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# STRUCTURAL ANALYSIS OF METAMORPHIC TECTONITES

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## CHAPTER 1

# SCOPE OF STRUCTURAL ANALYSIS

### HISTORICAL BACKGROUND

For over a century geologists have mapped and recorded the more conspicuous structural features of naturally deformed rocks and discussed their possible dynamic significance. Attention has been focused especially on planar structures—variously termed *schistosity*, *cleavage*, or *foliation*—and on the obvious tendency for certain minerals of foliated rocks, such as micas and amphiboles, to show some degree of parallel alignment—in modern terminology a state of preferred orientation. Schistosity has been attributed by some writers[1] to the influence of a perpendicular compressive stress, by others[2] to shear on the schistosity surfaces. Geologists of the Wisconsin school[3] have identified "flow cleavage" with the plane of maximum strain in the deformed body. There has been a good deal of speculation as to the relative roles of such processes as recrystallization under pressure,[4] or rotation of tabular bodies in a plastically strained matrix[5] in the evolution of preferred orientation of micas and amphiboles in schistose rocks. During the decades spanning the turn of the century there was little unanimity of opinion and some controversy on such matters. But it had become clear that many metamorphic terranes are characterized by great regularity in orientation of foliation and linear structures. Some corresponding regularity in the deforming process was implied. Moreover widespread simple geometric relationships came to be recognized between foliation (cleavage) and bedding in foliated and folded rocks. These

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[1] D. Sharpe, On slaty cleavage, *Geol. Soc. London Quart. Jour.*, vol. 5, pp. 111–115, 1849; H. C. Sorby, On the theory of slaty cleavage, *Philos. Mag.*, vol. 12, pp. 127–129, 1856; F. Becke, Über Mineralabstand und Struktur der kristallinischen Schiefer, *Akad. Wiss. Wien Denkschr.*, vol. 75, pp. 37–40, 1913; A. Harker, *Metamorphism*, pp. 153–155, 193–195, Methuen, London, 1932.

[2] G. Becker, Finite homogeneous strain, flow and rupture in rocks, *Geol. Soc. America Bull.*, vol. 4, pp. 13–90, 1893; Current theories of slaty cleavage, *Am. Jour. Sci.*, ser. 4, vol. 24, pp. 1–17, 1907.

[3] C. K. Leith, Rock cleavage, *U.S. Geol. Surv. Bull. 239*, pp. 112–116, 1905; C. K. Leith and W. J. Mead, *Metamorphic Geology*, pp. 117–179, Holt, New York, 1915.

[4] Becke, *op. cit.*

[5] Sorby, *op. cit.*

relationships have been explored, clarified, and successfully used to solve tructural problems.[6]

Between 1911 and the Second World War, the study of deformed rocks vas revolutionized by new methods and concepts developed in Austria, y B. Sander and W. Schmidt.[7] These were comprehensively set out in 930 and revised and amplified after the war.[8] Sander's work is the asis of the modern science of structural petrology. It was introduced o English-speaking geologists in 1933 by E. B. Knopf.[9] Sander's nethod is essentially a statistical analysis of the orientation and mutual eometric relationships of all measurable structural elements of the rock n some particular domain. Some structural elements—bedding, cleavge, fold axes, lineations, etc.—are measured in the field; others, such as ong axes of hornblende prisms, {001} cleavage of mica flakes, or optic xes of quartz grains, are measured in the laboratory. Many individual lements of each kind are measured; their attitudes are plotted on a uitable projection, and any tendency for regular orientation is apparent n the cumulative plot. Sander and his followers have demonstrated hat a high degree of geometric order commonly pervades a body of leformed rock. This order has found expression in the concept of a ectonite fabric. More particularly the orientation patterns of the individual elements, whether macroscopic or microscopic, tend to conform to common symmetry. Sander's emphasis on symmetry as the fundaental property of a naturally deformed rock is perhaps his most original nd significant contribution to structural geology. His interpretation f rock structure—necessarily a speculative field—is based on the assumpion that the symmetry of the structure is influenced by the respective ymmetries of structural anisotropy in the parent rock and of the forces, tresses, and internal movements involved in deformation.

Many of the methods and ideas presented in this book are essentially hose of Sander. Some of his ideas have here been modified in the light f recent experimental and field studies on rock deformation; others have een rejected. Illustrative examples include many new ones drawn from

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[6] E.g., W. J. Mead, Studies for students: folding, rock flowage and foliate strucres, *Jour. Geology*, vol. 48, pp. 1007–1021, 1940; G. Wilson, The relationship of aty cleavage and kindred structures to tectonics, *Geologists' Assoc. Proc.*, vol. 62, . 263–302, 1946; M. P. Billings, *Structural Geology*, 2d ed., pp. 345–351, Prenticeall, Englewood Cliffs, N.J., 1958.

[7] If possible the student should read the classic introductory paper: B. Sander, ber Zusammenhänge zwischen Teilbewegungen und Gefüge in Gesteinen, *Tscheraks mineralog. petrog. Mitt.*, vol. 30, pp. 281–314, 1911.

[8] B. Sander, *Gefügekunde der Gesteine*, Springer, Berlin, Vienna, 1930; *Einführung die Gefügekunde der geologischen Körper*, Springer, Berlin, Vienna, Pt. I, 1948, . II, 1950.

[9] E. B. Knopf, Petrotectonics, *Am. Jour. Sci.*, vol. 25, pp. 433–470, 1933. See o E. B. Knopf and E. Ingerson, Structural petrology, *Geol. Soc. America Mem. 6*, 38.

publications in English. While we do not claim to have mastered completely Sander's philosophy, his profound influence on this presentation will be obvious to any reader. However, for any views or concepts misinterpreted during translation from Sander's writings or erroneously attributed to Sander, we take full responsibility.

Of increasing importance in modern structural analysis of deformed rocks are concepts relating to the geometric properties of folds and to the persistence of structure in the direction of fold axes. These were developed especially by geologists of the Swiss school,[10] and were introduced to English-speaking geologists by D. B. McIntyre who used them to elucidate the structural relationship between contiguous Moinian and Dalradian rocks in a small sector of the Scottish Highlands.[11] Much earlier F. C. Phillips[12] had employed Sander's techniques to clarify the kinematic significance of lineation and accompanying orientation of mica and quartz in Moinian rocks over a much wider area. Stimulated by such studies and by the superb tradition of orthodox structural mapping long established by the Highland school of geologists under the Scottish Geological Survey, geologists of Imperial College, London, led first by H. H. Read and later by J. Sutton, have combined intensive mapping and statistical analysis in the Highlands with conspicuous success. From their work is emerging a uniquely comprehensive picture of deep-seated metamorphism and repeated deformation in a sedimentary pile and its underlying basement. For this reason in discussing analysis on the field scale we have drawn freely from studies published by the Imperial College school.[13] These emphasize the geometric properties of folds (both simple and complex), foliation, and lineation, rather than preferred orientation of mineral grains.

The interpretive side of structural analysis has been influenced to a growing degree by the results of experimental studies of rock deformation at temperatures and pressures consistent with natural environments of metamorphism. Most of these studies, initiated largely through the influence of E. B. Knopf,[14] have been pursued in the United States. A

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[10] E.g., E. Argand, Les Nappes de recouvrement des Alpes pennines et leurs prolongements structuraux, *Matériaux Carte géol. Suisse*, n.s., 31, 1911; E. Wegmann, Beispiele tektonischer Analysen des Grundgebirges in Finnland, *Comm. géol. Finlande Bull.*, vol. 87, no. 8, 1929.

[11] D. B. McIntyre, The tectonics of the area between Grantown and Tomintoul (mid-Strathspey), *Geol. Soc. London Quart. Jour.*, vol. 107, pp. 1–22, 1951.

[12] F. C. Phillips, A fabric study of some Moine schists and associated rocks, *Geol. Soc. London Quart. Jour.*, vol. 93, pp. 581–620, 1937.

[13] E.g., J. G. Ramsay, Superimposed folding at Loch Monar, Inverness-shire and Ross-shire, *Geol. Soc. London Quart. Jour.*, vol. 113, pp. 221–308, 1958; J. Sutton and J. Watson, Structures in the Caledonides between Loch Duich and Glenelg, Northwest Highlands, *Geol. Soc. London Quart. Jour.*, vol. 114, pp. 231–257, 1959.

[14] E.g., E. B. Knopf, Study of experimentally deformed rocks, *Science*, vol. 103, pp. 99–103, 1946.

program of experimental deformation, concentrating at first upon marble, calcite, and quartz, was started by D. T. Griggs at Harvard and continued after the Second World War at the Institute of Geophysics of the University of California. For the past decade a parallel and complementary program, exploring the behavior of other rocks such as dolomite and quartz sand, has been carried on by J. Handin and associates at the Shell research laboratories at Houston, Texas. From these investigations has accrued a mass of information on such topics as strength, ductility, creep, and mechanisms of flow of minerals and rocks, evolution of preferred orientation patterns, and relations between stress, strain, and rock fabrics. Our picture of the genesis of tectonite fabrics has been clarified and broadened; and at the same time we have gained a clearer perception of how structural analysis of tectonites—especially on the microscopic scale—may be applied to problems of metamorphic deformation. Certain aspects of the interpretive philosophy of the Austrian school, such as the significance of fabric symmetry, have been confirmed and strengthened. Others, especially those relating to mechanisms responsible for preferred orientation of minerals in tectonites, have received no experimental confirmation and must be abandoned.

Structural analysis as developed by Sander has always combined field with microscopic investigation. Today there is a greater emphasis than thirty years ago on folds and related foliations and lineations as observed in the field. Analysis of preferred orientation of tectonite minerals is a further refinement which can clarify deductions based on field data and which makes it possible to correlate mineralogical and structural evolution of tectonites. The picture of progressive deformation that so emerges must be consistent with experimentally tested behavior of minerals and rocks under geologically significant conditions of high confining pressures and temperatures and slow rates of strain.

## STRUCTURAL ANALYSIS

**Definition and Purpose.** The field of study with which this book is concerned is known in German as *Gefügekunde der Gesteine.* This has been variously translated into English as *petrofabrics, structural petrology,* and *structural analysis.* The first two of these terms now unfortunately carry a connotation of microscopic study. Such is not implied by Sander who views all rock bodies, regardless of size, as isotropic or anisotropic units whose internal structural elements commonly have a regular configuration in space. One aim of the structural geologist is to explore and interpret this regularity of structure within units ranging in size from an aggregate of a few hundred mineral grains to a major portion of an orogenic zone.

In this book *structural analysis* is synonymous with Sander's *Gefügekunde der Gesteine.* It involves two philosophically distinct procedures. First is the study and description of a rock body in its present state—a study as free as possible from inference and extrapolation, except to the extent imposed by limitations of poor exposure in the field. Then comes genetic interpretation of the descriptive data, an attempt to reconstruct the structural evolution of the body in question.

It is emphasized that structural analysis of deformed rocks is complementary to stratigraphic investigation and other conventional geologic procedures. In the Highlands of Scotland, for example, orthodox mapping followed by the brilliant structural syntheses of Peach and Horne, Bailey, and others has revealed a broad picture of prolonged sedimentation and subsequent Caledonian deformation and metamorphism. Structural analysis in the same region is now filling in the details of a deformational history of hitherto unsuspected complexity. Ultimately the stratigraphic and structural history of the whole of this sector of the Caledonian orogen will be revised and modified in the light of this newer work.

**Factors in Structural Analysis.** The structural complexity of deformed rocks derives in part from the nature of the initial rock—igneous, sedimentary, or metamorphic—and in part from the deformation process. The principal factors concerned are as follows:

1. Internal structural order and correlated physical properties of the initial rock body
2. External forces and surface tractions acting upon the body during deformation
3. Internal stresses resulting from reaction of the body to external forces
4. Displacements, strains, rotations, and differential movements of different domains within the body, by which stresses become eliminated or reduced to some value below a flow threshold
5. Internal structural order and correlated physical properties of the rock body after deformation

Sander[15] emphasized the necessity of visualizing these contributing factors separately, and of drawing a clear distinction between the observed geometric and physical properties of a rock body (item 5 above) and their genetic interpretation in terms of factors 1 to 4. The geometric data of a deformed rock mass collectively constitute a property analogous to the symmetry and structure of a crystal. Different observers, working on the same body of rock, should obtain identical reproducible geometric data. Interpretation, for example, reconstruction of a picture of internal movements or of external forces concerned in deformation,

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[15] Sander, *op. cit.*, p. 2, 1930.

necessarily is more speculative. Interpretations of the same geometric data by different geologists, even in the light of the same experimentally confirmed theories of flow and deformation, may be widely different.

**Geometric, Kinematic, and Dynamic Analysis.** *General Statement.* The geometric data of deformation may be interpreted either kinematically or dynamically. Physicists distinguish clearly between such interpretations. Thus Clerk Maxwell, referring to motion of a system, wrote as follows:[16]

> We have hitherto been considering the motion of a system in its purely geometrical aspect. We have shown how to study and describe the motion of such a system, however arbitrary, without taking into account any of the conditions of motion which arise from mutual action between bodies.
>
> The theory of motion treated in this way is called Kinematics. When mutual action between bodies is taken into account, the science of motion is called Kinetics, and when special attention is paid to force as the cause of motion, it is called Dynamics.

From geometric data the geologist can expect to learn a good deal about the relative movements of different domains within a deformed body. These may be expressed in terms of purely kinematic concepts—strains, rotations, translations, and so on—without taking account of physical factors operating between the domains concerned. Fortunately structural features inherited in distorted or modified form from the parent mass (folded beds, deformed oolites, etc.) commonly furnish markers from which much may be inferred as to the kinematics of deformation. Dynamic interpretation of geologic data is generally more uncertain. The physical state of a rock mass under conditions of flow during metamorphism is most imperfectly known, so that although a pattern of flow may be deduced kinematically, it is generally somewhat hazardous to attempt reconstruction of forces and stresses concerned.

Complete structural analysis of a body of deformed rock thus falls into three phases—geometric, kinematic, and dynamic. These are discussed below in order of decreasing certainty regarding the concepts on which they are based.

*Geometric, or Descriptive, Analysis.* Geometric analysis comprises direct measurement and observation of the geometric and physical properties of the deformed body. Only geometric properties are necessary if subsequent analysis is to be purely kinematic; but for later dynamic analysis other physical properties such as elasticity and ductility become significant. Ideally geometric analysis is descriptive and free from inference.

*Kinematic Analysis.* From the data of geometric analysis an attempt is made to reconstruct movements—strains, rotations, translations, and so on—that took place within the body during deformation. Such kinematic analyses can be made in two ways:[17]

1. The geometric features of a deformed body can be interpreted directly in terms of kinematic concepts on the empirical assumption that the nature of the geometric order of the body reflects the geometric order of the differential displacements, rotations, and strains that must be present during deformation of a real polycrystalline body. These relative motions Sander collectively designates the *movement picture* of the deformation (page 367). It is in the evaluation of the movement picture that symmetry principles are of greatest importance.
2. The observed final state of a deformed body is compared with some assumed initial state, and a path of kinematic development is proposed. But even from the same observations and the same assumptions regarding parent states more than one kinematic reconstruction is possible. For example, a plunging recumbent fold may develop along any of at least three alternative paths from sedimentary beds assumed to have been initially horizontal and planar:

    *a.* A fold forms about a horizontal axis which subsequently becomes tilted.
    *b.* The beds are first tilted and then folded about a plunging axis.
    *c.* The fold and the axial plunge develop simultaneously in a single deformation.

The validity of a kinematic analysis of this second kind depends on the soundness of assumptions regarding the initial state. Strain may be estimated with confidence from the shape of deformed fossils of a well-known species. It is reasonable to assume that strained oolites were once spherical, less so to assume that deformed pebbles were initially spherical, and so on. Many kinds of layering and foliation in metamorphic rocks were almost certainly planar in the first instance; and inherited sedimentary bedding must once have been substantially horizontal.

*Dynamic (Including Kinetic) Analysis.* The aim of dynamic analysis is to reconstruct stresses within a geologic body and "external" or "impressed" forces and surface tractions or body forces in reaction to which the internal stresses developed. Analysis can profitably be applied only to a body with well-defined margins and with an internal structure differing from that of adjoining bodies in the earth's crust. Such, for example, is the body, consisting of deformed Dalradian and Moinian rocks, lying between the Highland Boundary fault and the Moine Thrust in Scotland. Or again it might ultimately be possible to attempt a kinetic analysis of the western foothill region of the Sierra Nevada of California.

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[16] J. Clerk Maxwell, *Matter and Motion*, p. 26, Dover, New York.

[17] Sander, *op. cit.*, p. 170, 1948.

Where deformation of a body is the result of flow in the solid state, dynamic interpretation of strain depends on the rheologic condition of the body. Questions such as these must be answered: Was flow essentially elastic or "plastic" (irreversible)? Taking into account the extremely slow rate of much geologic strain, did the body perhaps behave more as a viscous liquid than as a plastic solid within familiar laboratory experience? And, remembering the possibility of "viscous" behavior, what magnitude of stress, applied over geologically long periods of time, is necessary to produce strain on the observed scale? Unambiguous answers to such questions are not yet forthcoming, so that dynamic analysis of rock structure remains correspondingly controversial and speculative.

## SIGNIFICANCE OF SYMMETRY

Throughout his writings on *Gefügekunde der Gesteine* Sander has repeatedly stressed the prime significance of the overall symmetry of rock structures as a key to kinematic analysis. As structural analysis has progressed in many parts of the world, and as laboratory experiment has yielded information as to the symmetry relations of stress to strain and of strain to structure, the genetic significance of structural symmetry has become increasingly apparent. The concept has recently been revised and expanded by Paterson and Weiss[18] whose conclusions will be elaborated in later sections of this book. Sander's view that symmetry of strain and movement is reflected in symmetry of structure is a symmetry argument in the sense discussed by Paterson and Weiss as follows:

> By a symmetry argument is meant a deduction concerning the symmetry of an unknown quantity from a knowledge of the symmetry of interrelated quantities. . . .
>
> Such considerations of symmetry enable certain minimum deductions to be made in the study of phenomena for which insufficient information is available for a complete analysis to be made. For this reason, symmetry arguments have been invoked in geology where quantitative information on past physical influences is frequently unavailable and quantitative measurements on the physical properties of the rocks in question have not been made. On the other hand, in physics, where quantitative information on all aspects of a phenomenon can be obtained in the laboratory, symmetry relations are not usually discussed explicitly, although they are implicit in a more complete quantitative description of the phenomenon.
>
> An analogy may be drawn between symmetry arguments and dimensional analysis. Thus, in any equation relating the physical quantities concerned in a given phenomenon, the dimensions must be the same on both sides of the equation and use of this fact has frequently been made when more complete knowledge of the quantities is lacking. Similarly, there are general rules governing the symmetry of such quantities. . . . Sander's symmetry rule in structural analysis can therefore be viewed as an application of such symmetry considerations to geological phenomena in order to enable some conclusions to be drawn even though full details are not known.

How the symmetry principle may be applied and the restrictions it places upon kinematic and dynamic analysis of geologic bodies will become apparent in chapters dealing with interpretation of structural data. In the meantime we reemphasize the importance of symmetry of structure as one key to its interpretation.

## SCOPE OF BOOK

This book is concerned with descriptive analysis and interpretation—on all scales from microscopic to that of a geologic map—of structure in rocks that have been deformed during metamorphism. With the aim of, as far as possible, separating fact from inference we have presented the material in three parts, as follows:

Part I deals principally with observations on the geometric properties of tectonite fabrics and with techniques of measurement, recording, and representation of these properties.

Part II is concerned largely with experimental data bearing upon problems of tectonites.

Part III is largely interpretive and outlines current theories of kinematic and dynamic significance of the special features of tectonite fabrics, with particular reference to published examples.

Our main aims are:

1. To demonstrate the use of statistical analysis of geometric data (by means of projections) in establishing the internal geometric and physical order that exists in bodies of deformed rock on any scale
2. To coordinate and summarize experimental data relating to strain of minerals and rocks
3. To demonstrate the possible use of geometric data, in the light of experiment and physical theory, in exploring the geometric properties and deformational history of rock bodies

The deformational history of a region is only one aspect of its total geologic history. This book, therefore, is concerned with only one phase of geologic investigation which, while complete in itself, gives information that must ultimately be supplemented by deductions drawn from more orthodox geologic study.

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[18] M. S. Paterson and L. E. Weiss, Symmetry concepts in the structural analysis of deformed rocks, *Geol. Soc. America Bull.*, vol. 72, pp. 841–882, 1961.

## CHAPTER 2

# INTERNAL ORDER IN DEFORMED GEOLOGIC BODIES: THE TECTONITE FABRIC

### GEOLOGIC BODIES AND SCALE

**Geologic Bodies.** In the title of his great two-volume treatise on structural analysis, Sander[1] uses the term *geologic body*. This has been employed widely in geology to denote somewhat loosely any volume of rock selected for study or comment, without restriction as to size. Thus, the great granite pluton of the Sierra Nevada in California, the volume of metamorphic rocks lying between the Moine Thrust and the Highland Boundary fault in the Scottish Highlands, a nodule of actinolite schist a few inches in diameter enclosed in serpentinite, and the aggregate of quartz grains comprising a thin section of any sandstone are all geologic bodies. Some geologic bodies, such as those cited, have structural or compositional unity and naturally defined bounding surfaces; others, such as the rocks exposed in any area covered by a single topographic quadrangle map, are outlined arbitrarily by nongeologic criteria.

**Scale of Geologic Bodies.** For convenience in observation, geologic bodies may be assigned to several "absolute" size ranges, which are termed *scales*. Each scale requires a different technique of investigation. The four scales adopted here are as follows:

1. Submicroscopic scale: covering bodies too small or too fine-grained to be studied by optical methods. Observation and analysis are by means of X rays. Although widely used in study of single crystals, this method of structural analysis hitherto has not been extensively applied to crystalline aggregates such as rocks.

2. Microscopic scale: covering bodies, such as thin sections or polished surfaces, that can be conveniently examined in their entirety with a microscope.

3. Mesoscopic scale: This term has been introduced[2] to cover bodies that can be effectively studied in three dimensions by direct observation

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[1] B. Sander, *Einführung in die Gefügekunde der Geologischen Körper*, Springer, Berlin, Vienna, Pt. I, 1948, Pt. II, 1950.

[2] L. E. Weiss, Structural analysis of the Basement System at Turoka, Kenya, *Overseas Geology and Mineral Resources*, vol. 7, no. 1, p. 10, London, 1959.

(with or without a low-power hand lens). They range from hand specimens to large but continuous exposures.

4. Macroscopic scale: covering bodies too large or too poorly exposed to be examined directly in their entirety. Such bodies are observed indirectly by extrapolation from and synthesis of mesoscopic observations. They range from groups of isolated exposures to the largest mappable bodies.

Many complete geologic investigations involve observations made on only the three larger scales. Although techniques of investigation are different, aims of geologic studies on the three scales are the same, namely, to determine the structure, composition, and, if possible, the history of development of the body concerned.

## HOMOGENEOUS AND HETEROGENEOUS GEOLOGIC BODIES

**The Notion of Homogeneity.** The geometric phase of structural analysis is concerned with the internal geometric order of a geologic body, as determined by observation of easily accessible parts and extrapolation between these parts. Before such extrapolation is significant, spatial uniformity in internal constitution of the body must be established. Such uniformity is best expressed by the notion of *homogeneity*.

**Strictly Homogeneous Bodies.** A body is strictly homogeneous if any two identically oriented equal-volume units or samples are identical.[3] The nearest approach to strict homogeneity found in a natural body is in a single crystal or in an unstrained glass of uniform chemical composition; and this homogeneity is reflected in uniformity of physical properties such as refractive index or density.

**Statistically Homogeneous Bodies.** Strict homogeneity is not achieved in nature because of the fundamental discontinuous character of matter. A crystal can be considered homogeneous only where samples compared are large in relation to the discontinuities in structure and composition that are implicit in the periodicity of a crystal lattice: even a glass is homogeneous only with respect to samples notably larger than the ionic groups—imperfect crystal nuclei—that locally develop within it. In nature, therefore, a body can be homogeneous only in a statistical sense, where samples compared are sufficiently large in relation to heterogeneities in structure so that each contains a representative distribution of these heterogeneities. Such samples are statistically identical and the body concerned is *statistically homogeneous*.[4] Such a body can appear heterogeneous on a smaller scale if subdivided into samples small enough for structural differences between them to be perceptible. To demonstrate that a body, which is heterogeneous on a small scale, is homogeneous on a large scale it is usually necessary to compare samples that are large fractions of the whole body.

These relations are clearly shown in crystalline aggregates such as rocks. Two equal-sized hand specimens of a fine-grained plutonic rock may have identical geometric and physical properties, because statistically the same number of grains of each mineral arranged in statistically the same fashion are present in each. However, a small volume of the same rock, such as a fragment a few millimeters in diameter, is not statistically homogeneous if subdivided into samples each containing only a few grains. The discontinuous nature of the aggregate becomes significant on this scale, as shown in Fig. 2-1.

Because of the absence of strict homogeneity in matter, the term *homogeneous* is used here to denote bodies that are statistically homogeneous on some particular stated scale. This usage implies that smaller parts of the body may be heterogeneous and also that the body may form part of a larger unit that may be either homogeneous or heterogeneous.

**Structural Homogeneity.** A body can be homogeneous or heterogeneous with respect to a variety of characteristics or physical properties. Most obvious in this respect are the related characteristics of composition and structure. Here we are concerned ultimately with structural homogeneity which implies identity with respect to all possible structural features in a rock body; but such identity is not easily established. Where structural homogeneity is established in a rock body it is generally with respect to specific geometric features of the body, and may disappear where additional geometric features are considered. For instance, a large body of horizontally bedded sedimentary rock can be considered structurally homogeneous with respect to the bedding when in any one portion the geometric properties of the bedding are statistically the same as in any other portion. The same body may be structurally heterogeneous with respect to linear structures such as groove or flute casts lying on bedding surfaces, because these linear structures may be impersistently developed and vary widely in orientation from one part of the body to another.

All bodies that are not homogeneous on a given scale are termed *heterogeneous*. Most large arbitrarily outlined bodies of rock are heterogeneous on the scale of the whole body, although they may be subdivisible into homogeneous portions. Even those large bodies that are effectively

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[3] Lord Kelvin and P. G. Tait, *A Treatise on Natural Philosophy*, 2d ed., Pt. II, sec. 675, Cambridge, 1883: "A body is called 'homogeneous' when any two equal, similar parts of it, with corresponding lines parallel and turned towards the same parts, are indistinguishable from one another by any difference in quality."

[4] M. S. Paterson and L. E. Weiss (Symmetry concepts in the structural analysis of deformed rocks, *Geol. Soc. America Bull.*, vol. 72, p. 854, 1961) define statistical homogeneity as follows: ". . . a body is statistically homogeneous on a certain scale when the average of the internal configuration in any volume element is the same for all volume elements with dimensions not smaller than the scale of consideration."

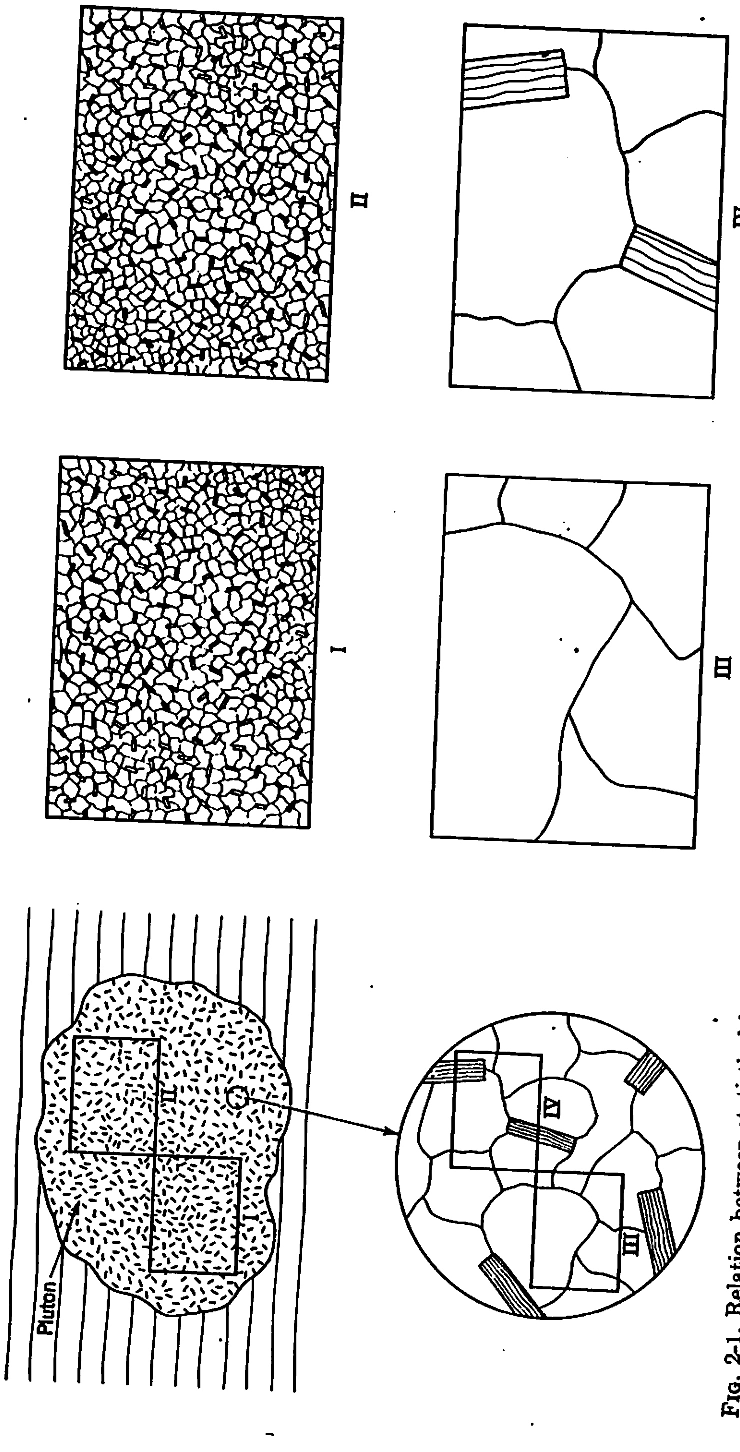

FIG. 2-1. Relation between statistical homogeneity and scale. Size of samples is exaggerated with respect to whole body. Samples I and II are statistically identical. On this scale the body is statistically homogeneous. Samples III and IV of a much-smaller portion of the body are not statistically identical. On this scale the body is heterogeneous.

homogeneous in composition, such as some granite plutons, can be heterogeneous in structure; and those homogeneous in structure, such as certain bodies of sedimentary and metamorphic rock, can be heterogeneous in composition.

## FABRIC OF GEOLOGIC BODIES

**Fabric.** The term *fabric* is the accepted English translation of the German word *Gefüge*, used by Sander[5] to denote the internal ordering of both geometric and physical spatial data in an aggregate. Paterson and Weiss[6] comment on the concept of fabric as follows:

> . . . the "structure" of a noncrystal is the internal geometric configuration of its elementary parts and of any characteristic features to which the arrangement of these parts gives rise. Examples of such internal geometric configurations are seen in the preferred orientation of individual crystals in deformed metals or rocks, the slag stringers in wrought iron, the foliations and lineations in deformed rocks, and the fibrous character of wood and similar materials. This "structure" or configuration of particles (crystalline or otherwise) in an aggregate has been widely termed *texture* in physical and metallurgical literature. The geological term *fabric* (*Gefüge*) is synonymous with texture in this usage but is preferred in geology because texture has other meanings. . . . Sometimes the term "texture" or "fabric" is used for the body itself but it should be borne in mind that, strictly speaking, the fabric refers to the internal configuration of the body. Moreover, since no account is to be taken of any boundaries, a fabric can be considered to be of infinite extent.

The concept of a single crystal as a body with an ordered internal arrangement of invariant component parts (ions, atoms, or molecular configuration) is one familiar to all students of geology. The internal order in a crystal is primarily recognized by a similar ordering of physical properties. This order can be expressed in an abstract way in terms of its point-group or space-group symmetry. The concept of fabric extends the notion of internal spatial order to nonlattice bodies such as crystalline aggregates, geologically familiar as rocks. The component parts in aggregates are crystalline grains, and their spatial arrangement and mutual relations constitute the internal order of the fabric. In an aggregate the arrangement of components is not generally subject to the three-dimensional translational periodicity and the energy-dependent packing laws of the crystal lattice, so that the kinds of permissible order differ in some respects from those of crystals. But a close analogy can be pointed between the single crystal and the aggregate, because both possess abstract geometric properties or form and both possess physical properties that reflect in some fashion this form. For example, depending

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[5] B. Sander, *Gefügekunde der Gesteine*, p. 1, Springer, Berlin, Vienna, 1930.

[6] Paterson and Weiss, *op. cit.*, p. 854.

upon its symmetry class, the elastic properties of a crystal are expressible by a fixed number of constants; likewise, upon the geometric order within a fabric depend its physical properties such as elasticity, thermal conductivity, and permeability.

The concept of a fabric, therefore, embodies not only a geometric or morphologic aspect expressible in terms of the geometric arrangement of components, but also a functional or behavioral aspect which is concerned with the directional physical properties that are a necessary correlate of geometrically regular organization of matter. To differentiate the two aspects of fabric, Sander[7] terms them respectively *formal* or *configurational* (*gestaltlich*) *fabric* and *functional* or *physical* (*funktional*) *fabric*. In this context form or configuration implies the abstract geometric order of a fabric divorced from the functional or physical properties that reflect it. The term *fabric* as used in this book covers aspects of both form and function. The term *geometry* can be used instead of form or configuration where a complete geometric abstraction is implied.

A fabric can be considered to be of infinite extent. Neither the bounding surfaces nor the shape of a body are part of its fabric. The geometric and symmetric properties of fabrics are therefore similar to those of other infinitely extended structures like crystal lattices. Implicit, therefore, in the concept of fabric is that of homogeneity.

**Fabric Domains.** The term *domain*[8] is here used to specify any finite three-dimensional portion of a rock body that is statistically homogeneous on the scale of the domain. Domains are usually outlined by boundaries that are natural surfaces of major discontinuity in structure or composition. A portion of a particular domain may be termed a *subdomain*.

Any homogeneous or heterogeneous body can be subdivided on some scale into homogeneous domains. These domains commonly differ in kind and degree of internal order, both amongst themselves and with respect to the body in which they occur. Each therefore has a fabric regardless of whether the whole body concerned is homogeneous and has a fabric, or is heterogeneous and does not. Such domains may be termed *fabric domains*. In rocks they are of two kinds, as follows:

1. Crystallographic domains: These are individual unstrained or weakly strained mineral grains. Strictly speaking, such domains have no fabric because their internal order is controlled by the laws of crystallography. The structure of all domains of the same composition is more or less the same in a given body.

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[7] Sander, *op. cit.*, pp. 2, 3, 1948.

[8] The terms *area* (L. E. Weiss, A study of tectonic style, *Univ. California Geol. Sci. Pub.*, vol. 30, pp. 1–102, 1954) and *field* (L. E. Weiss, Geometry of superposed folding, *Geol. Soc. America Bull.*, vol. 70, pp. 91–106, 1959) have been used in the past in this sense. We now believe that *domain* is a preferable term and so have adopted it.

2. Noncrystallographic domains: These are homogeneous domains on some scale larger than that of a single crystal, and consist of aggregates of grains. The internal order of these domains is not directly subject to the laws of crystallography and is expressed by a fabric. This fabric may vary from domain to domain in a body of uniform composition.

? **Fabric as an Array of Discontinuities in Structure.** For most purposes, such as determination of elastic, thermal, or electrical properties, a crystal can be treated as a homogeneous continuum. Understanding of the geometric and symmetric properties of crystals, however, is possible only where the crystal is viewed more rigorously as a periodic array of structural discontinuities.[9] Similarly, a homogeneous fabric, although in large domains conveniently treated as a structural continuum, must be examined in terms of small-scale discontinuities or local heterogeneities in its structure before the geometric and symmetric properties of its internal order can be expressed and the concept of a fabric becomes significant. A fabric can be treated, therefore, as a three-dimensionally ordered array of structural discontinuities: one aim of structural analysis is to establish this order and represent it in a graphic form. ?

**Discontinuities in Crystallographic Domains.** The planes and lines of structural discontinuity in crystals (that is, lattice planes and directions) are not directly observable because they occur on the atomic scale. Their orientation can be determined, however, either optically—on the basis of known relations between optical properties and crystallographic features—or, more directly, by observing related physical discontinuities on a much larger scale (cleavages, twin lamellae, partings, and so on). X-ray analysis gives a complete picture of the internal surfaces of discontinuity within crystals.

Because a crystal is a homogeneous domain on all but the smallest scales, one observation serves to define the orientation of a particular structural plane or line for the whole crystal. Such discontinuities in structure are here termed *penetrative* because they are repeated at distances so small, compared with the scale of the whole crystal, that they can be considered to pervade it uniformly and be present at every point.

Examples of planar and linear penetrative discontinuities in crystallographic domains commonly studied in structural analysis are as follows:

1. Planar discontinuities: any determinable crystallographic plane in a grain, for instance; $\{001\}$ in mica (defined by visible cleavages); $\{01\bar{1}2\}$ in calcite and $\{02\bar{2}1\}$ in dolomite (defined by visible twin lamellae); $\{10\bar{1}1\}$ in calcite and dolomite (defined by visible cleavages).

2. Linear discontinuities: any determinable crystallographic line in a grain, for instance; $[0001]$ in quartz (defined by optic axis); $[0001]$ in

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[9] P. Niggli, *Geometrische Kristallographie des Diskontinuums*

Berlin

calcite and dolomite (defined by optic axis or known angular relation to $\{01\bar{1}2\}$ or $\{10\bar{1}1\}$).

Some discontinuities, for example, [0001] in quartz or $X$, $Y$, and $Z$ of the olivine indicatrix, are unique for a given crystallographic domain. Others, such as $\{01\bar{1}2\}$ in calcite, are symmetrically repeated to conform to the particular symmetry class of the crystal. If the object of analysis is to determine the orientation of one kind of penetrative discontinuity, for example, $\{01\bar{1}2\}$ in the domain of a calcite crystal, all possible discontinuities of the same kind (three in calcite) must be recorded as of equal value, even though only one or two may be rendered visible by discrete discontinuities (twin lamellae in calcite). For some purposes it may be necessary to distinguish between lattice planes paralleled by visible discrete continuities and the latent invisible lattice planes of the same kind. Here the recorded visible discrete discontinuities (cleavage cracks, twin lamellae, and so on) fall into the nonpenetrative category on the scale of the grain (see below).

**Discontinuities in Noncrystallographic Domains.** *Penetrative and Nonpenetrative Discontinuities.* Structural discontinuities that are not crystallographically controlled can occur in individual mineral grains, for example, the bounding surfaces of *kink bands.*[10] In one sense such surfaces make a crystal a noncrystallographic domain because they destroy homogeneity with respect to lattice orientation and convert the original crystal to an aggregate of crystals.

In noncrystallographic domains all surfaces of discontinuity are made up of grain boundaries. Where anhedral grains are in contact, these boundaries, even though they may be approximately planar, have no rational relation to the crystal lattice. But some common minerals tend to develop idioblastic outlines, and domain boundaries may then show the influence of crystallographic control. For instance, mica commonly crystallizes with a tabular habit parallel to $\{001\}$; hornblende prisms are habitually bounded by $\{110\}$. All larger-scale discontinuities are systematic arrays of grain boundaries. Even a nearly perfectly planar surface of discontinuity, such as a bedding surface separating a fine-grained limestone from a fine-grained mudstone, is defined statistically by a planar alignment of boundaries between microscopic grains.

The relations between grain boundaries and other noncrystallographic discontinuities are illustrated in Fig. 2-2. Fig. 2-2*a* shows part of an aggregate on a microscopic scale. Even on this scale the grain boundaries have a weak preferential orientation. On a larger scale (Fig. 2-2*b*) the arrangement of grain boundaries in planar parallel orientation imparts to the whole aggregate a penetrative planar structure parallel to $S_1$. On this scale the planar discontinuity $S_1$ is a penetrative family of statisti-

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[10] See, for instance, C. S. Barrett, *Structure of Metals*, 2d ed., pp. 375, 376, McGraw-Hill, New York, 1952.

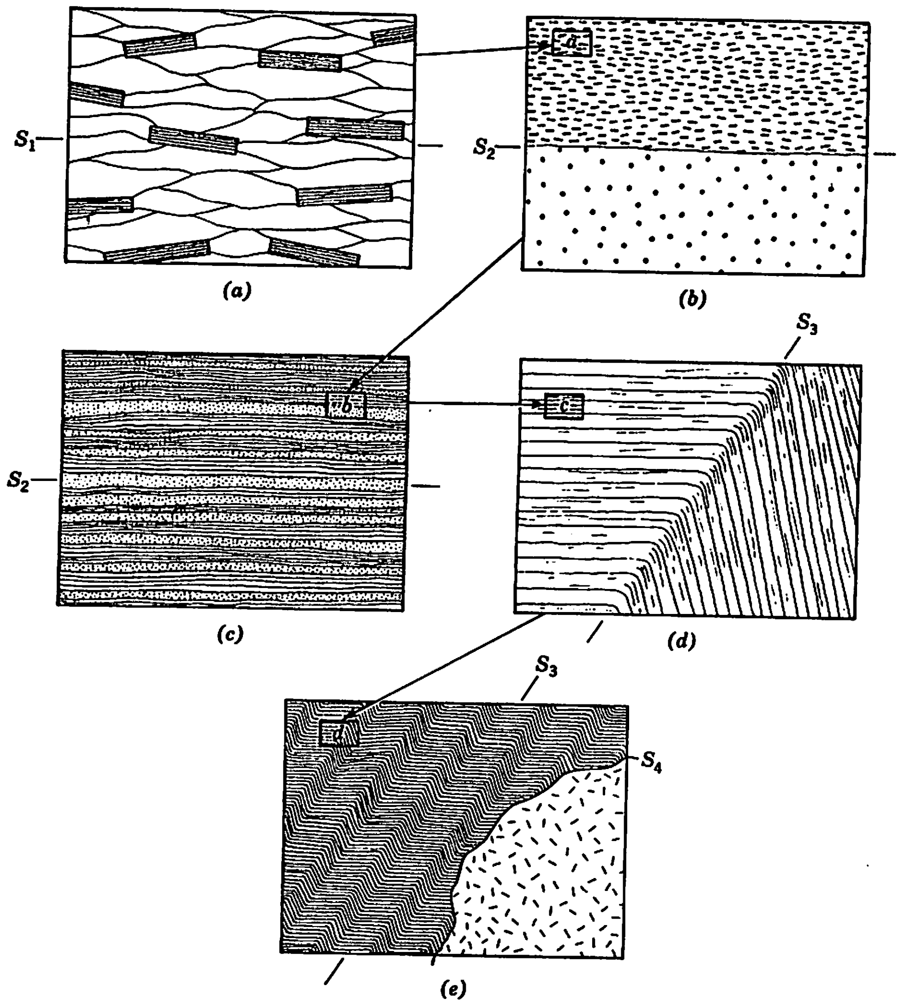

FIG. 2-2. Planar discontinuities in the same body on five different scales. (*a*) Microscopic scale; planar preferred orientation of grain boundaries defines a weakly penetrative planar structure $S_1$. (*b*) Mesoscopic scale; grain boundaries define a penetrative planar structure $S_1$ in the upper layer. Discontinuity $S_2$ between layers of different composition is nonpenetrative on this scale. (*c*) Larger mesoscopic scale; alternating layers parallel to $S_2$ make this a penetrative planar structure. (*d*) Macroscopic scale; kink surface $S_3$ divides the body into two homogeneous domains with different orientations of $S$ and $S_2$. $S_3$ is nonpenetrative. (*e*) Larger macroscopic scale; $S_3$ becomes a series of closely spaced kink surfaces and is penetrative. A new surface of discontinuity $S_4$ divides the body into unlike domains and is nonpenetrative on all scales.

cally defined parallel surfaces, present in every sample of moderate size. Because their attitude in the domain is not controlled crystallographically, homogeneity in nature and orientation of $S_1$ must be determined by comparison of measurements made on individual surfaces of discontinuity in different parts of the domain.

On the scale shown in Fig. 2-2*b* another kind of surface of discontinuity appears. This is the *nonpenetrative* surface $S_2$ that separates the fabric described from a different fabric below. On a yet larger scale, as shown in Fig. 2-2*c*, the aggregate takes on a finely laminated aspect owing to the rapid alternation of layers of the kind separated by $S_2$ in Fig. 2-2*b*. On this scale $S_2$ also becomes a penetrative discontinuity that is statistically present in every sample of the fabric. On a still larger scale (Fig. 2-2*d*) the aggregate is traversed by yet another surface of discontinuity—$S_3$, which divides the aggregate into noncrystallographic domains that are effectively internally homogeneous. Although this is a discrete surface of discontinuity on the scale shown, on a larger scale $S_3$ could become penetrative. On the other hand, surfaces such as $S_4$ divide the geologic body into completely unlike domains and are clearly nonpenetrative on all possible scales (Fig. 2-2*e*).

Noncrystallographic discontinuities are classified as nonpenetrative on a scale small enough for them to remain discrete surfaces separating domains of significant size. Those discontinuities classified as penetrative are generally so on macroscopic or mesoscopic scales (for example, bedding in most sediments and foliation in many kinds of metamorphic rock); but they can be penetrative also on a microscopic scale (for example, bedding in a shale and slaty cleavage).

In this book structural discontinuities of any kind occurring in rock bodies are termed *structures*. The various kinds of planar (including curviplanar[11]) and linear noncrystallographic discontinuities common in geologic bodies are summarized below.

1. *Nonpenetrative planar discontinuities.*
    - *a.* Faults. Faults may separate like fabric domains without sensibly interrupting geometric continuity of penetrative structures (Fig. 2-3*a*), or they may separate unlike domains (Fig. 2-3*b*). Commonly—especially in the case of normal, reversed, or strike-slip faults—they are unrelated geometrically to the penetrative discontinuities that pervade the adjacent fabric domains. Thrust, glide, or slide surfaces, however, tend to be more closely related geometrically to the fabrics of the domains they separate (Fig. 2-3*c*). A glide or slide surface may be indistinguishable from a single surface in a family that collectively defines the penetrative discontinuity known as *foliation*.[12]

    - *b.* Igneous contacts. Except where they separate igneous bodies of common origin, igneous contacts generally separate unlike fabrics. Geometrically they may be unrelated to either of the fabrics they separate (Fig. 2-4*a*). But some intrusive contacts have a geometric relation either to the country rock (foliation or bedding parallel to the margins of the sill shown in Fig. 2-4*b*), or to the igneous rock (flow structures parallel to the margins of the pluton shown in Fig. 2-4*c*), or to both (Fig. 2-4*d*).
    - *c.* Erosion surfaces and unconformities. Most rock bodies studied by geologists have one bounding surface that is erosional and separates the body from the atmosphere or the hydrosphere. The geometric properties of such a topographic surface may be unrelated

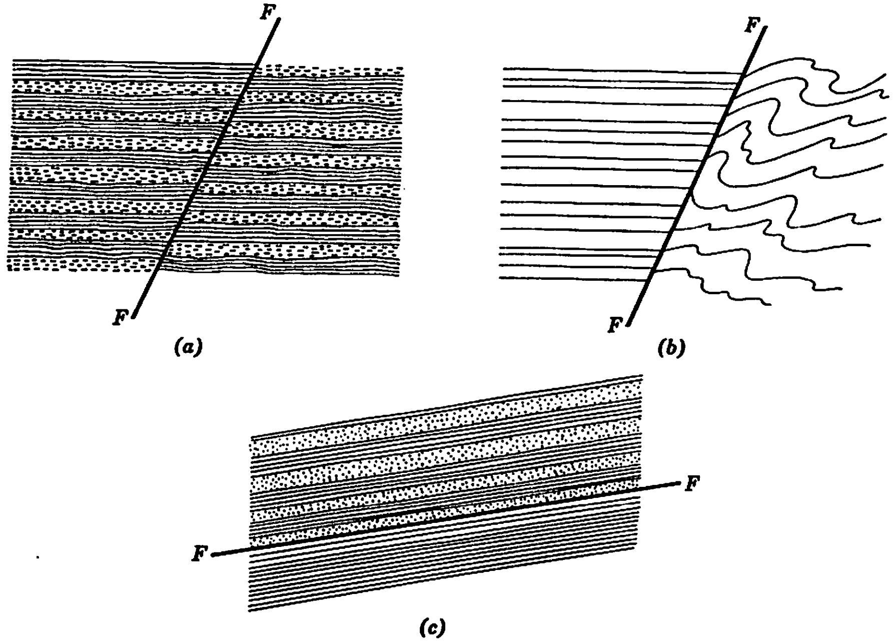

FIG. 2-3. Faults $F$ as domain boundaries. (*a*) Fault is transgressive to fabrics of wall rocks. These fabrics are geometrically identical and are effectively uninterrupted by the fault. (*b*) Fault is transgressive to fabrics of wall rocks. The fault separates unlike domains and is a surface of discontinuity. (*c*) Fault is not transgressive to fabrics of wall rocks. These fabrics are geometrically identical and are effectively uninterrupted by the fault.

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[11] G. Oertel, Extrapolation in geologic fabrics, *Geol. Soc. America Bull.*, vol. 73, p. 326, 1962.

[12] E. Greenly, Foliation and its relation to folding in the Mona Complex at Rhoscolyn (Anglesey), *Geol. Soc. London Quart. Jour.*, vol. 86, pp. 185–187, 1930; E. B. Bailey, The structure of the south-west Highlands of Scotland, *Geol. Soc. London Quart. Jour.*, vol. 78, p. 86, 1922

to those of the rock body they bound, or there may be recognizable geometric control of the surface by the fabric of the body.[13] Unconformities are former erosion surfaces. They can have a variety of geometric relations to the fabrics of the domains they separate. Figure 2-5*a* shows an unconformity geometrically unrelated to either fabric. A planar unconformity, on the other hand, is usually concordant with the stratification of the rocks above and discordantly related to the rocks below (Fig. 2-5*b*). A disconformity has a strong geometric relation to both fabrics and, like some glide or slide surfaces, is not a visible surface of geometric discontinuity but a surface of stratigraphic discontinuity (Fig. 2-5*c*).

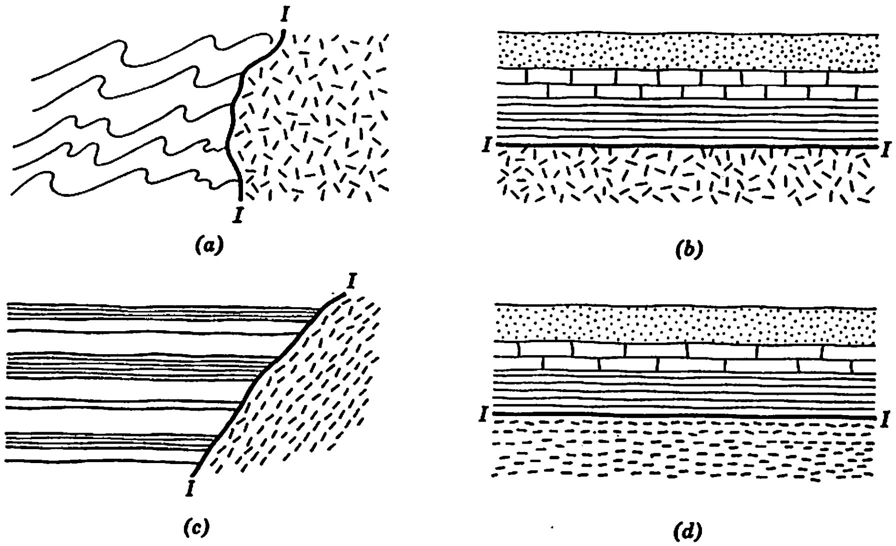

FIG. 2-4. Igneous contacts *I* as domain boundaries. (*a*) Contact surface is transgressive to unlike fabrics. (*b*) Contact surface is transgressive only to fabric of igneous rock. (*c*) Contact surface is transgressive only to fabric of country rock. (*d*) Contact surface is not transgressive to igneous and country rocks and geometrically is not a surface of discontinuity.

*d.* Metamorphic *fronts* and isograd surfaces. These are boundary surfaces either between metamorphosed and unmetamorphosed rocks (fronts) or between zones showing demonstrably different degrees of metamorphism (isograds). Such surfaces, along with fronts of migmatization and perhaps granitization, are thought by some geologists to migrate through a geologic body and partially or completely to reconstruct the fabric of the rocks through which they pass. Fronts are sometimes depicted as discrete surfaces of discontinuity. More commonly they are thought to be finite domains with parallel boundaries, in which a mineralogic and thus a geometric gradient exists from one margin to the other. Such heterogeneous domains are not true surfaces of discontinuity.

*e.* Joints. Joints are only nonpenetrative on certain scales of observation. Where they are expressed as closely spaced microfractures they are more akin to penetrative discontinuities. They resemble penetrative discontinuities also in always separating like fabrics; but their geometric relation to penetrative discontinuities within these fabrics is commonly tenuous or inconsistent. Certain sets of joints, however, consistently have some fixed geometric relation to penetrative discontinuities. In unfolded sediments, joints are commonly developed normal to bedding. In deformed rocks, joints tend to develop subnormal to fold axes and lineations, or in conjugate sets symmetrically intersecting these structures. In structural analysis of deformed rocks, therefore, it is common practice to measure and consider joints that fall into one or other of these categories.

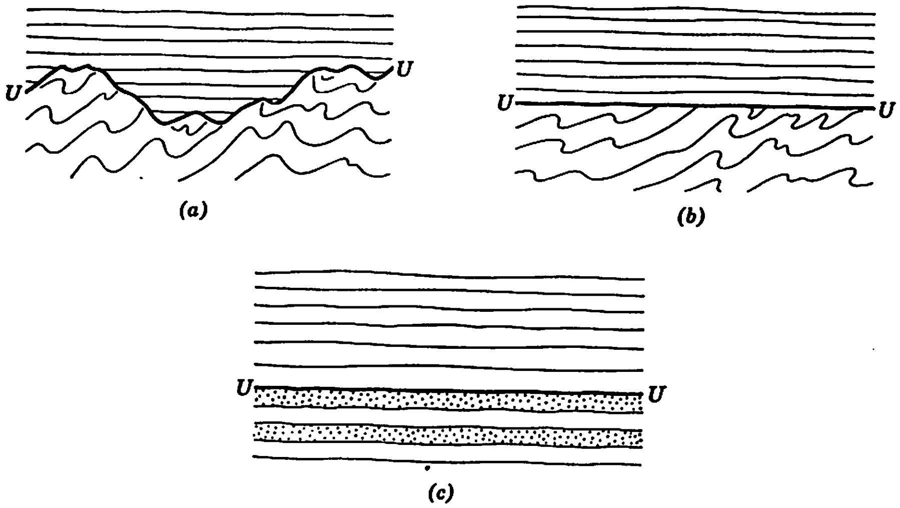

FIG. 2-5. Unconformities *U* as domain boundaries. (*a*) Unconformity transgressive to unlike fabrics. (*b*) Unconformity transgressive only to fabric of rocks below. (*c*) Disconformity is not transgressive to fabrics of rocks above or below and geometrically is not a surface of discontinuity.

In the above discussion the nonpenetrative surfaces of discontinuity have been treated as discrete surfaces with no volume. In natural examples the surfaces are generally marked by a thin more

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[13] F. J. Turner, "Gefügerelief" illustrated by "schist tor" topography in central Otago, New Zealand, *Am. Jour. Sci.*, vol. 250, pp. 802–807, 1952; G. Wilson, The influence of rock structures on coast-line and cliff development around Tintagel, North Cornwall, *Geologists' Assoc. Proc.*, vol. 63, pp. 20–58, 1952.

or less parallel-sided domain whose fabric differs from the fabric on either side. Examples of such domains are slickenside films; thin layers of mylonite, crushed rock, or gouge paralleling fault surfaces; narrow zones of disordered and compositionally mixed material locally margining igneous contacts; and the conglomeratic or atypically coarse-grained layers developed above, and the weathered zones developed below, unconformities. Some of these thin local fabrics are of structural importance (for instance, a slickenside film on a fault may indicate the direction and sense of fault movement); but in the fabric of a large body of rock they are generally unimportant and can be neglected.

2. *Penetrative planar discontinuities.*
   a. Bedding (including gravitationally controlled layering in igneous rocks). Bedding is defined most commonly by alternating layers of different lithologic type. In individual layers of a particular kind (for instance, a sandstone bed made entirely of nearly spherical quartz grains with a random arrangement of [0001]), penetrative discontinuities parallel to bedding may be lacking. But most layers contain inequant grains lying with their long dimensions in the bedding surfaces, so that even on a small scale a penetrative discontinuity defined by grain boundaries is then present. In a large domain (for instance, a thick formation of bedded rocks) the bedding lamination itself becomes a penetrative discontinuity (see Fig. 2-2*a*, *b*, *c*). The simple geometric properties of normal bedding can be complicated by the presence of closely related structures such as graded bedding, cross-bedding, and a variety of local linear flow structures, such as groove and flute casts.
   b. Foliation. This is defined by the metamorphically produced penetrative surfaces of discontinuity in deformed rocks, including structures known as schistosity, cleavage, and so on. Structurally they resemble bedding in that they are defined by arrangements of grain boundaries or by lithologic lamination. All, like bedding, are present on most scales of observation as penetrative statistically defined parallel families. Some bodies contain more than one foliation. A common type is subparallel to the axial planes (page 108) of folds affecting an earlier set of surfaces. In a large body of rock the axial planes of folds themselves may be considered penetrative surfaces of discontinuity.

Sander[14] has proposed the term "*s*-surface" to denote any kind of penetrative planar structure in rocks. The term covers bedding, foliation, and some kinds of joints. Strictly one should speak of a set or family of *s*-surfaces where all the surfaces in the family are

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[14] B. Sander, Über Zusammenhänge zwischen Teilbewegung und Gefüge in Gesteinen, *Tschermaks mineralog. petrog. Mitt.*, vol. 30, p. 286, 1911.

to be specified; but such a family is sometimes more conveniently designated an *s*-surface.

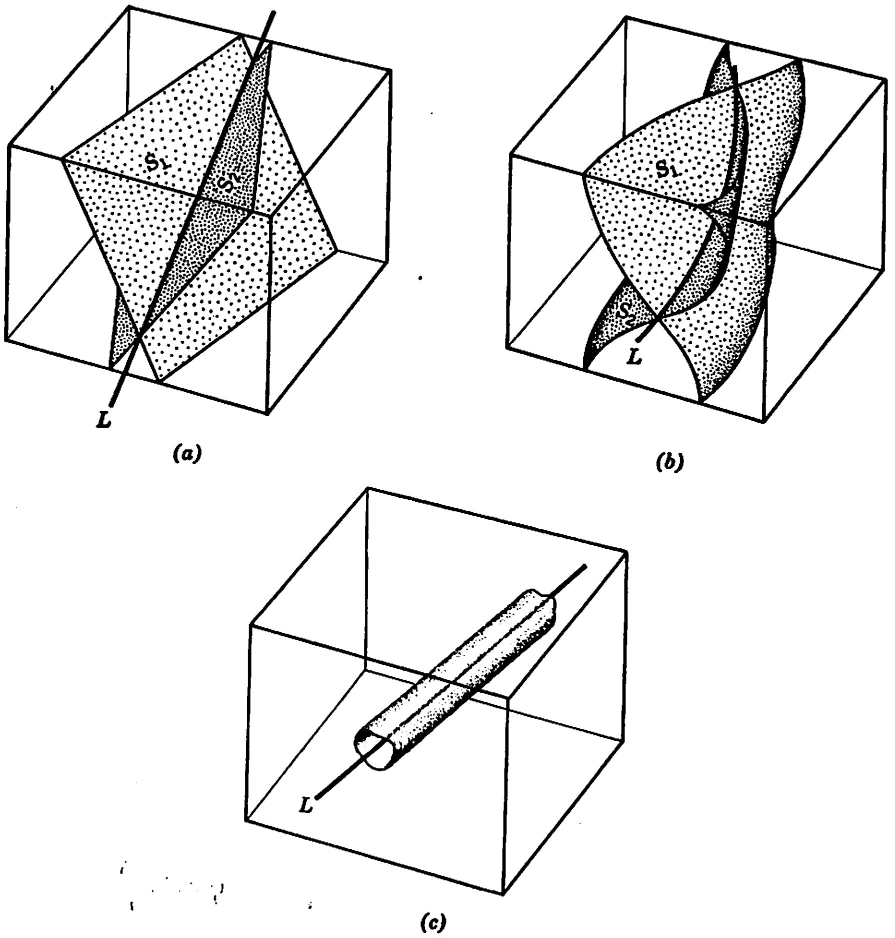

FIG. 2-6. Nonpenetrative linear discontinuities *L*. (*a*) Rectilinear intersection of two planar nonpenetrative discontinuities $S_1$ and $S_2$. (*b*) Curvilinear intersection of two curviplanar nonpenetrative discontinuities $S_1$ and $S_2$. (*c*) Bounding surface of small cylindrical or prismatic domain.

3. *Nonpenetrative linear discontinuities.* Linear discontinuities in fabrics arise as modifications of planar discontinuities, as follows:
   a. The line of intersection of two nonparallel, nonpenetrative surfaces of discontinuity is a nonpenetrative linear discontinuity. Where both surfaces are planar the linear discontinuity is rectilinear (Fig. 2-6*a*); where one or both are curviplanar the linear discontinuity is in general curvilinear (Fig. 2-6*b*). An example of a discontinuity of this kind is the line of intersection of one contact of an

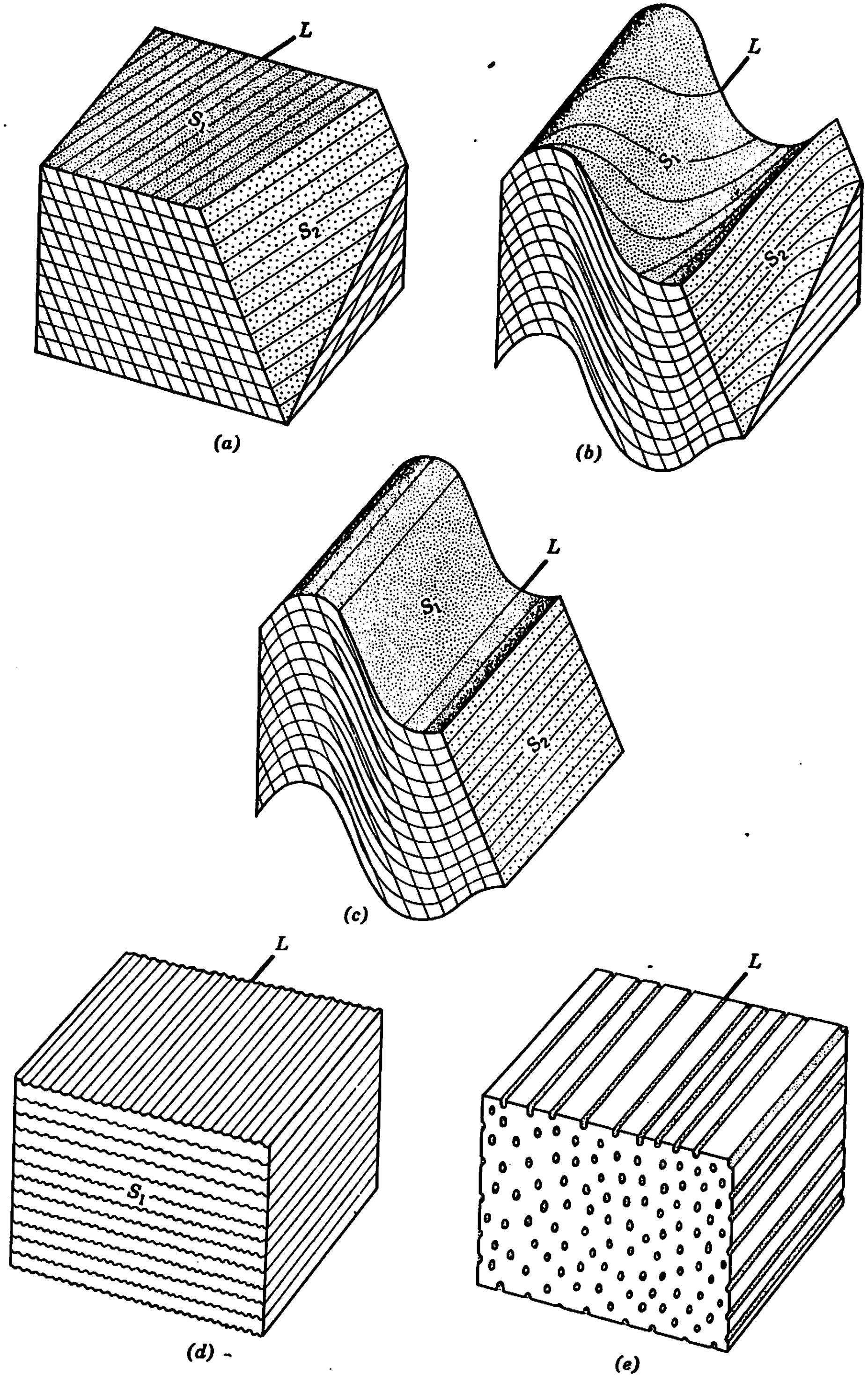

FIG. 2-7. For descriptive legend see opposite page.

dike with a thin planar vein. Such nonpenetrative linear discontinuities are widely used in graphic solution of fault problems in structural geology.

*b.* A two-dimensionally penetrative linear discontinuity arises by the intersection of a set of penetrative surfaces with a nonpenetrative surface. Examples of such structures are lines of intersection (traces) of bedding on a fault or a topographic surface. These linear structures are not truly penetrative in three dimensions and are not true lineations.

*c.* Where individual prismatic or cylindrical domains can be outlined in a fabric, a nonpenetrative linear discontinuity is present (Fig. 2-6*c*). On a microscopic scale a single prismatic grain is such a domain; on a mesoscopic or larger scale a *rod* of one lithologic type enclosed in a matrix of another, *mullion* structures defined by cylindrically curving surfaces of discontinuity, and the hinges of large folds in a particular surface are linear discontinuities of this kind.[15]

4. *Penetrative linear discontinuities.*

*a.* The three-dimensional array of lines of intersection of two sets of penetrative planar discontinuities is a penetrative linear discontinuity (Fig. 2-7*a*). Examples are the lines of intersection of bedding and cleavage in a slate, or of two foliations in a schist. Where the surfaces are planar the linear discontinuity is rectilinear. Where one set or both sets are curviplanar the linear discontinuity is curvilinear (Fig. 2-7*b*); an exception is the geologically common condition in which the line of intersection of the surfaces is also the axis of curvature in one or both sets (for instance, the lines of intersection of axial-plane foliation with folded bedding, as in Fig. 2-7*c*). Many *lineations* in deformed rocks are expressions of these geometric relations. All true lineations are penetrative discontinuities.

*b.* Regular crenulations of a set of penetrative surfaces define a direction that is unique in the penetrative surface (Fig. 2-7*d*). On a microscopic scale a lineation arises in this way; on larger scales, a fold axis.

*c.* Elongated prismatic or cylindrical domains of small size by alignment of their long axes define a penetrative linear discontinuity

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[15] G. Wilson, Mullion and rodding structures in the Moine Series of Scotland, *Geologists' Assoc. Proc.*, vol. 64, pp. 118–151, 1953.

FIG. 2-7. Penetrative linear discontinuities *L*. (*a*) Rectilinear intersection of two planar penetrative discontinuities $S_1$ and $S_2$. (*b*) Curvilinear intersection of a curviplanar penetrative discontinuity $S_1$ with a planar penetrative discontinuity $S_2$. (*c*) Rectilinear intersection of a folded penetrative discontinuity $S_1$ with a penetrative planar discontinuity $S_2$ containing the axis of folding. (*d*) Regular crenulations of a set of penetrative surfaces $S_1$. (*e*) Preferred orientation of cylindrical or prismatic domains.

in a large domain of fabric (Fig. 2-7*e*). Such elongated domains may be individual grains such as hornblende prisms, or noncrystallographic domains of a particular composition (for example, trains of quartz or feldspar grains in a gneiss, elongated pebbles in a deformed conglomerate).

**Fabric Elements and Fabric Data.** Within a homogeneous domain—be it a thin section, a hand specimen, or a mountain range—only structures that are penetrative on the scale of the domain contribute to the fabric. Structures in aggregates falling into this category are defined by the following features:

1. Lattice planes and lines within individual grains
2. Shapes of inequant grains
3. Arrangements of grains of particular kinds in layers, linear bodies, and other inequant configurations

Such structures are termed *fabric elements* of the fabrics defined by their three-dimensional configuration, where this is statistically homogeneous. This term has been used by Sander[16] to denote the actual equivalent domains of which a body is composed, whereas Fairbairn[17] defines a fabric element as " . . . a single crystal or group of crystals which act as a unit with respect to the forces applied to it." Neither of these definitions embraces statistically pervasive features such as foliations and lineations since such features are not domains of a body but are surfaces and lines of structural discontinuity within or between domains of the body. All fabric elements as here defined can be viewed on some scale as surfaces and lines of structural discontinuity. For example, features defined by planar and linear preferred orientations of inequant grains are, in detail, also penetrative families of surfaces of discontinuity defined by the grain boundaries. Likewise, lattice planes and lines in individual crystals are planes and lines of discontinuity on the ionic or molecular scale.

In tectonite fabrics, therefore, we recognize two kinds of fabric element:

1. *Crystallographic fabric elements.* These are lattice planes or lines in individual grains, e.g., $\{001\}$ planes in mica (determined from visible cleavages), $\{01\bar{1}2\}$ planes in calcite and $\{02\bar{2}1\}$ planes in dolomite (determined from visible twin lamellae), $[0001]$ directions in quartz (determined as the optic axes), and $[0001]$ directions in calcite and dolomite (determined as the optic axes or from known angular relations to cleavages and twin lamellae). Each element, according to the demands of crystal symmetry, must be accompanied by all other elements of the same crystallographic form. Thus in calcite $(10\bar{1}1)$ is necessarily accompanied by $(\bar{1}101)$ and $(0\bar{1}11)$. The attitude of a crystallographic element commonly is determined by measuring some individual visible structure such as a $(10\bar{1}1)$ cleavage or a twin lamella $(01\bar{1}2)$ in calcite. If these visible elements only are recorded they should be treated as noncrystallographic elements; a twin lamella may even be regarded as a distinct fabric domain.

2. *Noncrystallographic fabric elements.* These are visible structural discontinuities or heterogeneities in an aggregate. Planar noncrystallographic elements—*s*-surfaces in Sander's terminology—are structures such as bedding and foliation which are defined by preferred orientation of grain boundaries or by lithologic layering. Some aggregates contain more than one foliation. One of these may be parallel to axial planes of folds affecting an earlier foliation. Axial planes of folds may themselves be considered as fabric elements on a larger scale. Linear noncrystallographic fabric elements are structures such as lineations and fold axes. Lineations can be defined by such features as lines of intersection of two planar fabric elements, crenulations in a planar fabric element, alignment of boundaries of elongated grains, and so on.

The rigorous definition here adopted restricts the term "fabric element" to plane and rectilinear segments of noncrystallographic discontinuities. Crystallographic fabric elements are correspondingly plane and rectilinear. A fabric, therefore, is viewed as a three-dimensional array of plane and rectilinear segments even though a number of these may collectively define folded surfaces in the fabric. Our view of fabric elements and fabrics involves more precisely defined concepts than those current among most structural geologists; but we believe that it conforms closely to Sander's idea of *Gefüge*. Moreover it is only plane and rectilinear structures that can be measured by ordinary field and laboratory methods. And homogeneity and space-group symmetry (see page 42)—the very essence of fabric—can be rigorously defined only in terms of an infinite array of plane and rectilinear features.

Fabric elements, like fabrics, have both a geometric and a functional aspect. The descriptive phase of structural analysis is concerned mainly with geometric fabric elements divorced from the functions they reflect. Thus, we can speak of the spatial arrangement of lineations or mineral grains in a fabric in an abstract geometric sense without implying a related spatial arrangement of physical (functional) properties such as permeability or linear thermal expansion. Where genesis of a fabric is to be studied, however, the function of observed fabric elements in development of the fabric becomes important.

The attitude of any fabric element can be specified by its angular relation either to chosen orthogonal

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[16] Sander, *op. cit.*, p. 5, 1948.

[17] H. W. Fairbairn, *Structural Petrology of Deformed Rocks*, 2d ed., p. 3, Addison-Wesley, Reading, 1949.

labeled *a*, *b*, and *c*, or to geographic coordinates. The measurements that specify the attitudes of fabric elements are termed *fabric data.*

A fabric is defined by the spatial array of all its elements. However, it is frequently sufficient or convenient to consider the array of only one kind of element. This array is called by Sander a *Teilgefüge* and here a *subfabric.*[18]

In a given fabric there may be many kinds of different elements and correspondingly numerous subfabrics. In practice, a few easily measurable elements are chosen and the subfabrics defined by these are combined to define the geometric properties of the fabric as a whole. For instance, in a quartz-mica schist some easily measurable subfabrics are defined by:

1. Attitude of one type of foliation
2. Attitude of one type of lineation
3. Preferred orientation of [0001] in quartz
4. Preferred orientation of {001} in mica

Although other subfabrics can be defined (for instance, by the preferred orientation of [100] in mica) their determination presents practical difficulties and does not always add materially to the geometric properties of the total fabric.

## ISOTROPIC AND ANISOTROPIC FABRICS

**Preferred Orientation of Fabric Elements.** In the spatial arrangement of fabric elements two aspects are implicit:

1. The elements have *orientation;* that is, they have attitudes with respect to selected fixed reference axes (for instance, the attitude of a foliation surface as expressed by its strike and dip).

2. The elements have *location;* that is, they have a definite position with reference to elements of the same or different kinds (for instance, a slaty cleavage may be present in a shaly bed in a thick series of deformed sediments, but absent in a sandy bed).

Where fabric elements are not randomly oriented in a fabric they are said to possess a *preferred orientation.*[19] A random orientation of elements is extremely rare in nature. The elements in some igneous rocks and in hornfelses which have crystallized without deformation under effectively hydrostatic pressure most nearly approach random orientations. Even in these fabrics, however, sufficiently refined measurements

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[18] Sander, *op. cit.*, pp. 5, 6, 1948. The term *subfabric* was introduced by Paterson and Weiss (*op. cit.*, p. 863).

[19] A comprehensive account of preferred orientation of grains is to be found in E. B. Knopf and E. Ingerson, Structural petrology, *Geol. Soc. America Mem. 6*, pp. 7–22, 1938.

on a sufficiently large number of elements will generally establish weak preferred orientation.

Preferred orientations are statistically defined so that they are of different degrees. A preferred orientation is generally expressed by the percentage of measured elements which have attitudes lying between arbitrarily chosen limits.

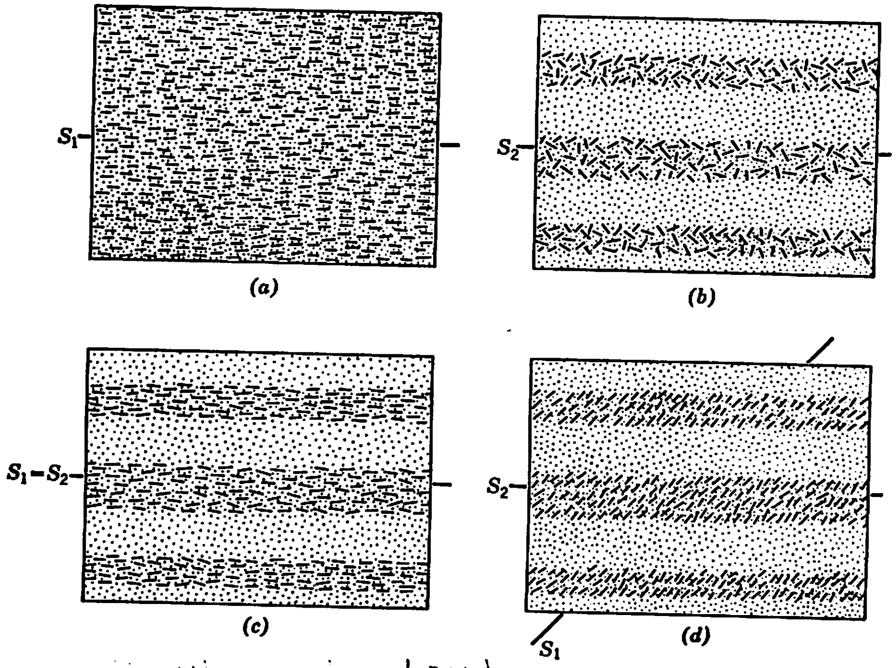

Fig. 2-8. *S*-surfaces defined by preferred orientation and preferred location of fabric elements. (*a*) Preferred orientation alone defines *s*-surfaces $S_1$. (*b*) Preferred location alone defines *s*-surface $S_2$. (*c*) Combination of (*a*) and (*b*) defines single *s*-surface, $S_1 = S_2$. (*d*) Combination of (*a*) and (*b*) defines two *s*-surfaces, $S_1$ oblique to $S_2$.

In structural analysis, fabric elements are said to possess preferred orientation where:

1. The preferred orientation is easily detectable by normal procedures employed in analysis (page 58). Some very weak preferred orientations detectable by special techniques are neglected in structural analysis of deformed rocks.

2. The pattern of preferred orientation is reproducible in comparable samples of the same elements similarly distributed in the same homogeneous domain.

A preferred orientation as defined above is a penetrative property of a body and is thus an aspect of its fabric. The preferred orientation exists whatever may be the position or location of elements in the body. Location of structures is by definition a nonpenetrative feature. Nevertheless, penetrative structures can be defined by preferred location of fabric elements as illustrated in Fig. 2-8, which shows the arrangement of planar elements such as {001} of mica crystals, lying normal to the plane of the figure. In Fig. 2-8*a* parallel preferred orientation of planar elements defines the family of penetrative surfaces $S_1$. In Fig. 2-8*b* similar elements lack preferred orientation but by their preferred location define nonpenetrative surfaces of discontinuity $S_1$. On a larger scale than Fig. 2-8*b* the surfaces $S_1$ could be a penetrative feature of a body and would then be fabric elements. In Fig. 2-8*c* a preferred orientation is combined with a preferred location to define a single surface $S_1$, and in Fig. 2-8*d* to define two mutually inclined surfaces $S_1$ and $S_2$ independent of each other in attitude.

**Anisotropy of Fabric.** A fabric lacking any preferred orientation or location of fabric elements is said to be isotropic. Conversely, an anisotropic fabric is a homogeneous fabric in which fabric elements are preferentially oriented or located. Because isotropy and anisotropy, like homogeneity, are statistically defined, both phenomena are dependent upon scale of domain.

Most fabrics—especially those of deformed rocks—are markedly anisotropic. Not every kind of fabric element present in a fabric need have preferred orientation for the fabric as a whole to be anisotropic. For instance, in some mica schists quartz and feldspar have no preferred orientation of lattice directions, so that the subfabrics for these crystallographic fabric elements are isotropic. In the same rock, however, {001} in mica may be in a state of strong planar preferred orientation. The subfabric for this element is anisotropic. A fabric is isotropic only where all determined subfabrics are isotropic.

## THE CONCEPT OF THE TECTONITE FABRIC

**Fabric and Deformation.** Something of the origin and evolution of any rock is recorded in its fabric. Deformed rocks have the most diverse origins and the longest and most complicated histories of development. Their fabrics are likely to be correspondingly complex and they pose problems in fabric interpretation that are less amenable to conventional methods of geologic investigation than are the fabrics of undeformed sedimentary rocks. This is why structural detail of regionally metamorphosed rocks has been largely neglected in much routine geologic mapping.

Historically, structural geology begins almost with geology itself; but at first it was virtually synonymous with stratigraphy. Concern was initially mainly with fossiliferous rocks which, by their very nature, are relatively weakly deformed or internally reconstructed. Their structures are generally simple and were most easily studied as a corollary to stratigraphy and paleontology. The work of Lapworth[20] in the Lower Paleozoic rocks of the Southern Uplands of Scotland is an example of the way in which paleontology and stratigraphy complement each other in structural studies. Although the existence of isoclinal folds was established by Lapworth, their full geometric properties were not determined, nor was the nature of the internal movements accompanying the formation of the folds fully appreciated.

In 1843 John Phillips published a paper entitled "On certain movements in the parts of stratified rocks"[21] in which he noted the distortion of fossils in folded rocks. Sharpe[22] in 1846 noted the same phenomenon and stated that the internal structure of a rock is changed by differential movements of its smallest parts during the formation of large folds. He mentioned that fossils in some folded and cleaved rocks are distorted to some degree in every part of the rock. In this paper Sharpe also cautioned against confusion of bedding with cleavage, and noted that in many gneisses the foliation and layering that resemble bedding are more closely related to cleavage, which he correctly interpreted as being of dynamic origin. These early writers were among the first geologists to realize that deformation penetrates a rock body on all scales, that the formation of even a simple open large fold is effected by intergranular and even intragranular adjustments throughout the body.[23] Moreover, because the structural changes on different scales in the same act of deformation can be correlated with each other, the distortion of a small volume such as a fossil or even a group of grains tells something about the distortion of the whole body.

**Componental Movements.** Many strongly deformed rocks, which on the basis of laboratory behavior under room conditions would be classified as rigid and brittle, show evidence of a previous mobility similar to that of viscous fluid or a plastically flowing solid. To denote the process whereby a rock is deformed continuously in space without loss of cohesion, the descriptive term *flow* is used. The mechanisms of flow in solid rocks are varied and imperfectly understood. Certainly they include intracrystalline plastic flow (translation and twin gliding), intergranular slip and rotation, cataclasis, recrystallization, and neomineralization. Such relative movements of component particles of crystals or rocks Sander[24] called *componental movements* (*Teilbewegungen*). He recognized two kinds:

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[20] C. Lapworth, The Moffat Series, *Geol. Soc. London Quart. Jour.*, vol. 34, pp. 240–346, 1878.

[21] J. Phillips, *Brit. Assoc. Adv. Sci.*, pp. 60–61, 1843 (Cork).

[22] D. Sharpe, On slaty cleavage, *Geol. Soc. London Quart. Jour.*, vol. 3, pp. 74–104, 1846.

[23] Sander, *op. cit.*, pp. 281–314, 1911.

[24] Sander, *op. cit.*, p. 115, 1930.

1. *Direct componental movements*, in which the relative movements of particles are highly correlated in a direct way, as in gliding processes within grains, and shearing and sliding movements between them.
2. *Indirect componental movements*, in which the correlation of relative movements can only be defined statistically, as in processes like ionic diffusion and migration along grain boundaries during recrystallization and neomineralization.

It is difficult to make any hard and fast distinction between these two kinds of movement.

The relative importance of these various processes in the history of most deformed rocks is unknown, but it may be presumed to influence their patterns of preferred orientation of grains or other structural features. Thus the patterns of preferred orientation of grains that arise when diffusion processes predominate will probably be different from those to which deformation by translation and twin gliding lead. However, our concern here is not with the patterns of preferred orientations themselves but with their symmetry, and from Curie's principles we may expect the symmetry of patterns of preferred orientation arising in given circumstances to be the same whatever the mechanism of deformation.[25]

**Tectonites.** *Definition.* Continuous solid flow of an aggregate is compounded of local componental movements differing amongst themselves and separated by discontinuities. Deformation is apparently continuous and homogeneous only in domains that are large in relation to these discontinuities in movement. On a microscopic scale surfaces of discontinuous movement in a flowing aggregate are either intragranular (surfaces of translation and twin gliding) or intergranular (boundaries between grains). Such movements together with indirect componental movements can lead to a preferred orientation of grains that is in some way an imprint of the deformation. Larger-scale discontinuities in movement occur (1) along discrete slip surfaces composed of aligned grain boundaries, that transgress a rock generally in parallel families, and (2) along surfaces which, while not actual slip surfaces, mark some change in the character of deformation—for instance, axial surfaces of some folds.

On a certain scale, penetrative discontinuities in structure are penetrative discontinuities in movement during flow, since on a smaller scale they separate domains with different kinds of behavior. Therefore a fabric that has been deformed by flow in the solid state preserves in the preferred orientation and disposition of its fabric elements a record of the nature and extent of deformation. Such fabrics Sander[26] termed *tectonites*. In much the same way a worked metal retains in its grain fabric a complete or partial record of the manner and degree of working, and the alignment of inequidimensional particles suspended in a fluid indicates geometric features of flow.

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[25] Paterson and Weiss, *op. cit.*, p. 860.

[26] Sander, *op. cit.*, p. 62, 1930.

Sander divides all rocks into tectonites and nontectonites. "Nontectonites have fabrics whose every individual component acquired its position and orientation uninfluenced by movements of neighboring grains. Processes forming nontectonite fabrics include mechanical settling, precipitation from solution or fusion, progressive crystallization at a migrating nonpenetrative surface, and so on. Most veins are nontectonites possessing growth fabrics? Most sedimentary rocks and some igneous rock thus are not tectonites but have depositional or growth fabrics. However, even compaction following sedimentation involves some direct componental movements; and in diagenetic processes indirect componental movements play a role that may be highly correlated with compaction. As so often happens with regard to rock classification it is neither possible nor desirable to distinguish sharply between the two contrasted classes; some rocks are transitional between tectonites and nontectonites.

For practical purposes a rock is here termed a tectonite if its fabric clearly displays coordinated geometric features related to continuous flow during its formation.

*Types of Tectonite.* Knopf and Ingerson,[27] following Griggs, recognize several types of tectonite, as follows:

1. Primary tectonites: those in which fabric components have responded to movements in an enclosing medium without themselves undergoing deformation. Into this category fall igneous rocks in which early formed crystals become aligned by continuous movements in an enclosing melt—"fusion tectonites" in Sander's terminology. Here also belong many current-laid sediments, such as dune sands, whose bedding and ripple patterns reflect the flow of air from which they were deposited.
2. Secondary tectonites: those in which components and fabric elements have responded directly to moving influences. Most or all deformed rocks fall into this category.
3. Mimetic tectonites: those in which growth or enlargement of grains by post-tectonic recrystallization or neomineralization has been influenced by the anisotropy of an existing tectonite fabric. Componental movements affecting mimetic fabrics are entirely indirect; structures initially present may be greatly intensified by growth of new grains in parallel preferred orientations. The new grains may be preferentially grown from existing nuclei or may arise by nucleation in a structurally anisotropic field. The mica fabrics of many post-tectonically crystallized schists are mimetic in that the parallel orientation of newly crystallized mica flakes preserves and intensifies preexisting structural surfaces.

The above categories are defined on a genetic basis. Sander[28] has also subdivided tectonites descriptively into *S*-tectonites, which have fabrics

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[27] Knopf and Ingerson, *op. cit.*, pp. 40, 41.

[28] Sander, *op. cit.*, p. 58, 1930.

dominated by planar features, and *B*-tectonites, which have fabrics dominated by linear features. There is no sharp line of demarcation between the two classes, and the distinction will be pursued no further.

*Metamorphic Tectonites.* The present work excludes weakly deformed rocks and both sedimentary and igneous tectonites of the primary class. Analysis of the fabric of primary igneous tectonites presents special problems of procedure and interpretation that have been developed in H. Cloos's classic treatment of "granite tectonics."[29] This book is restricted to metamorphic tectonites, the geometric features of whose fabrics clearly reflect the componental movements—direct or indirect—of flow in the solid state. The term tectonite is used henceforth in this restricted sense.

**Fabric Elements of Tectonites.** In general, tectonites have geometrically more complicated fabrics than do other rocks. Sedimentary rocks normally contain only one planar fabric element (bedding), commonly in a state of planar preferred orientation or some other geometrically simple condition; and only relatively rarely do they contain strongly defined linear fabric elements (for instance, groove and flute casts, lines of intersection of normal bedding and cross-bedding, and so on) of nontectonic origin. Most of these sedimentary structures have developed at an interface between the sediment and the medium of deposition (water, air, or ice); and they represent variations at this interface in time as well as in space, the record being but slightly modified by diagenetic processes.

In most tectonites, on the other hand, initially simple fabrics of sedimentary or igneous origin have been grossly modified, and their planar and linear features geometrically transformed by deformation. New structural features have appeared as a result of solid flow. Some tectonites have been formed from earlier tectonites by repeated deformation giving rise to complicated fabrics difficult to interpret. Sander[30] has distinguished between complete obliteration (*Umprägung*) of all initial geometric features of a fabric, and overprinting (*Uberprägung*) of new features on initial features without obliteration. Fabrics developed by the former process are relatively simple geometrically because only structural features that may be correlated directly with deformation are present. But such fabrics cannot be fully interpreted kinematically because no transformed structures inherited from the initial fabric remain as markers to show the nature and magnitude of deformation. Fabrics developed by overprinting, on the other hand, contain structural features inherited from one or more previous conditions of the fabric, together

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[29] E.g., H. Cloos, *Einführung in die tektonische Behandlung magmatische Erscheinungen*, Pt. I, Bornträger, Berlin, 1925; E. Cloos, The application of recent structural methods in the interpretation of the crystalline rocks of Maryland, *Maryland Geol. Survey*, vol. 13, pp. 36–49, 1937.

[30] Sander, *op. cit.*, pp. 29–31, 1930.

with structural features imposed entirely by deformation. Such fabrics commonly have great geometric complexity, but, because they contain fragments of their past history as distorted and transformed markers, they are the most fruitful subjects for structural analysis.

Most tectonites are products of overprinting. The fabric of a tectonite, therefore, generally contains fabric elements of the following kinds:[31]

1. Elements inherited in a transformed but recognizable condition from an initial or earlier fabric—*inherited fabric elements.* They may be geometrically transformed so that their orientation has changed with respect to external coordinates; but they have retained their identity as planar or linear elements. Examples are planar sedimentary bedding surviving in tectonites such as the "pebble-free bands" in a deformed conglomerate described by Flinn,[32] and the transformed linear structures described from parts of the Scottish Highlands by Ramsay.[33]
2. Elements imposed entirely by deformation—*imposed fabric elements,* e.g., slaty cleavage and other kinds of secondary foliation.
3. Elements arising by geometric combination of inherited and imposed elements—*composite fabric elements,* e.g., any fold axis formed in inherited bedding or foliation; or lineations marking the intersection of a transformed inherited *s*-surface and an imposed foliation.[34]

A similar terminology can be applied conveniently to the subfabrics defined by the spatial arrangement of elements. Thus a given tectonite fabric can contain inherited, imposed, and composite subfabrics as parts of its total fabric. Also, subfabrics which are composite or imposed at one stage in the evolution of a complex tectonite may become inherited subfabrics at a later stage. A given subfabric cannot always be assigned to one of the above categories, particularly where patterns of preferred orientation of crystallographic fabric elements are concerned. In the experimental deformation of Yule marble[35] an initial pattern of preferred orientation of [0001] in calcite is found to be progressively modified during deformation; but the final pattern always shows the influence of the initial pattern even where strain of specimen is large and the initial pattern itself has been completely obliterated (cf. pages 349 to 351).

The kinematic information provided by the three categories of subfabric is discussed in Chap. 10.

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[31] See also Paterson and Weiss (*op. cit.*, pp. 876–879) for a more extended discussion.

[32] D. Flinn, On the deformation of the Funzie conglomerate, Fetlar, Shetland, *Jour. Geology*, vol. 64, p. 491, 1956.

[33] J. G. Ramsay, The deformation of early linear structures in areas of repeated folding, *Jour. Geology*, vol. 68, pp. 75–93, 1960.

[34] See for instance, L. E. Weiss and D. B. McIntyre, Structural geometry of Dalradian rocks at Loch Leven, Scottish Highlands, *Jour. Geology*, vol. 65, pp. 583–587, 1957.

[35] See, for instance, F. J. Turner, Lineation, symmetry and internal movements in monoclinic tectonite fabrics, *Geol. Soc. America Bull.*, vol. 68, pp. 12–16, 1957.

## SYMMETRY OF TECTONITE FABRICS

**Notion of Fabric Symmetry.** The notion of fabric symmetry has been discussed in detail by Paterson and Weiss,[36] upon whose analysis the following general discussion is based.

The symmetry of a rock fabric has much in common with that of a crystal lattice. Both are infinitely extended structures so that their symmetry operations form space groups.[37] The symmetry of a fabric differs from that of a crystal lattice, however, in that it is defined statistically. The symmetry of a fabric, like that of a crystal, can be expressed in terms of the point-group symmetry (finite-body symmetry) of a small representative sample of the fabric, because to define statistical symmetry only arbitrary translations in all directions need be added to the operations of point-group symmetry. In a heterogeneous situation—e.g., in an individual small fold within a large array of similar folds—translations are absent and the symmetry of the heterogeneous structure is strictly of the point-group type. Individual fabric elements likewise have point-group symmetry; and this of course may differ from the space-group symmetry of their three-dimensional array in a subfabric.

The different types (point-groups) of fabric symmetry referred to below may conveniently be denoted by the standard Schönflies symbols of the crystallographer.[38] The reader should familiarize himself more particularly with the five types listed on page 44, as represented in natural rock fabrics. The symmetry of a fabric depends upon the symmetry of its subfabrics; and this in turn depends on the symmetry of the component fabric elements.

**Symmetry of Fabric Elements.** Fabric elements of tectonites are lines and planes of discontinuity in the fabric. With rare exceptions, such as graded bedding and primary flow structures inherited from sediments, they are nonpolar; and in structural analysis of tectonites any polar structures that may be measured have customarily been treated statistically as if nonpolar. Thus the symmetry of the individual fabric element has a unique axis of infinite symmetry (normal to a planar, parallel to a linear element) and perpendicular to this a plane of reflection. It is of the Schönflies type $D_{\infty h}$—the symmetry of a nonpolar line. Combinations of related noncrystallographic elements may have symmetry lower than $D_{\infty h}$. A fold is fully specified by an axial plane within which lies the fold axis. The symmetry of the combined elements of the fold is $D_{2h}$—orthorhombic symmetry with three mutually perpendicular planes of symmetry, each normal to a twofold axis of symmetry.

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[36] Paterson and Weiss, *op. cit.*, pp. 863–870.

[37] For discussion of space-group and point-group symmetry the reader is referred to standard texts on crystallography, e.g., F. C. Phillips, *An Introduction to Crystallography*, pp. 221–272, Longmans, London, 1946. Statistical symmetry is discussed by Paterson and Weiss, *op. cit.*, pp. 853–856.

[38] Paterson and Weiss, *op. cit.*, Table 2, p. 849, 1961.

Unique crystallographic elements such as {001} in mica or [0001] in quartz also have nonpolar axial symmetry $D_{\infty h}$. However crystallographic elements that are symmetrically repeated within each crystal will have other classes of symmetry. For example, the three $\{01\bar{1}2\}$ planes of calcite—even though they may be located by measuring a single visible $(01\bar{1}2)$ twin lamella plus the optic axis [0001]—collectively define a fabric element with symmetry $D_{3d}$—a triad axis normal to which are three diad axes of symmetry. Again {110} in amphibole constitutes a fabric element with orthorhombic symmetry $D_{2h}$. Note that if only one of the crystallographically similar planes or lines is considered—e.g., the most conspicuously twinned of the three $\{01\bar{1}2\}$ planes in any grain of calcite—its symmetry is now $D_{\infty h}$.

Where fabric elements with crystallographic symmetry have a preferred orientation, the subfabric that they define can have pseudocrystallographic point-group symmetry, which is unlikely to arise from noncrystallographic elements. However, pseudocrystallographic symmetry does not necessarily follow from the preferred orientation of such fabric elements; for example, a calcite aggregate in which an *a* axis for each grain had for some reason become aligned parallel to a unique direction, but without accompanying alignment of *c* axes, would have symmetry $D_{\infty h}$. Pseudocrystalline symmetry occurs if there is preferred orientation of a set of equivalent nonunique crystallographic planes or lines. An example of a tectonite with pseudocrystallographic symmetry is the Poughquag quartzite studied by Higgs, Friedman, and Gebhart.[39]

**Symmetry of Subfabrics and Fabrics.** Because only centrosymmetric fabric elements have been measured so far in structural analysis only centrosymmetric subfabrics have been encountered. The study of natural tectonites has shown that, with respect to fabric elements of the kinds discussed in the previous sections, the natural tectonite fabrics have very few different kinds of symmetry. Excluding pseudocrystallographic symmetries defined by fabric elements with other than axial symmetry (that is, elements with symmetry other than $D_{\infty h}$), only 1-, 2-, and ∞-fold rotation axes, and planes and centers of symmetry, can be expected to arise. Therefore by putting $n = 1$, 2, and $\infty$ in a list of possible centrosymmetric groups of a homogeneous continuum,[40] only $S_2$ $(C_i)$, $C_{2h}$, $D_{2h}$, $D_{\infty h}$, and $K_{\infty h}$ are obtained.

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[39] D. V. Higgs, M. Friedman, and J. E. Gebhart, Petrofabric analysis by means of the X-ray diffractometer, *Geol. Soc. America Mem. 79*, chap. 10, fig. 6E, p. 285, 1960. This example has been considered in detail by Paterson and Weiss, *op. cit.*, pp. 864–865.

[40] Paterson and Weiss, *op. cit.*, p. 849, table 2.

These five symmetry classes are the observed classes of subfabrics of tectonites, and are named as follows:[41]

1. *Spherical fabrics*, symmetry $K_{\infty h}$: Fabrics have the symmetry of a sphere. Ideally this symmetry is shown by a random orientation of fabric elements and is therefore generally only approached in natural tectonites. Some hornfelses have subfabrics approaching this symmetry.
2. *Axial fabrics*, symmetry $D_{\infty h}$: Fabrics have the symmetry of a spheroid, that is, a unique axis which is the line of intersection of an infinite number of symmetry planes and is normal to another plane.
3. *Orthorhombic fabrics*, symmetry $D_{2h}$: Fabrics have the symmetry of a triaxial ellipsoid, that is, three mutually perpendicular planes of symmetry (plus three diad axes normal to them).
4. *Monoclinic fabrics*, symmetry $C_{2h}$: Fabrics have a single plane of symmetry (plus one diad axis normal to it).
5. *Triclinic fabrics*, symmetry $S_2 = C_i$: Fabric has no planes of symmetry.[42]

Each of the last three types has the symmetry of the holosymmetric class of the corresponding crystal system—(3) $m\,m\,m$; (4) $2/m$, (5) $\bar{1}$.

The symmetry of the total fabric is given by superposing the respective symmetries of the component subfabrics. Thus similarly oriented symmetry elements that are common to all the subfabrics are also symmetry elements of the total fabric. Symmetry elements not present in *all* subfabrics are not symmetry elements of the total fabric; and so the symmetry of a fabric cannot be higher than that of any of its subfabrics. Therefore, the five important types of symmetry listed for subfabrics above are also the important types that occur in fabrics.[43]

A subfabric can have the same symmetry as a total fabric, or it can have higher symmetry; it cannot have lower symmetry. This is in some respects analogous to the crystallographic situation where a given form can have the same symmetry as the crystal or a higher symmetry, depending on whether it corresponds to a general or a special form (e.g., {111} and {110}, respectively, in the orthorhombic sphenoidal crystal class 222). Fabrics in which all subfabrics agree in symmetry are termed by Sander[44] *homotactic fabrics;* those in which the subfabrics do not agree are termed *heterotactic fabrics.*

Experience shows that a few of the many possible subfabrics of a given fabric suffice to determine the symmetry of the total fabric. Thus if

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[41] See also, Sander, *op. cit.*, p. 146, 1930, and *op. cit.*, p. 26, 1950.

[42] Figures 3-13 and 3-14 show patterns of preferred orientation of fabric elements with the five kinds of symmetry.

[43] Examples of natural tectonite fabrics on various scales analyzed in terms of superposition symmetry of their subfabrics are given by Paterson and Weiss, *op. cit.*, pp. 869–870.

[44] Sander, *op. cit.*, p. 165, 1930.

account is taken of the preferred orientation of axial crystallographic elements of two major, dissimilar minerals (e.g., quartz and mica, or calcite and mica) together with that of noncrystallographic elements such as foliations and lineations, the total symmetry so defined generally remains unchanged when other subfabrics are also taken into account. Structural analysis can be greatly simplified by careful selection of the elements to be measured.

The symmetry of a bulk physical property of a rock is likewise a guide to symmetry of its fabric (functional fabric). Neumann's principle[45] states that the symmetry element of any physical property of a crystal must include all the symmetry elements of its geometric (morphologic) symmetry. Where this principle is applied to aggregates, the study of easily determinable physical properties (such as bulk electrical, magnetic, or thermal properties) may be a convenient guide to the geometric symmetry of its fabric by showing which symmetry elements are lacking. Further, the measurement of properties such as piezoelectricity allows detection of the absence of a center of symmetry, not otherwise possible. Such investigations are likely to be most useful in determining fabric symmetry in very weakly deformed rocks where conventional methods of geometric analysis yield conclusions of doubtful statistical significance, and in very fine-grained rocks in which conventional microscopic study is impossible.[46] However, it must be remembered that the symmetry of a bulk physical property need not be the ~~*same* as~~ the structural symmetry of a body; it need only include the symmetry elements of the body (page 386). For example, the optical properties of an isometric crystal have spherical symmetry whereas the crystal structure is less symmetrical. On the other hand, examination of several bulk physical properties will generally reveal the true symmetry of the body.

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[45] E.g., Paterson and Weiss, *op. cit.*, p. 857.

[46] E.g., R. Brinkmann, W. Giesel, and R. Hoeppener, Über Versuche zur Bestimmung der Gesteinsanisotropie, *Neues Jahrb. Geologie u. Paläontologie Mh.*, 1961, pp. 22–33, 1961.