Park FOUNDATIONS OF STRUCTURAL GEOLOGY 2nd edition Blackie

Foundations of Structural Geology

SECOND EDITION

R.G. PARK, BSc, PhD, FGS

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University of Keele, UK

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To many generations of students who have unwittingly provided the inspiration for this book, and to my wife, for typing and support.

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Preface

In the Preface to the first edition of this book, published in 1983, I explained my reasons for writing the book as follows.

'There are already a number of excellent books covering the various aspects of Structural Geology. Among these are works by Hobbs, Means and Williams, Jaeger and Cook, Price, Ramsay, and Turner and Weiss, all of which I have used extensively in preparing this book and have listed therein as further reading. However, these textbooks are rather advanced for many students commencing the study of geology, and for many years I have been aware of the lack of a suitable elementary book which I could recommend to beginners. My purpose in writing this book, therefore, was to supplement existing textbooks by providing an introduction to the subject which will convey enough information over the whole field of structural geology to stimulate the reader's interest and encourage further study of more advanced textbooks and scientific papers.'

In the intervening six years since these words were written, the demand for a short, inexpensive, and reasonably comprehensive *elementary* textbook has continued to be just as great.

The revised edition contains a number of completely new sections. Extensional and strike-slip tectonics, and terrane accretion, are dealt with for the first time, reflecting the tremendous growth of interest in these topics among structural geologists over the last few years. I have responded to pleas from Scandinavian colleagues to incorporate a section on stereograms (which forms the Appendix) and an introductory section on elementary geometry and basic concepts, so that the book can be used, if necessary, as the sole introductory text on structural geology. The new introductory section also contains definitions and explanations of a number of important stratigraphic and structural concepts that need to be understood in the early stages of learning structural geology from geological maps. It must be stressed, however, that geological map interpretation must be carried out as a complement to any theoretical treatment of the subject, in order to appreciate structure in three dimensions.

I have also made numerous corrections and improvements to the text and also to the illustrations, many of which have been replaced. In doing this, I have incorporated many helpful suggestions from colleagues and reviewers. In particular, I should like to thank Alan Wright of Birmingham University, who supplied a most helpful and detailed list of suggested improvements. I wish to re-iterate my indebtedness to Paula Haselock, Nick Kusznir, and Rob Strachan (all at that time at Keele), and to two anonymous reviewers who read the draft of the first edition and made many useful suggestions for its improvement. I am especially grateful to Rob Standley, then of City of London Polytechnic, for his meticulous checking of the original manuscript and for a host of valuable suggestions. Many of the original diagrams were drawn by Paula Haselock, whose willing and cheerful help made the task of writing the book much easier.

Finally I wish to make it clear that I have ignored many pieces of good advice in relation to both the first and second editions, usually because of my overriding desire to make the book as short as possible, and that any remaining deficiencies are entirely my own responsibility.

RGP

Introduction

Meaning and scope of structural geology. It is easier to give examples of geological structures than to define them. The word 'structure' means 'that which is built or constructed'. Structural geologists use the word to signify something that has been produced by deformation; that is, by the action of forces on and within the Earth's crust. Structures consists of a *geometric arrangement*— of planes, lines, surfaces, rock bodies, etc. The form and orientation of this arrangement reflect the interaction between the deforming forces and the pre-existing rock body.

Description and classification of structures. Because the geometry of structures is so important, a large body of descriptive nomenclature and classification has grown up, which it is essential to master if we wish to describe and understand structures. The arrangement of this book reflects my belief that there is little point in discussing such matters as stress, strain and processes of deformation before learning what it is that we wish to explain by such processes. Thus I have discussed the more descriptive aspects of structural geology (*morphology*) in Part 1 before proceeding to discuss deformation in Part 2.

Deformation. This is the process that changes the shape or form of a rock body—in other words, the process responsible for the formation of geological structures. To understand deformation, it is necessary to understand *stress* and *strain*, which deal with the manner in which material reacts to a set of forces. We must also discuss the *behaviour of materials*, since the way that a rock deforms is dependent on the physical properties of different rocks and on how these change with changes in temperature and pressure, and with time. We can then apply the principles of deformation to the formation of specific types of structures such as faults and folds.

Geotectonics. In the third section of the book, I have attempted in a very selective way to show how structures and deformation may be related to large-scale Earth processes. The subject of geotectonics essentially covers large-scale structural geology—that is, the study of large Earth structures such as mountain belts and continental margins. The advent of *plate tectonics* has meant that many types of hitherto unrelated geological phenomena can be explained in terms of a unifying theory of crustal movements and processes. It is essential for the structural geologist to see individual structures or deformed areas in their context and to try to relate them to some large-scale pattern, even if the attempt subsequently proves to have been a failure. Only in this way will our understanding of the Earth progress.

Other related topics. There are some topics which I have omitted, partly because I wished to keep the book as short as possible, and partly because they are only of marginal concern and are adequately dealt with in other textbooks. One of the more important of these is *sedimentary structures.* Structures produced as a result of processes associated with sedimentation are not of great concern to most structural geologists, who are more interested in the deformation of solid rocks. However, there are areas of overlap between sedimentary and structural geology that should not be forgotten. One important problem for the field geologist is distinguishing between sedimentary and deformational structures. This problem is particularly acute in highly deformed metamorphic terrains where the origin of early and poorly-preserved structures is often unclear. Fold-type structures produced by soft-sediment slumping and other processes are open to misinterpretation. When fold-type structures are confined to a single layer (particularly if they are truncated by the layer above) they are likely to be of sedimentary origin and must be treated with caution.

Many sedimentary structures are, of course, of indirect interest to the structural geologist since they reflect tectonic control. Thus features indicating slumping or sliding of soft or unconsolidated sediments are often a direct result of tectonic processes such as earthquakes, fault movements, etc. Certain sedimentary structures are also of value to the structural geologist as indicators of the younging direction of the strata. Cross-bedding, graded bedding and other 'way-up' structures have been used extensively in highly deformed terrains to elucidate the large-scale structure (see Figure 2.5).

Another important topic that is avoided is the interpretation of geological structures from maps and aerial photographs. I hope that students who read this book will have had, or will gain, some experience in this subject since it is essential to the three-dimensional appreciation of structural geometry. There are a number of excellent textbooks on geological maps and air photo interpretation that the reader may consult. However, certain basic stratigraphic and geometric concepts relating to map interpretation of structure are outlined below.

Stereographic projection, an essential geometric tool in structural geology, is dealt with in the Appendix.

Warning to students! It is easy for a student to be misled into regarding what is printed in a textbook as unquestioned and immutable truth. However, in geology, perhaps more than in other sciences, today's facts may become tomorrow's discarded theories. Much of the material of this book is based on the opinion of established experts based on sound evidence. Some of it is disputed. Be sceptical!

Many textbooks attribute all statements to their original author by liberal reference to published work. In this way an impression is conveyed of a changing body of fact built up by numerous individual scientists, sometimes with opposing ideas. This is of course the correct scientific procedure. However, I have chosen in this short book not to follow this procedure because I feel that large numbers of references break up the smooth flow of the text and make for less easy comprehension. Instead, I have listed selected references for further reading at the end of each section, hoping that the reader will be encouraged to sample some of the original contributions to the subject and to proceed to more advanced texts.

Basic concepts

Bedding or stratification: definitions and geometry. A *bed* is a layer of rock deposited at the Earth's surface and bounded above and below by distinct surfaces (*bedding planes*); these usually mark a break in the continuity of sedimentation, i.e. a cessation of sedimentation, or a period of erosion, or a change in type or source of sediment. Beds are normally sedimentary, but may also consist of volcanogenic material. A thickness in the range cm to m is normally implied. 'Bed' is more or less synonymous with *stratum*, but the latter term is normally used only in the plural (e.g. 'Silurian strata'). Beds may be relatively homogeneous in composition and internal structure, and represent more or less continuous deposition. However, the term is also used for a sedimentary unit composed of numerous thin distinct layers. The term *bedded* means composed of beds: thus 'bedded rocks', 'thin-bedded', 'cross-bedded' etc.; *bedding* is used as a collective noun for the beds in a particular outcrop or area: thus, 'the bedding dips to the west'. The term is also used to describe various characteristics of the beds, such as 'cross-bedding' and 'graded bedding'.

The simplest type of bedding geometry consists of a set of parallel planes, representing a group of beds, or a *formation*, of uniform thickness. However, in practice, beds and formations vary laterally in thickness, in which case the geometry of the formation must be described by two non-parallel bounding surfaces. Thickness variation in such a formation may be described by a set of *isopachytes* (see below).

Onlap and offlap. Onlap is the term used to describe a structure formed where successive wedge-shaped beds extend further than the margin of the underlying bed, such that they lie partly on older basement (see Figure BC.1A). Such a structure is typical of sedimentary sequences in expanding basins with transgressive shorelines. The term *overlap* is synonymous. *Offlap* is the structure formed where successive wedge-shaped beds do not extend to the margin of the underlying bed, but terminate within it (see Figure BC.1B). Such a structure is typical of sedimentary sequences in contracting basins with regressing shorelines.

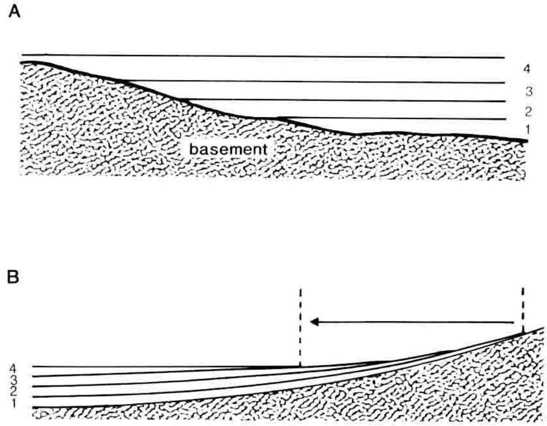

Figure BC.1 Cross-sections showing *onlap* and *offlap*. *A*, *onlap* of successive beds 1–4, each resting partly on older basement; *B*, *offlap* of successive beds 1–4, associated with a regressive shoreline.

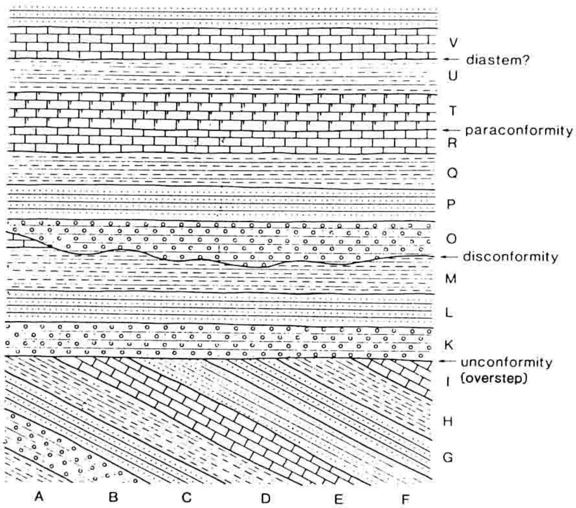

Figure BC.2 Schematic cross-section illustrating the various types of *stratigraphic break*. From Roberts (1982).

Unconformities and allied structures. Breaks in the stratigraphic record, representing intervals of geological time not marked by sediment deposition, are known variously as *diastems, non-sequences, paraconformities, disconformities* and *unconformities* (see Figure BC.2). *Diastems* represent pauses in sedimentation, marked by abrupt changes in sediment type, producing surfaces of discontinuity (bedding planes) but no other evidence of a time gap. *Non-sequences* (or *paraconformities*) are similar to diastems but exhibit faunal or other evidence of a time gap. *Disconformities* are marked by evidence of erosion during the sedimentary break, but the bedding below the erosion surface is parallel to that above, i.e. there has been no deformation of the lower series of beds prior to erosion.

Unconformities are distinguished from other stratigraphic breaks by angular discordance between the older beds below the unconformity surface, and the younger beds above. Hence an unconformity represents the following sequence of events:

(i) deposition of lower strata
(ii) tilting or other deformation of lower strata
(iii) erosion
(iv) deposition of upper strata.

The structure produced by the discordance of younger upon older strata is termed *overstep*, and the basal beds of the younger series are said to 'overstep' the various strata of the older series truncated by the erosion surface (see Figure BC.2). A *non-conformity* is a type of unconformity where younger strata rest on an erosion surface cut across non-bedded igneous rocks.

Geometry of inclined planes and lines. The attitude of an *inclined plane* such as bedding, foliation, faults etc. is conventionally described in terms of the *strike* and *dip* of the plane (see Figure BC.3A). The *strike* is the unique direction of a horizontal straight line on the inclined plane and is recorded as a bearing (azimuth). The *dip* is the inclination or tilt of a planar surface, e.g., bedding or foliation. The *true dip* of a plane (the angle from the horizontal to the plane) is measured in a vertical plane perpendicular to the strike, and is the maximum angle from the horizontal that can be measured for a given plane. Lines in any other orientation on the plane are at a smaller inclination to the horizontal; these angles represent apparent dips. The *apparent dip* is thus the angle of inclination of a given plane with the horizontal, measured in a plane that is not orthogonal to the strike. The angle of apparent dip measured in a series of vertical planes varies from zero (parallel to the strike) to a maximum in the direction of true dip. If the angle of apparent dip in two different directions is measured, the true

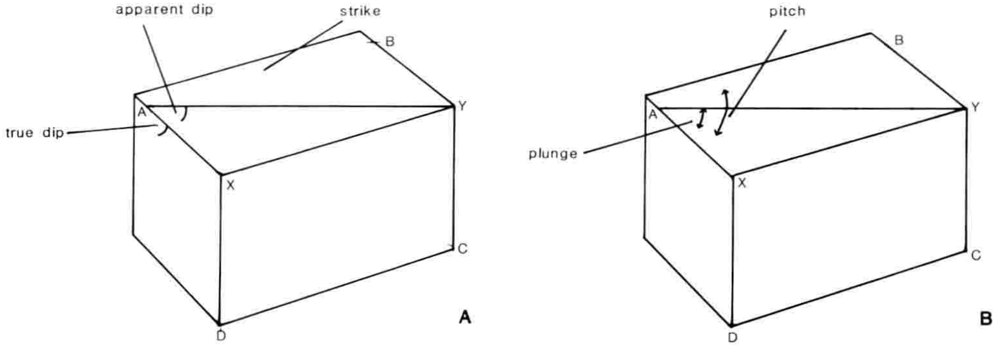

Figure BC.3 Inclined planes and lines. *A*, *strike* and *dip* of an inclined plane: the *true dip* of the plane ABCD is the angle XAD: the angle YAC is an *apparent dip*; *B*, *plunge* and *pitch* of an inclined line: the *plunge* of the line AC is the angle YAC: the *pitch* is the angle BAC.

dip can be calculated using a stereogram (see Appendix).

The *direction of dip* (i.e. the direction in which the plane dips downwards from the surface) is measured either directly as a compass bearing (azimuth) or in relation to the strike direction, which is 90° from the dip direction. Thus a bed may be said to dip at 30° SE, if the strike direction is specified, or at 30° to 110° if it is not. A dip arrow is the conventional representation of dip direction on a geological map. The position of the observation is indicated by the arrowhead, and the amount of dip in degrees is placed alongside the arrow. On many maps, this symbol is replaced by a line parallel to the strike, with a short tick indicating the dip direction.

The orientation of a *linear structure* (e.g. a fold axis) is measured in terms of *plunge* or *pitch*. The *plunge* is the angle between the line and the horizontal in the vertical plane. The plunge is given as an angle and a bearing (azimuth), which is the direction of plunge, thus, 30° to 045° or 30° NE. The *pitch* is the orientation of a line, measured as an angle from the horizontal, in a specified non-vertical plane. A measurement of pitch must give the strike and dip of the plane of measurement, plus the angle of pitch and the strike direction from which the pitch angle is measured (since there are two possible directions in a given plane for the same pitch angle)—see Figure BC.3B. This method is useful in the field where precise measurements of angles within inclined joint, foliation or bedding planes are more convenient than direct measurement of the plunge. The plunge may be easily derived using a stereogram (see Appendix). The instrument used in the field to measure the inclination (dip) of a planar surface or the plunge of a lineation is termed a *clinometer* and is often combined with a compass in order to measure the orientation of planes or lines with reference to geographic co-ordinates.

Representation of structures on geological maps. On geological maps, the attitude of planar beds etc., may be recorded by a set of *strike lines* drawn parallel to the strike of the plane or set of planes in question. If the dip of the planes is constant, the strike lines are straight, with uniform spacing. An increase in dip produces a decrease in spacing and a decrease in dip produces an increase in spacing (see Figure BC.4A). A surface with variable strike is represented by curved strike lines known as *structure contours* (Figure BC.4B). Structure contours follow a constant height on a geological surface, and a set of such contours, drawn at uniform height intervals, represents the three-dimensional shape of the surface in the same way that topographic contours represent the height variation of the land surface on a topographic map. A less precise but often more

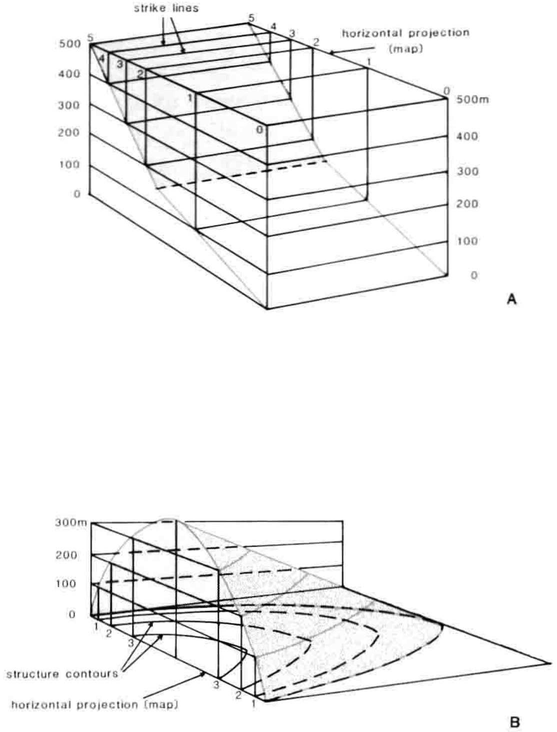

Figure BC.4 *Strike lines* and *structure (stratum) contours. A, strike lines* at heights of 0 to 500 m on the inclined plane (coloured) project as a set of parallel *strike lines* (labelled 0–0, 1–1 etc.) on the horizontal plane (map); the spacing is closer on the steeper part than on the shallower part of the inclined plane; *B*, an inclined cylinder (plunging fold) intersects a set of horizontal planes at heights of 0–500 m in curved lines termed *structure* or *stratum contours*: these project on the horizontal plane (map) as shown to give a map representation of the shape of the structure.

convenient method of portraying the structure on a map is to use *form lines*. These are lines drawn on a map to indicate the general direction of the strike of a folded surface (e.g. see Figure 2.13). A tick on the line indicates the dip. A set of form lines will illustrate the geometry of the folding in a similar way to the outcrop pattern of the strata, for example, but are more precise, and are not affected by topography. They can therefore be used in areas where individual formations have not been mapped. A set of form line contours can be drawn in a precise manner such that the spacing is proportional to the dip. A contoured map constructed by this means will illustrate the shape of a folded surface in the same way that a topographic contour map displays topographic relief (see Ragan, 1973). A *form surface* is any planar surface that intersects the ground surface as form lines and which may be used for structural mapping.

An *isopachyte* is a line joining points of equal stratigraphic thickness of a formation or group of strata. An isopachyte map is contoured to indicate the three-dimensional shape of a unit of variable thickness. The technique is used for example in the study of sedimentary basins and in portraying the geometry of stratigraphic units cut off by unconformities. Isopachyte maps may be prepared from borehole data from which thicknesses are directly obtainable, or by geometric construction using stratum contours for the top and base of the unit, and subtracting the lower from the higher values where they intersect. The line of intersection of a stratigraphic boundary with a higher stratigraphic boundary such as an unconformity is marked by the zero isopachyte of the rock body between the two boundaries in question. This line is often termed the *feather edge*, e.g. 'the feather edge of the base of the Coal Measures on the base of the Triassic'.

A related term is *subcrop*, which is the sub-surface 'outcrop' of a rock unit. A stratigraphic formation may intersect a sub-surface plane, e.g. an unconformity or fault, in a subcrop, which represents the area of the plane lying between the lines of intersection (*feather edges*) of the boundaries of the formation.

Topographic effects. In areas of horizontal or gently-dipping strata, outcrop patterns are controlled mainly by the topographic relief. Younger beds occur at higher topographic levels and older at lower levels. Outcrops of younger rock completely surrounded by older are termed *outliers*, and correspond to hills separated by erosion from other outcrops of the same beds (Figure BC.5). Conversely, an *inlier* is an area of older rocks surrounded by younger, e.g. in a valley cut through younger strata. Both outliers and inliers may be created by the interaction of structures with topography. For example an anticline or a horst (see Figure 1.9) crossing a valley may form respectively a fold or a fault inlier.

It is usually necessary to supplement the two-dimensional information on the geological structure of an area provided by the geological map by *cross-sections*, which are diagrammatic representations (normally constructed in the vertical plane) of the geology of an area. Reasonable assumptions are made about the way in which structures visible at the surface continue down-

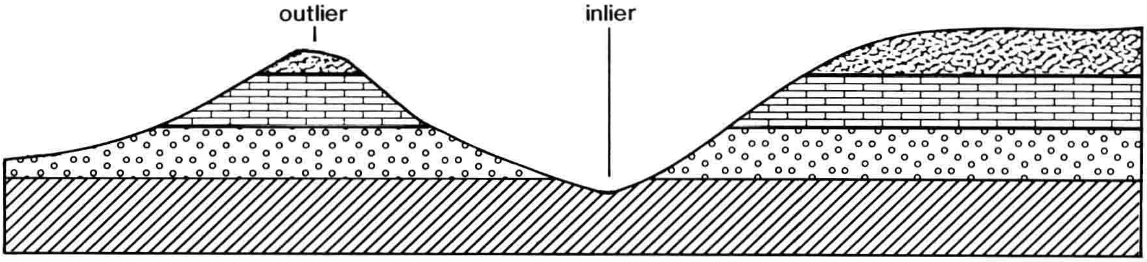

Figure BC.5 *Outlier* and *inlier* produced by the intersection of horizontal strata with topographic relief: the hill produces an outcrop of younger rock surrounded by older (*outlier*) and the valley an outcrop of older surrounded by younger (*inlier*).

wards, and the surface information may be supplemented by data from boreholes, wells, etc. Cross-sections may be drawn along a particular line or lines on the map, chosen to illustrate the vertical structure most effectively. The combination of map and cross-section should ideally give a good three-dimensional picture of the geological structure of an area. In complex areas, several lines of section may be used to give a better coverage of the structural variation.

Instead of a vertical section, a *down-plunge projection* may be employed; this is a reconstructed profile or cross-section of a fold structure drawn perpendicular to the plunge of the fold axis. This is done to give a more accurate representation of the fold geometry (see section 10.2).

It is important in interpreting the history of an area to be able to visualize the original geometry of a set of rocks before deformation. A geometrical reconstruction, in the form of a map or cross-section, is often employed for this purpose, and is termed a *palinspastic* reconstruction. *Balanced sections* (see section 8.7) are a special type of palinspastic reconstruction much used in the interpretation of complex fold/fault belts.

Further reading

Butler, B.C.M. & Bell, J.D. (1988) *Interpretation of Geological Maps*, Longman Scientific and Technical, Harlow, Essex.
Phillips, F.C. (1971) *The use of Stereographic Projection in Structural Geology*, Edward Arnold, London.
Roberts, J.L. (1982) *Introduction to Geological Maps and Structures*, Pergamon, Oxford.
Ragan, D.M. (1973) *Structural Geology: an Introduction to Geometrical Techniques* (2nd edition), Wiley, New York.

Contents

Part 1: Morphology—how to describe and classify structures

In this part of the book, the various kinds of geological structure are described and classified in terms of their shape or form (*morphology*). We shall deal in turn with *faults and fractures*, *folds*, *foliation, lineation and fabric* and *igneous bodies*.

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1 Faults and fractures

1.1 Rock fractures

Rock fractures are the commonest type of geological structure, and may be seen in any rock exposure. They are cracks across which the cohesion of the material is lost, and may be regarded as planes or surfaces of discontinuity. Where there is a measurable displacement across the fracture plane, that is, where the rock on one side has moved along the fracture relative to the other side, the fracture is termed a *fault*. Where there is no displacement, or where the displacement is too small to be easily visible, the fracture is termed a *joint*. Although the distinction between the two appears somewhat artificial, and depends on the scale of observation, in practice, the great majority of fractures show no, or negligible, displacement and are classified as joints.

Fractures are important in a number of ways. Their presence significantly affects the strength of a rock, and they must be carefully studied in civil engineering operations such as those involved in the construction of tunnels and dams. They are also important sites of mineralization, since dilational fractures developed under *extensional stress* are normally occupied by vein material deposited in the space created as the fracture opens.

1.2 Fault geometry and nomenclature

Definition of a fault. A fault is a planar fracture across which the rock has been displaced in a direction that is generally parallel to the fracture plane.

Geometry of displacement. The main elements of the displacement geometry of a fault are shown in Figure 1.1. Where the fault plane is non-vertical, the block above the fault is referred to as the *hangingwall* block and the block below the fault as the *footwall* block. The inclination of a fault plane may be given as a *dip*, in the same way as bedding (see Figure BC.3A), but is often measured as the angle between the fault plane and the vertical, in which case it is termed the *hade*. The displacement of the fault plane between the two blocks may take any direction within the fault plane. Faults with a displacement parallel to the strike of the fault plane are termed *strike-slip* faults and those with a displacement parallel to the dip of the fault plane are termed *dip-slip* faults. Faults with oblique-slip displacements are regarded as having strike-slip and dip-slip components, as shown in Figure 1.1. Strike-slip faults may also be called *wrench*, *tear* or *transcurrent* faults.

The measurement of the displacement on dip-slip faults is often made with reference to the horizontal and vertical components of the displacement, which are termed respectively the *heave* and the *throw* (Figure 1.2). It is the throw,

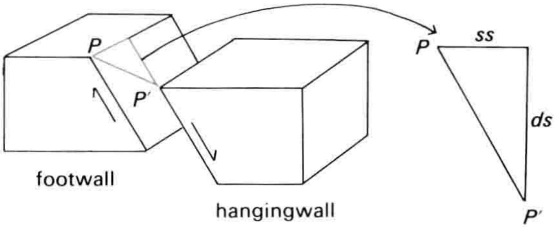

Figure 1.1 Components of fault displacement: *ss*, strike-slip component; *ds*, dip-slip component; *PP′*, true displacement vector.

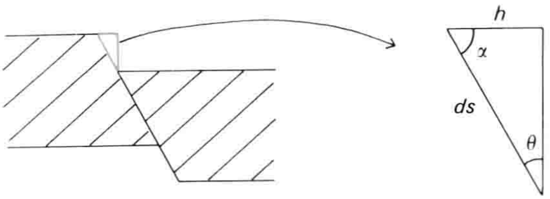

Figure 1.2 Geometry of dip-slip fault displacement: h, heave; t, throw; α, angle of dip; θ, angle of hade ($= 90° -$ dip angle); ds, dip-slip component of displacement.

or vertical displacement, that is normally quoted for a dip-slip fault rather than the true displacement. The relationship between these elements is given by

$$\tan\alpha = \frac{\text{throw}}{\text{heave}} = \frac{t}{h}$$

and

$$\sin\alpha = \frac{\text{throw}}{\text{true displacement}} = \frac{t}{ds} \qquad (1.1)$$

where α is the dip of the fault.

It is important to realize that fault displacements are difficult to measure in practice because it is frequently impossible to match precise points on each side of the fault. If bedding is displaced, we cannot be certain how much of the apparent displacement is due to dip-slip and how much to strike-slip movements (Figure 1.3*A*, *B*). The problem is overcome if the direction of movement on the fault plane is indicated by *slickenside striations* (see section 1.4) or if there is a measurable offset on a vertical structure, such as a dyke, which can be used to measure the strike-slip component (Figure 1.3*C*).

Sense of displacement. The sense of relative displacement on faults is important and depends upon the orientation of the fault with respect to the stress axes (see section 9.2). In the case of strike-slip faults, the displacement is termed *sinistral* (or left-lateral) if the opposite block moves to the left, and *dextral* (or right-lateral) if the opposite block moves to the right, as viewed by an observer standing on one side of the fault (Figure 1.4).

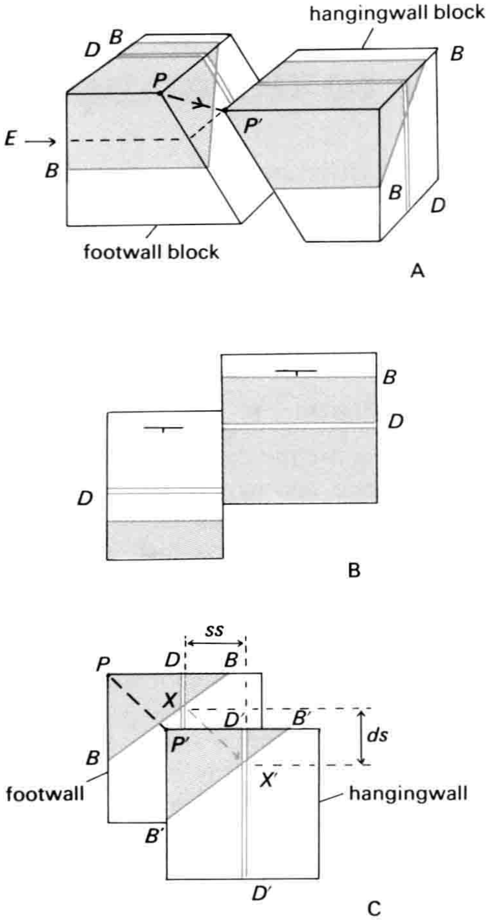

Figure 1.3 Measurement of fault displacement. (*A*) The fault affects dipping bedding *B*–*B* and vertical dyke *D*–*D*. The true displacement vector is *P*–*P*′. (*B*) Map at erosion level *E* of *A* shows horizontal displacement of bedding and dyke along fault. Note that the amount of displacement appears to be different. The true horizontal displacement is shown by the vertical dyke *D*–*D*. (*C*) View of fault plane looking down from the right, showing the trace of bedding *B*–*B* and dyke *D*–*D* on the footwall displaced to positions *B*′–*B*′ and *D*′–*D*′ on the hangingwall. The true displacement *P*–*P*′ is given by the movement of intersection *X* of *B*–*B* and *D*–*D* to position *X*′. The strike-slip component *ss* is given by the displacement of the vertical dyke *D*–*D* to *D*′–*D*′. The dip-slip component *ds* must be measured using both dyke and bedding displacements.

In the case of dip-slip faults, the displacement is termed *normal* when the hangingwall moves down and *reverse* when the hangingwall moves up, relative to the footwall (Figure 1.5). An alternative way of expressing the displacement

Figure 1.4 Sinistral and dextral displacements on strike-slip faults (plan view).

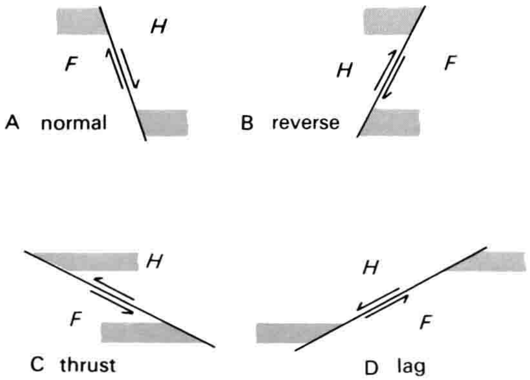

Figure 1.5 Normal and reverse displacements on dip-slip faults (vertical sections). *F*, footwall; *H*, hangingwall. *A*, normal fault; *B*, reverse fault; *C*, thrust; *D*, lag (low-angle normal fault).

in dip-slip faults is to refer to the direction of throw. The direction of dip of normal faults is towards the *downthrown* side, whereas in reverse faults the dip is directed towards the *upthrown* side. The sense of displacement in a reverse fault results in lower rocks (normally older) being placed above higher (normally younger), whereas the opposite is true in normal faults.

Thrusts and lags. Faults dipping at less than 45°, or low-angle faults, are distinguished from high-angle, dip-slip faults. If the sense of movement is reverse they are termed *thrusts*, and if the sense of movement is normal they are termed *low-angle normal faults*, or *lags*. Thrusts are particularly important in orogenic belts and often have displacements of many tens of kilometres. The Moine thrust which marks the north-western margin of the Caledonian orogenic belt in north-western Scotland (see Figure 15.7) has an estimated displacement of about 100 km. *Thrust*, *extensional* and *strike-slip fault systems* involve complex geometries and nomenclature, described in sections 9.4–9.6.

1.3 Rocks produced by faulting (fault rocks)

Fault breccia and gouge. Many faults are marked by a zone of broken and crushed rock fragments of varying size. This material is called *fault breccia* where the visible fragments make up an appreciable proportion of the rock. Where the bulk of the rock consists of fine powder, the material is termed *fault gouge*. Since such zones are normally softer and more easily eroded than the unfaulted rock, they give rise to the marked topographic depressions often associated with fault outcrops.

Cohesive crush rocks. Fault breccia and gouge are essentially loose-textured fault rocks found near the surface. At greater depth, various kinds of cohesive crush rocks are found where the rock is lithified and the increased pressure has, in many cases, caused partial recrystallization of the rock texture. Such rocks are termed *crush breccias*, where visible fragments dominate the rocks, or *cataclasites* where the fine-grained matrix makes up an appreciable proportion of the rock.

Mylonites. Structural geologists generally attempt to distinguish rocks formed under brittle conditions by breaking and crushing of the material (*cataclasis*) from those formed under ductile conditions by continuous recrystallization or flow (see section 7.3). Finer-grained rocks produced by the latter process are hard and 'flinty' with a platey or streaky texture. Such rocks are termed *mylonites* (Figure 1.6*A*). Where recrystallization is dominant, the rock is termed *blasto-mylonite*.

Ultramylonite and pseudotachylite. Extreme crushing produces a rock composed of broken fragments in a dark, often black, matrix of ultramicroscopic grains. Such material is termed *ultramylonite* (Figure 1.6*A*). Frictional heating caused by rapid relative movement along the fault may be sufficient to melt some of this material, forming a glassy substance, often containing spherulites, termed *pseudotachylite*, which forms veins intruding the adjacent frac-

Table 1.1 Classification of fault rocks. From Sibson (1977).

		Random-fabric		Foliated		
Incohesive		Fault breccia (visible fragments > 30% of rock mass)		?		
		Fault gouge (visible fragments < 30% or rock mass)		?		
Cohesive	Glass/devitrified glass	Pseudotachylite		?		
	Nature of matrix Tectonic reduction in grain size dominates grain growth by recrystallization and neomineralization	Crush breccia		fragments > 0.5 cm)		90–100% (*Proportion of matrix*)
		Fine crush breccia		(0.1 cm < frags. < 0.5 cm)		
		Crush microbreccia		(fragments < 0.1 cm)		
		Protocataclasite	Cataclasite Series	Protomylonite	Mylonite series	50–90%
		Cataclasite		*Phyllonite varieties*: Mylonite		10–50%
		Ultracataclasite		Ultramylonite		0–10%
	Grain growth pronounced	?		Blastomylonite		

tured rock (Figure 1.6*B*, *C*). Since the glassy material is usually devitrified, and contains a high proportion of unmelted fragments, it is often difficult to distinguish from ultramylonite except under high magnification. Pseudotachylite is apparently formed only at depth in the crust under moderate load pressure and a relatively rapid deformation rate. Thus a fault exhibiting soft gouge at the surface might develop pseudotachylite at intermediate depths, and at deeper levels might be replaced by a mylonite.

1.4 Features associated with fault planes

Slickensides. Fault planes frequently show shiny or striated surfaces caused by the rubbing or polishing action of the opposite face as it moved across. Such features are termed *slickensides*, and