes giving a reedy or fibrous structure. Both granulation and recrystallization destroy these gliding planes, and if abundant evidence of either of these processes is present, they may hide the evidence of gliding.[a] For this reason the part gliding has played in flattening and elongating mineral particles can not be determined certainly from a study of the metaclasic rocks themselves. Its relative importance may be argued only from the presence of evidence of crystallization adequate alone to explain the observed facts. Experiments by Professor Adams still in progress are likely to show to what extent gliding may be effective.

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[a] Adams, F. D., Experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1901, pl. 24, fig. 4. Mügge, O., Ueber die Plasticität der Eiskrystalle: Neues Jahrbuch für Mineral., etc., vol. 2, 1895, pp. 212–228.

GRANULATION.

This process probably is most effective in its assistance to rotation and recrystallization (p. 76), but even where recrystallization or rotation is practically absent, it may still produce a very imperfect parallel structure.

Granulation may leave residual flattened particles. When a rock is put under pressure and fracturing occurs, the fractures are usually highly inclined to the greatest pressure, as shown on p. 112. Probably where the material is not confined on the sides, the fractures for the most part have positions inclined less than 45° to the greatest pressure. However, where the material is not ideally brittle or is confined on all sides it has sometimes been observed that the fractures tend to take positions at angles greater than 45° to the greatest pressure, carving the grains into flattened cones or lenticular forms, with diamond-shaped cross sections. It may be that the flatness of the residual grains is in part really due to the minor recrystallization or gliding of the particles and not to the direction of fracture. Such flattened particles, when formed by fracture without the aid of the processes above outlined, will have their greater dimensions parallel, and so this process must be mentioned as one of the possible ones in the production of parallel structures. It is simply one of the results of granulation.

A better parallel arrangement is developed where the granulation occurs mainly along one set of shearing planes rather than along two intersecting sets, taking off slices or minute granules from the side of the original particles and leaving the remnant of the particles as thin, ribbon-like fragments with parallel arrangement.[a]

While granulation usually fractures particles in such a way that the resulting smaller particles have no great differences in dimensions, it has been observed that the material broken from the particles is sometimes in slices whose long dimensions follow the directions of fracture (figs. 15, 16, and 17). The length of such slices is not infrequently 5 or 6 times the thickness, although a ratio of 3:1 is more common. At the time and place of breaking these particles may be arranged with their longer diameters at angles 45° or less to the general plane of rock cleavage. The special kind of granulation that results in parallel slices is for convenience of discussion called "slicing" in this report.

The phenomenon of slicing may be particularly well seen in a mineral which itself has a good cleavage to control the direction of slicing. In hornblende, for instance, slicing with little or no rotation has been observed to divide a large particle into a number of thin ones lying with their greater diameters at a low angle to the plane of

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[a] See discussion of Adams's anorthosite, p. 37.

schistosity (fig. 7, p. 30). Where slicing follows the mineral cleavage, stages of its gradation into gliding are to be observed.

Assistance of granulation to recrystallization.—Granulation forms small particles and brings about a state of strain in particles, both of which are favorable to recrystallization. With a given mass the finer the subdivision the greater the surface. The finer the subdivision, therefore, the greater the reaction, ceteris paribus, between mineral and solvent. Also, the deformation leading up to granulation induces a state of strain in a mineral in which energy is potentialized. Minerals thus strained are attacked much more readily by solvents than minerals not so strained. A further and important assistance is rendered by the development of heat due to the mechanical crushing.

Assistance of granulation to rotation.—Granulation aids rotation in two ways. It produces smaller particles and allows greater freedom of movement. So far as slicing occurs, the greater dimensions of the slices just after granulation may lie at angles not larger than 45° to the plane of rock cleavage, from which position a comparatively slight amount of rotation will carry their longer diameters into the plane of rock cleavage. Evidence of such rotation frequently accompanies slicing. In many observed instances the fractures are at even smaller angles to the plane of cleavage, and a small amount of rotation has induced a close approach to parallelism.

THE COMBINED EFFECT OF RECRYSTALLIZATION AND GRANULATION ON SIZE OF GRAIN.

As a matter of observation recrystallization tends to increase the size of the particles in a rock mass undergoing rock flowage; but to varying extents in particles of different mineral species. The increase in size comes from the fact that small particles present greater surface per unit volume for the action of solvents than larger particles, and the material of the smaller particles goes into solution and is ultimately added to the larger particles because of the "surface tension which exists on the boundary surfaces between solids and liquids, as on those between liquids and gases—the so-called free surfaces of liquids. This tension acts so that the surfaces in question are reduced in size, with the consequent enlargement of individual crystals (the total amount of precipitate remaining practically unaltered), i. e., with the coarsening of the grains."[a] Granulation tends to subdivide the particles of a rock mass undergoing rock flowage, but to varying extents with different minerals. Other things being equal, the larger particles of the rock are likely to feel more of the differential pressure, and to be granulated to a greater extent than the smaller ones. Whether acting separately or together, recrystallization and granula-

[a] Ostwald, W., The Scientific Foundations of Analytical Chemistry, Macmillan & Co., London, 1895, p. 22.

tion tend to cause a uniformity in the size of particles of the same mineral species in a rock, a fact of direct observation in cleavable rocks. But in a given rock the uniform size of the particles of one mineral species thus produced is not the same as that of another mineral species.

This difference in size of grain in different mineral species results not only from difference in mineral habit, but from the fact that recrystallization and granulation affect different minerals to different degrees. In some minerals, under given conditions, recrystallization or granulation occurs, one almost to the exclusion of the other, and in other mineral particles both processes occur. The size of grain depends upon the balance obtained between the two; in other words, it is the net result of a contest between the constructive process of recrystallization, tending to produce larger grains at the expense of smaller ones, and the destructive process of granulation tending to break down the larger particles. The recrystallization of micas and hornblende, without granulation, produces a characteristic uniformity of grain for each of these minerals. Granulation of quartz and feldspar particles, without recrystallization, produces a characteristic uniformity of size of grain for each. Granulation and recrystallization, acting together on quartz and feldspar, tend to cause uniformity of size of grain in each. As would be expected, the mineral particles showing evidence of recrystallization alone, such as mica and hornblende, are larger than the ones in which the process of granulation or of granulation and recrystallization combined have been effective, such as quartz and feldspar.

It should be remembered that rocks with secondary cleavage are composed very largely of mica, hornblende, quartz, and feldspar, and for the most part of two or three of these minerals, and hence there are usually, as shown by observation and measurement, but two or three characteristic sizes of grains, giving, in connection with parallel arrangement, a striking impression of uniformity of grain, in marked contrast to the grain observed in many of the rocks before rock flowage has developed a cleavage in them.

After rock flowage has ceased it not infrequently happens that recrystallization continues or again begins, and then the tendency of large grains to develop at the expense of small ones is not opposed by the tendency of granulation to break down the larger particles as they form. To this condition may be ascribed the porphyritic crystals frequently seen in cleavable rocks which have developed apparently without regard to the prevailing cleavage in the rock, and show included in them other constituents of the rock with a dimensional arrangement parallel to the plane of rock cleavage (Pls. III and XIII). The principal cleavage-giving minerals—mica, hornblende, quartz, and feldspar—may be sometimes observed to develop under these conditions. The minerals characteristic of cleavable rocks, but not having any great effect on rock cleavage—such as garnet, tourmaline, chloritoid, andalusite, chiastolite, staurolite, etc.—are known to develop commonly under such conditions and only rarely during rock flowage.

SECTION II. RELATIVE IMPORTANCE OF PROCESSES OF ARRANGEMENT IN INDIVIDUAL MINERALS.

MICA.

The origin and parallel arrangement of mica plates in the micaceous schists, slates, and phyllites are believed for the most part to be the result of crystallization or recrystallization, for the following reasons:

Micaceous schists are rocks which are known in many cases to have been in the zone of rock flowage, under conditions of high pressure and heat, and with a considerable water content; all of these are conditions favorable to the development of mica by crystallization or recrystallization. Mica certainly is not a characteristic mineral of the belt of weathering.

The micaceous schists and phyllites are very common products of the alteration of water-bearing feldspathic sandstones or graywackes and shales or muds, originally containing little mica, and they are also the result of the metamorphism of various igneous rocks with or without mica as an original constituent.

The occurrence of mica in large flakes in schists derived from rocks originally containing small flakes or none at all is the most decisive evidence that can be offered of its development by recrystallization.

In certain cleavable rocks derived from sediments the mica plates can be seen to stand at right angles to the original bedding, and this original bedding may not show deformation sufficient to warrant the assumption that the micas now found at right angles to the bedding were originally parallel to the bedding and owe their present positions to rotation. They could not have been originally deposited in this position; they could not have been rotated; the alternative explanation is crystallization in situ.[a] (Pl. XIV, A.)

The common association of the micas in cleavable rocks with secondary minerals, such as garnet, staurolite, etc., well known to be secondary developments by new crystallization, is presumptive evidence that the micas themselves may have resulted from secondary crystallization.

When the original nature of the rock is in doubt, certain features to be observed in the micas of metaclasic rocks with secondary cleavage are evidences of recrystallization. Petrographers sometimes discriminate secondary mica from original mica by criteria of color, shape, or distribution. The micas commonly lack strain effects such as would be

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[a] Sp. 14745, sl. 9380, Little Falls, Minn.

expected in minerals of their shape if original and rotated to their present position. They have more uniformity in size and in general a larger size than mica particles in noncleavable rocks. Their manner of feathering out against each other precludes the idea of their rotation as original minerals to this position.

The micas may be found in layers, these layers alternating with quartz layers which have certainly been recrystallized. The association of the quartz and biotite and the nature of the contact of the two minerals are good evidences of their new crystallization (Pl. IX, *B*).

Sericite is a common development in the peripheral granulation of quartz and feldspar, assuming a characteristic parallel position (fig. 26). That the parallel position of the sericite is due to crystallization in situ is scarcely open to doubt.

Rotation of original grains and the retention of the arrangement of favorably orientated original micas probably enter also to a very limited extent into an explanation of the present arrangement of the micas. In a rock with secondary cleavage developed from a rock originally containing mica it is probable that some of the flakes now present were originally present, and have either retained their original positions or have been rotated. The micas lying with their cleavage plates at a low angle to the plane of rock cleavage would be the most likely to be rotated to this plane. Occasionally there may be observed the actual bending of mica plates in a common direction, showing the direction of rotation. In the false cleavage described on pp. 25–26 the parallel mica plates may be seen in various stages of subsequent rotation along certain zones.

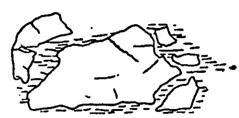

FIG. 26.—The secondary development of parallel sericite by crystallization in cracks formed by fracture. (H. 1040 Sericite-schist. Tamus.)

Two other processes may have a slight effect in arranging the micas, gliding and slicing—that is, the differential movement between cleavage laminæ without actual fracture and similar differential movement with fracture. It is doubtful whether mica shows to any extent true gliding in the cleavable rocks, but it is certain that many mica plates owe their arrangement to the slicing of larger mica plates along cleavage planes and the strewing out of the slices along parallel planes. This differential movement or slipping of the mica plates has been frequently observed and described. It is to be noted, however, that this process is not likely to be effective unless the cleavage of the original mica particles is at low angles to the plane of rock cleavage.

The micas which sometimes appear with their dimensional axes parallel to the prevalent cleavage of the rock, but with their mineral cleavage inclined to this plane (figs. 3, 4), may owe their unusual position to granulation or slicing which has not been controlled by the mica cleavage, much as the pyroxenes in the mashed anorthosite, described by Adams,[a] are strewn out by granulation in bands with the pyroxene cleavage at any angle to the rock cleavage. But there is good evidence that associated quartz in bands is itself recrystallized, and it seems probable therefore that recrystallization has affected the mica also.

As we are concerned mainly with parallel structures, it is scarcely necessary to discuss the origin of the random mica particles developed with their own cleavage and longer diameters inclined to the prevalent cleavage of the rock mass (Pl. III). It is easy to prove that such minerals are for the most part porphyritic developments after the rock flowage developing the prevalent cleavage had ceased; the proof is on the same kind of evidence used to prove the later development of garnets, tourmaline, chloritoid, and other minerals of that class.

HORNBLENDE.

It is clear that newly crystallized or recrystallized hornblende particles, which are observed in schists, very greatly preponderate over original particles, and hence that the arrangement is due largely to recrystallization, for the following reasons:

Hornblendic schists are characteristic developments from rocks which have been in the zone of rock flowage under such conditions of great pressure and temperature as to afford favorable conditions for recrystallization.

In many cases the hornblendic schists have resulted from the metamorphism of greenstones or basic igneous and sedimentary rocks in which the hornblende as an original constituent was either wanting or in subordinate quantity. Numberless gradations from such original rocks to typical hornblendic schists have been noted in many regions by many observers.

Where original and recrystallized hornblende occur together in a slide, the new hornblende may sometimes be discriminated by its lighter color or its occurrence as enlargement borders of the original hornblende.

Uniformity of size is characteristic of hornblende particles in cleavable rocks, and this has been shown to be an evidence of recrystallization.

Hornblende particles observed in rocks with secondary cleavage have a greater length relative to breadth or thickness than the hornblendes observed in original igneous rocks, as shown by the measurements given on page 31. In the few specimens measured the average length also was found to be somewhat greater than that of original hornblendes; but many more measurements would be necessary to warrant a positive generalization on this point. The additional relative or absolute

[a] Loc. cit.

length is reached without fracturing, and recrystallization is the only process to which it can be attributed.

Hornblende may frequently be seen to have developed through alteration of feldspar and other material. In the mashed rhyolite-gneiss from Berlin, Wis., it is developed in the tails of the granulated feldspars and does not itself show granulation. In these tails it is parallel to similar hornblende occurring in the groundmass.

White hornblende crystals in cleavable rocks are frequently considably broken and have many irregularities in arrangement, in general they show a degree of parallelism in their different parts and to the plane of rock cleavage and freedom from strain effects which can not be expected in hornblende crystals owing their parallel arrangement to rotation alone. The natural inference is that both the arrangement and origin of the particles must be due to recrystallization. In a hypothetical case, if a rock in which are numerous slender hornblende crystals with random arrangement be deformed by rock flowage, the hornblende crystals interfere, and, because of unequal transverse support, break or bend at numerous places in order to accommodate themselves to the new conditions. They may become only imperfectly arranged parallel to a plane or line. This interference of the particles in a mass undergoing strain can be shown to be a mathematical necessity. In the rocks with secondary cleavage bending and breaking, due to interference, are subordinate phenomena, and hence it is concluded that crystallization has been important.

From the facts above cited it is concluded that recrystallization of hornblende under pressure has produced the greater part of the hornblende making up the hornblendic schists; hence that recrystallization is mainly responsible for the parallel arrangement, although doubtless it has been assisted somewhat by rotation.

So far as parallel hornblendes now present in rocks with secondary cleavage are original constituents (for the above reasons they are believed to be subordinate in quantity) it must be supposed that they were either in their present position before deformation commenced, or were in a favorable position for rotation to their present position, or are the result of slicing of larger original hornblendes.

Slicing has certainly been instrumental in bringing about the arrangement of many of the hornblendes in hornblendic schists developed from original hornblendic rocks.[a] In a number of rocks have been observed all stages in the process of slicing which has followed the direction of the cleavage of the hornblende (fig. 7). Slices when first formed are likely to be at almost any angle except 90° to the plane of rock cleavage, but it is clear that the majority of them were already at angles less than 45° to the plane of rock cleavage before any rotation occurred.

[a] Sp. 40685, sl. 15360; sp. 40690, sl. 15363, Mesabi district, Minn.

In slides of hornblende-schists there are freqently to be observed random hornblende crystals which lie with their columnar development at high angles to the plane of rock cleavage. These may be original or secondary developments with exceptional arrangement due to local variation in stresses; they may be original crystals which have not been rotated during rock flowage, or they may be secondary developments after deformation has ceased.

QUARTZ.

The quartz particles described under (1) page 31, as having modified crystal outlines and rounded subangular shapes show no direct evidence of granulation or recrystallization or gliding, and in the absence of such evidence, no opinion is offered as to the cause of their parallel arrangement, so far as they have any.

The quartz particles described under (2) pages 31–33, are clearly, both in shape and in arrangement, the result of granulation and slicing, with or without subsequent rotation. Evidence of this has already been presented and will not be repeated.

The quartzes in elongated lenses and spindle-shaped grains described under (3) pages 33–35, may in part develop by granulation or slicing in the manner described under (2) pages 31–33, but most of them, and especially those with more or less even and rounded outlines lacking strain effects, are believed to owe their origin and arrangement, or at least their final configuration, mainly to recrystallization, for the following reasons:

(1) Many rocks with secondary cleavage containing quartz in this form are known to have contained considerable moisture and to have been in the zone of rock flowage under conditions of severe metamorphism favorable to recrystallization. The alteration of muds and sands under such conditions has frequently yielded such forms.

(2) Where the quartz in this form is associated with secondary hornblende or mica in cleavable rocks, as it commonly is, and arranged with its longer diameters parallel to the longer diameters of these minerals, which are characteristic secondary minerals resulting from recrystallization, the presumption is that recrystallizing forces have also affected the quartz. Other common associates of quartz in this form are garnet, staurolite, tourmaline, ottrelite, etc., which are known to be new developments. The manner of association of quartz and mica is also in some cases evidence of recrystallization. The parallel mica plates may be observed to occur strictly parallel to the periphery of flattened quartz individuals, and the ends of the mica plates not infrequently project into clear, limpid quartz which has evidently grown around the mica. (Pl. IX, *A*, *B*.)

(3) In the metaclasic rocks, which have evidently undergone much deformation, the elongated and spindle-shaped quartz forms described

under this head are commonly larger than the quartz grains in undeformed rocks in the same rock mass. Rocks become deformed and cleavable in parts, and such parts may be coarser grained than the remainder of the formation. If an increasing size of grain in a formation is found to correspond with the greater metamorphism occurring at any place, it may be inferred that some constructive process has occurred to increase the size of the grains. Recrystallization is the only constructive process known.

In the Black Hills of South Dakota is a great series of rocks with secondary cleavage which have resulted from the metamorphism of fine-grained banded sediments. The size of the grain in these rocks varies with the amount of metamorphism, and in general not with the original character of the graywacke and slate, although in earlier stages the size of the recrystallized grains corresponds roughly with that of the original grains; it is possible to select a graded series of rocks resulting from the metamorphism of a graywacke slate in which the grain increases as the cleavage and metamorphism are more advanced. This is but one of many illustrations that might be cited.

(4) As important as the size of the grain is the evenness of grain in determining recrystallization. While different degrees of metamorphism are likely to be associated with different sizes of grain, rocks showing the extremes of metamorphism, the best cleavage, and abundant evidence of recrystallization have a curious uniformity of grain in particles of the same mineral species. There are no phenocrysts nor matrices. Quartz in the elongated lenses is seen to share in this uniformity of grain, affording confirmatory evidence that its development in such cases is by recrystallization.

(5) In a rock with secondary cleavage quartz particles are frequently seen to lie in narrow layers of rather uniform thickness composed of numerous narrow individuals lying side by side, as shown in fig. 4 and Pls. VII–X. The individuals are frequently joined by narrow zones of diffuse extinction, due to the inclination of the contact plane. The layers for a considerable distance, while extinguishing in various parts, are still continuous crystalline masses of quartz without mechanical breaks and without other strain effects commensurate with the deformation they must have undergone. It is believed that these features can be explained best by recrystallization. It is perfectly clear that the long band as it now stands could not have been rotated to its present position as a whole. It is possible, and indeed probable, that some of the individual parts represent small quartzes or fracture pieces of quartz which have been rotated into approximate parallelism or carved in situ by granulation or slicing. However, the continuity and evenness of banding can not be explained in any such way. Granulation or slicing could scarcely yield such close fitting parts, and these processes would furthermore result in the development of

minute granules strewn out in the plane of rock cleavage. Even if granulation and slicing could yield elongated individuals so peculiarly fitted together, they would be likely to taper off at the ends and give way to finely granulated material, as in the case of the granulated feldspar figured on p. 37, which shows the best parallel arrangement due entirely to granulation which has been observed in this investigation. The absence of associated granulated material with the quartz bands is evidence that either granulation has never occurred or if it has occurred that recrystallization has coalesced the separate granules; and if this has happened, it is reasonable to assume that recrystallization has also affected the original residual particles.

The narrow quartz bands frequently resemble veins at first glance. If they were veins they would still be the result of crystallization. But close examination shows points in which they differ from veins. The individual quartzes in a vein do not have great elongation in the direction of rock cleavage; they form a mosaic. If a vein, there ought to be found discoloration of some sort due to weathering along the walls of the vein; this is uniformly absent, and even if present, it might still be explained as material pushed aside during the recrystallization of the quartz. No common conditions are known in which numerous veins would develop in this way parallel to the plane of rock cleavage for long distances without breaking across it at places, although this might happen exceptionally in planes of cleavage along which minute jointing had occurred. Neither do veins show the evenness and parallelism shown by these bands. Lastly, the material of these bands in many cases is the only other material present in the rock besides the micas or feldspars. If the quartzes represent veins, we must suppose the rock before the vein action commenced to have been entirely composed of parallel mica plates or layers of feldspar, which is not probable.

(6) In the case of the quartz-porphyry of the Thüringer Wald, so frequently referred to, the shape of the quartzes is again indicative of recrystallization. The long curving tails on these quartzes, which show undulatory extinction and minor fracturing, but still retain their essential unity, could scarcely have resulted from any other process.

(7) Where the quartzes are seen to have cores of older quartz surrounded by rims of new quartz, usually divided by a ring of ferrite or other inclusions, there is conclusive proof of the partial recrystallization or growth of the quartz. The old and the new quartz are in crystallographic continuity. The new quartz, while in optical continuity with the original quartz, is usually added only along directions of easiest relief.

Quartz is sometimes seen completely inclosing other minerals which are original. While this might supposedly happen before the final solidification of the rock from a magma, in rocks with secondary cleavage it probably commonly indicates recrystallization of the quartz subsequent to the original solidification of the rock.

(8) If in a rock which had been clearly subjected to great pressure, as evidenced by the breaking of the feldspars and of some of the quartzes, some of the quartzes are comparatively free from strain effects or fractures, it can be supposed that the quartzes have readjusted themselves to the prevailing conditions by crystallization or recrystallization, thus obliterating their strain effects. Of course, strain effects may still be present and recrystallization have occurred. Indeed, in most cases recrystallization is believed to lag behind deformation to such an extent that some strain effects are visible. The statement should perhaps be that if the quartz shows any less fracturing or strain shadows than other minerals of the rock, this is evidence of the recrystallization of the quartz.

A characteristic strain effect in quartz is the inclusions so frequently observed. These are commonly in planes which in slides appear like lines. They consist largely of cavities containing gas and water and minute mineral particles. Observation shows these planes of inclusions to be closely associated with other pressure effects, such as undulatory extinction and fracturing. There is frequently complete gradation from tenuous and ill-defined planes of inclusion to well-marked planes and fractures.[a]

Further, these inclusions may be in planes intersecting one another at high angles, frequently at an inclination of 45° to the plane of greatest diameters of the quartz or to the plane of rock cleavage. According to principles given, pp. 121–124, they may be phenomena of fracture in shearing planes. In a quartz in which there has been no strain it is believed that these planes of inclusions are less numerous and have less regularity of arrangement; but this is hard to prove, as it is so extremely difficult to find a rock containing quartz which can be proved not to have undergone strain.

When tested by the above criteria the shape and arrangement of the elongated quartz bands or elongated spindle-shaped quartz masses (3), seem probably to have resulted mainly from recrystallization. Yet there may have been also subordinate gliding, granulation, and rotation, for recrystallization obliterates evidences of these processes.

When the quartz grains are nearly equidimensional, or the grain is finer, the above criteria are less effective. Many quartz crystals which are nearly round and show no evidence of recrystallization by any of the above criteria, have undoubtedly been recrystallized. Where the grain is exceedingly fine it is impossible to apply these criteria, and one is unable to tell by direct observation what processes

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[a] See figs. 3 and 4 of Van Hise's paper on the pre-Cambrian Rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, pp. 216, 217.

or what combination of processes have been effective in producing the fine-grained groundmass of many cleavable rocks.

Quartz crystals have been made to glide under pressure experimentally, but it is certain that little or no evidence of such gliding is now to be observed in the quartz of the cleavable rocks. If gliding has occurred, evidence of it has been obliterated by recrystallization and granulation. The only strains in quartzes now to be observed that are of the same order as those of gliding are those of undulatory extinction, and the comparative absence of this phenomenon, as seen above, is regarded as evidence that recrystallization has occurred.

In general the quartz particles showing evidence of recrystallization in cleavable rocks are not so numerous as those lacking such evidence, but if this statement is confined to quartz particles showing parallel arrangement, the evidence of recrystallization preponderates over that of any other processes causing such a parallel arrangement. Recrystallized quartz particles are certainly less abundant than recrystallized mica or hornblende, and probably more abundant than recrystallized feldspar. Evidence of granulation and rotation is more abundant in quartz particles than in mica or in hornblende particles, and probably less abundant than in feldspar particles, but these processes have yielded but a poor arrangement. So far as recrystallization works upon granulated and rotated particles it tends to obliterate evidence of granulation and rotation, and hence the evidence now observable may not in all cases measure the extent to which granulation and rotation has actually occurred.

FELDSPAR.

In the presentation of the facts of arrangement of the feldspars the feldspar particles were classified according to shape.

The feldspars occurring with more or less modified crystal outlines and random arrangement described under (1) on page 35 may be either original or recrystallized. From their shape they could not have been granulated. The crystals described under (1a), which have random arrangement and around which the other constituents of the rock bend, are original as compared with other constituents, for they have evidently acted as rigid units during the deformation of the rock, the other constituents being crowded about them and thus frequently showing strain effects. If recrystallized, they would be likely to have a parallel arrangement or to include the other constituents, as in the case described below.

The crystals with random arrangement described under (1a) as not crowding the other constituents of the rock but containing them in lines parallel to the plane of rock cleavage must be recrystallized, for the minerals contained are quartz and mica in parallel bands which themselves can be proved to be recrystallized. The development of the feldspars must have been subsequent to the recrystallization of the quartz and mica. If original in their present form and arrangement the crowding must inevitably have occurred during the development of the parallel arrangement in the other constituents of the rock. Furthermore, they lack strain effects which they must have shown if they were there during the deformation of the rock. Their large size as compared with that of other constituents results from the fact that their development by recrystallization occurred after the rock deformation ceased, when granulation no longer breaks down the grains as fast as recrystallization builds them up.

Crystals with more or less modified crystal form occurring in dimensional parallelism to the plane of rock cleavage (1 b, pp. 35-37) owe their shape and probably their parallel arrangement to recrystallization. That recrystallization is responsible for their development is proved by the evidence cited above, that is, the presence of recrystallized quartz and mica through the feldspars without change of direction and further by the lack of strain effects commensurate with the deformation which the rock has evidently undergone. In some cases, also[a] such crystals have been observed to be the alteration products, with mica and garnet, of a larger feldspar crystal. The association with other recrystallized minerals such as hornblende, is further presumptive evidence of recrystallization. Rarely the feldspar crystals under this head have received their arrangement through slicing along feldspar cleavage planes and rotation.[b]

The angular particles described under (2) on pages 37–39 might be either in original form, granulated, or recrystallized, but their shape is probably in most cases, if not in all, either original (i. e., the same as in the undeformed rock from which the cleavable rock is derived) or due to granulation. If recrystallization has affected them it has left them with a shape quite different from that characteristic of recrystallized particles described above and below. All stages of granulation from the original mineral to the finely granulated particles may actually be seen in many slides. Where such gradations are absent the angular form is itself presumptive evidence that the form is due either to granulation or original character. Evidence of the rotation of such granulated particles toward the common plane of cleavage is almost uniformly present. In certain cases, as in the anorthosite described by Adams (pp. 37–38 and figs. 13 and 14) the elongated forms are clearly the result of granulation or slicing along the peripheries, leaving residual parallel grains. In many other cases the evidence for recrystallization or granulation is not decisive.

The lenticular and ribbon forms of feldspar described under (3) on page 39 are in part, both in shape and arrangement, the result of

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[a] Sp. 6021 W., Wausau, Wis. [b] Sp. 6021 W. in part, Wausau, Wis.

recrystallization. The criteria for determining this are identical with those used in determining the origin and processes of arrangement of similar bands of quartz (pp. 82-86).

In general the feldspars, which clearly owe their shape and parallel arrangement to recrystallization, are relatively rare as compared with particles lacking such evidence and probably arranged largely by rotation and granulation or as compared with still more abundant particles lacking the parallel arrangement. Feldspars without parallel arrangement, but showing evidence of recrystallization, are often observed. Cores and enlargements and new growths along cracks are not uncommon phenomena, but such recrystallization has not yielded a parallel structure and thus does not properly come within the limits of this discussion. Many feldspars show evidence that some combination of these processes of arrangement has been effective, but usually the one or the other is preponderant.

Gliding is not observed to be important. While secondary twinning as an initial stage in granulation is a common phenomenon, in no case has this twinning been observed to have caused any appreciable flattening of the mineral. Where any such possible flattening is present with the twinning, evidence of granulation, rotation, or recrystallization is commonly more conspicuous.

In an exceedingly fine-grained groundmass it is practically impossible to determine, from any phenomena shown by the particles themselves, what processes have been effective, though it may be possible to determine their probable origin by ascertaining the dominant processes which have affected the coarser constituents of the rock.[a]

CALCITE.

In explaining the parallel arrangement of calcite grains several processes may be considered, the common ones—recrystallization, granulation, and rotation—and gliding. Any or all of these processes may be effective in given cases, and it is extremely difficult to determine criteria by which to separate them. Granulation and accompanying rotation are mainly responsible for the shape and arrangement of the angular fragments described on page 41. This is evidenced mainly by the shape of the fragments and their gradation to unbroken crystals. The process determining the shape and arrangement of the small ellipsoidal particles (described on p. 41) is not so clear, but it is thought to be mainly recrystallization, because of the general evenness of texture of the grains, their ellipsoidal outlines, and their comparative freedom from strain effects. Yet it is apparent that granulation may have aided recrystallization and that its characteristic evidences may have become obliterated by recrystallization.

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[a] Sp. 14929, sl. 9460, Black Hills, South Dakota.

Gliding may have been partly effective in any of the above cases. In experiments on the deformation of marble under pressures, Adams has shown that deformation of the calcite crystals may occur by gliding along twinning planes of the crystal $-\frac{1}{2}$ R. This results in dimensional parallelism of the crystals and not in crystallographic parallelism, for gliding may occur, no matter what the original arrangement of the calcite is, and no amount of the gliding will make parallel the relative crystallographic directions of different crystals. The main criterion by which gliding is determined is the increased amount of twinning to be observed. Where the movement occurred by gliding, the crystals were found to be finely striated by polysynthetic twinning grading into minute fractures, giving a reedy or fibrous appearance (Pl. XV). In the calcite particles occurring in cleavable rocks more or less of such twinning is to be observed, and the presumption is that at least some of it is a secondary phenomenon due to pressure and is accompanied by a change in form. But the difficulty lies in ascertaining how much of the twinning is original and how much is secondary, and thus in determining the amount of the deformation brought about in this way. In the particular slides examined, in but few cases did the twinning lines seem to be much more numerous than that common for an unmashed marble. If gliding had occurred extensively, subsequent recrystallization may have obliterated it. In connection with his description of his experiments on the flowage of marble, Adams publishes descriptions of 42 cleavable marbles for comparison. He concludes that while recrystallization undoubtedly plays an important and in many cases probably a chief part in the deformation of marble, the processes of gliding and granulation are also effective.[a]

The facts observed in this study seem to indicate that recrystallization and granulation are by far the most common of the processes producing the arrangement of calcite grains in cleavable rocks. The ease of recrystallization of calcite has been commonly recognized. It is beautifully illustrated under conditions of low pressure by the cementation of marl and by the common change of limestone to marble.

The process of gliding has probably assisted both of the above processes, though in the particular rocks examined in this study the evidence of such assistance has been slight. In the observations of cleavable marbles made by Adams more evidence of gliding was found, and in his experimental work the process has been demonstrated to occur.

If the parallel arrangement of the calcite crystals of schistose marbles is often clearly the result of recrystallization, and calcite is

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, vol. 195, 1901.

known for other reasons to recrystallize very easily, the question naturally arises why parallel structures in marbles are not more general, for it is exceedingly rare to find marbles with a parallel structure. Crystalline granular marbles without parallel structure frequently appear between very schistose gneisses. In the exceptional cases where parallel arrangement is attained the conditions must be somewhat unusual. Following Van Hise,[a] it may be suggested that the ready recrystallization of calcite and its consequent tendency to develop large individuals by the merging of smaller ones may soon obliterate evidence of parallel arrangement after rock flowage has ceased, and that a parallel arrangement appears only when the rock flowage and development of a parallel structure has occurred so recently that subsequent recrystallization has not had time or the proper conditions to obliterate the parallel structure. In other words, the parallel structure developed by granulation or recrystallization under dynamic conditions may be obliterated by subsequent recrystallization under static conditions.

CHLORITE.

No presentation of evidence is necessary to show that chlorite in parallel flakes in cleavable rocks is a development by crystallization or recrystallization. The development of chlorite from other minerals has been so frequently observed and described that its secondary nature is accepted as a matter of course.

In many schists chlorite is partially or wholly pseudomorphous after the micas, in which case its parallel arrangement is that of the mica. In other cases chlorite is a development from minerals of appropriate composition which originally had no parallel arrangement. In either case the shape and arrangement are due to recrystallization.

TREMOLITE, ACTINOLITE, GRÜNERITE, AND OTHER AMPHIBOLES.

These minerals are in all cases certainly the result of crystallization in metaclasic rocks, as may be proved by field occurrence, where their development may be traced from rocks originally having none of these minerals. Their arrangement in certain cases in the plane of rock cleavage may be explained (1) by recrystallization during rock flowage; (2) by recrystallization after movement ceased, the plane of rock cleavage affording directions of easiest development of the crystals; (3) by rotation of recrystallizing and recrystallized particles. What combination of these factors in a given case has been effective in producing the very partial arrangement observed in these minerals is difficult to determine. If (1) were effective we should expect to find

[a] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 754-755.

a better arrangement than we do find. If (3) were effective we should expect to find considerable breaking and interference of the fibers. Explanation (2) seems to afford the best explanation of the facts observed and this is accordingly given emphasis, although it is not meant to imply that the two others may not have been effective to a subordinate degree.

GARNET, STAUROLITE, TOURMALINE, ANDALUSITE, CHLORITOID, ETC.

Garnet, staurolite, tourmaline, andalusite, chloritoid, and the other crystals of this class in cleavable rocks are uniformly porphyritic. Their development in such rocks is largely by recrystallization, which occurs after rock flowage has ceased and is favored by high pressure and temperature, as is evidenced by their high specific gravity and characteristic association with great masses of intrusive igneous rocks. Evidence of their development by the recrystallization of the rock mass and recrystallization later than the rock flowage that has produced cleavage is shown by the following facts: (1) They appear in rocks clearly derived by rock flowage from rocks originally lacking such minerals. (2) They frequently lie at high angles to the prevailing cleavage in the rock. (3) They do not show the degree of mechanical deformation that they would necessarily show had they developed in their present positions before rock flowage had ceased. Many of the crystals are long and acicular, and would surely have been broken if any considerable movement had occurred subsequent to the development. (4) They include, within their outlines, minerals in part similar to those in the remainder of the rock with an arrangement of their greater diameters in the plane of rock cleavage (Pl. XIII), an arrangement in part at least developed during rock flowage. (5) The mica and the other constituents of cleavable rocks, which are certainly developed by recrystallization during the process of deformation, are frequently seen to end abruptly at the periphery of the minerals of this group and to pass them by without any change of direction or crowding. If rock flowage under which the micas developed had occurred subsequent to the formation of the porphyritic crystals, crowding and bending of the micas must inevitably have occurred and would doubtless not be obscured by their subseqent recrystallization. (6) The usual large size of minerals of this group, as compared with their associated mineral particles, is due to their development subsequent to rock flowage, when granulation is no longer acting to break down the crystals.

While the development of this group of crystals is believed to have been mainly subsequent to the development of the rock cleavage, it is true also that in some cases further flowage occurred subsequent to their development, as shown by fracturing of the crystals and the crowding of the other constituents. The very fact that the effects of further movement are so conspicuous confirms the conclusion that the crystals not showing these effects developed after the movement ceased.

SECTION III. GENERAL PREDOMINANCE OF PROCESS OF RECRYSTALLIZATION.

By comparing the discussion of the cleavage-producing capacity of mica, hornblende, quartz, and feldspar which make up the great bulk of the rocks with secondary cleavage, with the discussion of the processes which have determined their shape and arrangement, it appears that the mineral grains yielding the best flow cleavage are the ones which are described as showing conspicuous evidence that their shape is due to recrystallization, and if our idea of the factors and conditions controlling recrystallization is correct, the arrangement of such recrystallized particles is also due largely to the same process. It is an observed fact that in general, so far as evidence of recrystallization is absent, the parallel arrangement also is lacking. (The reverse proposition does not hold.) Yet there is evidence, also, that granulation and slicing occasionally develop an excellent parallelism and may have been effective also in producing the parallel arrangement of particles which clearly bear the stamp of recrystallization as the last and dominant process. Evidence of rotation of original and granulated particles unaccompanied by recrystallization is conspicuous only in certain original and granulated mineral particles which are not so well adapted to give a good rock cleavage as the particles in which evidence of recrystallization is apparent. It is certain, however, that rotation has accompanied recrystallization in many grains which now show evidence only of recrystallization, for during the rock flowage which developed the cleavage rotatory stresses must have been generally active, as will be shown on a subsequent page (pp. 109–118). There is practically no evidence of gliding in these principal cleavage-giving minerals.

The relative importance of the various processes giving the parallel arrangement to the remaining minerals of metaclasic rocks is a matter of little consequence for the reason that such minerals have for metaclasic rocks as a whole so little effect on rock cleavage. In calcite all processes, recrystallization, granulation, gliding, and rotation are effective; the order given is probably also the order of their importance. Calcite is the mineral best adapted to change its form by gliding, and is the only one in which this process has yet been shown to be effective, but even here this process is probably subordinate to recrystallization. From evidence to be observed in the rocks themselves, gliding is therefore practically negligible. In the remainder of this group of minerals the origin is almost entirely recrystallization, and the arrangement, so far as there is arrangement, is doubtless due mainly to the same cause, although rotation may have had some effect.

Investigations have shown in certain instances that the cleavability of a rock varies with its composition.[a] This expresses also the fact that cleavability varies with mineralogical composition. In the development of flow cleavage in a noncleavable rock there is both chemical and mineralogical change and redistribution of substances. This occurs through recrystallization. Hence the close relation not only between cleavability and composition, but between these two and recrystallization.

SECTION IV. ORDER OF RECRYSTALLIZATION.

It has been seen that certain minerals develop secondarily in cleavable rocks by recrystallization more readily than others. It is not possible to make definite statements concerning the order of facility of crystallization or recrystallization of different minerals, because of the fact that certain of the cleavage-making minerals, such as hornblende, usually develop to the exclusion of others, such as micas; the cleavage rocks in which hornblende and biotite or hornblende and muscovite occur together are very few. We know definitely that quartz generally recrystallizes before feldspar, and mica and hornblende before quartz and feldspar. In a few cases[b] we know also that the biotites have developed before the hornblendes, but how generally this statement can be made to apply is a matter of doubt. As to the micas, it is certain that the muscovite and biotite, when they occur together, usually develop simultaneously; they are interleaved in a most intricate fashion, and the development of one or the other is apparently a matter of the substances available. Exceptionally the muscovite evidently crystallizes before the biotite. The recrystallization of calcite has not been compared directly in the same slide with the development of the minerals above named, but it is known that this mineral recrystallizes very easily and probably relatively early in rock flowage. Chlorite perhaps in some cases develops simultaneously with the micas, but it is certain that in other cases it develops later as an alteration of micas or other minerals. Where it is developed to the exclusion of the micas it is of course difficult to compare its ease of recrystallization with that of the micas. Actinolite, grünerite, and tremolite are certainly in many if not in most cases crystallized out later than the principal cleavage-making minerals, as is evidenced by their unbroken form and random arrangement in rocks which show parallel arrange-

[a] See articles by Reade and Holland in Proc. Liverpool Geol. Soc. for 1899-1900, pp. 463-478, and for 1900-1901, pp. 101-127. See also Harker, Rept. 55th Meeting Brit. Assoc. Adv. Sci., 1885, p. 828.
[b] Sp. 18037, sl. 9589, near Hudson River, New York.

ment by crystallization or recrystallization of other constituents. The same statement may be made with reference to the group of heavy minerals, such as garnet, staurolite, andalusite, chloritoid, tourmaline, etc. They are all developments by crystallization very late in the process of deformation or after deformation has entirely ceased. Their development is also later than the recrystallization of calcite or chlorite and, in most cases at least, of actinolite, grünerite, and tremolite.[a]

It is interesting to ascertain whether or not the order of recrystallization or crystallization of the various minerals of cleavable rocks bears any uniform relation to any of their mineral properties, and to attempt to ascertain what properties have caused the minerals to recrystallize in this order during rock flowage. So far as one can judge from the above facts, there is no obvious arrangement of the mineral properties corresponding with the order of recrystallization. The specific gravity in the four principal schist-making minerals—mica, hornblende, quartz, and feldspar—ranges roughly from higher in the easiest and first recrystallized to lower in the last recrystallized. In chemical composition there is apparently no order. The symmetry shows no regular variation. The mineral habit varies from greater inequality of the dimensional axes to less inequality. In the less important minerals which undoubtedly crystallize later in rock flowage, there is the same irregularity and uncertainty in the order of properties. Instead of having a lower specific gravity than the principal cleavage-giving minerals above named, these minerals have a higher one. In symmetry and shape they show greater variety; in some instances the crystals have less inequality of dimensional axes than the principal cleavage-making minerals and in other cases more.

The conditions determining the order of development of the various cleavage-making minerals by crystallization or recrystallization during rock flowage are evidently somewhat complex, and not evidenced by a simple graded series of mineral properties. The form and kind of mineral developing at any stage in the process may be conditioned by factors of temperature and pressure, substances available, crystal shape and symmetry of the particles which may develop at that point, their specific gravity, etc. For different minerals and conditions different factors are dominant, and a comprehensive discussion of the causes of the order of development during rock flowage would involve a detailed description of many factors affecting each mineral, which would make a paper in itself. Van Hise[b] has made an exhaustive study of these factors, and the reader is referred to his work on metamorphism. One principle, however, may be empha-

[a] See slides and specimens from Republic Mountain and Humboldt Mountain, Marquette district, Michigan.

[b] Van Hise, C. R., Mon. U. S. Geol. Survey, vol. 47, 1904.

sized. While the minerals developing at any place or time during rock flowage are limited in their variety by the substances available in the capillary and subcapillary solutions, it may be supposed that if at any point such substances are present that any one of several minerals might develop, the mineral best adapted by its high specific gravity and especially shape, as shown by the above facts, to the conditions of pressure there existing will be the first one to form, although other factors may have a modifying effect. It is an observed fact that minerals developed by recrystallization during rock flowage have as a rule higher specific gravities than the minerals originally present in the rock or minerals developed under conditions of weathering, and thus the development of a rock with a good cleavage through recrystallization means a diminution of volume. It is further a matter of observation, as shown in the foregoing pages, that the minerals showing the best evidence of recrystallization are the ones which by their shape and dimensions are best adapted to the conditions of unequal pressure which have existed during the deformation of the rock.

CHAPTER IV.

MISCELLANEOUS OBSERVATIONS ON THE INTERNAL STRUCTURE OF CLEAVABLE ROCKS.

SECTION I. WHY SOME MINERALS SHOW CRYSTALLOGRAPHIC PARALLELISM AND OTHERS DO NOT.

It has been shown that minerals of different kinds in metaclasic rocks do not exhibit a parallelism of their crystallographic or vector properties, but that particles of the same mineral species do show such parallelism in so far as these properties have uniform relations to the dimensions of the particles. In other words, the minerals are always controlled in their arrangement by their dimensions, and in so far as the vector properties happen to be in uniform positions with reference to such dimensions these properties are themselves parallel. The parallel crystallographic arrangement of particles of the same mineral is thus a phenomenon subordinate to, and dependent upon, the dimensional arrangement of the particles. This uniform relation of the crystallographic properties to dimensions and consequently the parallel arrangement of the crystallographic properties are found in cleavable rocks only in the particles of minerals which have a strong tendency to occur with strongly marked crystal habit, such as mica and hornblende. In developing by recrystallization during rock cleavage, as these minerals do for the most part in cleavable rocks, their tendency to take on definite crystal forms, working under the general law of dimensional control, requires that the crystallographic axes of the particle shall also be arranged in parallel positions. Minerals such as quartz, feldspar, and calcite, which lack a strongly marked crystal habit or cleavage form in metaclasic rocks, commonly do not show a parallelism of the crystallographic properties of the different particles. It is known that the tendency to the development of quartz and calcite in columnar forms is slight. Any small accident of crystallization may cause the development of short, stumpy crystals whose length is not greatly different from their thickness. This is shown in quartz by a tendency to develop terminal faces, manifesting itself in striations on the pyramidal faces, in this contrasting strongly with hornblende, which has a strong tendency to columnar habit without the development of terminal faces. For this reason in meeting the requirements of dimensional arrangement under rock flowage, quartz, and calcite in recrystallizing do not necessarily arrange their crystallographic axes. The tendency toward developing in characteristic crystal shape is not strong enough to orient the crystallographic properties when the mineral is arranging itself dimensionally under pressure. The same statements apply in a less degree to feldspar.

Under exceptionally favorable circumstances it would be natural to expect that the tendency, slight though it is, for quartz, feldspar, and calcite to take on characteristic crystal shape with characteristic dimensions, would cause the crystallographic properties to be parallel, and this, except for calcite, seems to be the case in exceptional instances, as shown in Chapter II.

The reverse proposition, that all minerals showing strongly marked crystal habit in cleavable rocks have also crystallographic parallelism, does not hold, for the fact has repeatedly been emphasized that many minerals, such as tourmaline, chloritoid, etc., and exceptionally even feldspar and biotite, develop late in the process of rock flowage or after rock flowage has entirely ceased, and usually lack not only crystallographic but even dimensional parallelism.

SECTION II. MOLECULAR SHAPE AND RECRYSTALLIZATION.

There is a significance in the entirely new development by recrystallization of minerals, such as mica and hornblende, with strongly marked crystal habits and with parallel dimensional and crystallographic arrangements. The outward form of a crystal is commonly taken to be a manifestation of its internal structure. The characteristic dimensions of a crystal may be supposed to be conditioned by the molecules themselves, because of their shape or manner of aggregation or both. It may be supposed further, then, that the dimensional control of the arrangement observed in the crystals developed entirely by recrystallization in metaclasic rocks will apply equally well to the very first molecule or group of molecules of these minerals which began to develop; in other words, that the very first molecule or group of molecules which were brought together by crystallization or recrystallization to make up the crystals of these minerals were controlled in their initial position by the conditions of unequal pressure existing during the rock flowage. They were actually squeezed or held in parallelism by the differential pressure. Whatever molecular property gives the characteristic shape to crystals causes the arrangement of the molecules under pressure. So far as fortunately oriented crystals survive or continue to grow, it may be that the molecular properties determining their shape meet the requirements of dimensional control. In discussions of the molecular structure of a mineral, it has ordinarily been assumed that the shape of crystals is due to molecular grouping, i. e., the molecules have been considered as essentially equidimensional bodies, and the differences in symmetry and shape of crystals have been considered to depend upon the spacing of the molecules. One would expect, therefore, that, as the first molecules of the newly developing crystal aggregated themselves in a rock undergoing flowage, their tendency to unequal spacing in different crystallographic directions would give the crystal at once unequal dimensions. This would cause its orientation with its shorter diameters parallel to the shortening of the rock mass, and in mineral particles so arranged the greater molecular spacing would be looked for in the direction of the greatest dimensional axes of the crystals—that is, normal to the shortening of the rock mass. But it has further been held by crystallographers that mineral cleavage is dependent upon the spacing of molecules, the molecules being spaced more closely in the planes of mineral cleavage than transverse to them. On such a hypothesis it must be assumed that in developing by recrystallization during rock flowage, the micas, for instance, take a position with the greater spacing of the molecules parallel to the shortening of the rock mass, a direction in which one would expect the molecules to be most closely spaced. If the molecules were most widely spaced in the direction of the least dimensional diameter of the mica, as required by the theory of mineral cleavage, it is difficult to understand how the minute beginnings of mica crystals, or the first aggregates of molecules which can be called crystals, could arrange themselves, as they unquestionably have, under the law of dimensional arrangement. Such considerations, together with the complete dimensional control of the arrangement of newly developing mineral particles in a rock undergoing rock flowage and the complete dependence of rock cleavage upon the parallel arrangement of unequidimensional mineral particles, suggest that possibly the more minute constituents or structural elements of these crystallographically parallel mineral particles may be arranged under similar laws; the molecules themselves may have unequal dimensions and be arranged under the law of dimensional control shown by the crystal particles. It would follow that minerals dimensionally and not crystallographically arranged, such as most quartz, calcite, and feldspar particles, have molecular shapes such that in the beginning of their development they may meet the requirements of dimensional control without necessarily arranging their crystallographic axes.

As another possibility the molecules might be both dimensionally arranged and unevenly spaced, giving several possible combinations of arrangements. It might well be that with the parallel dimensional arrangement of the molecules there is a wider spacing in directions normal to the greater diameters of the molecules. This would allow newly developing mica particles to meet the requirements of dimensional control and at the same time to arrange their mineral cleavage, assuming this to be conditioned by the wider spacing of the molecules in planes normal to the shortest dimensional diameter.

An interesting and perhaps significant fact in this connection is the common position of the optic axis a normal to the greater dimensions in such minerals as the micas. This means that the rays propagated normal to the plane of cleavage and vibrating parallel to it travel more rapidly than others. The behavior of light in such crystals may be influenced by the possible dimensional arrangement of the mineral molecules here suggested. However, a discussion of the possible nature of such influence must include so many factors, many of them of yet doubtful nature, that it must be left to some other time and place.

SECTION III. FLOW CLEAVAGE AS A MOLECULAR PHENOMENON

It is clear that as flow cleavage is a capacity to part, not an actual parting, whether along mineral cleavages or between mineral particles due to their weak adhesion, it is a molecular phenomenon. Parting can occur only by breaking certain bonds of molecular attraction. It is necessary only that the bonds of molecular attraction should be less strong along certain parallel lines or planes than along others. A definition of flow cleavage, in terms of molecular attraction, would thus read as follows: Flow cleavage is a capacity to part along parallel planes or lines or surfaces, due to weaker molecular attraction along such parallel planes or lines than in other directions in the rock. This allows of parting parallel to a number of sets of lines or planes, but where one set gives an easier parting than another only the easier one is likely to appear.

When a rock with flow cleavage is cleaved, it is observed that the parting occurs either between separate mineral particles, which act as units during parting, or along cleavage planes in the mineral particles themselves or commonly both. Where the mineral particles act as units, the parting has been observed to occur most readily along planes or lines in which the fewest mineral particles are to be met with. In the common cases this is obviously in the plane of the greatest and mean diameters, or in any planes or surfaces parallel to the greatest diameter of the mineral particles. The parting occurs less readily in the plane of the greatest and least axes, and still less readily, or not at all, in the plane of the least and mean axes of the particles. Where the particles act as units in the parting, the adhesion of the particles to one another is weaker than the internal cohesion of the individual particles. The planes of parting are separate entities; they are finite in number, and have definite positions in the rock. For convenience in discussing flow cleavage, the parting so occurring between the mineral particles rather than through them may be called intermineral or adhesive cleavage. Such cleavage is likely to yield few possible planes of parting visible in the hand specimen. Where during the parting of a metaclasic rock the particles do not act as units, but break along their own parallel mineral cleavages, the number of possible planes of parting through the minerals so arranged may be almost infinite in number. The cohesion of the substances of the particles is less than the adhesion of the particles to one another. Cleavage so produced may be called cohesion cleavage, to distinguish it from the intermineral or adhesion cleavage. Because of its fineness it might perhaps be distinguished as microcleavage. As already intimated adhesion and cohesion cleavage commonly occur together in rocks.

All flow cleavage belongs under one or both of these heads. The terms are superfluous for ordinary descriptive purposes, but are convenient in a discussion of this phase of the subject.

The preceding discussion of the effect of the individual minerals on the production of cleavage has given data for a general statement of the relative importance of intermineral and cohesion cleavage in metaclasic rocks as a whole.

Cohesion cleavage seems to be important so far as mica and hornblende are present in a metaclasic rock, and adhesion cleavage so far as quartz and feldspar are present. The presence of mineral cleavage faces in the rock cleavage partings is evidence of the cohesion cleavage, while their absence is taken as evidence of adhesion cleavage. But, while the presence of mineral cleavage faces on the rock cleavage parting surface is necessary when the rock is parted along cohesion cleavage planes, it does not follow that the presence of such mineral cleavage planes always indicates that the rock cleavage was of the cohesion variety alone, for the shapes of hornblende and mica particles in cleavable rocks are determined by mineral cleavage, and it is very difficult to tell on the rock cleavage surface whether the mica and hornblende there appearing have been parted along their own cleavages or are in their original forms. While adhesion cleavage can occur alone, cohesion cleavage is rarely, if ever, present to the exclusion of the adhesion cleavage. It is to be remembered that the micas and hornblendes never make up the entire mass of a rock, but are usually separated by layers of quartz or feldspar, or both, and even if these minerals were not present the cleavage would not be cohesion cleavage alone, but partly adhesion cleavage between different mica or hornblende individuals.

It can be said, then, that so far as quartz and feldspar appear on the cleaved surface of a metaclasic rock, as it does in many quartz-feldspar gneisses, the rock cleavage has probably been mainly of the adhesion variety. So far as mica and hornblende appear, the rock cleavage probably has been both of the adhesion and cohesion varieties. While adhesion cleavage is nearly always present, the fact that cohesion cleavage is certainly important for the micas and hornblendes indicates that cohesion cleavage in cleavable rocks may be as important if not more important on the whole than adhesion cleavage.

So far as chlorite is present in the rock the cohesion cleavage is dominant. So far as actinolite, grünerite, tremolite, staurolite, tourmaline, and chiastolite are present, and have parallel arrangement, probably the adhesion cleavage is important.

Calcite in finely fissile limestones or marbles yields an adhesion cleavage alone, as is evidenced by the characteristic absence of calcite cleavage on cleavage surfaces of such rocks and by the absence of parallelism of the calcite cleavage as observed microscopically.

CHAPTER V.

OBSERVED RELATION OF FLOW CLEAVAGE TO THE ELONGATION AND SHORTENING OF ROCK MASSES.

If the relation of flow cleavage to the elongation and shortening of rock masses is certainly known, its relations to pressure may be worked out. The relation of flow cleavage to elongation and shortening of a deformed rock mass may be shown by (1) the distortion of pebbles of a conglomerate, (2) the distortion of mineral crystals, (3) the distortion of volcanic textures, (4) the distortion of fossils, (5) the distortion of beds and attitude of folds, (6) relations of cleavage to intrusives, (7) the position of fractures. It is scarcely necessary to attempt an exhaustive discussion of each of these lines of evidence, they are so common and well known. But of each a few illustrations to show the nature of the evidence may be given.

(1) *Distortion of pebbles of a conglomerate.*—Schistose conglomerates show by the distortion of their pebbles, either with or without fracture, the directions of elongation and shortening, although it may sometimes be difficult to distinguish the shapes of undeformed pebbles from those of deformed pebbles. As illustrative examples may be cited: Conglomerates from the iron districts of the Lake Superior region[a] (See Pl. XXVII), from Crystal Lake in California, from the Black Hills of South Dakota,[b] from Madoc, Ontario,[c] from the Green Mountains of Vermont, and from the Front Range of Colorado. Sederholm[d] describes squeezed conglomerates from Finland, Harker[e] cites a number of instances in his discussion of rock cleavage, and Lehmann[f] figures several in his crystalline schist report. Instances could be cited from almost every known area of pre-Cambrian sedimentary rocks.

In all of these conglomerates the matrix is schistose or cleavable, and the schistosity or cleavage is approximately parallel to the greater

[a] Sp. 25718, north of Felch Mountains, Michigan; sp. 42094, fracture in pebble, north shore of Lake Superior; sp. 45810, Pine River, Wisconsin.

[b] Sp. 14818, Black Hills, South Dakota.

[c] Sp. 18391 and 18392, Madoc, Ontario.

[d] Sederholm, J. J., Archean sedimentary formations: Bull. Geol. Survey of Finland, No. VI.

[e] Harker, Alfred, Rept. 55th Meeting Brit. Assoc. Adv. Sci., held 1885, published in 1886, p. 837.

[f] Lehmann, Origin of the Crystalline Schists; Atlas, Pl. VII, figs. 5 and 6; Pl. XVII, fig. 4.

diameters of the flattened pebbles, although bending at the ends of the pebbles in following their peripheries. Where the flattening of the pebbles has been extreme, as in a specimen illustrated in Pl. XXVI, *A*, *B*, the longer diameters of the pebbles not only coincide with the cleavage of the rock, but at the squeezed end of the specimen the outlines of the pebbles may not be distinguished.

In some instances also, and probably in many, the flattening of the pebbles has resulted in developing a cleavage within them, and this cleavage has been observed to be parallel to the flatness of the pebbles. In a schistose quartzite conglomerate[a] from the Metropolitan district, Michigan (fig. 27), and in a schistose breccia-conglomerate from Madoc, Ontario, sections through the pebbles show that the individual quartzes making up the complex pebbles have been uniformly elongated by recrystallization in the same plane in which the pebble as a whole has been elongated. In the same rocks, also, there is evidence of slicing and granulation of certain particles in the pebbles, resulting in a parallel arrangement slightly inclined to the plane of elongation of the pebbles. Parallelism of constituent minerals is excellently developed in much elongated slate, schist, and diorite pebbles in a slate conglomerate from Pine River, Wisconsin (Pl. XXVII, *A*, *B*, *C*). While in a few cases the parallel arrangement of the mineral constituents may have existed in the pebble before it became a part of the conglomerate, there is no question that the prevailing parallel structure has been developed by the secondary deformation which has affected the rock as a whole. In these cases, and in others, the cleavage of the pebbles may be good or poor, depending on the nature of the constituents, and on the extent to which the matrix has taken up the deformation, but, such as it is, the cleavage is parallel to the longer diameters of the minute particles making up the pebbles, to the plane of elongation of the pebbles as a whole, and finally to the schistosity or cleavage of the rock mass as a whole.

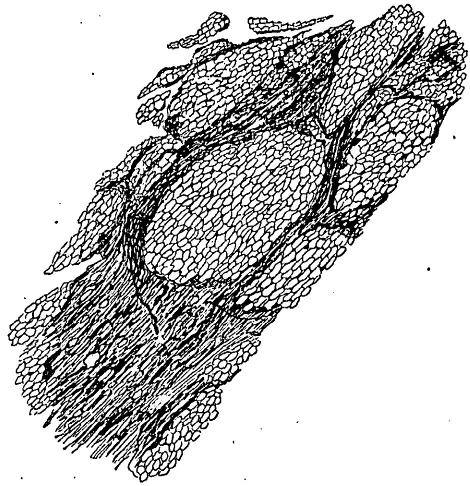

FIG. 27.—Pebbles of quartzite with constituent quartz grains elongated by recrystallization in the plane of elongation of the pebbles and of the rock as a whole. Schistose conglomerate from Metropolitan, Mich. Large slide.

[a] Van Hise, C. R., Principles of pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, Pl. CXV.

Illustrations might be multiplied, but the cases here cited will serve to show the bearing of this line of evidence on the subject in question.

(2) *The distortion of mineral crystals.*—The distortion of crystals, either by recrystallization or by granulation, is a commonly observed phenomenon. In the description of the features of occurrence in the rocks with flow cleavage in Chapter II instances of this are cited. Numerous slides have been observed in which the plane of cleavage is marked by mica plates or hornblende crystals, while the associated quartz and feldspars show fractures at angles with the plane of cleavage (figs. 9, 16, 17). Where, accompanying these fractures, there has been displacement of the parts, as is frequently the case, this displacement is observed to work toward extending the fractured particle in the plane of rock cleavage and shortening it normal to the plane of cleavage. Lehmann figures a number of instances of this.[a] Van Hise[b] quotes Keith as making the following statement:

> Near Blowing Rock, N. C., is a mashed porphyritic granite in which porphyritic crystals of feldspar are flattened in various degrees, and their greater diameters are upon the average parallel with the secondary structure. In many cases the feldspar crystals are fractured in a direction diagonal to the cleavage, and in some cases in a single feldspar crystal there are two sets of diagonal fractures approximately at right angles to each other and each inclined about 45° to the cleavage.

(3) *Distortion of volcanic textures.*—Ancient volcanics, particularly of pre-Cambrian age, rarely occur over considerable areas without showing cleavage structure in part. In the Lake Superior country a greenstone with original ellipsoidal parting frequently shows a flattening of the ellipsoids in one direction, with or without fracture, and in such cases the ellipsoids and matrix have a flow cleavage parallel to the longer diameters.[c] In the pre-Cambrian rocks of Lake Superior are many schistose volcanic rocks containing amygdules and spherulites. The elongation of the amygdules[d] and spherulites in planes parallel to the cleavage in the rock is of common occurrence. The elongation of spherulites and perlitic textures may be particularly well observed in certain areas of isolated pre-Cambrian volcanics in the Fox River Valley of Wisconsin. Here there is also an agreement in direction between cleavage and the greater diameters of the distorted fragments of a volcanic breccia. Harker[e] describes the agreement in direction of cleavage and flattening of the fragments in a schistose volcanic ash in the boulder clay at Nantlle. In specimens from the Black Hills, and from the Menominee district of Michigan, the flattening of fragments in breccias is to be observed.[f]

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[a] See figs. 1, 4, and 5, Pl. I, Lehmann's Atlas, cit.

[b] Van Hise, C. R., Deformation of rocks: Jour. Geol., vol. 4, 1896, p. 460.

[c] Clements, Mon. U. S. Geol. Survey, vol. 36, Pl. XI.

[d] Sp. 27750, Crystal Falls district, Michigan.

[e] Sp., 14823, Black Hills, South Dakota; sp., 25669, Menominee district of Michigan.

[f] Harker, Slaty cleavage: Rept. 55th meeting Brit. Assoc. Adv. Sci., held in 1885, published in 1886, p. 837.

(4) *Distortion of fossils.*—The elongation of fossils in the plane of cleavage has been observed in so many cleavable rocks that no reference will be made to the individual cases. Harker, in his article on slaty cleavage, cited, refers to a number of such cases. In these distorted fossils it has been observed that the mean axis of strain has been one of absolute elongation in many cases.

(5) *Distortion of beds and attitude of folds.*—Frequently there may be observed the thickening or thinning of a bed or layer of rock through the processes of rock flowage. Any cleavage which is present in such a distorted bed is likely to be normal to the shortening.

Folds often show the direction of shortening of the deformed rock mass. The well known relation of cleavage to simple folds, i. e., a position roughly parallel to their axial planes, shows plainly the development of cleavage normal to the greatest compression which the rock mass has undergone. Deviation from this attitude becomes apparent as shearing develops parallel to the limbs of folds, as discussed in a subsequent chapter (p. 152). Folds may be indicated by the distortion of bedding. Certain specimens from the Black Hills show that the bedding has been shortened in its own plane by minor crenulations, and the associated cleavage may be observed to be in all cases normal to the greatest shortening indicated by such folds.[a] Similar instances may be cited from the Lake Superior country and from almost any other district where cleavable bedded rocks, particularly slates, occur.

Sorby has figured and described undulations in a coarse sandy shale, which lies between beds of fine shaly slate showing cleavage but not folding. The axial planes of the undulation in the coarse rock coincide with the cleavage planes of the finer rocks. It is clear that the direction of compression as shown by the folds is at right angles to the cleavage planes in the slate above and below.[b] Harker says that similar phenomena may be observed in almost any of the slate quarries of northern Wales.

Folds may be indicated by the distortion of gneissic or original flowage structure. The distortion of gneissic banding in the pre-Cambrian gneisses is too common and widespread to need detailed reference.[c] Wherever, with this folding, a subsequent cleavage has been developed, this appears in planes normal to the shortening of the rock mass shown by the folds.

(6) *Relations to intrusives.*—Intrusions of great masses of igneous rocks, and particularly deep-seated batholiths, are known to compress the adjacent rocks in directions normal to the periphery of the intru-

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[a] Sp. 14974, sl. 7712, Black Hills, South Dakota.

[b] Harker, Slaty cleavage: Rept. 55th meeting Brit. Assoc. Adv. Sci., held in 1885, published in 1886, p. 824.

[c] Van Hise, C. R., Principles of pre-Cambrian geology, Pls. CX and CXVII and fig. 162. Lehmann, Atlas, Pl. XIV, figs. 2 and 4; Pl. XVI, fig. 1.

sive masses. Cleavage is commonly developed in the surrounding rocks parallel to the periphery of the intrusive masses. Its development in planes normal to the greatest compression is thus clear. An illustration, cited by Van Hise, is the Black Hills batholith of granite which has intruded a sedimentary series, and developed a cleavage parallel to the periphery of the granite.

(7) *Relations to fractures.*—Where fractures and cleavage have been developed simultaneously, as is possible in heterogeneous rocks, the displacement along the fractures may indicate the direction of shortening and elongation of the rock mass as a whole. This is partially covered in the above discussion of the distortion of pebbles, crystals, etc. Even if the displacement can not be observed, the position of the fractures may indicate the probable direction of the compression of the rock mass, for fractures are ordinarily developed in planes inclined to such compression, and hence when the cleavage plane is inclined to the planes of fracture (figs. 9, 16, 17) the presumption is that it is not in the shearing planes, but more nearly normal to the compression of the rock mass. This criterion affords only a suggestion of the relations of cleavage to shortening of the rock mass, for the precise relations vary with the nature of the deformation, as shown in subsequent chapters.

GENERAL.

From the lines of evidence above cited it appears that wherever the directions of shortening and elongation of a rock mass can be determined with certainty any flow cleavage which may be present is normal to the total greatest shortening which the rock has undergone. The greatest, mean, and least diameters of the particles may be observed to have a tendency toward parallelism with the greatest mean and least axes of strain in the rock mass.

But there are minor deviations from parallelism, some of which are due to the heterogeneity of the rock mass and some of which are due to the manner of deformation.

Says Van Hise: "It is a very common phenomenon in slates and schists, both macroscopically and microscopically, for the direction of the secondary structure to wrap around the harder particles. As a hard grain or pebble is approached the cleavage structure in the matrix opens out on each side of the grain, envelops it, and closes in again beyond it. The structures nowhere intersect, although upon opposite sides of a particle near the ends they converge, and in passing toward either end they turn and become parallel."[a]

In a few and rather exceptional cases, where the parallelism of the longer diameters of the mineral particles is clearly the result of granulation or slicing, as in certain sheared conglomerates and sheared

[a] Van Hise, C. R., Deformation of rocks: Jour. Geol., vol. 4, 1896, p. 460.

anorthosites described in foregoing chapters, the longer diameters of the particles may show uniform, though slight, tendency to deviate from parallelism with the elongation of the rock mass, as shown by the nature of the strain or by the position of the longer axes of other particles present which have received their position parallel to the elongation of the rock mass by recrystallization.

In Chapter VI it will be shown that the longer diameters of the mineral particles sometimes deviate from parallelism with the elongation of the rock mass as a whole, because of the changing relations of the strain to the stress producing it during a rotational strain.

The deviations from parallelism under these conditions might be considered as evidence that the parallel structure is developed in shearing planes or planes of maximum tangential strain inclined to the greatest elongation of the rock mass, for where the rock has been much shortened even structures developed in shearing planes may vary only a few degrees from parallelism to the elongation of the rock mass. But the deviation may be adequately explained otherwise. (See following chapter.) It is certain that in the absence of the modifying conditions referred to the parallelism of the longer diameters of the mineral particles and the longer axes of strain in the rock mass is close, and that no uniform deviation can be detected either by microscopical or macroscopical observation.

It is clear from phenomena of the kind above described that an excellent cleavage may develop with but a comparatively small shortening of the rock mass. But the excellence of the cleavage seems to be more a matter of the nature of the mineral constituents (each of them having its own uniform influence on cleavage) than a matter of the amount of deformation which a rock has undergone. Where the conditions have been favorable to the development of minerals such as mica and chlorite, for instance, a comparatively small amount of shortening of the rock mass has developed a good cleavage, while, on the other hand, a very considerable amount of shortening has sometimes failed to produce anything but a poor cleavage in a rock consisting mainly of quartz particles.

It is of interest to ascertain whether the mean axis of strain represents actual elongation or shortening of the rock mass. Many instances of elongation of the mean diameters may be cited in the distortion of original crystals, in the distortion of pebbles of conglomerates, in the distortion of original volcanic textures, and in a few cases in the distortion of folds. The shapes of newly developed minerals, and especially those of mica and chlorite, are themselves suggestive of the nature of the strain which the rock has undergone. The greatest and mean diameters of the mica and chlorite plates have practically the same dimensions, and if the greatest diameter represents elongation, as it does beyond reasonable doubt, the mean diameter also represents elongation. Instances of shortening of the mean diameter also may be observed in the distortion of all of the forms above named, and the shapes of certain minerals newly developed are again suggestive of shortening of the mean axes of strain in the rock. In hornblende the greatest diameters are far greater than the mean and least diameters, which do not differ widely from each other. If the least diameter represents a shortening of the rock mass it seems likely that the mean diameter does so also, leaving only one direction of elongation parallel to the longest diameter of the hornblende crystals. The shapes of the mica and hornblende crystals so characteristic of cleavable rocks is taken as one of the best criteria for determining the nature of the strain, and one is tempted to go even further and say that when the chemical and physical conditions are favorable for the development of either mica or hornblende, mica may develop when the conditions are such that there is elongation along the mean axes of strain in the rock and hornblende when there is shortening along the mean axes of strain in the rock. A review of the facts seems to indicate that in the development of cleavage there has been, for the most part, an actual elongation of the mean axes of strain in the rock rather than a shortening, and that the relative importance of elongation and shortening of the mean axes is about the same as the relative importance of mica and hornblende in the production of rock cleavage.

CHAPTER VI.

RELATIONS OF THE ELONGATION AND SHORTENING OF ROCK MASSES, AND HENCE OF FLOW CLEAVAGE, TO STRESS.

Thus far in the discussion there has been a basis of observed geological fact. It has been possible to observe the causal relation between parallel arrangement of mineral particles and flow cleavage, and between the parallel arrangement of the mineral particles and the direction of elongation and shortening of rock masses. It is not possible to observe directly the relations of cleavage to the stresses which have deformed the rock, but as the relations of cleavage to the elongation and shortening of rock masses are known and as the relations of elongation and shortening of solid bodies to deforming stresses may be worked out in their simpler aspects, both experimentally and mathematically, and are accepted as proved in physical and engineering treatises, the general relations of cleavage to the stresses producing it may be stated with some confidence. The first step in the discussion, then, is a summary of the simpler and most obvious relations of deformation of solid bodies to stress.[a]

STRAIN.

Strain means any change in the relative position of the particles of a body. The change may be either of form or volume, or both. When the form changes the strain is called distortion. When the volume changes, the strain is called dilatation.

Any small sphere in an unstrained mass becomes an ellipsoid after strain—i. e., a strain ellipsoid, the greatest, mean, and least axes of which are called the principal axes of strain. In a special case (simple dilatation) all diameters of this sphere are changed equally and the resulting ellipsoid is a sphere. If these axes remain constant in direction during strain, the strain is called "irrotational" strain; if not, it is called "rotational" strain.

[a] Hoskins, L. M., taken mainly from "Flow and rupture of rocks": Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845-872.

Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 636.

Thompson and Tait, Natural philosophy.

Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, p. 22; Jour. Geol. vol. 4, 1896, p. 430.

Young, Thomas, A Course of Lectures on Natural Philosophy and the Mechanical Arts, London, 2 vols., vol. 1, 1807, p. 135.

Peirce, C. S., Manuscript report to the Director of the U. S. Geol. Survey, 1897.

Any irrotational strain in which all three principal axes are changed in length in such a ratio that the volume remains constant, has been called "pure shortening" by Van Hise,[a] and this term will be used below. In a special case of irrotational strain without change of volume, one of the axes may remain unchanged in length; then the strain is known as a "simple shear" (Thompson and Tait[b]), or a "pure shear" (Becker[c]), or a "simple detrusion" (Young[d] and Peirce[e]). An irrotational strain is illustrated in two dimensions in figs. 28 and 29. Every particle of the body takes part in the deformation.

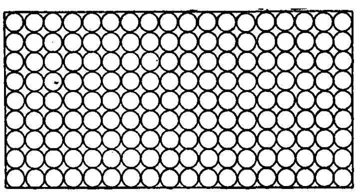

FIG. 28.

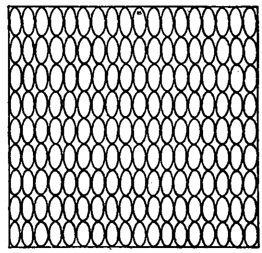

FIG. 29.

FIGS. 28 and 29.—Diagrams showing irrotational strain (pure shortening).

A rotational strain occurring without change of volume is illustrated by the deformation of a rectangle A—B—C—D (fig. 30) into a parallelogram A—B—C′—D′ whose base and altitude are equivalent to those of the rectangle. All lines parallel to A–B move parallel to it through distances proportional to their distances from A–B. It is a strain analogous to that assumed by a deck of cards in which each card has been slipped a small amount over the card next below. While there is differential movement between the planes, there is no distortion in the planes themselves. The strain is equivalent to an elongation and a shortening at directions at right angles to each other combined with a rotation. This strain has been called "simple shear" (Hoskins, Van Hise) and "scission" (Becker). Peirce, in the report referred to, prefers the term scission, and in the following discussion the term scission will be used. The plane of scission referred to on subsequent pages corresponds to the plane of slipping between the cards in the above illustration.

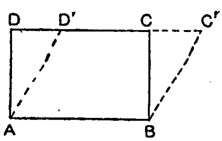

FIG. 30.—Diagram showing scission.

It has been proved that scission is equivalent to a pure shortening combined with a rotation of the body as a whole. In fig. 32 the flat-

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 636.

[b] Thomson and Tait, A Treatise on Natural Philosophy, 2d ed.

[c] Becker, G. F., Jour. Geol., vol. 4, 1896, p. 430.

[d] Young, Thomas, A Course of Lectures on Natural Philosophy and the Mechanical Arts, London, 2 vols., vol. 1, 1807, p. 135.

[e] Peirce, C. S., Manuscript report to the Director of the U. S. Geol. Survey, 1897.

tened ellipsoids have the position they would have if flattened by shortening along the direction P Q and then rotated until the line P Q takes the direction P′ Q′.

Given any strain ellipsoid, it is impossible to determine from the ellipsoid itself whether it was produced in its present position by a

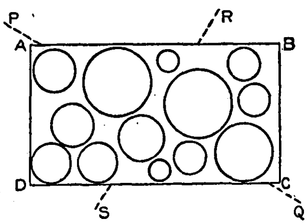

FIG. 31.

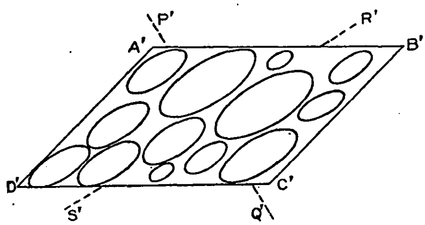

FIG. 32.

FIGS. 31 and 32.—Diagrams showing equivalence of a strain ellipsoid in scission to a strain ellipsoid in pure shortening combined with a rotation.

pure shortening, by pure shortening combined with rotation—by scission—or by any combination of these strains. For proof of this relation of scission to pure shortening see Hoskins.[a]

Rotational and irrotational strain may be combined with each other in any proportion, and either or both may be combined with a dilatational strain. All strains may be referred to these types of strain or some combination of them.

STRESS.

Stress is the action and reaction between two adjacent parts of a body. When a condition of stress exists at any point in a body there are always three rectangular planes, upon each of which the resultant stress is normal. Three intersecting lines normal to these three planes, respectively, are called the principal axes of stress.

The difference in the intensity of the greatest and least of the stresses acting on these three mutually perpendicular planes is called the stress difference.

A shearing stress is a stress acting tangentially to the plane separating two adjacent portions of a body between which there is a stress. This is always present on all planes except the three principal planes, unless the three principal stresses are of equal intensity and of the same kind. Since in any possible stress condition three rectangular planes through any given point are free from tangential stress, any possible stress may be regarded as equivalent to three normal stresses whose directions are mutually perpendicular.

[a] Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 862-865.

RELATION OF STRESS TO STRAIN.

In isotropic material, the axes of the strain that is occurring at any instant are coincident with the stress axes. If the stress axes remain constant in direction, the total strain will have its axes coincident with the stress axes; but not otherwise. Rotational strain in isotropic material will not occur unless the directions of the principal stresses vary. In irrotational strain the greatest, mean, and least axes of strain correspond, respectively, with the least, mean, and greatest axes of stress throughout the deformation. In a rotational strain the strain ellipsoid at any instant is the net result of all the strains developed at successive stages of the deformation; it is a compromise between the strain ellipsoid which is tending to be formed by the stresses then effective and the strain ellipsoids previously formed and rotated. Thus the directions along which elongation and shortening in the mass are occurring at any instant in rotational strain are not parallel to the axes representing the net result of all the elongation and shortening which the mass has undergone since the deformation started. At any instant the tendency toward shortening is in the direction of the greatest of the stresses, but the accompanying rotation prevents the continuation of the same relation of the stress and strain axes, and the axis of the greatest total shortening may be at that instant at any angle to the greatest axis of stress or the axis of shortening then occurring. When deformation occurs by fracture the fractures develop in planes inclined to the greatest principal stress as an expression of shearing stresses.

APPLICATION OF GENERAL PRINCIPLES OF RELATIONS OF STRAIN AND STRESS TO ROCK FLOWAGE AND FLOW CLEAVAGE.

Knowing the relations of flow cleavage to the axes of strain in a rock mass, the simpler relations of flow cleavage to stress may be deduced. These may be considered under two heads—(1) the cleavage strictly parallel to the axes of elongation of the rock mass, (2) the cleavage exceptionally inclined to such axes.

(1) Where cleavage is strictly parallel to the axes of elongation of the rock mass, as it is for the most part where the structure is due to recrystallization, and thus in the great majority of rocks with flow cleavage, the term flow cleavage may be substituted for the strain it represents in the above statement of the relations of strain and stress. In other words "plane of cleavage" may be substituted for the plane of the greatest and mean axes of the strain ellipsoid or "axis of cleavage" (when linear parallel) for the greatest axis of strain. The relations of flow cleavage to stress then may be stated as follows:

During irrotational strain, flow cleavage tends to develop uniformly in the plane normal to the greatest principal stress, or parallel to the least and mean stresses, or if linear parallel cleavage, it develops along the axis of least stress.

During rotational strain flow cleavage tends to develop at any instant in planes or lines normal to the greatest stress or in planes or lines in which elongation is occurring at that instant. But the cleavage tending thus to be formed is almost immediately rotated from its position normal to the greatest principal stress by variation in relative direction of the stress axes and strain axes, and becomes inclined to the plane or line in which new cleavage subsequently tends to develop. In other words, cleavage is at all times tending to develop normal to the greatest pressure in a rotational strain, but rotation constantly carries it from this position. Just as the total elongation of the rock mass in rotational strain is the net result of all the strains developed at successive stages of deformation, so cleavage, which by observation is approximately parallel to the final elongation of the rock mass, is the net result of all the strains, and its average position may be finally inclined somewhat to the greatest principal stress.[a]

It is probable that either dilatational strains alone or irrotational strains alone are of rare occurrence in a rock mass. The first of these requires three and the second two pairs of forces acting at right angles to one another with identical intensity. The common strain in nature is a combination of the forms of strain here called pure shortening, scission, and negative dilatation. These strains may occur simultaneously or at different times, or the same strains may recur several times. But the final result in any case is a strain ellipsoid, whose axes have relations to stress somewhat intermediate between those above described for pure shortening and for scission; in other words, for a rotational and irrotational strain. Hence the final position of cleavage is usually inclined to the axis of greatest stress of the force which has produced it, although tending throughout to develop normal to this axis.

Given a strain ellipsoid, there is no way of determining what stages or manner of deformation the ellipsoid has undergone to reach its present configuration. Likewise it may not be certainly determined what combination of stress and strain conditions have been present throughout the development of a given cleavage, although the relation of cleavage to the final total strain may be known. But it is believed that cleavage sometimes gives evidence of variations in stress and strain conditions during its development. Flow cleavage is dependent upon the parallel arrangement of its mineral constituents. If it be granted that these constituents have developed during successive

[a] In Daubrée's experiment cleavage was produced parallel to the elongation of the clay mass which was forced through a cylinder. While the relations of stress and strain are complex in such a case, there is nothing in Professor Daubrée's discussion of the subject which would indicate a development of the parallel arrangement under any laws different from those here summarized. (Loc. cit.)

stages of deformation of the rock mass, as they undoubtedly have, then if the strain has been a rotational one the particles developed at successive stages ought to lie at slight angles to one another. The recrystallized particles forming at any instant with their greater diameters exactly normal to the pressure during a rotational strain are constantly being rotated from this position. The result is that the longer diameters or direction of growth of particles developing by recrystallization at any instant normal to the greatest pressure do not quite correspond with the longer diameters or direction of growth of particles developed by crystallization in preceding instants, for these latter have been rotated from the most favorable positions. This is believed to be the main explanation of the feathering out of mica laminæ diagonally against one another where there are no other rigid particles present to cause local variation in stress (Pl. II, *A*, and figs. 2, 3, 4). The fact that the diagonal lapping of mica plates against one another occurs around rigid particles shows it to be a phenomenon caused by difference in stress directions, and hence its occurrence where such particles are absent offers evidence of its formation under changing stresses.

That cleavage by observation shows so little variation because of rotational strains may be due to the fact that recrystallization or granulation in later stages may have obliterated evidences of cleavage formed during the earlier stages of a rotational strain, or, more probably, to the fact noted on a subsequent page that the very development of parallel particles by recrystallization during rotational strain so modifies the stress conditions within the mass that the plane of easiest development for newly developing particles keeps up with the rotation to a greater extent than it otherwise would.

Relative positions of original and newly developing particles during deformation.—From analysis during an irrotational strain the greatest elongation of the rock mass is uniformly normal to the greatest pressure, and hence this is the constant plane or line of growth of newly developing or recrystallizing particles. In the early stages any rotating original particles may, however, vary in position from nearly parallel to the greatest pressure to normal to it. It is only after the deformation has progressed to a considerable extent, even supposing the rotating particles to have considerable freedom of movement, that the rotating original particles formerly at angles to the plane or line of elongation, or what becomes the surface of rock cleavage, bring their greater diameters to approximate parallelism to that of the newly developing or recrystallizing particles in the plane of cleavage. Where there is considerable interference with rotation a considerable amount of deformation may not bring about parallelism of the rotated particles.

If the deformation of a rock mass is a rotational one, as it commonly is, in the early stages there is likely to be the same difference in position between particles with original random arrangement and the plane or line of growth of newly developing or recrystallizing particles. But in deformation of this kind, all particles, both the particles already present with random arrangements and the newly developing and recrystallizing ones, are being rotated toward the plane of scission. Particles with original random arrangement during a rotational strain may be rotated toward the plane or line of easiest relief or easiest crystal growth, or away from it, depending upon the original position of the particles with reference to the plane of easiest growth. Starting with an unstrained rock, it is of interest to note that a rotational strain sufficient to produce elongation of the mass, say, at 35° to the plane of scission, will not rotate a particle originally normal to the plane of scission to such an extent as to make its greater diameters correspond with those of newly developing particles.[a]

Whether the deformation is by rotational or irrotational strain a sufficient amount of it may bring about substantial parallelism of all particles, new or old.

While analysis would seem to indicate that the relative positions of original and recrystallizing particles during deformation may be somewhat as above, it is not at all certain that this is actually the case in the metaclasic rocks; indeed, evidence has already been adduced to show that evidence of the rotation of original particles is insignificant as compared with the evidence of recrystallization in developing a parallelism. So far as recrystallization does arrange the minerals there may be no intermediate stages of arrangement. There is seldom to be observed in cleavable rocks stages intermediate between random arrangement and parallelism. The parallel arrangement usually appears first fully developed along certain zones while the intervening zones are comparatively unmodified, and where it thus appears, there is abundant evidence of its development entirely by recrystallization. If it be true that the parallel arrangement is due largely to recrystallization, and that intermediate grades of arrangement, which the stress and strain conditions in the rock mass would necessarily develop from the rotation of original particles, are absent, then mere parallelism of the mineral constituents becomes presumptive evidence that the parallelism has been produced by recrystallization with relations to stress and strain above indicated. This evidence could not stand by itself were it not supported by detailed evidence discussed in Chapter III.

Effect of heterogeneity.—The above statements are based on the assumption that the rock mass undergoing rock flowage and developing rock cleavage acts essentially like a homogeneous body in its stress and strain relations; but a rock is commonly a heterogeneous body,

[a] Hoskins, L. M., Sixteenth Ann. Rept. U. S. Geol. Survey; Van Hise, C. R., Deformation of rocks: Jour. Geol., vol. 5, 1897, p. 186.

and hence there are minor variations in the stress and strain relations, under the law stated on a preceding page that "in an isotropic material the axes of the strain that is occurring at any instant will, in general, differ in direction from the stress axes, the strain being in part governed by the structure of the material." The general effect of rigid particles is to transmit stresses locally in directions normal to themselves. The mesh structure which is frequently seen around the peripheries of large particles owes its origin to the local distribution of stresses caused by the influence of a rigid particle on the transmission of forces. Here is additional and most positive evidence of the development of cleavage in planes normal to the greatest stress, for it is evident that stresses are generally transmitted by rigid particles in directions normal to their peripheries. The feathering out of mica laminæ diagonally against one another about rigid particles, as described on pages 25–26, is probably to be explained in this manner.

Frequent reference has been made to the slicing or fracturing of rigid particles in planes, sometimes intersecting, that are inclined 45° or thereabouts to the plane of rock cleavage conditioned by the parallel arrangement of the micas and other constituents (see figs. 16, 17 and Pl. XI, *B*). As fractures develop in shearing planes inclined to the principal stresses, the presence of fractures inclined to the rock cleavage is itself evidence of the development of the prevailing cleavage in planes normal to the greatest stresses.

The influence of rigid particles in the transmission of forces during rotational strain is of interest: There is supposedly a rotation of the greater diameters of all particles, original and recrystallized, toward a common plane. These particles all act as transmitters of forces. The rotation being all in the same angular direction, the change in direction of transmission of pressure due to the rigid particles, is also all in the same direction. Hence, so far as rotation tends to bring about parallelism of the longer diameters of the particles themselves, it also tends to bring about parallelism of the transmitted pressures in a direction more nearly normal to the plane toward which the particles themselves are being rotated. Particles newly growing under these local transmitted stresses thus tend to bring their longer diameters more nearly into the plane which the rotated particles are approaching than they otherwise would. Particles newly developing under rotational strain are constantly being rotated from a direction normal to the greatest pressure of the rock mass, and hence from a position favorable to easiest growth, and because of rotation they are not parallel to the direction of growth of succeeding stages. But, so far as the particles themselves affect the transmission of forces, they tend to transmit forces such that newly developing particles in succeeding instants will develop in planes more nearly parallel to their own rotated planes than they otherwise would. For instance, suppose the longer diameters of a newly developing particle in fig. 33 to have the position AB in a rotational strain. At a later period the longer diameter may have the direction A′B′. If the stresses remain constant in direction, the plane of easiest growth still remains more nearly parallel to AB than to A′B′; in other words, the particle has been deflected from a position most favorable to its growth under the given stress conditions. But the rotating particle itself influences the direction of the transmission of stresses, with the result that a particle CD, newly developing under the influence of such local stresses, would tend to take a position not parallel to AB, but more nearly parallel to A′B′. This is made clear by simple resolution of forces. R_n, the transmitted normal component of the principal stress is proportional to the cosine of the angle α. When the angle α is 90°, this component becomes zero. When the angle α is zero, the component R_n has the full intensity of the unresolved force.

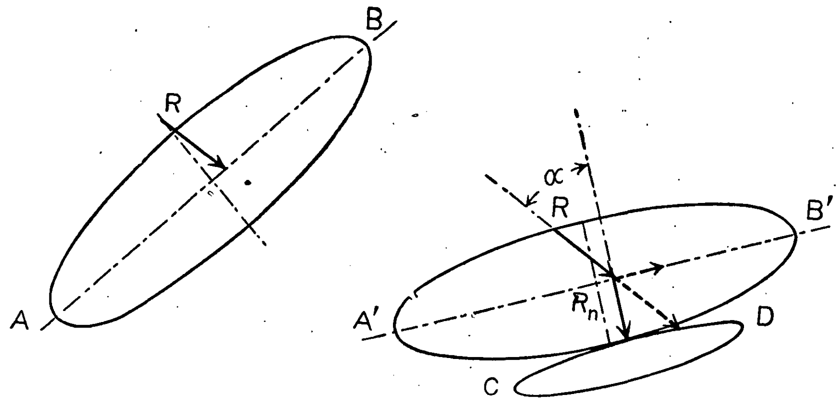

FIG. 33.—Diagrams illustrating rotation of particle during rotational strain and the resulting change in direction of transmitted stresses.

Where the rock mass is made up of many rigid particles their influence may be of considerable importance in keeping newly developing particles in the plane of rotated particles previously present or developed.

A special case of the influence of rigid particles exists where the particles have a previous parallel arrangement. The deflection in direction of transmission of pressure will be uniform, and any newly developing cleavage may be uniformly in planes somewhat inclined to those of ordinary development of cleavage in a homogeneous rock without a previous parallel arrangement. Discussion of the relations of cleavage to previous parallel structures is made on pp. 151–152.

(2) Where the flow cleavage is due largely to granulation or slicing and the longer diameters of the mineral particles are uniformly, though slightly, inclined to the axes of elongation of the rock mass, the relations to pressure may exceptionally be somewhat different from those above cited. The fractures are the result of shearing stresses inclined to the greatest normal stress (pp. 111–112), and the carving of parallel grains in situ by the kind of fracturing known as granulation

or slicing, causes a cleavage which can be said to have developed in shearing planes inclined to the greatest pressure. The cleavage of the deformed anorthosite described by Adams (p. 37) may be partly formed in this way, and many rocks, as noted in Chapter II, show evidence of such development in certain minerals. Fig. 13 represents an unmashed anorthosite, and fig. 14 its mashed equivalent. The elongated feldspar particles in fig. 14 are clearly the result of carving in situ by the process of granulation or slicing along the sides. All stages of the process may be observed in the rock mass. That granulation or slicing does not occur in planes normal to the greatest pressure, but is uniformly in planes inclined to this pressure, is a well-established principle of mechanics, and hence we may conclude that the elongated particles of feldspar seen in fig. 14 may be really carved in situ in shearing planes and lie essentially in shearing planes of the rock mass. On this explanation the longer diameters of the particles can not be parallel to the elongation of the rock mass represented by CC in fig. 14. To bring about the deformation shown in fig. 14, it is not necessary to assume that the movement was entirely parallel to AA, for the same result may have been brought about by a movement parallel to BB, and in any given case it is practically impossible to tell what combinations of strain have occurred.

It has been shown (pp. 31 and 37) that as a result of granulation and slicing in intersecting planes at low angles to the greater strain axes of the rock mass residual grains may lie with their longer diameters essentially parallel to these axes—in other words, parallel to the prevailing cleavage. Such cases are covered by the general statements under (1) above.

Summary.—Commonly flow cleavage has been developed both by recrystallization and by granulation or slicing; recrystallization of certain minerals and granulation of others close by, in which case the parallel arrangement developed by recrystallization is mainly in planes normal to the greatest pressure as in (1) pages 112–117, and the parallel arrangement developed by granulation or slicing is developed in shearing planes as in (2) pages 117–118. In the early stages the inclination of the parallel structure formed by fracturing to the parallel structure formed by recrystallization is apparent (p. 38), and this deviation is excellent evidence of the truth of the conclusion that flow cleavage may be developed both in normal and shearing planes.

The fact may again be emphasized that the parallel arrangement caused in indirect planes by granulation and slicing is a subordinate and exceptional phenomenon as compared with that developed by recrystallization, and even where present frequently causes only a local variation of cleavage from planes conditioned by arrangement of crystallized particles; hence flow cleavage is for the most part developed in planes normal to the greatest pressure, and in but small part in shearing planes inclined to the greatest pressure.

PART II.

FRACTURE CLEAVAGE, COMPARISON WITH FLOW CLEAVAGE, SUMMARY STATEMENT OF CAUSES AND CONDITIONS OF SECONDARY ROCK CLEAVAGE.

CHAPTER I.

FRACTURE CLEAVAGE.

Fracture cleavage may be defined as a cleavage dependent for its existence on the development of incipient parallel fractures or actual fractures which by subsequent welding or cementation remain planes of weakness. It is obvious that the development of such a structure is confined to the zone of "rock fracture." Rocks may be fractured along parallel planes quite independently of any arrangement which the mineral constituents may have, and the fractures may be cemented by infiltration of foreign material, by crystallization of new minerals, and by recrystallization of adjacent minerals, or may be welded by bringing adjacent minerals by compression under bonds of molecular attraction. After welding the rock may still have a capacity to part along such planes more easily than along others, which capacity by our definition is truly a cleavage. Such cleavage has been variously called in its different aspects false cleavage, close-joints cleavage, strain-slip cleavage, fault-slip cleavage, ausweichungs cleavage, rift, and fissility. All of these terms may not have quite this significance, as will be shown below, but they have been used to designate structures essentially developed as above stated. The reader will doubtless recall many instances of quarry rocks, apparently massive, which on the stroke of a hammer break along definite planes nearly or quite independent of any parallel arrangement of the mineral constituents that may be present. In the ancient crystalline rocks it is not uncommon to find apparently solid graywackes and slates which break into polygonal or rhomboidal blocks along weakly cemented or incipient planes of fracture intersecting one another at uniform angles.

This may not be apparent in the solid ledge, but becomes apparent on weathering or when artificially broken. Cleavage of this kind is often excellent; the planes of parting are smooth, even, and continuous for some distance. A distinctive feature is its intermitted character, by which is meant its confinement to certain definite planes separated by considerable thicknesses of rock which show no tendency to cleave. Another distinctive feature is its presence in two or more intersecting planes rather than one plane. It is apparent that such cleavage may be present in rocks both with and without parallel arrangement of the mineral constituents, and in the former case it may occur either parallel to the longer diameters of the mineral constituents or at any angle to them. Where parallel to the mineral arrangement it is practically indistinguishable from flow cleavage (pp. 130–133). In other cases there is little difficulty in distinguishing the two. (See Pls. XVII–XXIII.)

FIG. 34.—Fracture cleavage in slate emphasized by ferruginous staining. There are 360 cleavage planes to the inch. After Dale.

Many illustrations might be cited of closely spaced parallel slips along one or two sets of planes which have been cemented or welded, forming a fracture cleavage. The structure described by Sorby (p. 17) as "close-joints cleavage" is for the most part so developed. The cementation of any of the widespread structures which Van Hise (p. 17) has called fissility, yields a capacity to party which comes under this head. Pl. XVIII, *B* illustrates a marble which has been sliced into thin parallel layers, the rubbing along the fractures being followed by the development by recrystallization of new mica and chlorite, cementing the rock and giving it a fracture cleavage. Dale[a] figures an excellent example of this structure in closely spaced planes. The so-called "false cleavage" is usually the result of closely spaced, parallel, overthrust folds grading into minute faults crossing a previously developed flow cleavage.[b] (See Pl. XIV, *B*.) The "ausweichungs cleavage" is a name applied to a similar structure caused by the development of minute overthrust folds passing into faulting. (See Pls. XX, XXI.) Slip cleavage and strain-slip cleavage are for the most part other names for phenomena of the sorts above described.

[a] Dale, T. Nelson, Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, fig. 91.

[b] Sp. 14974, Black Hills, South Dakota; sp. 42089, north shore of Lake Superior.

The rubbing along fracture planes incidental to the development of fracture cleavage frequently and usually results in slickensides or the development of parallel arranged minerals, such as chlorite and mica, and these may cement the partings. These minerals are clearly the result of recrystallization, and may be supposed to develop in the same manner as flow cleavage during a rotational strain or scission; that is, to develop in normal planes, but to be rotated almost at once toward the plane of scission, which in this case is the plane of the fractures. It may be said, then, that one of the incidental results of the development of fracture cleavage is a parallel dimensional arrangement of the mineral particles. This parallel arrangement, however, affects only a minute film of the rock along the parting planes, and may have no connection with the texture of the minerals in zones intermediate between the fractures. If the fractures be closely enough spaced it might happen that nearly all of the constituents of the rock might be arranged with their longer diameters parallel as the result of the rubbing along fracture planes, but it is argued on a subsequent page that very closely spaced planes of fracture are very exceptional and lócal, except where secondary to a previously developed flow cleavage, and that it is doubtful whether such fractures are ever closely enough spaced, independent of any previously developed parallel structure, to develop a parallel arrangement of the mineral particles comparable with that shown in fissile schists or slates. In practice there is certainly little difficulty, with few exceptions, in distinguishing the parallel arrangement developed as a result of rubbing along shearing planes from the parallel arrangement developed in normal planes and effecting all the constituents of the rock.

RELATIONS OF FRACTURE CLEAVAGE TO STRESS.

The relations of fracture cleavage to stress and rock deformation are different from those of flow cleavage. In the latter the parallel arrangement of the mineral particles, and hence the cleavage, is developed in planes or lines essentially parallel to the elongation of the rock mass. In the former the cleavage is developed in planes inclined to the elongation of the rock mass.

In any distortional strain there are necessarily shearing stresses in planes inclined to the greatest pressure. These do not receive expression unless there is fracturing, but whether or not there is fracturing the elongation of the mass at any instant is normal to the greatest pressure. If fractures occur in irrotational strains, these follow intersecting planes approximately 45° to the greatest pressure—planes of greatest tangential stress. This angle varies somewhat with the nature of the substance and the stress conditions. With a substance not ideally brittle it is probable that this angle is somewhat more than 45° to the greatest pressure.[a] With brittle substances the angle is probably less than 45°.[b] Where the two lesser stresses are equal, conchoidal fractures are produced such as occur in ordinary building stone tests. The displacement of the fractured parts results in elongation or shortening of the mass in such manner that the axes of the strain for the body as a whole, if it be still considered as a unit, have the same relations to pressure as those above stated for flow cleavage.

If fracturing occurs in rotational strains the fractures are in an intersecting set in such a position that the line of greatest pressure intersects the obtuse angles made by the fissures, and makes a smaller angle with the short side of the parallelogram of cracks bounding the column of rock than with the long side.[c] However, as in the case of irrotational strain, the displacements following the fracturing are such as to elongate and shorten the mass in the manner just indicated.

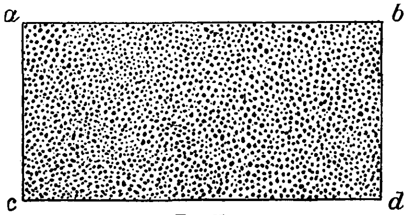

FIG. 35.

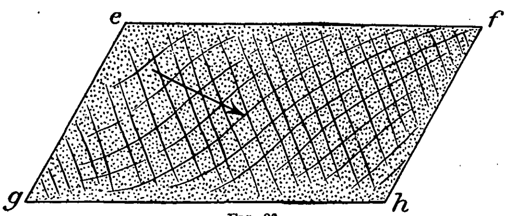

FIG. 36.

FIGS. 35 and 36.—Diagrams showing development of fissility, which, by cementation or welding, may yield fracture cleavage along the longer and shorter diagonals of the deformed portion of the rock stratum. After Van Hise. In the center of the stratum the fractures are in the planes of the greatest shearing, but on the outside of the layer the fractures are in lesser shearing planes, the direction of the fracture being controlled to some extent by bedding.

While in rotational strain the fractures may develop in two intersecting planes, they are likely to show differences in these two planes. If the rectangle *a–b–c–d* in fig. 35 be deformed to the parallelogram *e–f–g–h* in fig. 36, two sets of fractures will be formed, but in the direction *e–h* there is compression, and the rubbing along the fractures parallel to *e–h* produces slickensided surfaces, while along the diagonal *f–g* there is actual stretching of the material with the formation of cracks, and further deformation occurs more easily by the widening of these cracks than by the formation of new ones. The result is a fewer number of cracks normal to the longer diagonal of the rock mass than parallel to it. The curving of the fractures along the longer diagonal, shown in the figure, is due to the control and adjustment between bedding

[a] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, p. 57.

[b] Becker, G. F., op. cit.; Hoskins, L. M., Flow and fracture of rocks: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896.

[c] Becker, op. cit., p. 55.

planes, which in this case are assumed to be more numerous on the outside of the layer.

The intermitted character of the fracture cleavage is a characteristic phenomenon of fractures in homogeneous rocks. Hoskins,[a] from an analysis of the mechanics of the problem, has concluded that closely spaced parallel fractures probably do not form through considerable volumes of a homogeneous rock with no previous parallel structure, no matter what the nature of strain; and that the extensive development of closely spaced parallel fractures must have been conditioned by some previous parallel mineral arrangement which has controlled the directions of fracture. In this Hoskins is followed by Van Hise,[b] who concludes from field observation that fissility developing in shearing planes is usually secondary to cleavage which develops in normal planes, although locally a fine fissility may develop independently of cleavage. If the stress conditions are such that the rock may yield by fracture, it does so along a few separated planes inclined to the greatest pressure, under the laws above noted. These planes once formed, further adjustment to pressure is easier by displacement along such planes than by the formation of new fracture planes. After there has been as much displacement as possible in the readjustment, the stresses may again accumulate so that the fractured parts are again fractured, but, owing to the displacement which they have undergone, the later fractures may not be quite parallel to the earlier ones. This is illustrated on a small scale by the fractures to be observed in granulation. While in the early stages of the fracturing of a given mineral particle belonging to one set in an intersecting system the fractures are approximately parallel, in later stages they are in any possible direction.

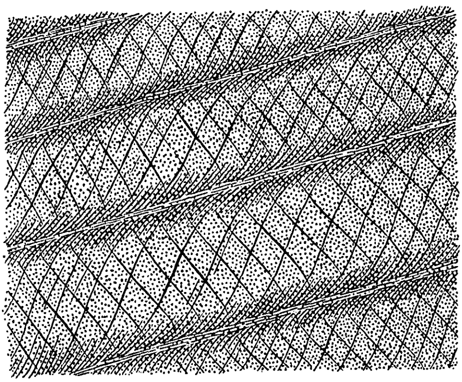

FIG. 37.—Fracture cleavage after fissility in bedded rocks, showing application of principles illustrated in figs. 35 and 36.

On the other hand, Becker[c] has maintained that parallel and closely spaced planes of weakness or fractures may and do develop independent of a previously existing arrangement of the mineral particles, the closeness of the spacing depending upon the wave length of the impulse producing the fracture.

[a] Hoskins, L. M., Flow and fracture of rocks: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 873.

[b] Van Hise, C. R., Principles of pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 655–6.

[c] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1895, p. 16.

There is practical agreement that closely spaced parallel fractures may and do develop, but there is not agreement as to causes or relative importance of the structure. Van Hise, on the one hand, maintains that such parallel fractures are for the most part easily discriminated from flow cleavage; that the structure has not been developed independent of a preexisting cleavage over any great area comparable in size to that in which original flow cleavage may be observed; and that the common development of this kind of structure is in planes somewhat separated by zones of noncleavable material. Becker, on the other hand, holds that closely spaced parallel fractures independent of any preexisting parallel arrangement do actually develop over wide areas; but when we remember that he regards flow cleavage, as well as fracture cleavage, as a structure developed in this way, the statement can not be set against that of Van Hise, for, as the present paper attempts to show, Van Hise and Becker are discussing different phenomena. An examination of the literature on the subject makes it clear that the cleavage variously called false cleavage, fault-slip cleavage, slip cleavage, ausweichungs cleavage, strain-slip cleavage, and rift, here grouped together under the term fracture cleavage, in a great majority of cases is a structure affecting well-separated planes with intervening zones of noncleavable material, and that only in exceptional instances and for limited areas does it occur in planes as closely spaced as the planes of flow cleavage and show external similarity to flow cleavage. From the observations which the writer has been able to make both in the field and laboratory, it seems doubtful whether fracture cleavage ever develops in planes as closely spaced as the planes of flow cleavage, as this is typically developed in slates and schists. Certainly by far the greater number of structures classed under the head of fracture cleavage show an intermitted character easily distinguishable from the closely spaced planes of parting of flow cleavage, and the statement is a safe one that fracture cleavage usually affects more widely separated planes than flow cleavage, and perhaps never affects planes so closely spaced as those of the most fissile slates or schists.

CHAPTER II.

COMPARISON OF FRACTURE CLEAVAGE AND FLOW CLEAVAGE.

Certain features of similarity and difference between fracture cleavage and flow cleavage have been already discussed, but they may be repeated as introductory to further considerations.

Fracture cleavage is conditioned by incipient parallel fractures or by the cementation or welding of parallel fractures, and the parallel arrangement of mineral constituents is in no way essential, although it may have been previously present or may be developed along thin films as a result of the rubbing along the parallel fractures. The planes of parting may be smooth and even, and may be equally good in two or more intersecting sets. They are commonly well separated by zones of noncleavable rock, but locally may be very closely spaced. The structure is developed in shearing planes inclined to the greatest pressure, under the normal conditions and laws of fracturing, in the portion of the lithosphere which Van Hise has called the zone of fracture.

Flow cleavage is always conditioned by the parallel arrangement of the mineral constituents, and is good in proportion to the excellence of the arrangement, the degree of the inequality of the axes, the arrangement of the mineral cleavages, and other features, as shown in Part I. The planes of parting are many and closely spaced, being separated only by the mineral particles or even by the cleavage plates of the mineral particles. The parting is usually parallel to one plane, but rarely in two or more intersecting planes, and in such cases one is far better than the other. The structure is developed in planes or lines parallel to the greatest elongation of the rock mass, usually with the same relations to pressure that the elongation of the rock bears. Flow cleavage is developed under conditions and laws of rock flowage in the deep-seated portion of the lithosphere which Van Hise has called the zone of rock flowage. The processes of recrystallization, granulation, and rotation are effective in flow cleavage, and not in fracture cleavage. The development of flow cleavage is accompanied by a diminution of volume through the development by recrystallization of minerals with higher specific gravity, a feature in which it differs from fracture cleavage, the development of which causes little change in the density of the rock.

EXPLANATIONS OF FLOW CLEAVAGE MAY NOT APPLY TO FRACTURE CLEAVAGE.

This is a self-evident proposition which scarcely needs discussion. Flow cleavage is by definition a cleavage conditioned by the parallel arrangement of the mineral constituents, and the causes of this arrangement are the causes of flow cleavage. Fracture cleavage is quite independent of a parallel mineral arrangement, except where superposed upon a preexisting flow cleavage, and hence the conditions and causes bringing about the parallel arrangement of mineral constituents are not processes and causes of fracture cleavage. Where fracture cleavage is superposed upon a previously existing flow cleavage the parallel arrangement of the constituents may have a strong modifying influence on the newly developing fracture cleavage, but the causes of the parallel arrangement can scarcely be said to be a cause of fracture cleavage; were the previous cleavage not present the fracture cleavage would develop, though perhaps not quite so readily or in the same planes or in planes so closely spaced. Again, the development of fracture cleavage may be accompanied by the rubbing of the sides against one another, developing slickensides or a parallel arrangement of the minerals in films adjacent to the fractures. The parallel arrangement in the films is probably developed largely through recrystallization as in rock flowage; indeed, the films may be said to have undergone rock flowage. Such a parallel arrangement is in no way essential to the existence of cleavage along the fracture planes; the welding of the fractures would yield a fracture cleavage as certainly if the parallel arrangement were not there.

EXPLANATIONS OF FRACTURE CLEAVAGE MAY NOT APPLY TO FLOW CLEAVAGE.

The reverse proposition that the explanation of fracture cleavage may not apply to flow cleavage is one of the essential points of this paper. King,[a] in 1875, emphasized the excellence of rock cleavage produced by the regelation of parallel joints, and showed that it possesses features in common with "slaty cleavage," supposedly due to parallel arrangement of the mineral constituents. He went still further and maintained that slaty cleavage itself is a close joint phenomenon, and that any parallel arrangement of the mineral constituents is merely an incidental phenomenon. Becker,[a] on a basis of experiment and mathematical analysis of the relations of stress to strain, has been positive in the statement that cleavage is not necessarily dependent upon the parallel arrangement of the mineral constituents, but can be induced as well in a homogeneous rock (a rock

[a] See discussion and references, pp. 14-15.

without discrete particles) as in a heterogeneous rock, thus implying that secondary cleavage in general may not be conditioned or caused by the parallel arrangement of the minerals. Doctor Becker recognizes the existence of a parallel arrangement of the mineral constituents in most cleavable rocks, but insists that this arrangement is incidental to rock cleavage, and is one of the results, not a cause or an essential condition. He maintains that cleavage is a capacity to part along certain planes along which the rock has been strained almost, if not quite, to the breaking point, giving it a weak cohesion along such planes, and that the development of a parallel arrangement of the longer diameters of the mineral constituents is possible only along and because of planes so formed, these furnishing directions of easiest relief.

It is here held that Doctor Becker's theory of the development of cleavage in shearing planes, which he applies to cleavage in general, applies only to what is here called fracture cleavage, and to this only with the modification that the parallel development of mineral constituents along shearing planes occurs as a result of actual rubbing after fracture has occurred rather than in planes of weakness along which no fracture has occurred. It is held also that Doctor Becker's theory will not apply to the structure here called flow cleavage, which is dependent on and conditioned by a parallel arrangement of mineral constituents, developed for the most part quite independently of shearing planes.

If Doctor Becker's view is the correct one, and the parallel arrangement of mineral constituents is a mere resulting incident and not a cause, then there would be no good reason why there should be any relation between the nature or excellence of the cleavage and the arrangement and shape of the particles themselves. The fact that there is this close dependence is shown by the following facts:

Flow cleavage always follows either the mineral cleavage or the peripheries of the mineral particles, or both.

The excellence of the flow cleavage varies directly with the degree to which the dimensional axes of the mineral particles approach parallelism.

The excellence of the flow cleavage varies directly with the degree of arrangement of the mineral cleavages.

The shape and dimensions of the particles in a rock with flow cleavage are always uniform and characteristic for minerals of the same kind, and thus not determined by the form of any preexisting plane or line of weakness.

Where a parallel arrangement of the mineral constituents is absent throughout the body of the rock any cleavage which may be present has the definite and distinctive characteristics above described for fracture cleavage, which are quite different from characteristics of flow cleavage. This is in itself sufficient evidence that the parallel arrangement of mineral constituents in some way affects the nature of rock cleavage.

It is known that the parallel arrangement of mineral constituents is developed under conditions of rock flowage, a process which, by observation and definition, occurs without fracture, and there is positive evidence, stated in Chapter III of Part I, that the parallel arrangement of mineral particles in flow cleavage has developed by processes entirely adequate to develop this parallel arrangement without the aid of previously existing parallel fractures.

It will be shown (Part III) that original cleavage presents analogies to flow cleavage. There can be no question that the parallel arrangement of minerals is the cause of original cleavage, and there can, further, be no question that this parallel arrangement is not determined by preexisting fractures in planes of weakness.

Hence, it is concluded that the parallel arrangement of mineral particles, far from being an incidental result of the development of cleavage is itself the fundamental condition for flow cleavage, by which is meant the structure, such as slatiness or schistosity, which is ordinarily referred to as cleavage.

That flow cleavage does not develop mainly in shearing planes in the manner of fracture cleavage is held to be shown by the parallelism of the longer diameters of the mineral particles and hence of the cleavage to the principal axes of elongation of the rock mass as a whole, evidence of which is presented in Chapter V, Part I. In this the writer only follows most other investigators of the subject. Doctor Becker would contend, because of the amount of shortening which the rock mass has undergone, that the longer diameters of the particles, developed according to his theory, would frequently incline so little to the principal axes of elongation of the rock mass that this inclination would be overlooked, and that the minute inclinations actually observed between different particles in a cleavable rock are explained by their development in inclined planes. It is believed that these slight variations, which are unquestionably present, have a subordinate effect upon cleavage (p. 118), and may be partly explained by local variations in stress because of the heterogeneity of the rock (pp. 106–108) and that the variations are too irregular to be explained by Doctor Becker's hypothesis.

Further, according to mechanical analysis by Hoskins,[a] it may be doubted whether closely spaced fractures or planes of weakness, required by Becker's theory, form in a homogeneous rock independent of a previouly existing parallel arrangement, and the observed

[a] Hoskins, L. M., Flow and fracture of rocks as related to structure: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845–874.

facts intensify this doubt. Any cleavage and resulting parallel arrangement thus developed is likely to be in well-separated planes. The parallel arrangement of flow cleavage affects all of the constituents in all planes, is not confined to separated planes of parting, and shows no evidence of actual rubbing (except when followed by subsequent fracture cleavage).

Doctor Becker[a] has described the artificial development of cleavage in the flattening of ceresin cylinders and has held this cleavage to be in shearing planes. Unfinished experiments of a similar nature, begun by Doctor Becker and the writer jointly, do not seem to the writer to show the parallelism of cleavage to shearing planes. Indeed, the flattened cylinders of ceresin cleave directly parallel to the flat sides, with only such minor variation near the edges as would be explained by the inclined stresses developed there through the compounding of

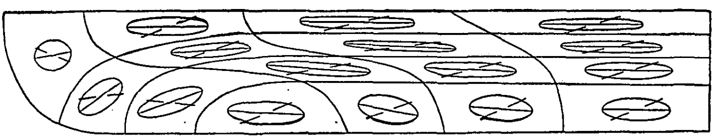

FIG. 38.—Diagram showing the theoretical position of strain ellipsoids in quadrant of ceresin block flattened between two plates with friction between quadrant of ceresin block and plates. After Becker, Bull. U. S. Geol. Survey, No. 241, Pl. III, fig. 11.

the normal stress flattening the mass and the inclined stress developed by friction of the mass with the plates confining it. The theoretical positions of the flattened strain ellipsoids in such a deformed disk are shown in fig. 38. The cleavage developed by splitting the plates seems to be absolutely parallel to the longer diameters of the strain ellipsoids as drawn in the figure. Furthermore, when shavings of the ceresin are examined it is found that it is not homogeneous, but is flecked with minute bubbles or cavities, which in the flattened disk have their axes parallel to the flat sides of the disk, to the strain ellipsoids as drawn in the figure,[b] and to the plane of cleavage developed by splitting the disk. These minute flattened air bubbles are apparently planes of weakness which control the cleavage of the mass in the same manner as minute parallel mineral flakes might control it. Because of these minute planes of weakness the experiments with ceresin apparently have no value in showing that a cleavage may be developed in a strictly homogeneous substance independent of any parallel arrangement of the mineral constituents.

[a] Bull. Geol. Soc. America, vol. 4, 1893, pp. 81–83; Bull. U. S. Geol. Survey No. 241, 1904.

[b] The photographs of cleaved ceresin disks on Pl. IV of Doctor Becker's bulletin seem to the writer fully to confirm the conclusions above reached. The crescentic breaking at the edge of the cake described as following the shearing planes according to his diagram, fig. 14 of Pl. IV, correspond equally well to the longer diameters of the strain ellipsoids shown in fig. 11 of Pl. III. On either theory crescentic parting must appear whenever the cleavage occurs on one side or the other of the medial plane of the disk parallel to the flattened sides, the only difference being that in one case the crescent-shaped edge of the disk bends away from the medial plane and in the other toward it.

On Doctor Becker's theory the cleavage ought in the centre of the disk to be in two intersecting planes considerably inclined to the flat surface of the disk. The observed cleavage actually runs through this portion of the disk readily in one set of parallel planes without change of direction other than a gentle curving parallel to the longer axes of the strain ellipsoids, as in fig. 38.

When a perfectly homogeneous substance is deformed by irrotational stress, under Doctor Becker's theory cleavage would tend to develop equally well in closely spaced intersecting planes. Cleavage equally good in two sets of very closely spaced intersecting planes has not been observed. If such planes are prerequisite to parallel arrangement of the mineral constituents, how shall a newly developing particle act at the intersection of these planes?

The same argument would apply in a rotational strain, although the planes of weakness developed along shearing planes would be mainly concentrated in one set and those in the intersecting set would be few and far between.

It is therefore concluded that secondary cleavage includes two distinct phenomena, here called fracture cleavage and flow cleavage, developed under different stress conditions, the one developing essentially in shearing planes and entirely independent of a parallel arrangement of the mineral constituents, the other developing essentially in normal planes and dependent for its existence on the parallel arrangement of the mineral constituents, and that any explanation of secondary rock cleavage, which does not take account of these distinctions, but treats cleavage structure as a unit, is sure to lead to confusion.

SUPERPOSITION OF THE TWO STRUCTURES AND GRADATIONS BETWEEN THEM.

As already noted, a rock in which fracture cleavage has developed (with, perhaps, incidentally and subordinately a slight tendency to parallel arrangement along slip fractures) may be brought under conditions favorable for the development of rock flowage, and a parallel arrangement of all the mineral constituents may develop, either parallel or at any angle to the previously existing fracture cleavage. The process of rock flowage being essentially through recrystallization, evidence of preexisting cleavage is likely to be obliterated, but in intermediate stages the fracture cleavage may remain. Instances may be cited of rocks which have been broken up into parallelopiped blocks by fractures in two intersecting sets of planes, these cemented, yielding a fracture cleavage, and the whole then strongly compressed, the intersecting planes of fracture cleavage being brought nearly into parallelism. On weathered surface erosion may work down along the fracture cleavage planes, leaving the intermediate areas protruding like pebbles in a mashed conglomerate. Indeed, a rock of this sort shows very close similarity to a mashed conglomerate, and in many cases, as in the acidic porphyries of the Vermilion Lake district of Minnesota, can be distinguished from true conglomerates only by the most careful observation. They differ from the true conglomerates in that pebbles and matrix show no variety; in that the pebble-like forms are nearly all the same size; and, finally, in that the planes of fracture cleavage intersect at acute angles around the ends of the pebbles, whereas in the true conglomerate deformed by rock flowage the cleavage, indicated by the longer diameters of the parallel-arranged mineral particles, does not intersect at the ends of the pebbles. King[a] supposed all cleavage to develop in this way by the compression of divisional fracture planes into substantial parallelism.

It is difficult to judge of the effect of fracture cleavage in determining the plane of newly developing flow cleavage, but it is likely that it has little effect, for during rock flowage the conditions of pressure

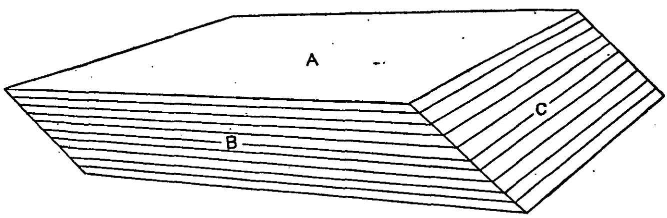

FIG. 39.—Diagram showing fracture cleavage parallel to B and C superposed on flow cleavage parallel to A.

are such that there is little opportunity for movement along shearing or fracture planes; the rock is elongated without regard to the existence of a previous fracture cleavage, and hence the parallel arrangement of the mineral constituents is developed without regard to the previous arrangement.

When flow cleavage comes under conditions of fracture we may have a fracture cleavage superimposed upon the flow cleavage, either parallel or inclined to it (fig. 39 and Pls. XXII, XXIII), and in this case the previously existing flow cleavage has a very marked effect on the position of the newly developing fracture cleavage. If the rocks were homogeneous the fractures would develop along intersecting planes of maximum shear, but the rock being already possessed of flow cleavage, the tendency is for the fractures to follow the cleavage planes already present, even if they are considerably inclined from planes of maximum shearing stress. Fracture cleavage is also likely to develop mainly in one plane parallel to the laminæ of a previously existing flow cleavage rather than along two or more intersecting planes, although the latter also occurs. As already noted, it is believed that a previously existing

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[a] Trans. Royal Irish Acad., vol. 25, 1875, pp. 605–662.

parallel arrangement furnishes the conditions under which closely spaced parallel fractures ordinarily develop.

Evidence of slipping along the greater diameters of parallel-arranged particles in rocks with flow cleavage is often observed, and it is perfectly evident that such slipping is controlled largely by the parallel arrangement, and that the parallel arrangement is in no wise dependent upon the slipping, although it may be somewhat modified or emphasized by it. The cleavage in such a case is conditioned primarily by the parallel dimensional arrangement of the mineral constituents, and the additional episode of slipping parallel to such flow

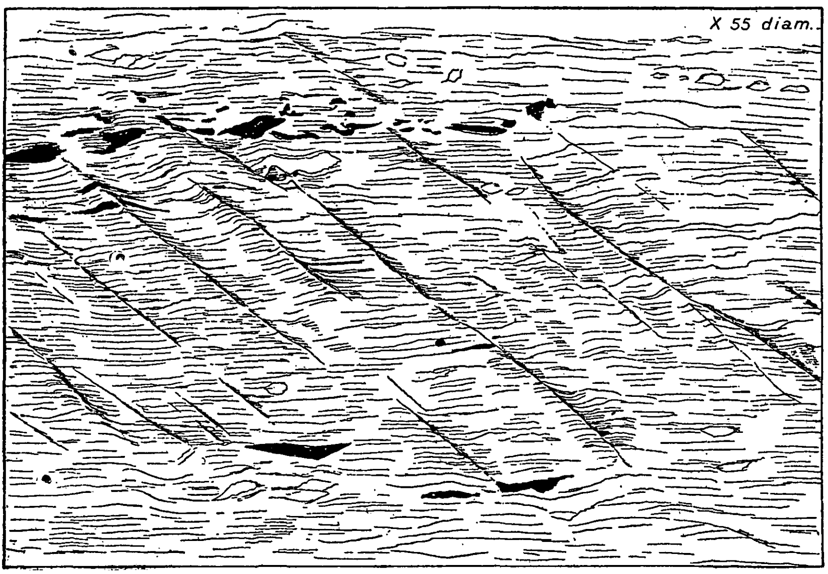

FIG. 40.—Fracture cleavage crossing flow cleavage. After Dale.

cleavage is a modifying condition rather than a primary cause of fracture cleavage, which, if the flow cleavage had not been present, would develop, perhaps not so readily and in different planes. As a matter of observation, it is believed that it is practically impossible to tell in many cases whether or not flow cleavage has been followed by the development of parallel fracture cleavage.

False cleavage, fault-slip cleavage, slip cleavage, strain-slip cleavage, rift, and ausweichungs cleavage may all in part represent fracture cleavage superposed upon flow cleavage (Pls. XIV, *B* and XX), although the previous existence of a flow cleavage is not necessary. These structures characteristically develop along well-separated planes, and are frequently followed by the rubbing of the parts and the development of new minerals parallel to the fractures.

The so-called "grain" of slates may be in some cases the result of the superposition of fracture cleavage on flow cleavage; at least a structure so developed has sometimes been called grain, but it is believed that for the most part it is due to weakness along the plane of the greatest and least diameters of parallel-arranged particles, and is a structure present in all rocks in which there is a good tri-dimensional parallelism of the mineral particles.

As folding and jointing or faulting may occur side by side, due to many varying conditions, though ordinarily developing in different zones, so we may have fracture cleavage and flow cleavage developing side by side, often with the most intricate relations. Folding commonly passes into faulting or jointing, and flow cleavage grades into fracture cleavage. In a given case it is frequently difficult to tell where one kind of cleavage begins and the other ends. Pl. XX, *A* illustrates a "fault-slip" cleavage. The layers of the rock have been minutely crenulated, and the folds have passed into minute fault-slips, the cementation of which by recrystallization of new minerals parallel to the slips has given a capacity to part along separated fault planes which is here defined as fracture cleavage. There has apparently also been developed a flow cleavage parallel to the axes of the minute folds, and it is exceedingly difficult to tell where the fracture cleavage ends and the flow cleavage begins.

RELATIVE IMPORTANCE OF FRACTURE CLEAVAGE AND FLOW CLEAVAGE.

It is very apparent from the above discussion of fracture cleavage and flow cleavage that they are correlative phenomena developed under different conditions. Flow cleavage is the better cleavage of the two in that it allows of closely spaced planes of parting, whereas fracture cleavage does not, and flow cleavage also is the kind which appears in rocks which we ordinarily associate with the term cleavage. The cleavage parallel to the longer diameters of particles in slates, phyllites, and schists is flow cleavage, and it is not necessary to argue that this structure is far more conspicuous, widespread, and characteristic of what are ordinarily thought of as cleavable rocks than the fracture cleavage developed in planes inclined to the longer diameters of the parallel minerals. Indeed, many writers use the term parallel arrangement of mineral particles and rock cleavage as essentially synonymous. Because of its manner of development flow cleavage obliterates evidence of previously existing fracture cleavage, while fracture cleavage is likely to emphasize, rather than to destroy, flow cleavage. It is concluded, therefore, that the most characteristic and widespread structure which we ordinarily think of as cleavage comes under the head of flow cleavage, but that there is also present abundantly in rocks of the lithosphere another kind of cleavage, here called fracture cleavage, developed under conditions quite different from those favorable to the development of flow cleavage, and not in any way dependent upon the parallel arrangement of the mineral particles.

CHAPTER III.

SUMMARY STATEMENT OF CAUSES OF SECONDARY ROCK CLEAVAGE.

Secondary rock cleavage is a property by virtue of which some rocks may be split along parallel surfaces and which is due to the weakness of molecular attraction along such surfaces as compared with the attraction in other directions. The property of cleavage is a capacity to part; actual partings are not included under this head. It is a phenomenon associated with the parallel arrangement of mineral particles, which in turn is induced during "rock flowage" under differential pressure. The relations of cleavage to the parallel arrangement of mineral particles; the relations of cleavage and parallel arrangement to differential pressure, and the processes through which the parallel arrangement of mineral particles has been brought about, have been matters of dispute among men who have attacked the subject from mathematical, experimental, and observational standpoints. The foregoing report is a presentation of evidence on this subject afforded by field and laboratory study of the structural and mineralogical characteristics of metaclasic rocks, with only incidental reference to the mathematical and experimental aspects of the question. It is believed that a sufficiently great variety and abundance of rocks have been examined, and that the facts observed are so uniform and significant as to warrant the following statement of the causes and conditions of secondary rock cleavage:

Secondary rock flowage is of two kinds, widely differing in essential causes and conditions. One has been called flow cleavage, because of its characteristic development during rock flowage, under conditions and laws of rock flowage and in the zone of rock flowage, and the other has been called fracture cleavage because of its characteristic development through fracture under laws and conditions governing fracture in the zone of rock fracture.

FLOW CLEAVAGE.

Flow cleavage conditioned primarily by the parallel arrangement of the principal diameters of unequiaxial mineral particles. It follows these principal diameters and thus intersects the fewest possible mineral particles. It is observed to vary in excellence with degree of arrangement, and with the inequality of the greater, mean, and least dimensional axes of the parallel arranged particles. It is linear parallel or plane parallel (parallel to a line or to a plane) and is in one plane or two intersecting planes (one of them representing grain), according to the degree of inequality of the greater, mean, and least dimensional axes of the parallel arranged particles. The ratio of the inequality of the axes has been found by measurement to be fairly uniform in particles of the same mineral species, and hence the particles of a mineral species wherever found with the same degree of arrangement have about the same effect in producing rock cleavage.

Flow cleavage is conditioned secondarily by the parallelism of the mineral cleavages of the parallel mineral particles. This is a condition clearly dependent upon the arrangement of the dimensional axes of the mineral particles; the dimensional axes of the particles must be parallel, if there is flow cleavage, while the mineral cleavages may or may not be parallel depending on the uniformity or lack of uniformity of their relations to the dimensional axes. Uniform relations are observed in cleavable rocks only where the particles have dimensions determined by uniform crystal habit, as in the micas, hornblende, chlorite, talc, rarely in feldspar, and in the group of characteristic but less abundant schist-making minerals which have been seen to have a poor dimensional arrangement, tremolite, staurolite, garnet, actinolite, chloritoid, andalusite, tourmaline, sillimanite, etc. So far as any of these minerals have dimensional parallelism there is a tendency toward parallelism of their mineral cleavages, and to this extent the mineral cleavage may cause a rock cleavage. The uniform relations of mineral cleavage to dimensions of the particles are not observed when the dimensions of the particles are independent of the crystal habit, as in calcite and the greater proportion of quartz and feldspar particles. In such particles the mineral cleavages are not parallel among different particles.

Parallel mineral cleavages may produce a flow cleavage in the same plane as that conditioned by the dimensional arrangement, as in mica and chlorite; parallel to the greatest axis of dimensional development, as in hornblende; or where the mineral has two cleavages one may aid the cleavage conditioned by the dimensional arrangement, while the other may give the rock a cross cleavage, as in feldspar.

Minerals of the same kind have a tendency to be concentrated into bands. As the minerals vary in their cleavage-producing capacity (that is, in shape, dimensional arrangement, and arrangement of their cleavages), the rock cleavage is likely to vary greatly in different planes, in some cases so widely that practically the flow cleavage is confined to a comparatively few and separated planes. When segregated in bands, also, difference in strength or cohesion of the different minerals may condition planes of weakness quite independent of the parallel dimensional arrangement.

According to the arrangement shown by the minerals, the parting following rock cleavage may be between mineral particles or through their mineral cleavages. If between the minerals, the flow cleavage may, for convenience in discussion of origin, be called intermineral or adhesion cleavage; if through the minerals because of their own cleavage, the flow cleavage may be called cohesion cleavage. In cleavable rocks as a whole probably intermineral cleavage is predominant; in the most fissile schists and slates both the intermineral and cohesion cleavages are present and the cohesion cleavage may be more effective than intermineral cleavage. In terms of individual minerals, intermineral cleavage is predominant in so far as quartz, feldspar, calcite, tremolite, actinolite, garnet, tourmaline, staurolite, chloritoid, andalusite, and sillimanite are present. Intermineral and cohesion cleavage together are effective in proportion to the amount of mica, chlorite, hornblende, and rarely feldspar, present.

The processes through which the parallel arrangement of minerals is brought about, are:

(1) Crystallization or recrystallization of minerals with their respective dimensions in common planes or lines, with or without contemporary or subsequent rotation. Evidence of this is conspicuous in the abundant parallel minerals which have been observed to afford the best flow cleavage, mica, hornblende, and chlorite, as well as in certain minerals which are less abundant in cleavable rocks and which have little effect on rock cleavage, such as calcite, tremolite, actinolite, garnet, tourmaline, staurolite, chloritoid, andalusite, and sillimanite. Evidence of recrystallization is present but less abundantly in certain parallel minerals, which have less effect on rock cleavage, such as quartz and feldspar.

(2) Rotation of all the particles in a rock toward dimensional parallelism. Rotation must always occur during the change in form induced by rock flowage. The evidence of rotation consists largely in the absence of evidence of other processes of parallel arrangement. On such evidence, rotation, while probably always present, is subordinate to recrystallization as a process of arrangement in the best cleavage-giving minerals, and is important only in minerals such as quartz and feldspar which have little effect in the production of cleavage when compared with mica, hornblende, and chlorite.

(3) Slicing and granulation, besides affording considerable assistance to recrystallization and rotation, are observed to yield a dimensional parallelism by themselves, by carving the original grains in situ into rough dimensional parallelism without any rotation, and by breaking slices from the mineral particles which, before any considerable rotation has occurred, may lie parallel. The longer diameters of particles arranged in a parallel position by these processes may be parallel or inclined to the longer diameters of particles developed in a parallel

position by recrystallization. These processes are observed to be of some little importance in arranging quartz and feldspar, and to a limited extent also are effective in arranging hornblende and mica. In any case, however, they are much less effective than either recrystallization or rotation and are important principally in the aid they give to recrystallization and rotation.

(4) Gliding, i. e., change of form by differential movements along definite planes in crystals without fracture. Evidence of this has been observed only in calcite, a mineral better adapted than any other to take a parallel arrangement through this process; yet even in this mineral gliding is clearly subordinate to recrystallization.

Relations of flow cleavage to differential pressure.—The simpler relations of stress to the directions of shortening and elongation in a rock mass during rock flowage are known. Observed relations of flow cleavage to such directions of shortening and elongation give the relations of the structure to pressure. Wherever the plane or line of elongation of the rock mass can be observed, the flow cleavage is observed to be approximately parallel to the greater elongation of the rock mass (or normal to the shortening), but is exactly parallel (with such minor deviations as are caused by the heterogeneity of the rock mass) only so far as the cleavage is conditioned by a parallel arrangement caused by recrystallization. Where the cleavage is locally conditioned by a parallel arrangement induced by granulation or slicing, it may at times be inclined to the greatest elongation of the rock mass.

Where the cleavage is exactly parallel to the axes of elongation of the rock mass, the relations of the cleavage to pressure can be stated by substituting the term cleavage for the axes of strain which it represents. If the strain is an irrotational one (pure shortening and elongation with or without dilatation), the greatest elongation, and hence the flow cleavage, is always developed normal to the greatest pressure. If the strain is a rotational one (scission or scission combined with pure shortening and elongation, with or without dilatation), at any instant the rock mass is being elongated, and hence rock cleavage is being developed normal to the greatest pressure, but, due to rotation, the total elongation of the rock mass (which represents at any instant the net effect of the stresses producing it) and the cleavage immediately become slightly inclined from its normal position to the greatest pressure, and inclined from the position of new cleavage subsequently tending to develop in planes where elongation is then occurring normal to the greatest principal stress. Hence cleavage is always tending to develop normal to the greatest principal stress, but its final position may or may not be inclined to the greater stress depending upon the nature of the strain.

Where the cleavage is conditioned in whole or in part by the parallel arrangement caused by granulation or slicing and is not parallel to the axes of elongation of the rock mass, its development has been in shearing planes inclined to the maximum elongation of the rock mass.

To these simple relations of cleavage to pressure there are a number of modifications, due to the variation in local stresses caused by the influence of rigid particles on the transmission of stresses, and due to the limitations of the processes of rotation and recrystallization in bringing or keeping the greater diameters of the rock mass in parallelism with the greatest lengthening of the rock.

FRACTURE CLEAVAGE.

Fracture cleavage is a capacity to part along parallel planes, usually in intersecting sets, along which there has been either incipient fracturing or actual fracturing followed by cementation or welding. It is a structure developed in shearing planes inclined to the greatest pressure under the laws of fracture and in the zone of fracture in the lithosphere. Fracture cleavage may or may not be accompanied by a parallel arrangement of the mineral constituents, but a parallel arrangement is not essential to its existence, and when present is only a modifying condition or result and not a cause.

RELATIVE IMPORTANCE OF FRACTURE CLEAVAGE AND FLOW CLEAVAGE.

Flow cleavage and fracture cleavage are correlative phenomena. Flow cleavage is a structure characteristic of rocks which we ordinarily associate with the term cleavage, such as slates, schists, phyllites, etc., and flow cleavage affords planes of parting more closely spaced than fracture cleavage and usually in one plane rather than in two or more intersecting planes. Fracture cleavage is obliterated by the subsequent development of flow cleavage, while flow cleavage may be destroyed or emphasized by the subsequent development of fracture cleavage in the same rock. The structures known as fault-slip cleavage, false cleavage, slip cleavage, and ausweichungs cleavage are in most cases varieties of fracture cleavage which have been superposed on flow cleavage.

CHAPTER IV.

COMPARISON OF PRESENT STATEMENT WITH PREVIOUS STATEMENTS CONCERNING SECONDARY CLEAVAGE.

Sorby,[a] Heim,[a] Harker,[a] and others have considered cleavage to include two classes of phenomena similar to those described in this paper under "fracture cleavage" and "flow cleavage." Van Hise's[a] discussion of "cleavage" would apply almost in toto to what is here called flow cleavage, and his discussion of "fissility" would apply not only to the parallel closely spaced fracturing which he termed fissility, but to the cleavage, or capacity to part, developed by the cementation or welding of such fractures, or to what is here called fracture cleavage. The writer is thus essentially in accord with Sorby,[a] Heim,[a] and Harker[a] in distinguishing two classes of phenomena under cleavage; and by correlating fracture cleavage with fissility in part, he is in accord also with Van Hise. He differs from those who have attempted to discuss cleavage as a single kind of phenomenon resulting from a single group of causes and conditions. King[a] and Becker[a] in particular have applied to cleavage in general an explanation which is here held to apply mainly, with certain modifications, to what is here called "fracture cleavage," and Becker's strong presentation of fact and argument has had much weight. In this report especial emphasis has been laid on the proof that the two phenomena are separate, resulting from different conditions and causes, and that the explanation of fracture cleavage will not apply to flow cleavage.

That a parallel arrangement of mineral particles is an essential and adequate cause of flow cleavage (or "cleavage" as this term is used by many writers) has been assumed by all writers except King[a] and Becker.[a] The points here added or emphasized are the nature of the parallel arrangement of the mineral particles and the dependence of cleavage on the parallel arrangement where such arrangement is present, as follows: (1) The control of the arrangement of the mineral cleavages by the dimensions of the mineral particles; (2) a statement of the relative effects of dimensional and mineral cleavage arrangement in the particles of different mineral species; (3) proof of the uniformity in shape, dimensions, and cleavage-producing effect of

[a] See discussion of literature on pp. 13-15.

particles of the same mineral species; (4) a determination of the relative importance of the dimensional arrangement of the mineral particles and the arrangement of the mineral cleavages in producing flow cleavage.

Concerning the processes through which the parallel arrangement of the mineral constituents in flow cleavage has been brought about, no new conclusions are offered, unless certain modifications of old ideas may be called new, but evidence is presented to show to what extent the several possible processes are effective. Recrystallization was hinted at by Sedgwick when he referred to the parallel arrangement as due to "crystalline forces." Sorby stated that the development of minerals such as the micas in cleavage planes "may have been a subsequent operation." Sharpe explained the parallel arrangement by the flattening of the individual particles in situ.[a] Such a result is likely to be produced by recrystallization, but Sharpe makes no statement as to the process through which it is obtained. While a number of other writers have discussed the solution and deposition of minerals (recrystallization) as a process active in the deformation of rocks, Van Hise was the first to show the predominance of the process of recrystallization in the development of a parallel arrangement of the particles. Moreover, his conception of the process and the conditions favorable to it is much more definite than that of his predecessors. The facts observed in the investigation above described are in accord with Van Hise's statement. The new features are the presentation of a number of criteria for discriminating the effects of recrystallization from those of other processes, and through this means the presentation of an additional proof of the predominating importance of recrystallization when compared with other processes, and finally a proof of dimensional arrangement and control of mineral particles through this process.

The development of a parallel arrangement by the rotation of random particles was first held by Sorby, who has been followed by most other writers. The present statement contains nothing new on this subject except evidence of its subordinate importance as a process in arranging the mineral constituents.

Gliding has been shown by Adams and others to be of importance in the production of parallel arrangement of calcite in metaclasic rocks. It is believed that the facts stated in this report demonstrate that evidence is lacking to show the importance of this process in metaclasic rocks in general as compared with the other processes described.

The processes of granulation and slicing which produce a parallel arrangement of mineral constituents, have been described by Van Hise,

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[a] See references on pp. 13-16.

Adams, and others.[a] In this paper the writer has attempted to determine the amount and nature of the evidence of this process in the metaclasic rocks.

The statement of the relations of flow cleavage to the shortening of the rock mass and to pressure is essentially the same as that of practically all others who have assumed the parallel arrangement of mineral constituents to be a necessary condition for the existence of cleavage, and is especially similar to the statements of Van Hise and Hoskins, but it varies from the conclusions of King and Becker,[b] that all cleavage is developed in shearing planes inclined to the greatest elongation of the rock mass. An advance is made perhaps in showing the reasons for slight variations from parallelism to be seen in cleavable rocks and the effect of rigid particles on the local distribution of stresses within the rock mass.

The explanation of the development of fracture cleavage in planes of maximum shear or jointing here given is essentially the same as that applied by King and Becker, especially Becker, to all cleavage, both fracture and flow cleavage (pp. 126–130). Van Hise's explanation of the relations of pressure to fissility (pp. 126–133) apply almost without change to the present statement of the relations of pressure to fracture cleavage.

It must now be apparent to the reader that the conclusions of the present report have many features in common with those long ago reached by Sorby, but that they correspond more nearly in emphasis and form with those of Van Hise. Sorby suggested most of the factors in the problem; Van Hise showed their relative importance and the predominance of recrystallization. Aside from new features above referred to, the writer differs from Van Hise only in confining fissility strictly to actual partings as defined by Van Hise and in applying the term fracture cleavage to the capacity to part formed by the welding or cementation of fissility partings. To this restriction of the application of the term fissility, and to the use of the term fracture cleavage, Van Hise assents.[c]

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[a] See discussion and references, pp. 14–17.

[b] See discussion and references, pp. 18–19.

[c] See discussion and references, pp. 19, 126–130. See also Treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904.

PART III.

ORIGINAL CLEAVAGE.

The term original cleavage may be used conveniently to designate the cleavage sometimes possessed by a rock on its first solidification from a magma, or deposition from water, as distinguished from secondary cleavage, which is produced by secondary processes accompanying rock flowage after the solidification or deposition of the rock. A brief discussion of rocks with original cleavage, or protoclases, is here given to show the main points of similarity and difference between original and secondary cleavage. Original cleavage is found in clastic sediments and in certain igneous rocks with a banded or flow structure.

BEDDING IN CLASTIC SEDIMENTS.

The bedding of sediments may be a capacity to part along parallel surfaces which, rather than an actual parting, is by our definition rock cleavage. Such cleavage is probably for the most part due to the differences which are found in the strength of the beds, and which allow rupture to occur more easily along softer strata, usually of a shaly nature, than along hard layers. But it is certain that the cleavage in mechanical sediments is due also to a dimensional arrangement of the mineral constituents. Waterworn particles or pebbles are commonly not round, but ellipsoidal or subangular. While the shape, of course, varies considerably with the nature and structure of the mineral or rock, averages of the greatest and least diameters of a large number of pebbles and of mineral particles from microscopic slides of finer sedimentary rocks show a rough uniformity, not far from 2 to 1. Unexquiaxial particles moved by water are deposited in a position determined by the configuration of the immediately underlying floor and by stresses there obtaining. These stresses are those of gravity alone or of gravity combined with moving water. The tendency is for gravity to bring the greater or mean axes of the particles toward a horizontal plane, assuming the floor to be horizontal, while that of moving water is to lay the greater diameters of the particles at some angle to this plane, usually low, under the law that the ellipsoid tends to take such a position that it presents the greatest surface to stresses acting upon it. Their combined forces deposit the particles in such a manner that they sometimes overlap, in the manner of shingles. Gravity is greatly predominant in original deposition and has a tendency to produce a horizontal arrangement. This tendency is likely to be somewhat emphasized later by the weight of overlying rocks. The arrangement may be such that all three dimensional axes of the various particles are respectively parallel, or such that only the least axes are parallel, and the other two are axes parallel to a plane and not to one another, or such that the particles may lack all but a faint tendency toward parallel arrangement, depending upon the configuration of the floor and upon whether gravity alone, or gravity combined with moving water, produces the result. A tendency to dimensional arrangement of the particles is thus one of the characteristics of sedimentary bedding. The alternation of bands of varying coarseness and varying mineralogical composition is also a characteristic feature. When a sediment has been cemented to a coherent solid, the bedding is not an actual parting, but may remain a plane of weakness with a capacity to part, and hence truly a cleavage—a cleavage primarily due to the dimensional arrangement of unequiaxial particles. It is scarcely necessary to add that cementation may be so thorough that the rock does not part along bedding planes any more readily than elsewhere. In coarse rocks the parallel arranged particles themselves may be composite, and the individual minerals making up the composite particles may have neither dimensional nor crystallographic arrangement. In finer rocks the dimensionally arranged particles may be mineral individuals. In such particles parallelism of crystallographic properties may be found if there are uniform relations of the crystallographic properties to the dimensional diameters of the particles. The degree of this uniformity varies with the different minerals and with the length of time during which the particle undergoes the wearing of water. Quartz grains in a sedimentary rock show little if any crystallographic parallelism. Feldspar may do so rarely in arkoses, clays, and muds, where the shape of the feldspar particles is conditioned by the normal habit or cleavage of the feldspar. Mica, when original in sedimentary rocks derived from the disintegration of granite or other mica-bearing rocks, shows characteristic crystallographic parallelism. It may frequently be seen in cleavage plates lying parallel to the bedding of quartzites and shales. Hornblende has little arrangement, probably due to its breaking down by water action. Other minerals less abundant in sediments may or may not show crystallographic parallelism, depending largely on their crystal habit and the length of time they have been subjected to the working of water, but they are normally in such small quantities in sediments that their arrangement and influence on bedding cleavage need not be discussed.

In general, then, the parallel arrangement of particles in sedimentary bedding is dimensional, and either complete or partial, usually the latter, depending upon the nature of the stresses exerted at the time of deposition and the evenness or irregularity of the floor. Where the constituent particles of the sedimentary rock are separate mineral individuals rather than pebbles made up of many mineral individuals there is present in some cases a crystallographic parallelism, depending entirely upon the uniformity of the relation between the crystallographic properties of the crystals and their dimensions. The parting occurs parallel to the longer diameters of the particles, usually between particles and not along the mineral cleavage, although in the case of the micas, the rock cleavage may follow the mineral cleavage, as evidenced by the corresponding mica spangles to be seen on both faces of a parted quartz-slate in which the parallel structure is entirely that of bedding. Parting along bedding is aided also by the difference in nature and texture of different beds.

In all of these phenomena the parallel arrangement of sedimentary bedding is closely similar in kind to the secondary flow cleavage incidental to rock flowage. There are, however, differences in the phenomena shown by sediments and rocks with flow cleavage, some in kind but mostly in degree. In both rocks the segregation into bands of minerals or particles of the same kind or size are characteristic features, resulting in planes of weakness perhaps entirely independent of a parallel arrangement of the mineral constituents. The particles in the flow cleavage rocks due to granulation probably have sharper angularities than the angular particles in the sediments. The most characteristic particles in flow cleavage rocks, i. e., those developed by recrystallization, have more unequal dimensions than particles of the same minerals in a sedimentary rock, the water having a tendency to minimize the differences in dimension. Characteristic arrangement due to dimensions is, accordingly, on an average, poorer in sediments than in rocks with secondary cleavage, although the differing processes bringing about the arrangement in the two cases modify the results. The crystallographic parallelism in sediments is not so good as in rocks with flow cleavage, for the reason that the rounding effect of the water is likely to modify the uniformity of relations between dimensions and crystallographic properties. These latter differences, however are not great.

These are the differences shown by the minerals appearing in both the sedimentary and secondary cleavage rocks, but there is an additional and very important difference. The relative abundance of the different minerals varies. Quartz and feldspar are characteristic of sedimentary rocks, while mica and hornblende, etc., are subordinate. In the rocks with secondary cleavage mica and hornblende are the characteristic minerals, as well as a long list of minerals only sparsely present in sediments, such as chlorite, actinolite, staurolite, garnet, sillimanite, andalusite, etc. These differences in minerals of course make wide differences in average dimensions of the particles present in the original and sedimentary rock (a difference in addition to the variations in dimensions shown by minerals appearing both in sediments and flow-cleavage rocks). These mineralogical differences have a further effect in determining the nature of the parting. In both sediments and rocks with secondary cleavage it is parallel to the longer dimensions of the particles, but in the former, where quartz and feldspar are dominant, the parting is mainly intermineral, while in the latter mica and hornblende are dominant and the best parting may follow the mineral cleavages, although both kinds of parting may be present in both classes of rocks.

In general it appears that so far as the structure itself is concerned there is no essential difference between potential parting in the bedding of an indurated sediment and that in a metaclase or rock with secondary cleavage. Both are due to differential pressure. Both are molecular phenomena conditioned by the same kinds of factors. However, in origin and in the range of the different factors favoring the parallel parting, the two structures are widely different and should of course be described under two names.

BEDDING IN NONCLASTIC SEDIMENTS.

Excellent bedding may sometimes be observed in nonclastic sediments which may or may not yield a rock cleavage. The most common of the nonclastic sediments—limestone—sometimes shows a good bedding cleavage and sometimes not. When present, it is clear that the bedding cleavage is not due to the parallel arrangement of mineral constituents, but to the intrinsic weakness of certain layers. The subsequent alteration of a nonclastic rock through chemical changes may emphasize the bedding, as by the segregation of limestone and chert in a limestone formation, or the segregation of chert and iron oxide in an iron formation resulting from the alteration of iron carbonate. Where the original bedding has been so emphasized the capacity to part is clearly due to interbanding of materials differing widely in nature, certain layers being weaker than others, or the layers of different character having weak adhesion (Pl. XXV).

FLOW STRUCTURE IN IGNEOUS ROCKS.

An original cleavage is sometimes found to have been induced in igneous rocks prior to or contemporaneous with their solidification from a magma. In the original flow structure of lavas there is a tendency for any unequidimensional crystals to be arranged with their greater diameters parallel to the flowage lines, and there is a marked tendency for minerals of the same kind to be concentrated into layers, both of which phenomena may yield a rock cleavage. The cause of the parallel arrangement of flowage is one which need not here be discussed beyond the general statement that the arrangement is probably due to rotation of random particles during the flowage of the lava, and perhaps also to development in situ under unequal stresses set up during later stages and caused by cooling of the mass. The arrangement of particles is dimensional. Commonly this arrangement is partial rather than complete, but dimensional axes of one kind in the different particles may be parallel, while the others are parallel to a plane and not to one another. A large proportion of minerals in an original rock have crystal shape or habit, and thus present uniform relations of their crystallographic axes to their dimensions, and hence their crystallographic axes are arranged to the same degree as their dimensions. This crystallographic arrangement is found in mica and hornblende, and partially also in feldspar. Pressure effects and breaking and separation of particles in the lines of flow are common.

Certain original gneisses should probably also be described in this connection, although it is believed that the majority of gneisses are the result of secondary metamorphic action and therefore should properly come under the discussion of secondary rock cleavage. The gneisses with original parallel structure are not surface rocks, but in many cases are found in dikes or in other forms whose structural relations show them to have undergone practically no deformation since solidification.[a] Such gneisses can be proved to be igneous in some cases at least, and are probably so in the majority of cases, and if their parallel structure is induced prior to solidification it may be in somewhat the same way that the flowage structure of lavas is induced, although the parallel development of minerals in situ due to differential stresses set up in the rock during the later stages of its cooling may be more important than the rotation of random original particles. There is a dimensional parallel arrangement of the particles of the gneisses, but the minerals possess characteristic crystal shape to a small degree and hence there is little crystallographic parallelism of the mineral particles. Mica and hornblende are the only ones which show crystallographic arrangement. Quartz and feldspar are exceedingly irregular in outline, and their dimensional parallelism would be likely to be overlooked in a hasty examination.

As in the comparison of the original cleavage of sediments and flow cleavage, all of the features above described for the original cleavage

[a] A clear case of the development of an original parallel structure in gneisses is found in the Animas Canyon of southwestern Colorado, where, according to Mr. Whitman Cross, dikes of gneiss have intrusive relations to ancient hornblende-schists. The dikes give no evidence of secondary deformation and presumably the parallel structure of the gneiss is original. The writer is indebted to Mr. Cross for an opportunity to examine specimens from this locality. (Specimens 10, 13, 152, 153, 2937, 2943, 2947, 2948.)

of igneous rocks are duplicated in secondary cleavage, but in varying degree. Indeed, the general aspects of the two are frequently surprisingly similar. This is well shown in the behavior of finer constituents in passing around phenocrysts in both original and secondary rocks. In kinds of minerals represented in the igneous rocks with original cleavage and in rocks with secondary cleavage there are differences. Probably mica and hornblende are relatively more important in the latter than in the former, while quartz and feldspar are relatively more important in the former, although both are present in both kinds of rocks. In shape of particles there are minor differences. Angular fragments due to granulation in the rocks with secondary cleavage probably do not have their counterparts in so great abundance in the original igneous rocks with cleavage. The crystals in the original rock are probably not so unequidimensional on an average as those in rocks with secondary cleavage and probably show differences in size, either larger or smaller, depending on the dominance of the processes of recrystallization or granulation in rock flowage. Differences in the relative dimensions of the greatest and least diameters of the particles in the original and secondary rocks seem to be indicated by measurements. For instance, secondary green hornblende in schists shows an average relation of length to thickness of about 100 : 20. Measurements of the same dimensions of similar hornblendes in unaltered rocks give a ratio of about 100 : 40. The parallel arrangement, even if brought about under the same conditions in the two classes of rocks, would not be expected to be equally uniform in both, and as a matter of observation, it is not, but the arrangement is brought about under different conditions and the cause may not be connected with the dimensions of the particles. The crystallographic properties, therefore, show less tendency to be parallel in the original igneous rocks than in the secondary rocks. The concentration of the hornblendes and micas in layers in the secondary rocks with cleavage affords an excellent parting not attainable in the original igneous rocks where these minerals, if present, are not concentrated to such an extent. The breaking of crystals and their separation in lines of flow are strikingly similar in original and secondary rocks.

It thus appears in the comparison of rocks with secondary cleavage and igneous rocks showing flow structure and cleavage that there is a similarity of phenomena throughout. In both the parting is a molecular phenomenon and thus a true cleavage. But still sufficient and characteristic differences are present to make discrimination possible in some cases. The original cleavage in an igneous rock showing flowage structure is in general far less ready than in either the indurated sediments or in the typical crystalline schists or slates.

MISCELLANEOUS.

There remains to be discussed a variety of original parallel structures, such as pegmatite, perthite, and parallel arrangements, particularly of feldspar crystals, in rocks both basic and acidic, perhaps due to original flowage and perhaps partly pegmatitic in origin. The parallel arrangement of pegmatites and perthites has little similarity with the secondary parallel arrangement incidental to rock flowage. In either case there is no dimensional arrangement of the minerals as a whole with reference to the pressure, but rather an intergrowth of two minerals and uniformity in arrangement only with reference to each other, due to causes not well understood. It is the peculiar control which the physical properties of a mineral sometimes exert on the arrangement of another mineral close at hand. The development of minute crystals of one mineral with different arrangement on the crystal surfaces of another is an illustration of such control. In pegmatites the cleavage is that of the constituent minerals, and may vary in direction from mineral to mineral; in rocks with secondary cleavage it is of the complex nature already described.

The characteristic arrangement of feldspar parallel to its tabular development found in many original basic and acidic rocks presents an interesting analogy with certain schists. This parallel arrangement is found in the banded gabbros of the Adirondacks[a] and northeastern Minnesota, the nepheline-syenites of central Wisconsin,[b] the porphyritic gneiss from the main shaft of the Hoosac tunnel, Massachusetts, and certain other labradorite-porphyrites from America and Europe. An examination of the feldspars of these rocks shows them to be simply twinned parallel to the clinopinacoid or brachypinacoid. In all cases also their tabular development is parallel to this plane, and they lie in the rock with these planes parallel. In some cases, as in the banded gabbro and in the nepheline-syenite, the parallelism goes still farther and the crystallographic axes in this plane are parallel, as shown by the parallelism of the basal cleavages. This arrangement of the feldspars gives the rock in which it occurs a cleavage parallel to the tabular development of the feldspar, and where the basal planes are parallel, a cleavage parallel to them. The rock cleavage so formed is mainly cohesion cleavage, as it follows the brachypinacoidal or basal cleavage of the feldspar. In certain schists a similar secondary arrangement of this kind has been found (pp. 35–37), but in this case the secondary feldspars have not nearly so great differences in dimensions as the original ones, and, furthermore, the rock cleavage is not conditioned by the feldspar mineral cleavage, but the feldspar is associated with mica and the rock cleavage is largely parallel

[a] Sp. 14764, sl. 9399, near Thompson, Minn.; sp. 18242, sls. 9754, 14972, 14973, 14974, Westport, N. Y.
[b] Sps. 5261, 5821, 5823, 5824, 5825, near Wausau, Wis. Cf. Weidman.

to this mineral. The similarity of the development and arrangement in the original and secondary rocks brings to mind the possibility that the original parallel structure may be due to differential pressure. The rocks showing this arrangement have in many cases certainly not undergone mechanical deformation. The parallel arrangement is found in fresh massive gabbro in which the feldspars almost certainly are original. If this arrangement were attained before the complete solidification of the magma, as seems most likely, it could come about either through rotation of unequidimensional particles or through development in situ. If such large feldspars were present in the magma before solidification, the viscous movement prior to cooling would undoubtedly have had a rotating effect on the crystals, and the tendency might be to bring them into dimensional parallelism. The same result might perhaps be attained by the rotation of such crystals under the differential stresses caused by the cooling of the magma. Brögger is strongly of the opinion that the forces in a cooling viscous magma are unequal in different directions; that at any point they may be resolved into three mutually perpendicular differential stresses. In neither case is it clear how a good tridimensional parallelism can result from the rotation of crystals of which two of the three dimensions are not far different. As an alternative the feldspars may be supposed to develop entirely after such differential stresses incidental to cooling have been set up. In this case it is analogous to the development of minerals by recrystallization under conditions of differential pressure in the development of cleavage during rock flowage. This seems to offer a basis for a more reasonable explanation of the excellent parallel, almost pegmatitic, structures observed in many of the original igneous rocks, than rotation of crystals previously formed.

Still another possible arrangement yielding parallel parting should be mentioned. It is conceivable that if in a rock, say a gneiss, the materials of differing strength are concentrated in alternate bands, there might be a tendency to part in parallel planes, even if the individual particles were not arranged. No case of this has appeared during this investigation.

CONCLUSION.

To the cleavage of original rocks, then, such as sedimentary bedding, flow structures in lavas, etc., statements similar to those made concerning secondary cleavage may apply. The cleavage is conditioned by the same factors of dimensional and crystallographic arrangement, although these factors have different ranges. The relations to pressure are probably similar, although observational evidence is partially lacking. The only essential difference is in the processes through which the arrangement is brought about. Pegmatites and perthites present no dimensional arrangement of the minerals, and their cleavage is essentially a local mineral cleavage differing in character from the rock cleavage under discussion in this paper. The cleavage in such rocks is coterminous with the individual minerals and does not extend in the same planes through any great mass of the rock; it is then properly not rock cleavage.

SUPERPOSITION OF SECONDARY FLOW CLEAVAGE ON ORIGINAL CLEAVAGE.

It is evident that secondary flow cleavage can develop in a rock which is either with or without any previous parallel structure, and may have any position relative to such previous parallel structure. If the flow cleavage is developed parallel to the earlier parallel structure, the latter is simply emphasized. If the flow cleavage is developed in planes inclined to the earlier structure, both the original and secondary structures may be present in the earlier stages of the development of the latter. In later stages the earlier parallel structure is necessarily destroyed by the development of the secondary cleavage. The secondary cleavage is conditioned by the dimensional arrangement of the particles, and the longer diameters of the particles in a rock can not be parallel to both original and secondary structures.

Secondary flow cleavage is very commonly developed in sedimentary bedded rocks, and here the original and secondary structure may be frequently recognized. The bedding may be indicated by actual fractures due to readjustment between the beds, by variation in texture of the different beds, or by variation in the mineral content of the different beds, even though all trace of the original parallel arrangement is entirely destroyed. Pl. XIV, *A*, shows a secondary cleavage crossing the bedding of a banded graywacke and slate.[a]

The long dimensions of the individual particles correspond in directions with the secondary cleavage. The original bedding is shown only in the alteration in coarseness and mineralogical character of the bands. In the hand specimen from which this slide is taken the parting is parallel to the secondary cleavage, and, while the original bedding shown by the banding is conspicuous, the parting parallel to it is practically nil.

In the instance cited the secondary parallel minerals developed by recrystallization across the bedding show greatly varying coarseness, and this coarseness corresponds roughly to the texture of the bands which they cross. Where an original bedding layer is coarse, the micas crossing it are in coarse conspicuous flakes; where the texture of the bedding layers is fine the mica crossing it is fine (Pl. XIV, *A*). This serves really to emphasize the original alternation in texture of the

[a] Sps. 14974, Black Hills, South Dakota; 7712, Menominee district of Michigan; 29217, Ocoee area, Tennessee; see also sps. 14858, 14981, 14861, 14862, Black Hills, South Dakota; 14745, Little Falls, Minn.; 25575 and 25584, between Thompson and Livingston, Ga.

For excellent illustrations of cleavage crossing bedding, see Dale's report in Nineteenth Ann. Rept. U. S. Geol. Survey, 1899, pt. 3.

bedding. Thus while original parallel arrangement is completely destroyed by the secondary arrangement, the bedding layers, as shown by alteration of textures, are even more conspicuous than before. It is believed that this correspondence in texture of original and secondary minerals in the early stages of recrystallization is a general phenomenon wherever recrystallization occurs—that is, the finer the original particles the finer the secondary ones developing among them. The micas developing in a slate, for instance, tend to be individually smaller than those developing in a coarser schist.

The attitude of secondary flow cleavage with reference to the major bedding structures in deformed sedimentary rocks has been observed for many years and the general relations of the two are known. As the sedimentary layers of the earth's crust have been originally almost parallel to the surface of the earth, and as the deformation of such rocks has been mainly through circumferential shortening of the outer portion of the lithosphere, it is in accordance with the law that cleavage develops normal to the shortening of the rock mass that cleavage is frequently highly inclined to bedding. However, in the deformation of bedded rocks of heterogeneous character the nature of the deformation must vary from bed to bed and from time to time, with corresponding variations in cleavage. A full discussion of the attitude of cleavage with reference to bedding is not essential to the purposes of this paper and will be omitted. However, there should be mentioned the well-known tendency of cleavage to cut across the harder layers at high angles and to curve toward parallelism with the bedding in the softer layers. This is because of a frequent difference in the nature of the strains in the hard and soft layers. If the strata have been shortened parallel to their own plane the cleavage in general has a tendency to develop normal to the beds; the strain is essentially pure shortening. But in the folding which accompanies shortening there must be readjustment between heterogeneous rocks or within the softer layers of the series. In the softer layers the strain is largely of the kind known as scission. Cleavage developing under scission is rapidly rotated toward the plane of scission, which in the case of the soft layers would be the plane of bedding; hence the frequent tendency of cleavage toward parallelism with the bedding in the softer layers, and the peculiar S curve so characteristic of cleavage in rocks of varying hardness (fig. 37).

SUPERPOSITION OF FRACTURE CLEAVAGE ON ORIGINAL CLEAVAGE.

It is apparent that fracture cleavage may be developed without in any way obliterating original cleavage, and indeed may emphasize it. As in the case of the superposition of a fracture cleavage on a flow cleavage the preexisting cleavage may determine the plane of parting even where this is inclined somewhat to what would be the plane of parting were the rock homogeneous. Thus it is we have common slips along bedding planes and more widely spaced fractures at angles to it. The statements made on pages 130–133 concerning the superposition of a fracture cleavage on flow cleavage will also apply in the main to superposition of fracture cleavage on original cleavage.

One of the results of the superposition of fracture cleavage on original cleavage is the development of "cleavage bands" resulting from the softening of material by shearing along the fracture cleavage, which allows such bands to weather out readily and gives the rock as a whole a conspicuous banding (Pl. XVII, *A*).

PLATES.

PLATE I.

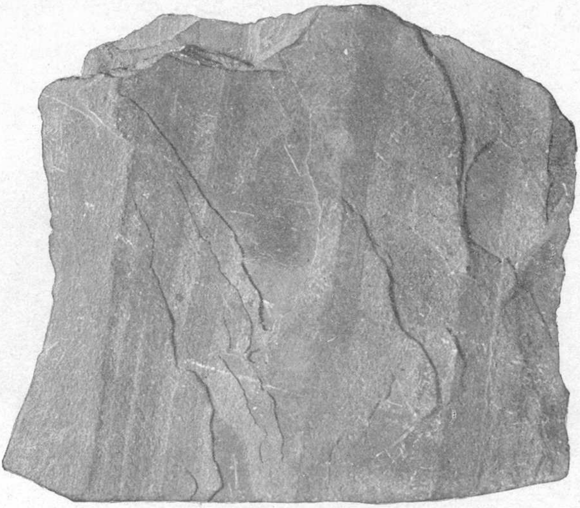
PLATE I.

SPECIMENS ILLUSTRATING PLANE-PARALLEL AND LINEAR-PARALLEL TYPES OF FLOW CLEAVAGE.

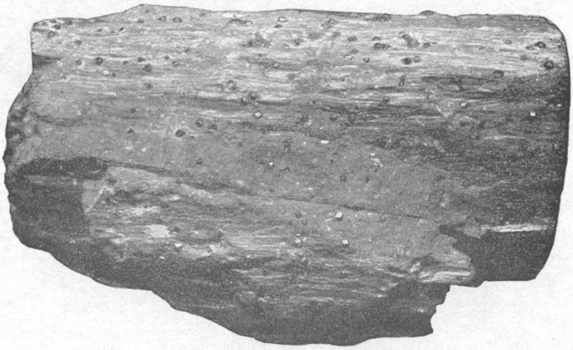
A.—Micaceous schist with plane-parallel type of cleavage. From Black Hills. Specimen No. 14858. The black bands represent bedding, and the cleavage is inclined to the bedding. Under the microscope all the constituents of the rock, mainly mica and quartz, are seen to lie with their greater and mean diameters in the plane of rock cleavage. It is indeed the tridimensional parallelism of these particles which gives the rock its plane-parallel type of cleavage.

B.—Micaceous schist with linear-parallel type of cleavage. From Black Hills. Specimen No. 14943. Under the microscope the constituents of the rock, mainly quartz and mica, are seen lying with their longer diameters parallel to a line and not to a plane. The micas are for the most part bent and contorted in all directions but one, the line of cleavage. The garnets have developed subsequent to the development of the cleavage.

C.—Micaceous schist with cleavage intermediate between plane-parallel and linear-parallel type. From Black Hills. Specimen No. 14959. The mica plates are bent and contorted and have the same arrangement on a minute scale as is shown by the rock surface on a larger scale. (See Pl. II, *B.*)



A



B

C

PLANE-PARALLEL AND LINEAR-PARALLEL TYPES OF FLOW CLEAVAGE.

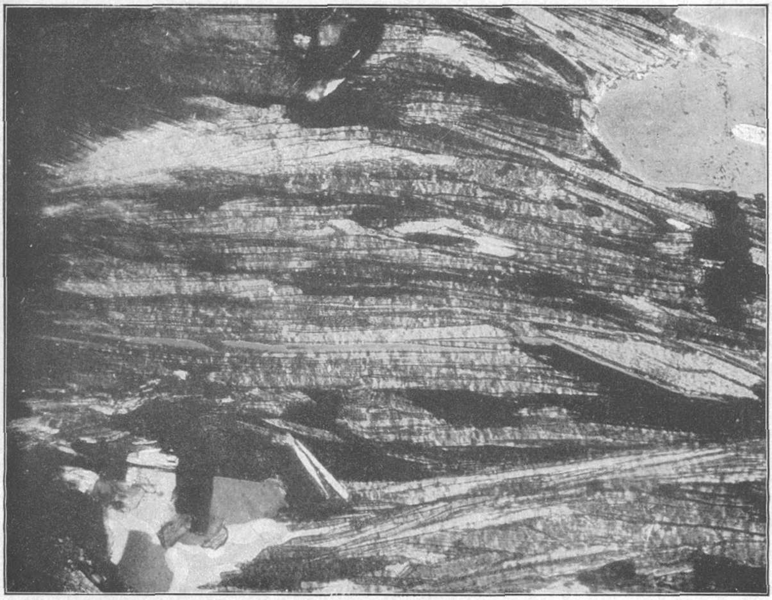
PLATE II.

PLATE II.

PHOTOMICROGRAPHS OF MICACEOUS SCHISTS.

A.—Photomicrograph of micaceous schist from Hoosac tunnel. Specimen No. 18062. With analyzer, x 96. The micas, which are entirely new developments by recrystallization, lie in flat plates with their greater diameters roughly parallel. Each individual exhibits several twinning lamellæ. It will be noted that, while there is apparently a bending and irregularity in the mica plates, the individuals are for the most part not deformed, and the impression of irregularity is caused by the individuals feathering out against one another at low angles. This sort of arrangement is frequently seen about rigid particles which have acted as units during deformation, indicating that the arrangement is due to differing stress conditions at different places. Where the harder minerals are not present it is believed that the feathering out of the mica plates results from changing conditions of stress at different times during the rock deformation, as well as changing conditions of stress at different places in the rock mass (pp. 113–114).

B.—Photomicrograph of micaceous schist. From Hoosac, Mass. Specimen H, 1061.2. With analyzer, x 40. In this rock the mica plates are new developments, but here they have undergone subsequent deformation and bending. The difference between this manner of deviation from parallelism and that shown in *A* is apparent.



A

B

MICACEOUS SCHISTS

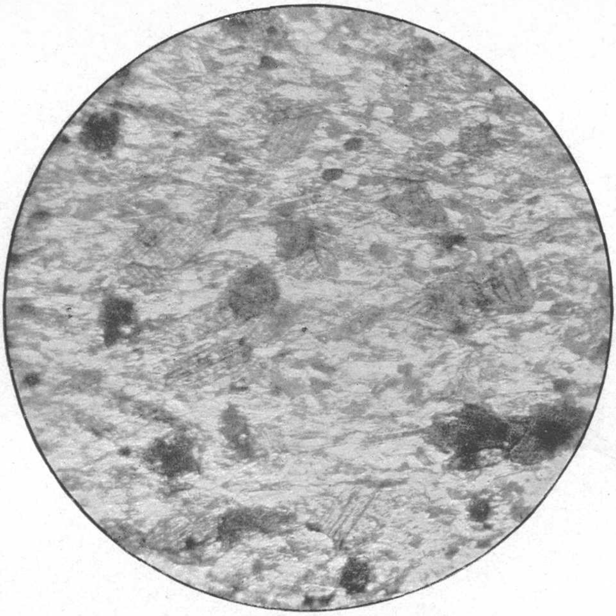
PLATE III.

PLATE III.

PHOTOMICROGRAPHS OF MICACEOUS SCHIST, SHOWING BIOTITE FLAKES LYING ACROSS THE SCHISTOSITY.

A.—Photomicrograph of a micaceous schist. From Gogebic district of Michigan. Specimen No. 14930. Without analyzer, x 40. Biotite crystals have developed in porphyritic fashion with their greater diameters or cleavage or both lying at various angles to the plane of rock cleavage. The biotites have the same occurrence as minerals such as garnet, chloritoid, tourmaline, etc., which have developed later than the deformation producing the flow cleavage.

B.—The same with analyzer.



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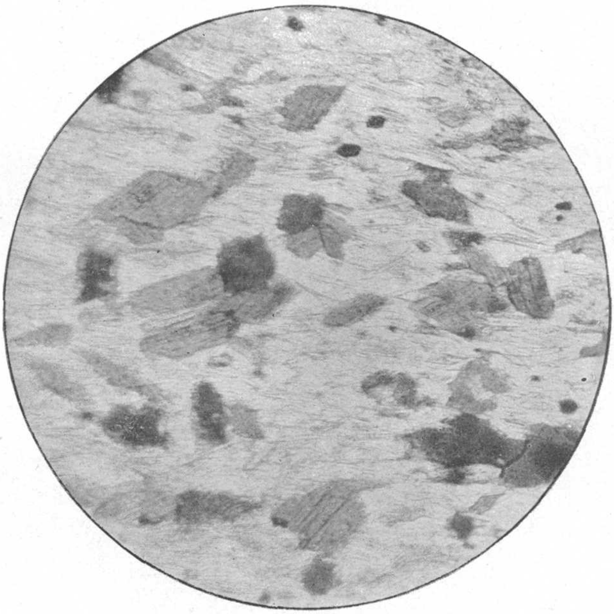


B

MICACEOUS SCHIST.

Showing biotite flakes lying acrcss the schistosity. *A*, Without analyzer; *B*, with analyzer.

PLATE IV.

PLATE IV.

SPECIMENS OF HORNBLENDIC SCHISTS, ILLUSTRATING PLANE-PARALLEL AND LINEAR-PARALLEL TYPES OF FLOW CLEAVAGE.

A.—Hornblendic schist with plane-parallel type of cleavage. From Mesabi district of Minnesota. Specimen No. 45379. The hornblende particles in this rock have a tridimensional parallelism, and the rock breaks easily parallel to the greatest and mean diameters, and less easily parallel to the greatest and least diameters.

B.—Hornblendic schist with linear-parallel type of cleavage. From Mesabi district of Minnesota. Specimen No. 40686. The longest diameters of the hornblende crystals lie parallel to one another, but their mean and least diameters are not mutually parallel. The rock accordingly cleaves in any plane parallel to the greatest diameters of the hornblende crystals.

A

B

HORNBLENDIC SCHISTS.

Illustrating plane-parallel and linear-parallel types of flow cleavage.

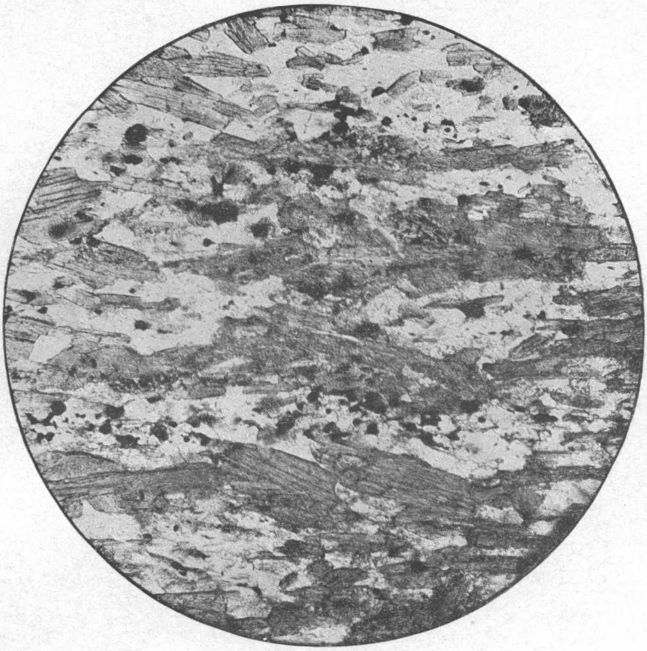
PLATE V.

PLATE V.

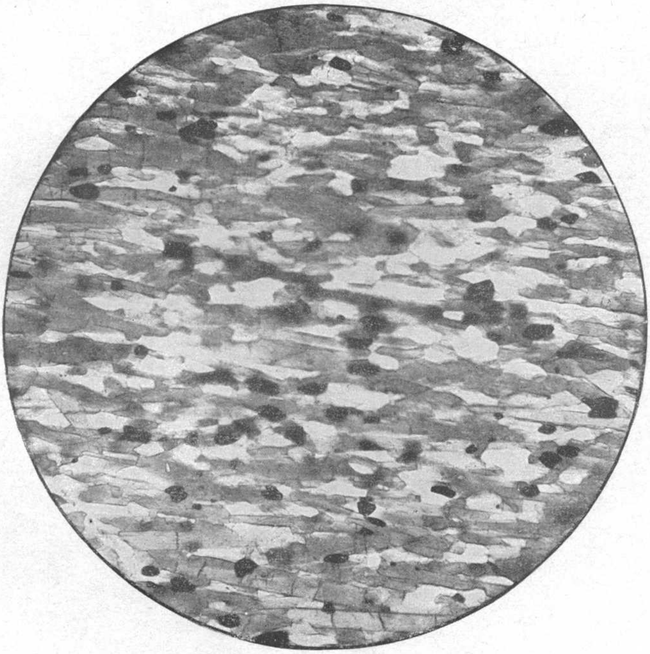
PHOTOMICROGRAPHS OF HORNBLENDIC SCHISTS, SHOWING ARRANGEMENT OF HORNBLENDE CRYSTALS PARALLEL TO COLUMNAR AXES.

A.—Photomicrograph of hornblendic schist from the Vermilion district of Minnesota. Specimen No. 28502. Without analyzer, x 75. While there are numerous minor irregularities, the general parallelism of the longer axes of the hornblende crystals is apparent.

B.—Photomicrograph of hornblendic schist from Menominee district, Michigan. Specimen No. 26148. Without analyzer, x 75. The parallelism of the green hornblende crystals is more marked than in fig. 1.



A



B

HORNBLENDIC SCHISTS.

Showing arrangement of hornblende crystals parallel to columnar axes.

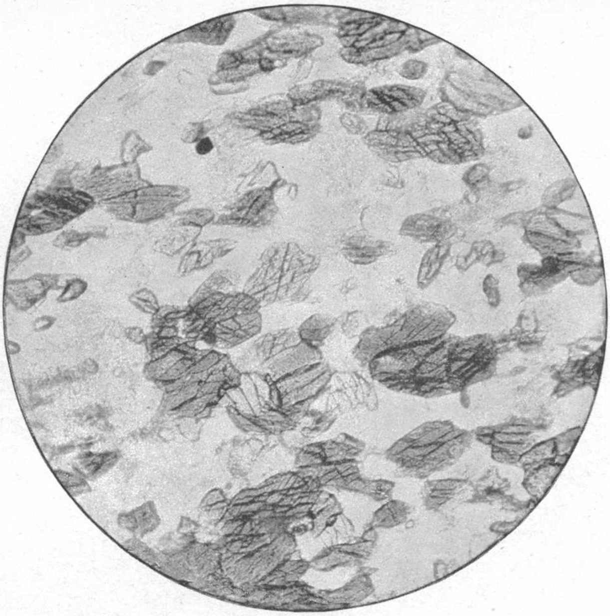
PLATE VI.

PLATE VI.

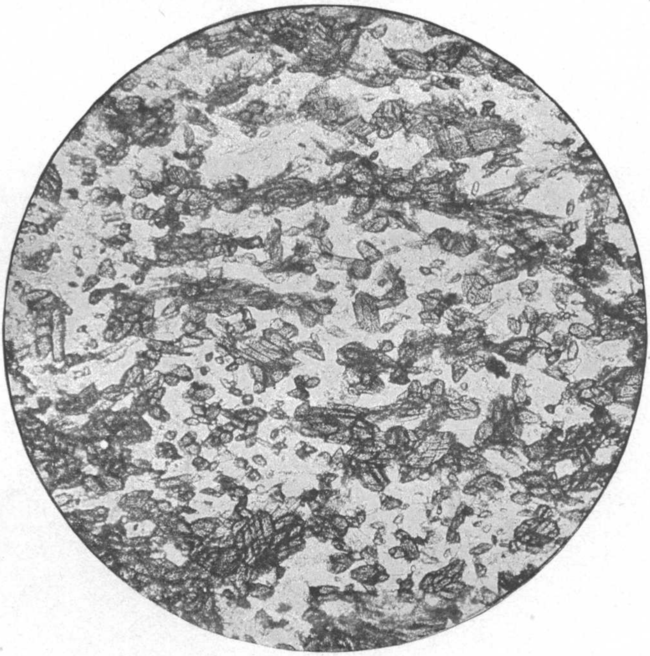
PHOTOMICROGRAPHS OF HORNBLENDIC SCHISTS, SHOWING THE ARRANGEMENT OF HORNBLENDE CLEAVAGE IN SLIDES CUT ACROSS THE SCHISTOSITY.

A.—Photomicrograph of hornblendic schist from Mesabi district of Minnesota. Specimen No. 45416. Without analyzer, x 75. The basal hornblende sections at first glance seem to have no orderly arrangement, but on examination it is seen that the acute angles of the prismatic cleavage have a slight tendency to parallelism:

B.—Photomicrograph of hornblendic schist from Vermilion district of Minnesota. Specimen No. 28501. Without analyzer, x 90. The acute angles of the prismatic cleavage of the hornblende have a faint tendency to lie in the same plane. This is scarcely apparent from the photomicrograph, but an examination of the slide itself leaves no doubt of its presence.



A



B

HORNBLENDIC SCHISTS.

Showing arrangement of hornblende cleavage in slides cut across the schistosity.

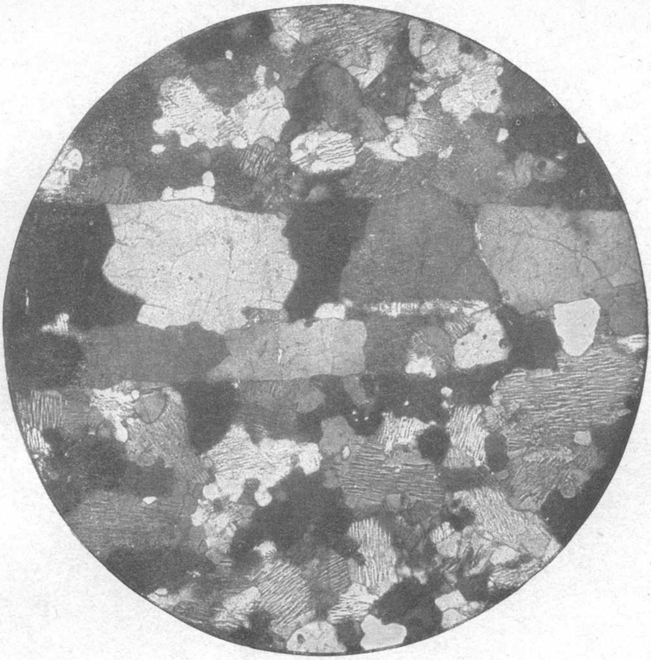
PLATE VII

PLATE VII.

PHOTOMICROGRAPHS OF LEAF GNEISS.

A.—Photomicrograph of leaf gneiss from the Laurentian area north of Montreal. Slides furnished by Frank D. Adams. With analyzer, x 60. Doctor Adams has described the leaf gneiss as resulting from granulation of a hornblende granite, all stages of the process having been noted. (See Part J of Vol. VIII of the Geological Survey of Canada, 1895.) The striated feldspars have irregular angular shapes such as characteristically result from granulation. The two bands of quartz crossing the slide evidently owe their form and arrangement finally to recrystallization, although granulation may have been an important initial process. The evidence for recrystallization is stated on pages 82–87. It will be noted that the quartz individuals have dimensional, but not crystallographic parallelism.

B.—The same; another view.



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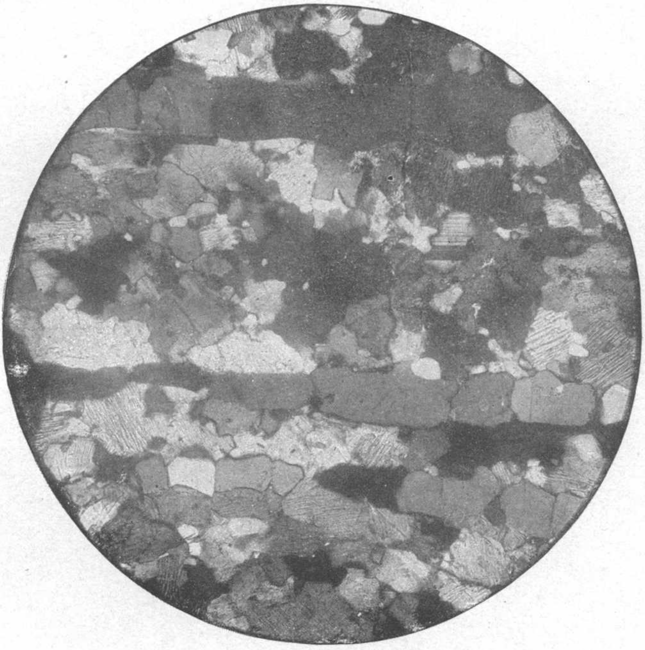


B

LEAF GNEISS.

Two views of the same specimen. After Adams.

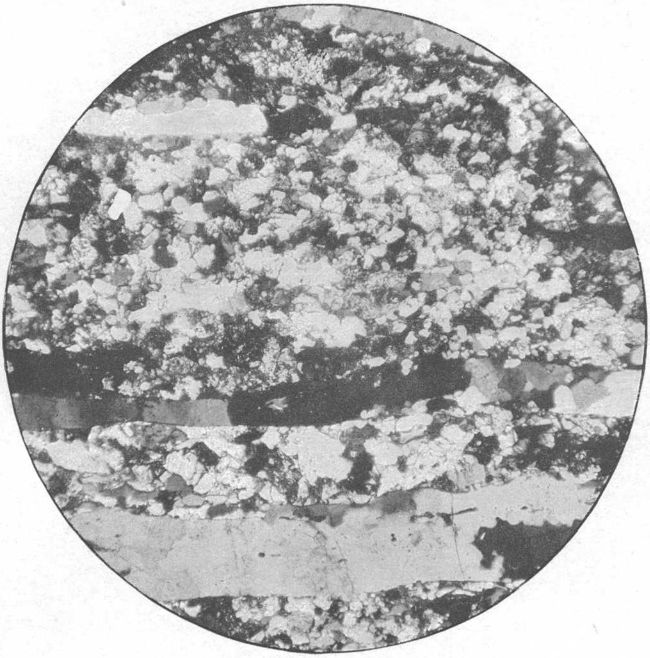
PLATE VIII.

PLATE VIII.

PHOTOMICROGRAPHS OF MICACEOUS AND QUARTZOSE SCHIST.

A.—Photomicrograph of micaceous and quartzose schist from near Westport, N. Y. Specimen No. 18259. With analyzer, x 25. The background is composed of quartz and feldspar, with a considerable amount of chlorite, magnetite, and other accessory minerals. The quartz and feldspar have irregular angular forms such as ordinarily result from granulation. They are similar in their form to the granulated feldspar particles shown in Pl. VII. The bands crossing the slide are quartz and have the same characters as the quartz bands shown in Pl. VII. Granulation probably has aided in the development of the quartz bands, but their final configuration is probably due to recrystallization. It will be noted that the quartz has dimensional but not crystallographic parallelism.

B.—The same without analyzer.



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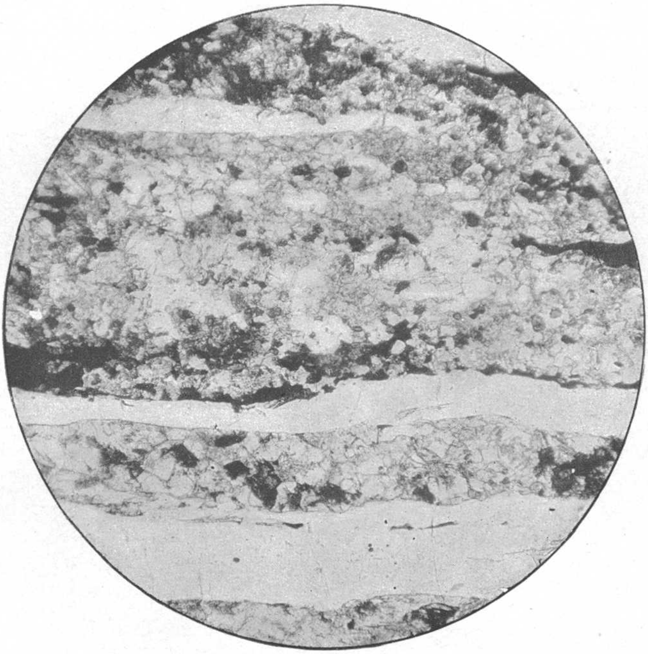


B

MICACEOUS AND QUARTZOSE SCHIST.

A, With analyzer; *B*, without analyzer.

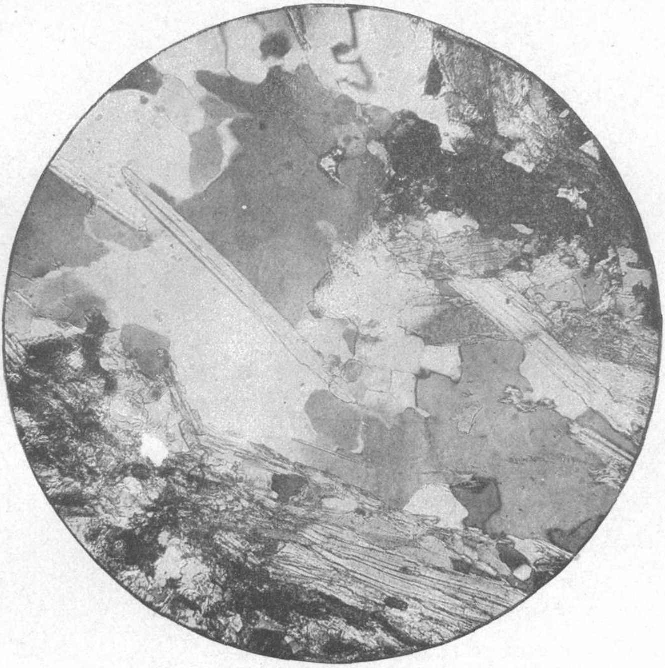
PLATE IX.

PLATE IX.

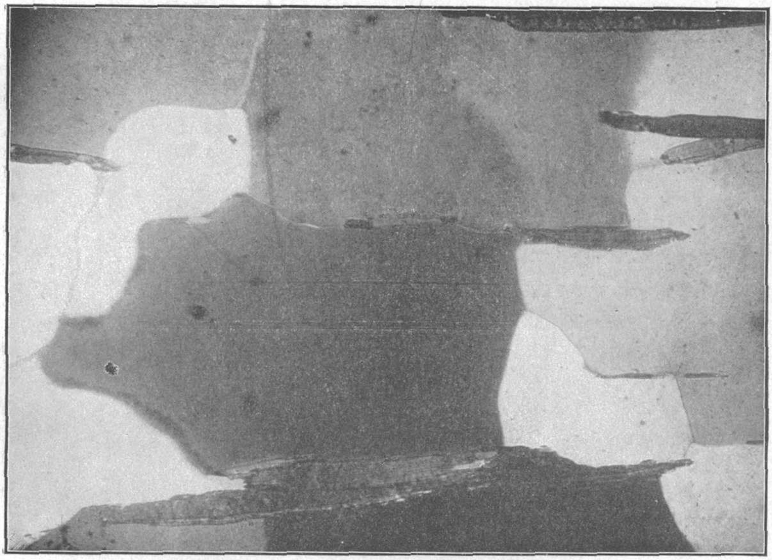
PHOTOMICROGRAPHS OF MICACEOUS AND QUARTZOSE SCHIST.

A.—Photomicrograph of micaceous and quartzose schist from Hoosac, Mass. Specimen H. 1061.3. With analyzer, x 60. The mica is clearly secondary and a result of recrystallization. The quartz is in clear limpid grains with their longer diameters nearly in a common direction. The grains are closely fitting, in bands, and strain effects are lacking, and these facts, together with the association with recrystallized mica, go to show that the quartz has itself been recrystallized. It will be noted that the quartz has no crystallographic parallelism.

B.—The same, with higher power, x 110. The view illustrates in detail the relation of recrystallized quartz grains to recrystallized mica flakes. The mica flakes for the most part separate different quartz individuals, but they may be seen to bound two or more individuals and to project well into them. It is not probable that such a relation could be brought about by granulation, slicing, or gliding, and it seems best explained by recrystallization.



A



B

MICACEOUS AND QUARTZOSE SCHIST.

Same specimen with different powers of analyzer.

PLATE X.

PLATE X.

PHOTOMICROGRAPHS OF MICACEOUS AND QUARTZOSE SCHIST.

A.—Photomicrograph of micaceous and quartzose schist from Hoosac Tunnel. Specimen No. 18062. With analyzer, x 40. The mica is clearly a secondary development by recrystallization, and the quartz in the clear bands has been as certainly recrystallized, as shown by criteria discussed on pages 82–87.

B.—The same, without analyzer; another view.

A

B

MICACEOUS AND QUARTZOSE SCHIST.

A, With analyzer; *B*, without analyzer.

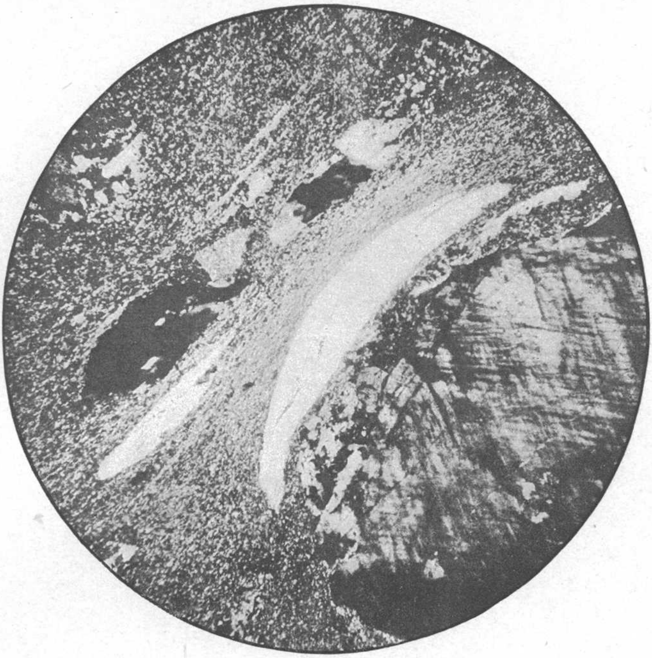
PLATE XI.

PLATE XI.

PHOTOMICROGRAPHS ILLUSTRATING RECRYSTALLIZATION OF QUARTZ AND SLICING OF FELDSPAR.

A.—Photomicrograph of recrystallized quartz from Thüringer Wald. After Futterer (fig. 1, Pl. II, of Ganggranite von Grosssachsen und die Quartzporphyre von Thal in Thüringer Wald: Mitt. Grossh. Badischen geol. Landesanstalt, vol. 2, Heidelberg, 1890). The white area represents recrystallized quartz drawn out about the periphery of a feldspar phenocryst, which has remained unaffected by recrystallization.

B.—Photomicrograph of schistose quartz-porphyry showing sliced feldspar phenocryst in planes inclined to the prevailing cleavage. After Futterer (ibid., fig. 2, Pl. III.).



A. RECRYSTALLIZED QUARTZ.

After Futterer.

B. SLICED FELDSPAR.

After Futterer.

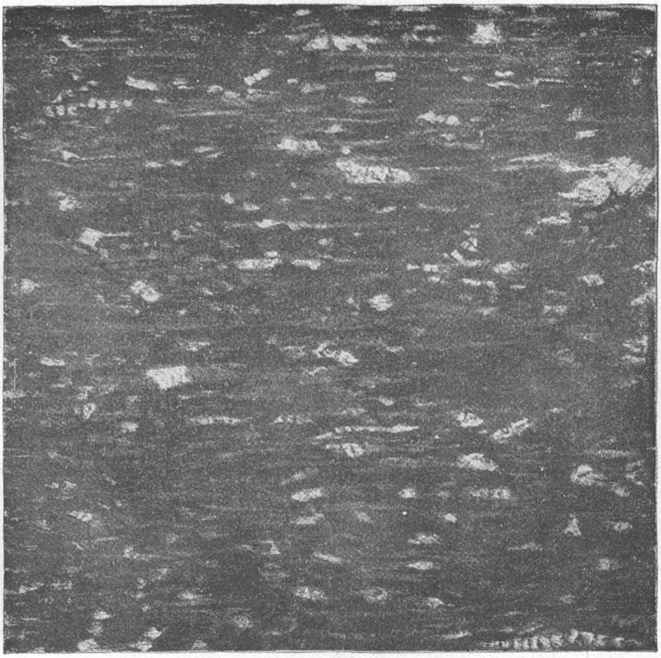
PLATE XII.

PLATE XII.

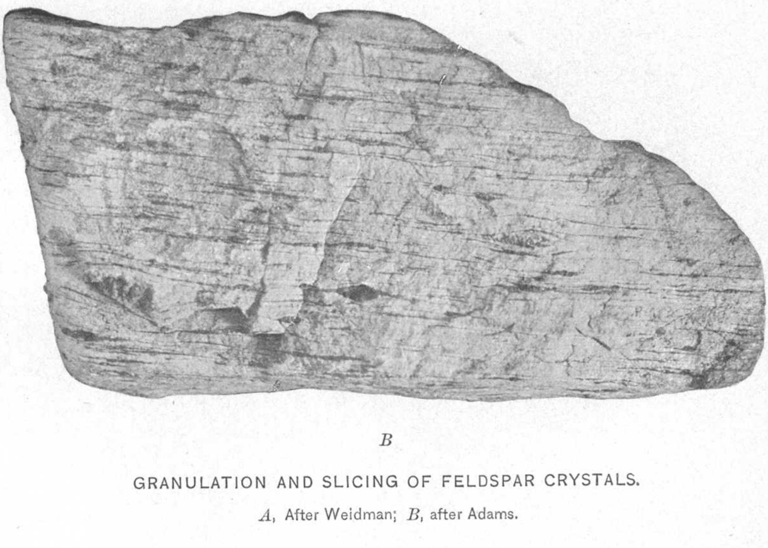
SPECIMENS ILLUSTRATING GRANULATION AND SLICING OF FELDSPAR CRYSTALS.

A.—Rhyolite-gneiss from Berlin, Wis. After Weidman (Pl. V of Bull. III, Wis. Geol. and Nat. Hist. Survey, 1898). The feldspar crystals have been crushed and strewn out by granulation and slicing. Minute granules may be seen in various stages of separation from the feldspars, and the larger feldspars may be seen in stages of breaking into slices with their longer diameters inclined to the prevalent cleavage of the rock mass.

B.—Schistose anorthosite from north of Montreal. After Adams (described in Part J of Vol. VIII, Geol. Survey of Canada, 1895). The feldspars and pyroxenes have been granulated and sliced and strewn out in the plane of rock cleavage. The granulation along the sides has left the residual feldspar particles in irregular lens-shaped individuals with their longer diameters parallel to the rock cleavage. Occasionally they are sliced by parallel fractures inclined to the plane of rock cleavage.



A



B

GRANULATION AND SLICING OF FELDSPAR CRYSTALS.

A, After Weidman; *B*, after Adams.

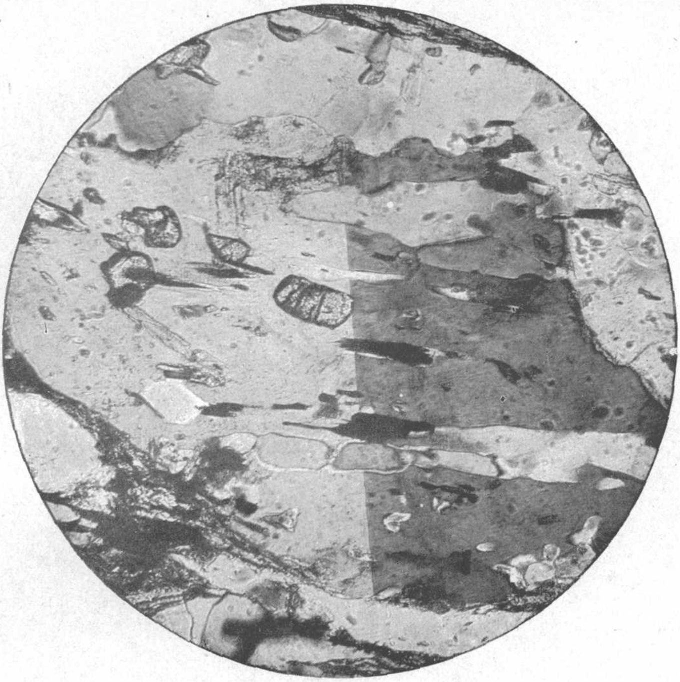
PLATE XIII.

PLATE XIII.

PHOTOMICROGRAPHS OF PORPHYRITIC CONSTITUENTS DEVELOPED AFTER ROCK FLOWAGE HAS CEASED.

A.—Photomicrograph of albite crystal in micaceous and quartzose schist, from Hoosac Tunnel. Specimen 18062. With analyzer, x 67. The field is occupied mainly by one large twinned albite. The numerous inclusions of quartz, mica, and other minerals to be observed in the feldspar have their longer diameters roughly parallel one to the other and to the prevailing cleavage in the rock mass. The albite crystal is supposed to have developed by recrystallization after rock flowage has ceased, using all the constituents necessary for its own growth and leaving the superfluous constituents as inclusions with their orderly arrangement unaffected.

B.—Photomicrograph of chloritoid crystal in micaceous and quartzose schist, from Black Hills. Specimen 14928. With analyzer, x 110. The chloritoid crystal here shown has developed later than the rock flowage producing the prevailing cleavage of the rock. The chloritoid has grown at the expense of the other constituents of the rock, using all the material necessary for its growth and leaving the excess of material in the form of inclusions, which retain their dimensional parallelism with the prevailing rock cleavage.



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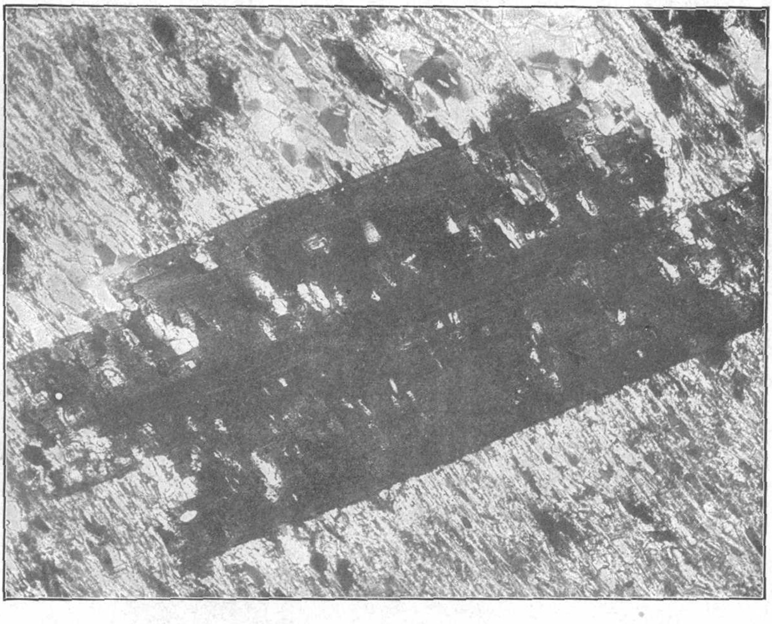


B

PORPHYRITIC CONSTITUENTS DEVELOPED AFTER ROCK FLOWAGE HAS CEASED.

A, Albite crystal; *B*, chloritoid crystal.

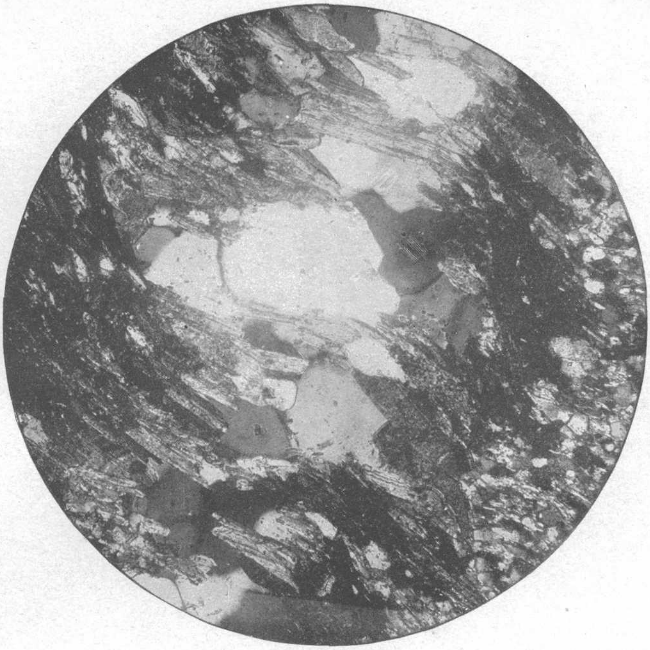
PLATE XIV.

PLATE XIV.

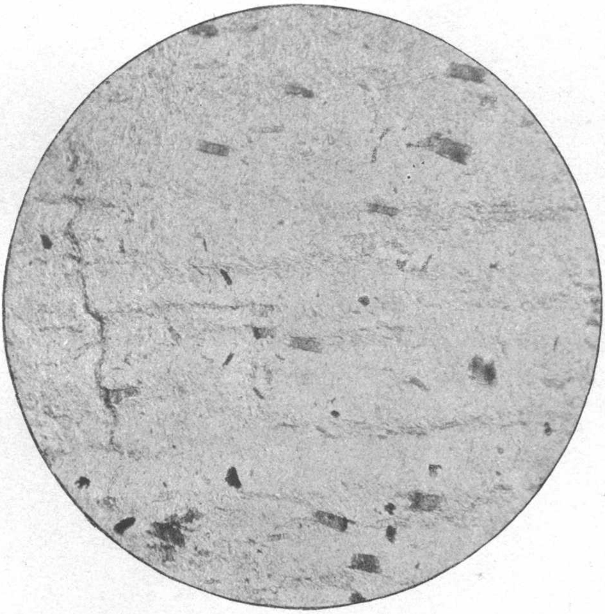
PHOTOMICROGRAPH OF MICACEOUS AND QUARTZOSE SCHIST WITH CLEAVAGE ACROSS BEDDING, AND PHOTOMICROGRAPH OF SLATE WITH FALSE CLEAVAGE.

A.—Photomicrograph of micaceous and quartzose schist with cleavage developed across original bedding, from Little Falls, Minn. Specimen 14745. With analyzer, x 60. A graywacke-slate, in which the banding has been marked by difference in texture as well as in composition, has been subjected to deformation, with the result that a cleavage has been superposed upon the original bedding at right angles to it. Originally the longer diameters of the particles of the bedded rock were parallel to the bedding. Accompanying the development of flow cleavage most of the constituents of the rock have been recrystallized. The quartz particles shown in the light band have been drawn out with their longer diameters nearly at right angles to the former plane of their longer diameters, and abundant new mica has developed with its greater diameters and mineral cleavage normal to the plane of bedding.

B.—Photomicrograph of slate with "false" cleavage, from Black Hills of South Dakota. Specimen 14974. Without analyzer, x 60. The longer diameters of the particles, mainly mica, quartz, and feldspar, lie, for the most part, in a plane intersecting the plane of the page and parallel to its longer sides, but in well-separated planes at right angles to this plane the longer diameters of the particles have been deflected into minute monoclinal folds represented by the darker cross lines. In these cross planes also porphyritic biotites have developed with their longer diameters parallel. The rock has two cleavages, one conditioned by the prevailing dimensional arrangement of the minute particles and the other conditioned by the planes of weakness along the axes of the minute monoclinal folds crossing the prevailing cleavage. The first cleavage is flow cleavage developed in normal fashion during rock flowage, and the second is of the nature of fracture cleavage developed later along separated shearing planes in the zone of fracture or in the zone of combined fracture and flowage. The rock cleaves into parallelopiped blocks.



A. MICACEOUS AND QUARTZOSE SCHIST WITH CLEAVAGE ACROSS BEDDING.



B. SLATE WITH FALSE CLEAVAGE.

PLATE XV.

PLATE XV.

PHOTOMICROGRAPHS OF ARTIFICIALLY DEFORMED MARBLE (AFTER ADAMS).

A.—Photomicrograph of Laurentian marble which has undergone granulation. After Adams and Nicolson (fig. 3, Pl. XXV, of vol. 195, Philos. Trans. Royal Soc. of London). With analyzer, x 47. Large crystals of calcite have been minutely granulated along their peripheries and the crystals themselves have been twisted and twinned as shown by their minute reedy striations.

B.—Photomicrograph of Carrara marble deformed artificially. After F. D. Adams and J. T. Nicolson (ibid., fig. 4 of Pl. XXIV). With analyzer, x 150. The marble was confined on all sides, was subjected to high temperature, and deformed by a piston. The rock flowed without losing its integrity. The flow took place by the processes of granulation and gliding. The calcite individuals changed their shape and were distinctly elongated without conspicuous fracture, but developed a reedy or fibrous structure, indicating their elongation by gliding along crystallographic planes.

A

B

ARTIFICIALLY DEFORMED MARBLE.

After Adams and Nicolson.

PLATE XVI.

PLATE XVI.

SCHISTOSE MARBLE.

Photograph of schistose marble from Talledega Mountain, Georgia. Specimen 25874. The rock is made up of minute granules of calcite showing dimensional parallelism, as illustrated by fig. 19, p. 41. There is no parallelism of the crystallographic properties of the calcite particles. The parting is determined by the plane of the greatest and mean axes of the parallel arranged granules.

SCHISTOSE MARBLE.

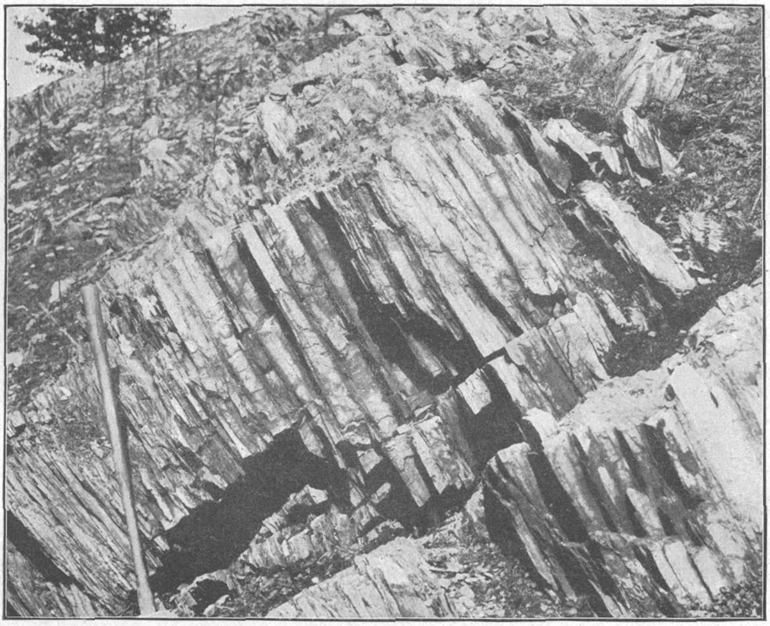
PLATE XVII.

PLATE XVII.

CLEAVAGE BANDS IN ORDOVICIAN SLATES AND PARALLEL QUARTZ VEINS IN CAMBRIAN SLATE.

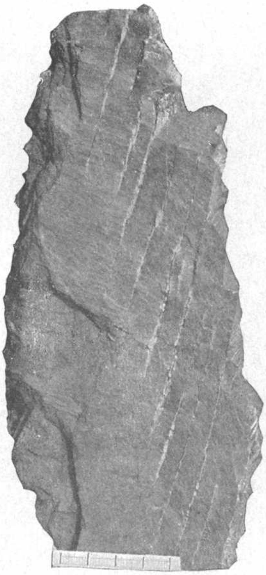
A.—Cleavage bands in Ordovician slate, from Rupert, Vt. After Dale (fig. B of Pl. XXX, of pt. 3 of the Nineteenth Ann. Rept. U. S. Geol. Survey). The material of this rock was originally nearly homogeneous, and the original bedding crosses the cleavage bands. The softer bands which have been eroded out are described by Dale as zones along which slip cleavage (here called fracture cleavage) has developed. The characteristic occurrence of the slip or fracture cleavage in well separated planes is to be noted.

B.—Parallel quartz veins in Cambrian slate, from Hampton, N. Y. After Dale (fig. A, of Pl. XXXII, of pt. 3 of the Nineteenth Ann. Rept. U. S. Geol. Survey). The veins represent planes of parting along the flow cleavage which by their cementation have yielded what is here called fracture cleavage.



A. CLEAVAGE BANDS IN ORDOVICIAN SLATES.

After Dale.



B. PARALLEL QUARTZ VEINS IN CAMBRIAN SLATE.

After Dale.

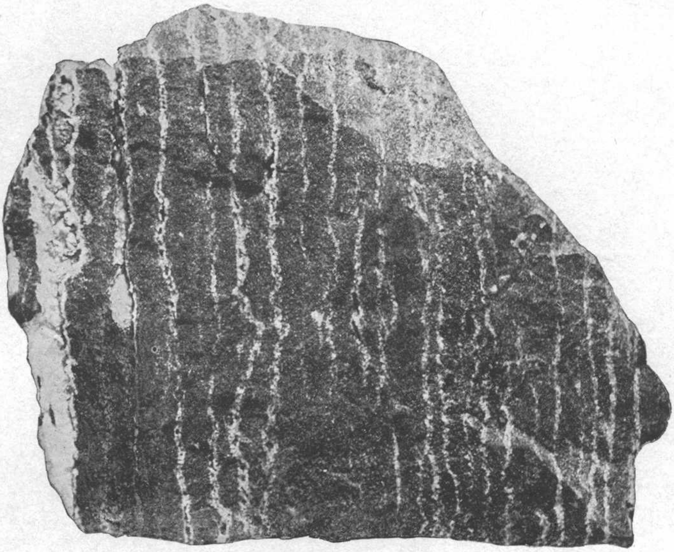
PLATE XVIII.

PLATE XVIII.

SPECIMENS ILLUSTRATING FRACTURE CLEAVAGE.

A.—Fracture cleavage developed by the cementation of fissility openings. From Great Basin, furnished by G. K. Gilbert. Specimen No. 42633. The rock has been separated into a series of parallel slices and has been subsequently cemented by the infiltration of calcite. The rock now has a capacity to part, or fracture cleavage, parallel to the calcite veins.

B.—Fracture cleavage in schistose marble. Southern Appalachians. Specimen No. S. 2. Each of the bends is made up of one or few calcite individuals with dimensional but not crystallographic parallelism. It will be noted that the individual bends commonly narrow and feather out. The intervening dark material is chlorite and mica, developed along planes of slipping. The closeness of the planes of parting is rather exceptional. It is to be noted, however, that they are definite in number and separated by zones of distinctly noncleavable material.



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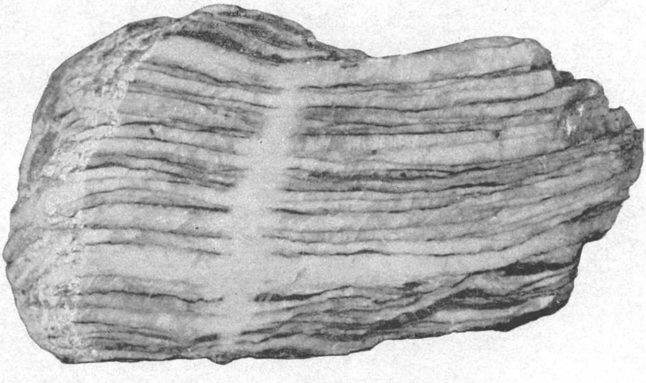


B

ILLUSTRATIONS OF FRACTURE CLEAVAGE.

PLATE XIX.

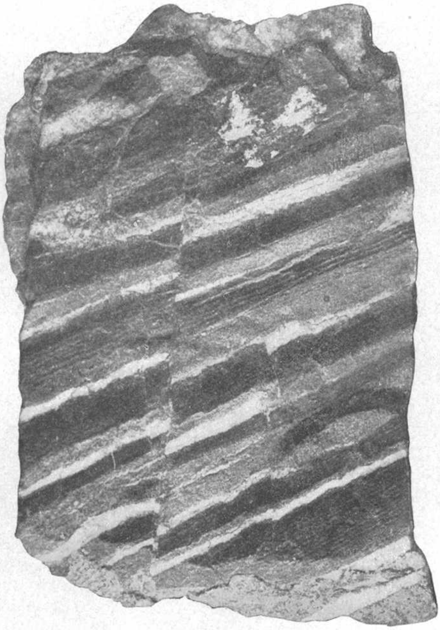
PLATE XIX.

SPECIMENS ILLUSTRATING FRACTURE CLEAVAGE.

A.—Fracture cleavage developed by the cementation of fissility openings. From the Vermilion district of Minnesota. Specimen No. S. 14. This is from an Archean jasper formation which has been much broken by fracturing. The closely-spaced parallel fractures in three sets have been cemented by the infiltration of quartz and now remain as potential planes of parting.

B.—Fracture cleavage developed by the cementation of fissility openings. From the Vermilion district of Minnesota. Specimen No. S. 9. Fracturing has occurred along one set of planes, followed by the infiltration of quartz. The rock has then been fractured and faulted again in planes crossing the first formed fractures and these fractures in turn cemented.

A



B

ILLUSTRATIONS OF FRACTURE CLEAVAGE.

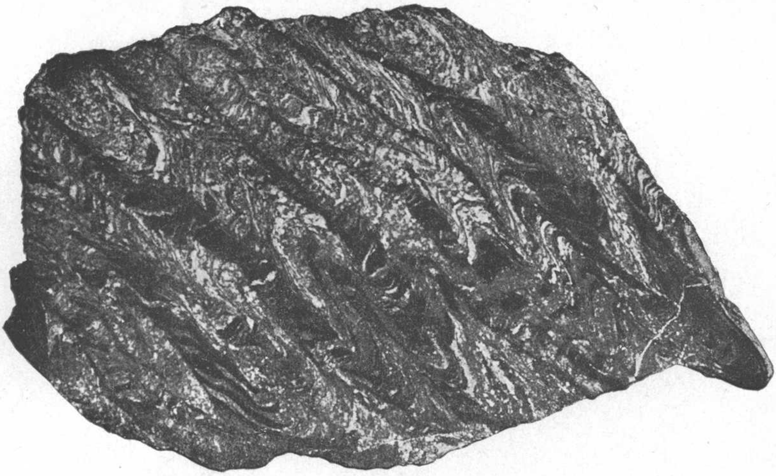
PLATE XX.

PLATE XX.

SPECIMENS ILLUSTRATING FRACTURE CLEAVAGE.

A.—Fault-slip cleavage in gneiss from southern Appalachians. Specimen No. 25602. The gneiss has been closely crenulated and the minute folds may be observed to pass into minute faults which now represent planes of fracture cleavage. The faults may have been cemented or may have been welded by actual pressure. Parallel to the faults there has also been developed a parallel arrangement of the mineral particles, perhaps due in part to the slipping along the fault planes, and it is exceedingly difficult to distinguish between the fracture cleavage and the flow cleavage.

B.—Schist from Taconic Range, showing minor folding grading into fault-slip cleavage. After Dale (Pl. XIV, *B*, Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3).



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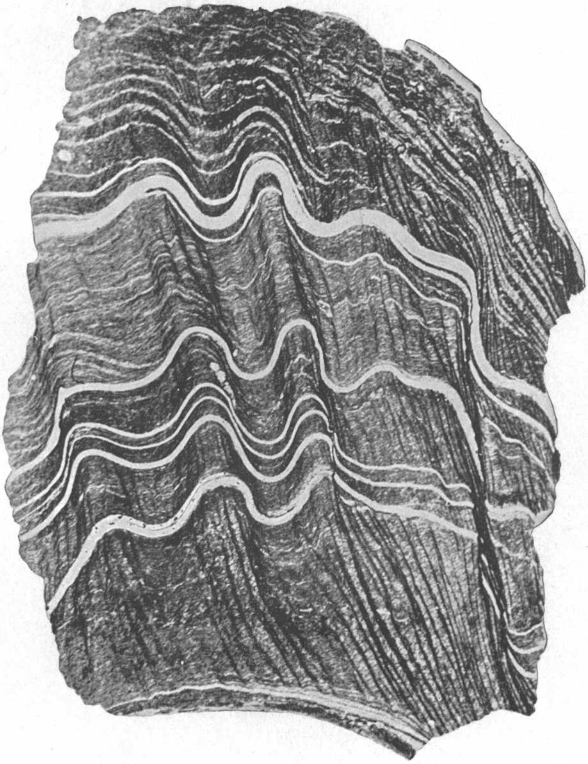


B

ILLUSTRATIONS OF FRACTURE CLEAVAGE.

After Dale.

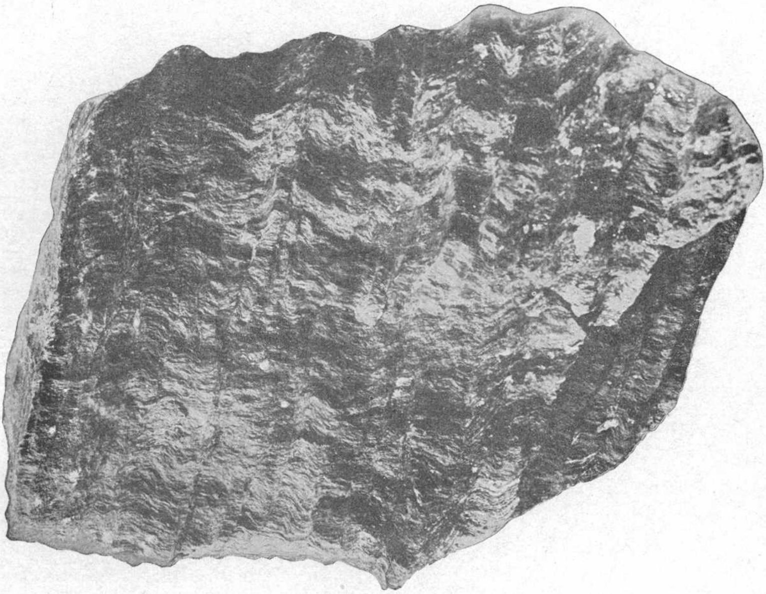
PLATE XXI.

PLATE XXI.

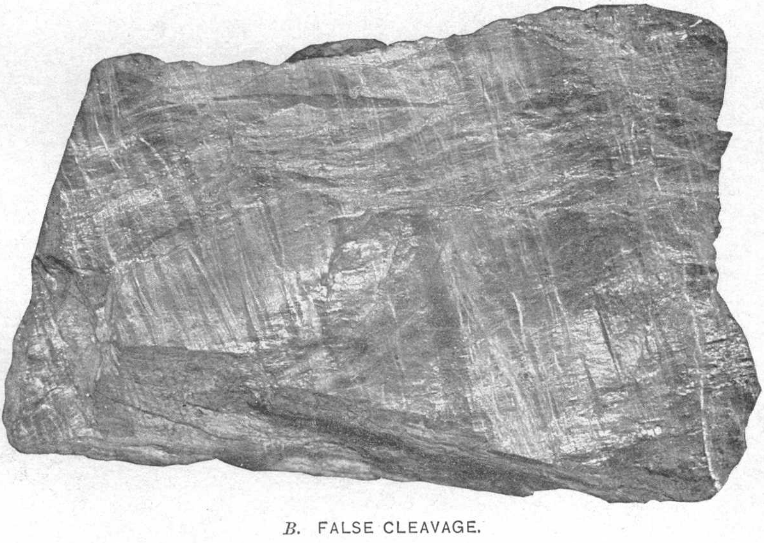
SPECIMENS ILLUSTRATING FRACTURE CLEAVAGE.

A.—Fault-slip cleavage developed in schist. From Marquette district of Michigan. Specimen No. 42617. The schist has been closely crenulated and minute folds may be seen to pass into faults. The rock cleaves parallel to the prevailing schistosity, marked by the longer diameters of the particles; it also cleaves parallel to the limbs of the minute crenulations and parallel to the faults. So far as the cleavage is parallel to the faults, it may be said to be fracture cleavage; so far as it is parallel to the longer diameters of the particles on the longer limbs of the minute folds parallel to the faults, it may be said to be flow cleavage, conditioned by minor bends in the prevalent parallel arrangement of the mineral particles. The rock then shows a fracture cleavage grading into a "false" cleavage along minute folds, both superposed upon an earlier cleavage marked by the prevalent schistosity of the rock mass (pp. 132–133).

B.—"Micaceous hematite." From the Lake Superior region. Specimen No. 25730. Parallel hematite flakes give the prevailing cleavage to the rock. Minute crenulations in this parallel arrangement afford planes of weakness which favor cross breaking. The term false cleavage has been applied to such a cross structure (pp. 25–26, 132–133).



A. FAULT-SLIP CLEAVAGE.



B. FALSE CLEAVAGE.

PLATE XXII.

PLATE XXII.

SPECIMEN SHOWING BOTH FLOW CLEAVAGE AND FRACTURE CLEAVAGE IN THE SAME BLOCK.

Slate from Somerville, Mass. The flat upper surface represents a plane of parting along flow cleavage parallel to the longer diameters of the constituent particles, and the ends and sides of the block represent parting along fracture cleavage independent of any parallel arrangement in the block. The block will cleave into smaller blocks of similar shapes.

FLOW CLEAVAGE AND FRACTURE CLEAVAGE IN THE SAME BLOCK.

PLATE XXIII.

PLATE XXIII.

SPECIMEN SHOWING BOTH FLOW CLEAVAGE AND FRACTURE CLEAVAGE IN THE SAME BLOCK.

Block of green schist showing both flow cleavage and fracture cleavage. From Menominee district of Michigan. Specimen No. 25664. The flat upper surface (the plane of the page) represents a plane of parting along flow cleavage parallel to the longer diameters of the constituent particles, and the ends and sides of the block represent parting along fracture cleavage independent of any parallel arrangement in the block. The block will cleave into smaller blocks of similar shapes.

FLOW CLEAVAGE AND FRACTURE CLEAVAGE IN THE SAME BLOCK.

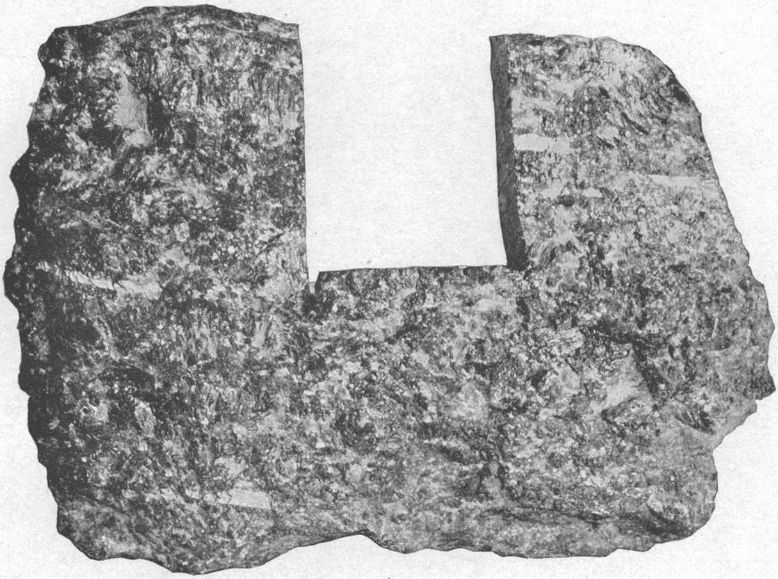
PLATE XXIV.

PLATE XXIV.

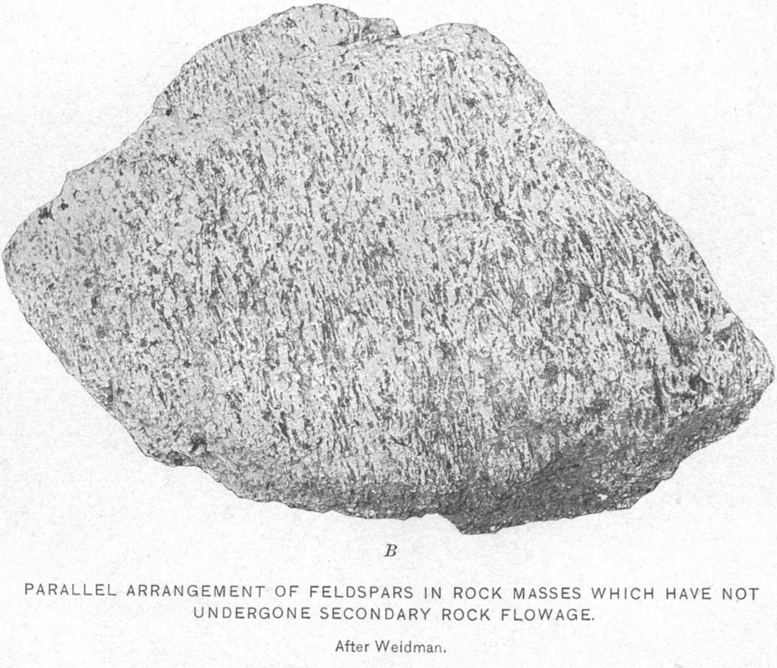
SPECIMENS ILLUSTRATING PARALLEL ARRANGEMENT OF FELDSPARS IN ROCK MASSES WHICH HAVE NOT UNDERGONE SECONDARY ROCK FLOWAGE.

A.—Gabbro from Westport, N. Y. Specimen No. 18242. The feldspars have tabular development parallel to the brachypinacoid, and lie in the rock not only with their tabular brachypinacoidal faces parallel, but with their basal cleavage faces parallel, as shown by the reflections of the basal cleavage faces. The feldspars are for the most part twinned parallel to the brachypinacoid, and the twinning plane thus bisects the basal cleavage plane parallel to its longest axis.

B.—Nepheline-syenite from central Wisconsin. After Weidman. (Bull. Wis. Geol. and Nat. Hist. Survey, in preparation.) The light colored protruding ridges represent feldspar crystals with an arrangement almost identical with that described for *A*.



A



B

PARALLEL ARRANGEMENT OF FELDSPARS IN ROCK MASSES WHICH HAVE NOT UNDERGONE SECONDARY ROCK FLOWAGE.

After Weidman.

PLATE XXV.

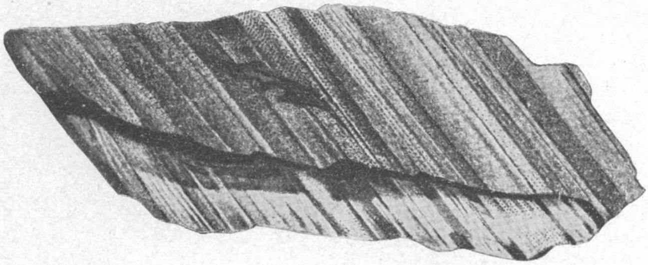
PLATE XXV.

CHEMICAL SEDIMENTS WITH CLEAVAGE.

A.—Cherty iron carbonate showing bedding. From Marquette district, Michigan. After Van Hise. (Fig. 2, Mon. U. S. Geol. Survey, vol. 28.) The iron carbonates show a very fine bedding, parallel to which there is a capacity to cleave.

B.—Ferruginous chert resulting from the alteration of iron carbonate with bedding much emphasized by the alteration. From Marquette district, Michigan. After Van Hise. (Fig. 1 of Pl. XX, Mon. U. S. Geol. Survey, vol. 28.) The alteration of the iron carbonates of the Lake Superior region characteristically produces ferruginous cherts and jaspilites in which the constituents are segregated into bands, strongly marking and emphasizing the original bedding. The banding gives a capacity to part along parallel planes, which is truly a cleavage.

C.—Cherty limestone with bedding marked by minute bands of chert. From north shore of Lake Huron. The segregation of the chert in bands is believed to be largely secondary. The rock possesses a capacity to part parallel to the bands, although the tendency is but a slight one. The fold passing into a fault illustrated in the photograph is a result of later deformation.



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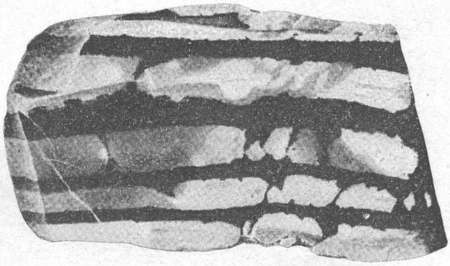


B

C

CHEMICAL SEDIMENTS WITH CLEAVAGE.

A and *B*, After Van Hise.

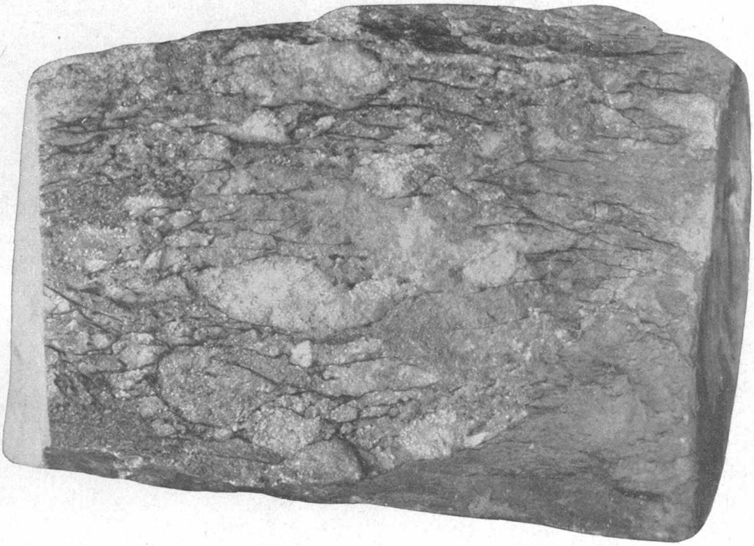
PLATE XXVI.

PLATE XXVI.

SPECIMEN SHOWING ELONGATION OF PEBBLES IN THE PLANE OF ROCK CLEAVAGE.

A.—Schist-conglomerate. From Black Hills, South Dakota. Specimen No. 14818. The longer diameters of the quartzite pebbles may be seen to lie parallel. This is due to the compression which the rock has undergone.

B.—Same, on opposite side of specimen. This side of the specimen has been compressed so closely and the pebbles so extremely elongated that they are almost indistinguishable. The parallelism of the cleavage with the longer diameters is marked. The rock cleavage follows not only the longer diameters of the elongated pebbles, but occurs within the pebbles themselves parallel to the elongated diameters.



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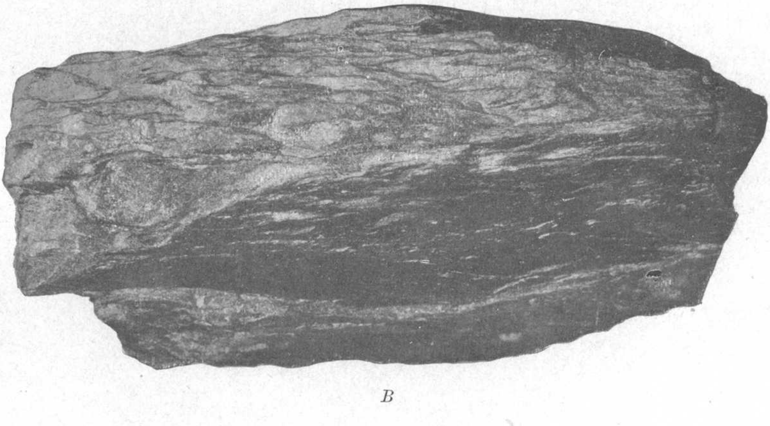


B

ELONGATION OF PEBBLES IN PLANE OF ROCK CLEAVAGE.

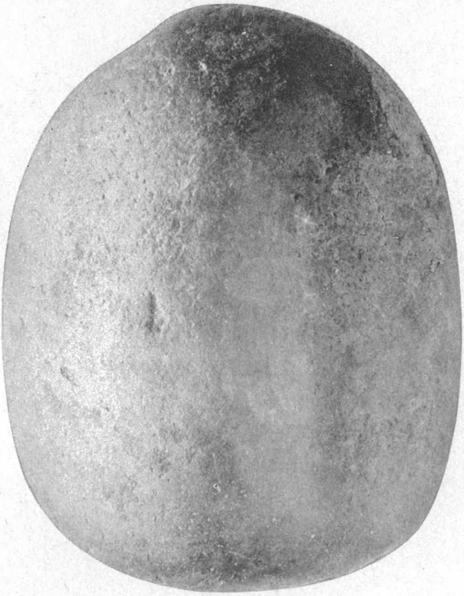
PLATE XXVII.

PLATE XXVII.

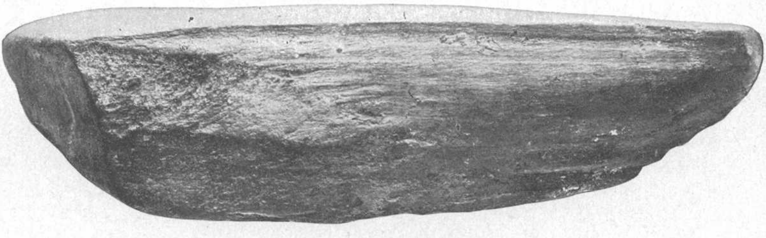
SPECIMENS SHOWING UNDISTORTED PEBBLE AND PEBBLES ELONGATED IN THE PLANE OF ROCK CLEAVAGE.

A.—Greenstone pebble, undistorted, from pre-Cambrian conglomerate. Pine River, Wisconsin. Specimen No. 45810.

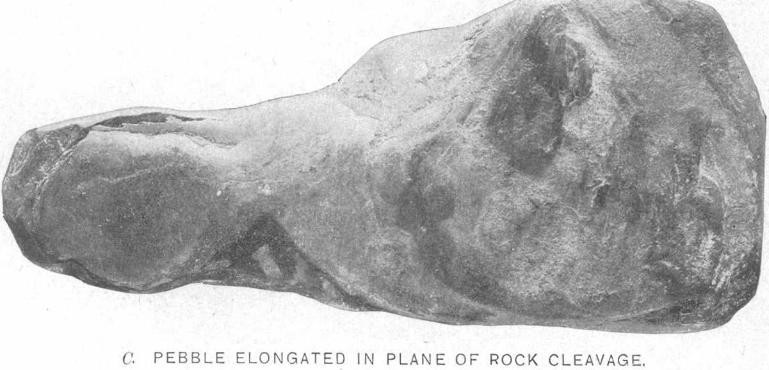
B, C.—Distorted pebbles, from pre-Cambrian conglomerate. Pine River, Wisconsin. Specimen No. 45810. The flattening of the pebbles was accompanied by development of an excellent cleavage in the matrix parallel to the longer diameters of the pebbles. The weathering out of this matrix has made it possible to recover the elongated pebble in this condition. The pebbles themselves have their mineral constituents elongated in the same directions, and the pebbles, as well as the matrix, cleave readily parallel to their longer dimensions. There is no possibility that the cleavage of the pebbles was present before the conglomerate was deformed, for in this case the cleavage of all the pebbles would not be so strictly parallel to each other and to the cleavage of the matrix. In *B* the flatness and cleavage of the specimen are normal to the plane of the page. In *C* the flatness and cleavage are parallel to the plane of the page.



A. UNDISTORTED PEBBLE.



B. PEBBLE ELONGATED IN PLANE OF ROCK CLEAVAGE.



C. PEBBLE ELONGATED IN PLANE OF ROCK CLEAVAGE.

INDEX.

O