ELEMENTS OF STRUCTURAL GEOLOGY

E. SHERBON HILLS FRS
Professor of Geology in the University of Melbourne

36 ESSEX STREET · LONDON · WC2

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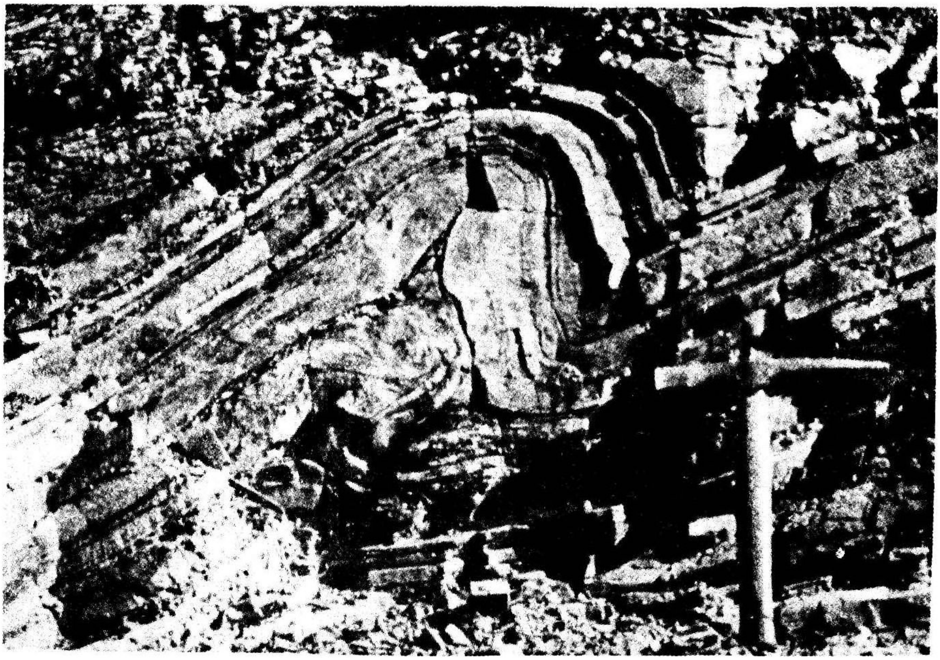

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Preface

The range of fundamental topics that should be included in a general work on structural geology is indeed very wide, but, despite the condensation needed to reduce these matters to a reasonable compass, I have tried to adhere to certain standards as to completeness of coverage, style of presentation, and adequacy of illustration.

Particular attention has been paid to definitions, both for the realities of structures and for concepts and notions, since definitions, far from being dry-as-dust material for rote learning, express much of what emerges from the systematization of knowledge, and it is desirable that the student should realize the extent to which they are conceptual and thus subjective. Experimental analogues and the relevant physical or chemical principles have been freely referred to, with as much discussion of pros and cons as is possible within the limits of a textbook. It is hoped that in these ways the reader may himself be induced to consider and weigh propositions, and thus to inculcate something of the author's own abhorrence of the cult of the fashionable theory, which so often in geology involves personal loyalties rather than intellectual integrity, and certainly does nothing to raise the scientific status of the subject.

For the Chapter on Geomorphology and Structure I have, of necessity, relied upon Davisian or genetic geomorphology, partly because quantitative terrain analysis, despite the 'precise and coldly analytical' methodology claimed for it, has not yet, so far as I am aware, included sufficient of structure in its premises to make it applicable to structural geomorphology, and partly because I have found Davisian principles, modified as required by new knowledge, most warmly satisfying in the field. It may, however, readily be foreseen that morphometric studies will in due course add their contribution to structural geomorphology and morphotectonics, at scales ranging from micro- to megatectonics. For the latter, I have briefly referred to several generalizations and theories, but have emphasized the need for further precise knowledge as to the morphological and geological data. Palæomagnetic results, although of great potential applicability in tectonics, are not discussed because the book deals mainly with the optically demonstrable features of rocks and rock masses, so that the implications of palæoclimatology, the past distribution of animals and plants, the distribution of magma-types and such and similar topics of significance in megatectonics are not dealt with.

Although the principles of structural geology are of general applicability, the particular needs of oilfield geology, engineering geology and mining geology call for certain specialized field and laboratory methods, including the geometrical processing of data according to the needs of particular problems. Detailed reference to such matters would be inappropriate in a book intended to deal with fundamentals, and indeed each of these specialities is itself treated in well-known textbooks. It is, however, well to note that, unless data are correctly diagnosed in the field, their geometrical processing is valueless, and the stress in this book is accordingly on the understanding of geological structures, although reference is made throughout to certain well-known methods of representation and reconstruction of structures.

The sequence of topics in my small 'Outlines of Structural Geology' has broadly been adhered to, as it permits a gradual introduction of notions, and appears to have been acceptable to many teachers, but I have not hesitated to make repeated reference to the same notion, for example, soft-rock deformation, under several headings, as the student often fails to transfer knowledge from one compartment of his mind to another.

The Chapter on Structural Petrology was kindly written at my request by my former colleague in Melbourne, Dr E. den Tex, now Regius Professor of Petrology in the University of Leiden, Netherlands. I am indeed grateful to him for having undertaken the difficult task of presenting this subject in a style and with a philosophy conforming generally with the rest of the book, and in so satisfying a manner in a single chapter.

I am much indebted also to Dr J. V. Harrison of Oxford for critically reading the MS. and for assistance in various other ways. It is a pleasure to acknowledge the kindness of those numerous colleagues who over the years have sent me their publications from many countries, as I have tried to draw examples and illustrations from a wide area, geology being *par excellence* a global science.

Acknowledgment is made to the under-mentioned Publishers, Journals and Serials for permission to use previously published illustrations as a basis for line drawings specially made in a uniform style for this book. Acknowledgment to authors, and to the sources of half-tone illustrations other than the author's own photographs, are made in the captions.

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Association of Petroleum Geologists, American Geophysical Union, American Journal of Science, Economic Geology, Geographical Review, Geologie en Mijnbouw, Geologische Rundschau, Geological Society of America, Geological Society of South Africa, Geological Magazine, Geologists' Association, Geological Society of London, Journal of Geology, Koninklijke Nederlandische Akademie Van Wetenschappen, Mineralogical Magazine, Neues Jahrbuch für Geologie, etc., New Zealand Journal of Science and Technology, N.V. de Bataafsche Petroleum Maatschappig, Physical Society of London, Royal Society of London, Royal Society of New Zealand, U.S. Geological Survey, Geological Society of Australia, Geological Survey of Great Britain, Geological Survey of Victoria.

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University of Melbourne, Victoria, Australia

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Contents

CHAPTER I

The Domain and Content of Structural Geology

The special province of structural geology among the branches of geological science lies in the recognition, representation, and genetic interpretation of rock-structures. Without for the moment defining precisely what is meant by rock-structures, let us consider any geological cross-section showing beds in various attitudes – flat-lying or inclined, folded or faulted – perhaps in places intruded by igneous rocks or covered with lava-flows, and again in places metamorphosed. Such a section shows the shape and attitude of the various rock-units present, and is said to represent the geological structure of that part of the earth, in the plane of the section. The shapes and attitudes of the several rock-units shown, as they now exist in the earth, are the result firstly of processes connected with their original formation when their *primary structures* were developed, and secondly of all later processes whether of mechanical deformation or chemical reconstitution, that have affected them. It is usual to distinguish those effects that are connected with the later stages of the formative processes of sedimentary or igneous rocks as *penecontemporaneous*, since they are intimately connected with the conditions that obtained during the origination of the rock in question, while structures of entirely subsequent formation are regarded as *secondary*. Uplift, tilting, faulting, or folding in general give rise to secondary structures, but although it is true that structural geology is very largely concerned with these, it is also clear that one must have a very good understanding of the objects that were thus deformed, and that attention must be devoted to the primary and penecontemporaneous structures of rocks before proceeding to treat with their secondary deformation.

The necessity for this is even more obvious if we consider how structural knowledge is gained in the field. When one observes a rock-exposure for the purpose of mapping, it is eventually necessary to record in the field-book some data on the geometry of the rocks, generally the dip and strike of some planar surface that one can identify in the exposure. It is therefore obvious that the real nature of such a surface must be recognized by the field-geologist. It is a common enough error to measure cleavage in slates in mistake for bedding, and other misconceptions are equally possible. In order to map structural data, the geologist working in the field must be able to recognize what he is mapping, which implies a very complete knowledge of the primary structures of sedimentary and of igneous rocks, as well as of secondary structures such as jointing, cleavage, foliation, and the like.

Although too much emphasis on primary structures in a work on structural geology might be regarded as usurping the field of interest of petrology or of sedimentation, many fundamental advances in our knowledge of sedimentation have in fact been made of recent years by structural geologists who have carefully examined the primary structures of sedimentary rocks. This is true particularly of the processes of subaqueous slumping and of deposition from turbidity currents. These topics are treated along with the primary structures of sediments in Chapter II of this book, which is followed in Chapter III with a discussion of penecontemporaneous structures and of structures which, although of secondary origin, are not the result of diastrophism, but of gravitational forces acting on soft or yielding rocks at or near the earth's surface.

Before proceeding further with secondary structures, those physical principles that are particularly applicable to the interpretation of rock-deformation are dealt with in Chapters IV and V, following which discussion we are equipped to proceed to what may be regarded as the core of the subject, that is to say with joints, faults, folds, and slaty cleavage. In the study of these we shall find that we are concerned with various types of planar and linear structure-elements both megascopic and, especially in metamorphic rocks, in the crystallographic elements of their component grains.

Structure and Fabric

In describing the geometry of rock-masses in terms of the various linear and planar structure-elements two distinctly different methods have been developed. The first recognizes and describes rock-structures which are actual entities or groups of entities such as folds, faults, and joints. The position of each of these is mapped, its form and other characteristics are described or illustrated, and its origin is debated. The chief methods of representation are by maps, cross-sections, block diagrams, and photographs. The second method treats with the geometry of rock-structures very largely on a statistical basis. The attitude of a great many individual structure-elements is mapped and plotted to reveal the statistical grouping of the elements – their attitude relative to geographical co-ordinates, and their mutual geometrical relationships – which together constitute the *fabric* of the rocks. Fabric studies are based on hundreds of observations recorded as notes and later transferred to *fabric diagrams*, which facilitate statistical analysis. Little may be plotted on the map as to the actual position of the many individual elements such as joint planes or dip readings which are measured. To illustrate the two methods, a house might be represented in plan and elevation by an architect's detailed drawings of the actual structures in the edifice; the fabric, however, might be said to exhibit strong maxima for vertical planes in two directions at right angles (the walls), and a third horizontal direction of planes – a flat roof, floors, and ceilings. The two methods supplement each other, but in many practical matters it is the location and attitude of actual structural entities that is in the long run essential, as in mining and in petroleum and engineering geology. Fabric analysis has been applied particularly to the microscopical and semi-microscopical features of rocks, including grain-shape, various crystallographic directions and planes (optic axes, twin planes, etc.), and small-scale structures seen in hand specimens. This is variously known as structural petrology, petrofabric analysis, or micro-tectonics. The term fabric, however, includes not only the microfabric but also the megascopic structures, and statistical treatment may usefully be applied to these latter. Accordingly the opportunity is taken in Chapter VI to give an introduction to the graphical representation of statistical data, which is of general applicability throughout the book. A more complete account of fabric analysis is given in Chapter XIII which treats with Structural Petrology and which, apart from the remarks on cleavage in Chapter X, affords the chief account of metamorphic rocks in this book. Igneous rocks are dealt with in Chapter XII. They are unique in that they preserve many structures that originated in the fluid phase and the presence of fluid also affects their space relationships in the stress-strain pattern of a region.

Geotectonics

The study of a small area inevitably leads the structural geologist to consider the 'setting' of his area in the broader framework of the surrounding region. He wishes to fit his mapped beds, folds, and faults into the pattern of folded or faulted belts of the whole country, and soon finds that he is thinking on a continental scale. While there seems no logical reason from considerations of size or area alone to divorce such broad investigations and research from structural geology, traditionally the wider aspects of continental and oceanic, and eventually of global structures, are referred to as *tectonics* or *geotectonics*. Some treatment of major fold belts, fault zones, and the like is essential in any course on structural geology and these topics are discussed in Chapter XI, but structural geology is concerned essentially with the outer layers of the globe, and detailed discussion of topics that involve the geophysics of the deep interior of the earth are accordingly omitted from this book, or mentioned only briefly as the occasion may demand.

Following Chapter XIII on Structural Petrology, much of which is concerned with micro-tectonics, the scale of our observations again changes vastly, to that of the landscape, in dealing with Morphotectonics in Chapter XIV. This is a fruitful field which no field-geologist can afford to neglect, and it is pleasing to note a revival of interest in geomorphology and its structural implications among geologists, after a long period of neglect.

The Literature of Structural Geology

At fairly frequent intervals, one or other branch of structural geology has been given a fresh outlook by the introduction of some new concept or, perhaps more often, by the realization some that idea, previously expressed but long neglected, is, in fact, useful and stimulating. Even if at times such saltations in thought have had their opponents and have led to controversy, the lively discussions that have resulted have often stimulated further interest and research. Topics such as folding, faulting, nappe structures, cleavage-formation, the structures of igneous rocks, petrofabric analysis, gravitational sliding, or the influence of basement structures on superincumbent rocks or on younger structures, to name only a few, will amply repay historical review by the serious student.

Indeed there are so many ancillary ideas, illustrations, and facts stored in the voluminous literature of structural and regional geology that it is both profitable and pleasurable to pursue bibliographic research in these fields. The references given throughout this book are regarded as those most useful on any particular topic but are far from exhaustive. The chief textbooks in languages other than English are listed at the end of this Chapter.

Brief acquaintance with the literature will immediately reveal to the student the unfortunate circumstance that there are wide variations in meaning attached to many terms in structural geology, even for some that are most fundamental and, if one recalls one's elementary instruction in geology, apparently simple, such as 'unconformity'. The following passage is taken from a recent text: 'Almost every separation plane in a stratigraphic sequence is an unconformity of some duration.' The student may be pardoned for wondering what meaning the term unconformity actually has, when it can be so used for the separation planes in a series of beds which would, by all the usual standards, be termed a conformable series. Although alternative usages are mentioned in this book, an attempt has usually been made to arrive at what appears to be the most acceptable definition, and in places new definitions are proposed. Where there has been an agreed change in nomenclature, the older usage is referred to, as with 'pitch' for the currently used 'plunge' of folds, because it will be found in the literature and on maps antedating the change.

The best geological writings contain much fine description and sound thought, and it is essential for every student to read original works for himself. It is, however, equally imperative for him to keep an open and critical mind, and also, since the eye generally sees what the mind expects it to see, to learn in the field the art and skill which De la Beche so aptly named as that of the 'Geological Observer'.

Foreign Textbooks

V. V. Beloussov, *Basic Problems of Geotectonics*, Moscow, 1954 (in Russian).
J. Goguel, *Traité de Tectonique*, Paris, 1952.
K. Metz, *Lehrbuch der Tektonischen Geologie*, Stuttgart, 1957.

Depositional Textures and Structures

BEDDING

The most obvious and characteristic feature of sedimentary rocks is *bedding*,[1] by which is meant both the presence of recognizably different beds or strata in a sedimentary succession, and the presence within any one bed of depositional

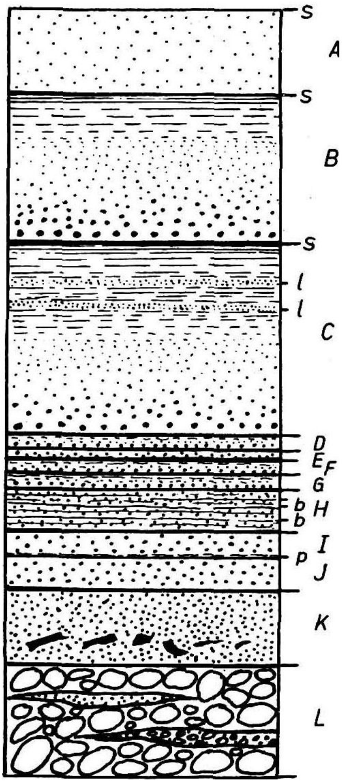


FIG. II–I. TYPES OF BEDS
Beds are bounded by separation planes (S).
A. Uniform, massive sandstone.
B. Simple graded bed, with uniform grading from grit below to shale above.
C. Complex graded bed with thin sandstone laminae (l, l) in the shale.
D, E, F, G. Thin individual beds (e.g. glacial varves).
H. Single sandstone bed with discrete bedding planes (b, b, etc.).
I. & J. Two standstone beds separated by shale parting (p.)
K. Heterogeneous bed of sandstone containing angular shale fragments.
L. Heterogeneous bed of conglomerate containing lenses of sand and gravel.

surfaces which are the bedding planes (Fig. II–1). In general each bed is fairly homogeneous and may be distinguished from other beds by some characteristic feature such as texture (e.g. shale, sandstone, conglomerate), com-

[1] W. H. Twenhofel, *Treatise on Sedimentation*, London, 2nd edn., 1932, pp. 603–756. K. Andrée, 'Wesen, Ursachen und Arten der Schichtung', *Geol. Rundsch.*, Vol. 6, 1916, pp. 351–97. G. W. Tyrrell, *Principles of Petrology*, London, 3rd edn., 1934, pp. 196–202. J. Bokman, 'Terminology of Stratification in Sedimentary Rocks', *Bull. Geol. Soc. Amer.*, Vol. 67, 1956, pp. 125–6. A. Lombard, *Géologie Sédimentaire*; Paris, 1956.

position (e.g. coal, limestone, shale), colour, hardness, or the like. Individual beds may, however, be recognized in certain sequences of uniform lithology by weathering of the separation planes between strata of similar lithological type or by the presence of very thin 'partings' of different rock, as for example of shale in sandstone. Rock-exposures usually reveal the stratification by differences in the weathering characteristics of the beds (differential weathering).

Although many beds are homogeneous, some show considerable variation, especially graded beds, in which there is a passage from coarser to finer particles towards the top; lateral gradation may also be found. Again, thin laminae or layers, differing somewhat in colour or texture, may be present without causing a bed to lose its individuality. It is the sum of its lithological features that characterizes a bed, with the implication that it was laid down under a particular set of conditions, either uniform, or systematically varying. Although the decision must often be arbitrary, some very thin strata are best regarded as beds rather than as laminae within a bed. Thus in glacial varves, each annual desposit is clearly worthy of recognition as an individual bed even though its thickness is to be measured in inches or fractions of an inch, whereas sandy laminae in a graded greywacke are but parts of the whole graded unit.[1]

The upper and lower surfaces of adjacent beds combine to form the *separation planes* in a sedimentary succession. Since they often mark a change in conditions of sedimentation and also a time-gap they may be of almost equal significance with the beds themselves in the history of sedimentation, and the top and bottom features of beds thus acquire special significance which is more fully discussed below (see p. 19). In addition, most beds possess an inner structure marked by *bedding planes* (*stratification planes*; the 'bed' of quarrymen), along which the rock will readily split. The bedding in detrital sediments in which the component grains were washed into place by currents, represents successive upper surfaces of the bed as the detritus was laid down, but in rapidly deposited sands and gravels the majority of such surfaces would almost instantaneously have been buried. Indeed the preservation of fine stratification is generally an indication of rapid deposition, for with very slow accretion the chances of disturbing thin deposits by waves and currents and by organisms are greatly increased. Stratification is revealed by slight differences in colour and texture and is usually best seen on weathered surfaces, but in some beds of very uniform lithology it is virtually invisible and may then be found by splitting the rock. Fossils such as graptolites and plant remains generally lie on bedding planes, and the parallel

[1] The distinction sometimes made between lamina, layer, and bed according to thickness alone is not only entirely arbitrary, but contrary to common usage whereby one speaks of a 'bed of laminated shale or limestone', a lamina being part of a bed. The term 'layer' has not gained general acceptance in the sense of a thin bed, and is best used in its evervday sense rather than as a technical term.

orientation of detrital mica-flakes may reveal the bedding in massive sandstones or mudstones. Shales and laminated brown coals (*Blätterkohle*) will split into very thin sheets parallel to the bedding.

The fissile nature of shales is largely due to the parallelism of micas and clay-mineral flakes, resulting partly from deposition, partly from the compaction of the deposit, and perhaps also from plastic flow parallel to the bedding under load.[1] Flaky particles such as mica generally lie flat in the stratification planes during sedimentation, even from currents, but in a slurry of mica mixed with other grains many flakes will come to rest in other attitudes. During compaction these are rotated, and the result is a tendency to parallelism. Flat pebbles laid down in the beds of streams or on stony beaches are often piled against each other, leaning at an angle to form *edgewise conglomerates*. In streams the pebbles lean down-stream, and on beaches away from the water's edge. The resultant texture of the conglomerate is misleading as to the true bedding, but is also to be distinguished from cross-bedding, especially as the dip of the pebbles is in the opposite direction in relation to the current, from that in cross-bedding.

Thus in describing bedding or stratification it is necessary to distinguish firstly between bedding or stratification *planes* which are individual structural entities such that each planar surface may be seen and traced, and depositional *textures*, which result from the parallel orientation of particles throughout a bed. Both are primary depositional features, and may be either parallel or inclined to the separation planes bounding beds (Fig. II – 2). Both bedding planes and depositional textures are included under the term *depositional fabric*, which has been discussed by Sander and others.[2] Use may be made of the orientation of pebbles and boulders in glacial tills, but the fundamental principles underlying their interpretation are not yet fully established.[3]

In addition, various textures, for example that due to the parallel orientation

[1] J. V. Lewis, 'Fissility in Shales and its Relations to Petroleum', *Bull. Geol. Soc. Amer.*, Vol. 35, 1924, pp. 557–90.

[2] B. Sander, *Einführung in die Gefugekunde der Geologischen Körper*, Vienna, 1948, pp. 312 ff.; *idem*, 'Contributions to the Study of Depositional Fabrics', *Amer. Assoc. Petrol. Geol.*, Tulsa, 1951, 160 pp. E. C. Dapples and J. F. Rominger, 'Orientation Analysis of Fine-Grained Clastic Sediments: A report of Progress', *Journ. Geol.*, Vol. 53, 1945, pp. 246–61. W. Schwarzacher, 'Grain Orientation in Sands and Sandstones', *Journ. Sed. Petrol.*, Vol. 21, 1951, pp. 162–72.

[3] C. D. Holmes, 'Till Fabric', *Bull. Geol. Soc. Amer.*, Vol. 52, 1941, pp. 1299–1354; R. F. Sitler and C. A. Chapman, 'Microfabrics of till from Ohio and Pennsylvania', *Journ. Sed. Petrol.*, Vol. 25, 1955, pp. 262–9; R. G. West and J. J. Donner, 'The Glaciations of East Anglia and the East Midlands. A Differentiation based on Stone Orientation Measurements of the Tills', *Quart. Journ. Geol. Soc. Lond.*, Vol. 112, 1956, pp. 69–91; J. W. Glen, J. J. Donner, and R. G. West, 'On the Mechanism by which Stones in Till become Orientated', *Amer. Journ. Sci.*, Vol. 255, 1957, pp. 194–204; D. W. Harrison, 'A Clay-Till Fabric: Its Character and Origin', *Journ. Geol.*, Vol. 65, 1957, pp. 275–308. See also G. Lundquist, 'The orientation of block material in certain species of flow earth' in '*Glaciers and Climate*', *Geogr. Annaler*, Hft. 1–2, 1949, pp. 335–49.

FIG. II–2. TYPES OF BEDDING

A. Sandstone with discrete bedding planes parallel to separation planes. (Parallel depositional structure.)

B. Sandstone with discrete bedding planes inclined to separation planes (cross-bedding). (Inclined depositional structure.)

C. Conglomerate with long axes of pebbles statistically parallel to separation planes. (Parallel depositional texture.)

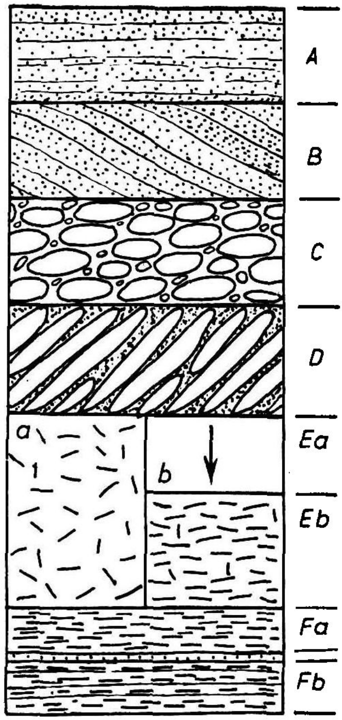
D. Edgewise conglomerate with long axes of pebbles inclined to separation planes. (Inclined depositional texture.)

E. (a) Uncompacted mud with random orientation of mica flakes and clay particles. (Random depositional texture.)

E. (b) Compacted mudstone with flaky particles statistically parallel, and parallel with separation planes. (Parallel compactional texture.)

F. (a) Mudstone with mica flakes deposited parallel to separation planes, but lacking discrete bedding planes (parallel depositional texture, cf. C above).

F. (b) Mudstone with mica flakes deposited parallel to separation planes, and showing discrete bedding planes. A thin bed of sandstone lies between the two mudstones.



of mica-flakes, may be induced by post-depositional effects such as compaction, extrusion of connate water, and perhaps other causes. These are post-depositional fabrics, but in many instances will be very difficult to separate from true depositional fabrics.

Pseudo-bedding. – Structures resembling bedding are fairly common especially in metamorphic rocks. Strong cleavage or regular parallel jointing in sandstones and limestones often gives a false appearance of bedding on weathering, but the true bedding may usually be recognized by careful examination of the rock to reveal fine stratification planes or orientated fossils (Fig. II – 3). In schists and gneisses, however, the original bedding may be almost obliterated by shearing and recrystallization along parallel planes (transverse schistosity, foliation, banding). In such rocks it may be difficult to identify and map original bedding. Structures closely simulating bedding are also formed in solifluxion masses and hill-creep material by differential flowage within the moving heterogeneous masses, giving rise to parallel orientation of pebbles, and layering of different grades of particles (Fig. V – 22, p. 125). Colour banding and layers of concretions may form in sedimentary rocks in almost any direction and also require to be carefully distinguished from bedding.