An Introduction to Geological Structures and Maps is a concise text that leads the student by easy stages from the simplest ideas on geological structures right through a first course on geological mapping. The approach that Dr Bennison adopts is designed to help students working with little or no supervision: each new topic is simply explained and illustrated by text-figures, and exercises are set on succeeding maps. If the students are unable to complete the problems they should read on to obtain more specific instructions on how the theory may be used to solve the problem in question. In addition, problems relating to certain published geological survey maps are given at the end of most chapters.

Changes in ideas on teaching geological map interpretation have suggested revisions to the book. Apart from general amendments such as the updating of terminology, three main changes have been made: the topic of isopachytes, of wide application in economic geology, is introduced; more emphasis is placed on subsurface problems than in previous editions; and maps based on geological survey maps are introduced as are additional exercises on survey maps.

This new edition brings a popular text up-to-date.

24 maps 40 line diagrams

G. M. Bennison is Senior Lecturer in Geology at the University of Birmingham and has been a Consulting Geologist in the U.S.A.

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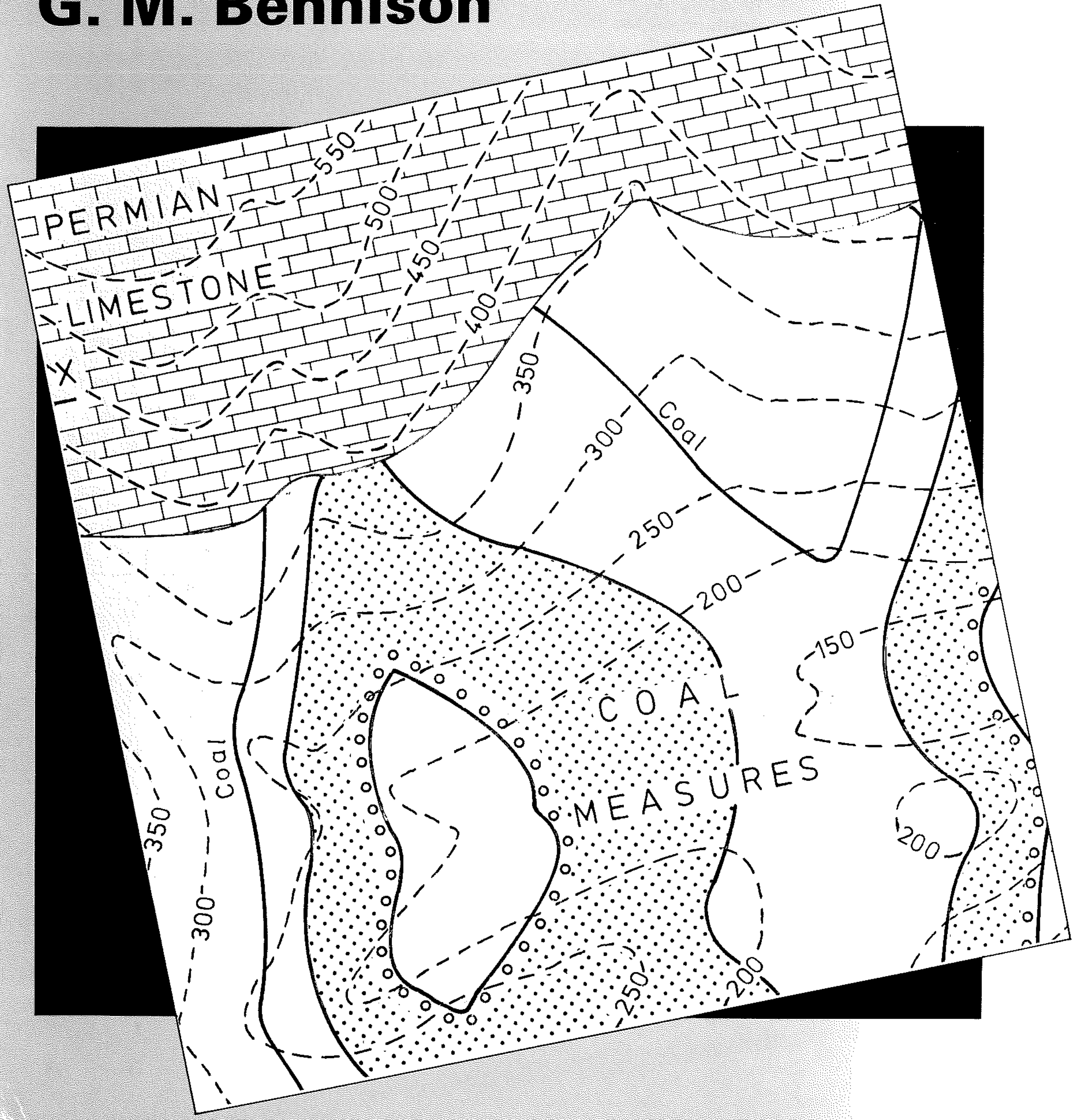
Bennison **An Introduction to Geological Structures and Maps**

An Introduction to Geological Structures and Maps

Fourth Edition

G. M. Bennison



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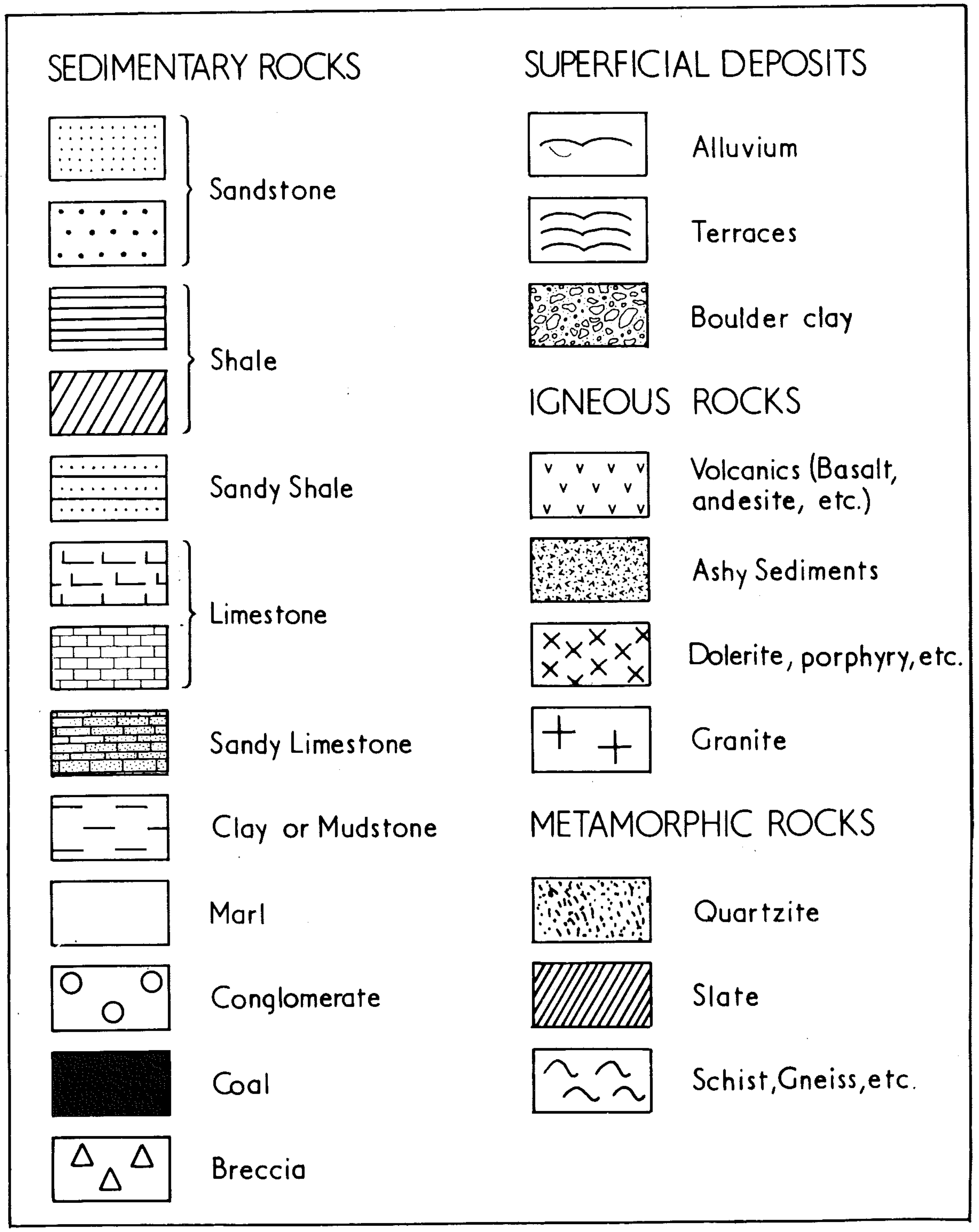


Key to shading widely used on geological maps and text figures.

Preface to previous editions

This book is designed primarily for university and college students taking geology as an honours course or as a subsidiary subject. Its aim is to lead the student by easy stages from the simplest ideas on geological structures right through the first year course on geological mapping, and much that it contains should be of use to students of geology at GCE 'A' level. The approach is designed to help the student working with little or no supervision: each new topic is simply explained and illustrated by text-figures, and exercises are set on succeeding problem maps. If students are unable to complete the problems they should read on to obtain more specific instructions on how the theory may be used to solve the problem in question. Problems relating to certain published geological survey maps are given at the end of most chapters. Some of the early maps in the book are of necessity somewhat 'artificial' so that new structures can be introduced one at a time thus retaining clarity and simplicity. Structure contours (see p. 10) are seldom strictly parallel in nature; it is therefore preferable to draw them freehand, though – of course – as straight and parallel as the map permits. In all cases except the three-point problems, the student should examine the maps and attempt to deduce the geological structures from the disposition of the outcrops in relation to the topography, as far as this is possible, before commencing to draw structure contours.

The author wishes to thank Dr F. Moseley for making many valuable suggestions when reading the manuscript of this book, Dr R. Pickering and Dr A.E. Wright for their continuing help and interest.

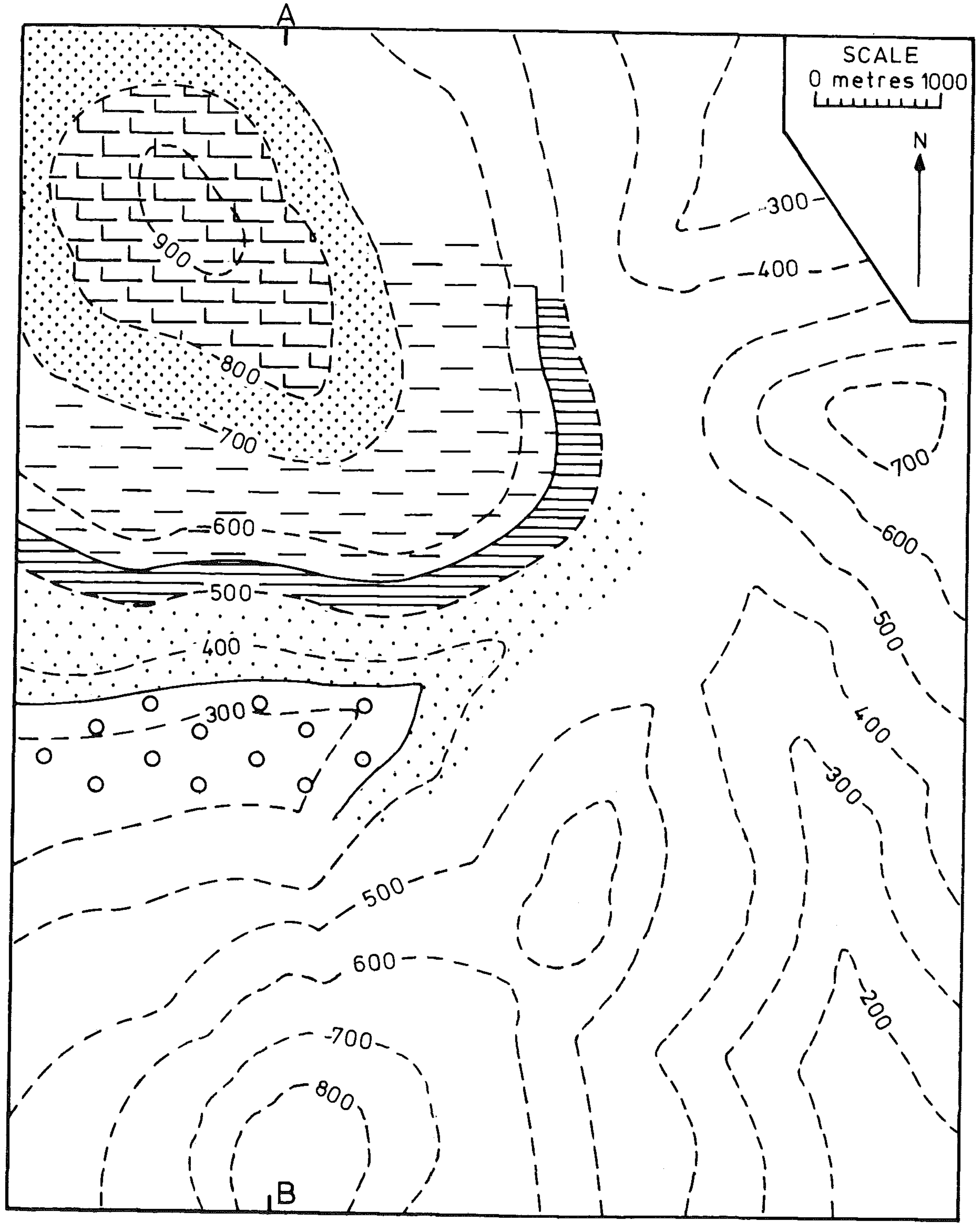
Preface to this edition

Changes in ideas on teaching geological map interpretation for first year degree course level, and for 'A' level syllabuses, indicated that some modifications might be made to the latter part of this book. Apart from minor amendments and the updating of terminology, three main changes have been made. First, the topic of isopachytes (see p. 30) is generally taught in degree courses but is not to my knowledge dealt with in any book on geological maps. Problems of overburden isopachytes are introduced first, being applied to Map 9 and a redrawn Map 10, while bed isopachytes are covered by two new maps, 18 and 19. Second, rather more emphasis is placed on subsurface problems. Third, in the last decade maps set by several 'A' level examining boards have been line drawings based on geological survey (BGS) maps. Their solution depends not on the construction of structure contours but on broad interpretation of outcrop patterns. Of course, all maps should be approached in this way, first deducing the general structures before drawing any constructional lines. Three maps, one new to this edition, are based on geological survey maps and additional exercises on survey maps are included. Where possible, terminology has been explained in the text, but if necessary, readers can consult a specialist dictionary, such as Monkhouse and Small, *A Dictionary of the Natural Environment*, (London, Edward Arnold, 1978), or Whitten and Brooks, *A Dictionary of Geology*, (Harmondsworth, Penguin, 1978).

My thanks are due to colleagues named above for their continuing interest and helpful suggestions, to Dr D.E. Roberts and especially to Dr R. Pickering, and to Mr Carl Burness for drafting my new and amended maps to such a high standard.

Birmingham
September 1984

G.M.B.



Map 1

1 Horizontal and dipping strata

Contours

Hills and valleys are usually carved out of layered sequences of rock, or strata, the individual members - or beds - differing in thickness and in resistance to erosion. Hence diverse topography (surface features) and land-forms are produced. Only in exceptional circumstances is the topography eroded out of a single rock-type.

In the simplest case we can consider strata are horizontal. Rarely are they so in nature; they are frequently found elevated hundreds of metres above their position of deposition, and tilting and warping has usually accompanied such uplift. The pattern of outcrops of the beds where the strata are horizontal is a function of the topography; the highest beds in the sequence (the youngest) will outcrop on the highest ground and the lowest beds in the sequence (the oldest) will outcrop in the deepest valleys. Geological boundaries will be parallel to the contour lines shown on a topographic map for they are themselves contour lines, since a contour is a line joining an infinite number of points of the same height.

Section drawing Draw a base line the exact length of the line A–B on Map 1 (19.0 cm). Mark off on the base line the points at which the contour lines cross the line of section: for example, 8.5 mm from A mark a point corresponding to the intersection of the 700 m contour. From the base line erect a perpendicular corresponding in length to the height of the ground and, since it is important to make vertical and horizontal scales equal wherever practicable, a perpendicular of length 14 mm must be erected to correspond to the 700 m contour (since 1000 m = 2 cm and 100 m = 2 mm) (Fig. 1). Sections can readily be drawn on metric squared paper (or on 1/10″ in some cases).

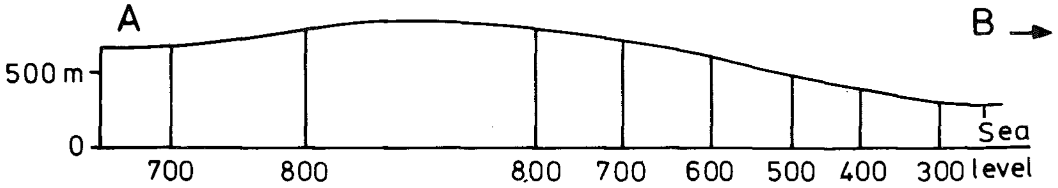
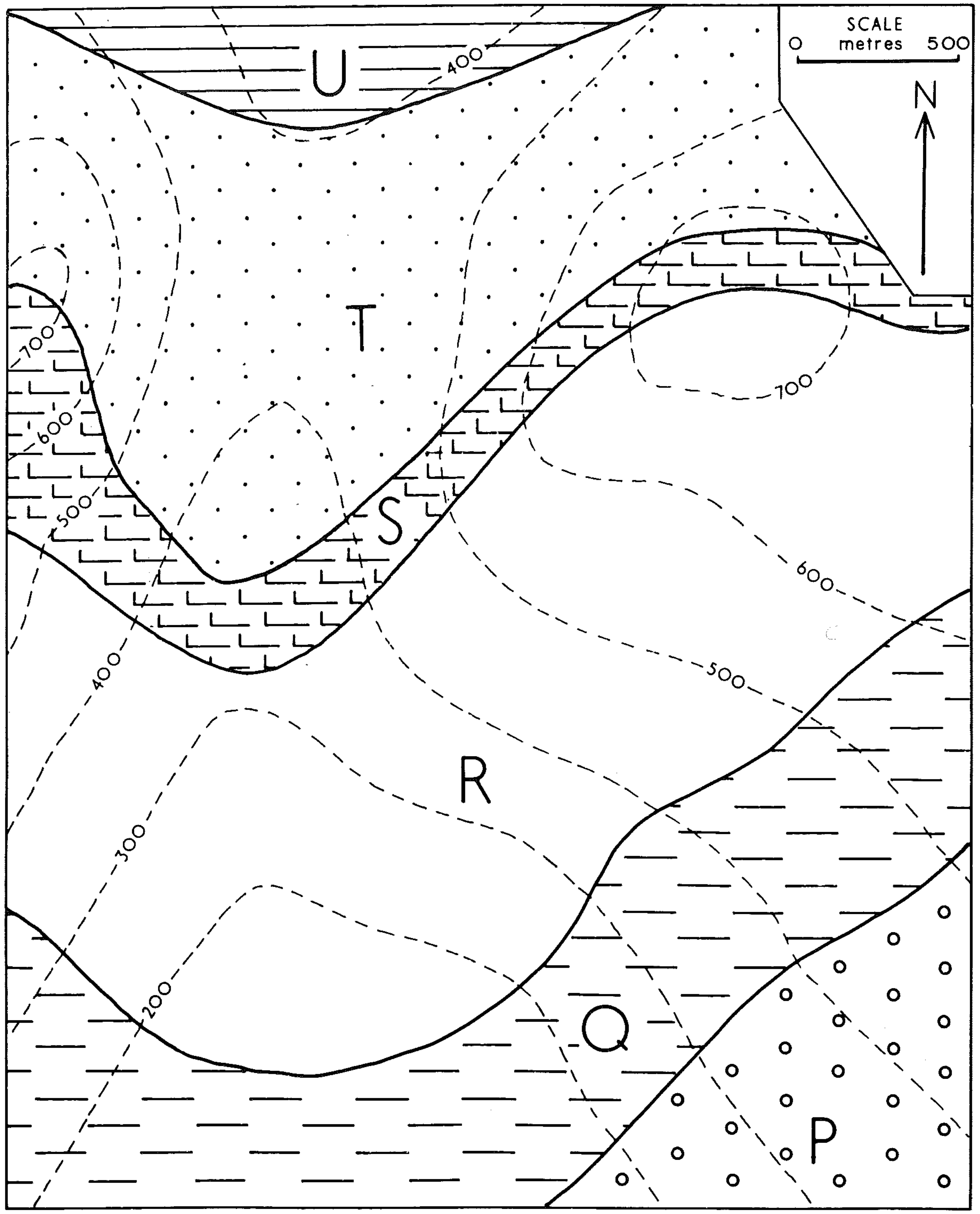


Fig. 1 Part of a section along the line A–B on Map 1 to show the method of drawing the ground surface (or profile).

Map 1. The geological outcrops are shown in the north-west corner of the map. It can be seen that the beds are horizontal as the geological boundaries coincide with, or are parallel to, the ground contour lines. Complete the geological outcrops over the whole map. Indicate the position of a spring-line on the map. How thick is each bed? Draw a vertical column showing each bed to scale, 1 cm = 100 m. Draw a section along the line A–B. (Contours in metres.)



Map 2

Inclined strata are said to be dipping. The angle of dip is the maximum angle measured between the strata and the horizontal (regardless of the slope of the ground) (Fig. 2).

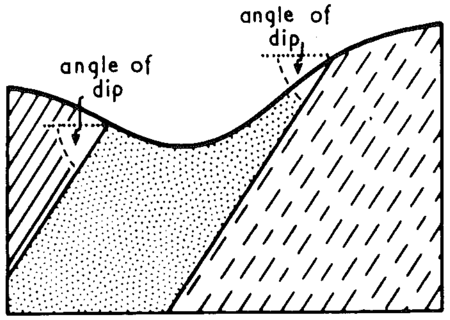


Fig. 2 Section showing dipping strata. The angle of dip is measured from the horizontal.

In a direction at right angles to the dip the strata are horizontal. This direction is called the strike (Fig. 3). An analogy may be made with the lid of a desk. A marble would roll down the desk lid in the direction of maximum dip. The edge of the desk lid, which is the same height above the floor along the whole of its length, i.e. it is horizontal, is the direction of strike.

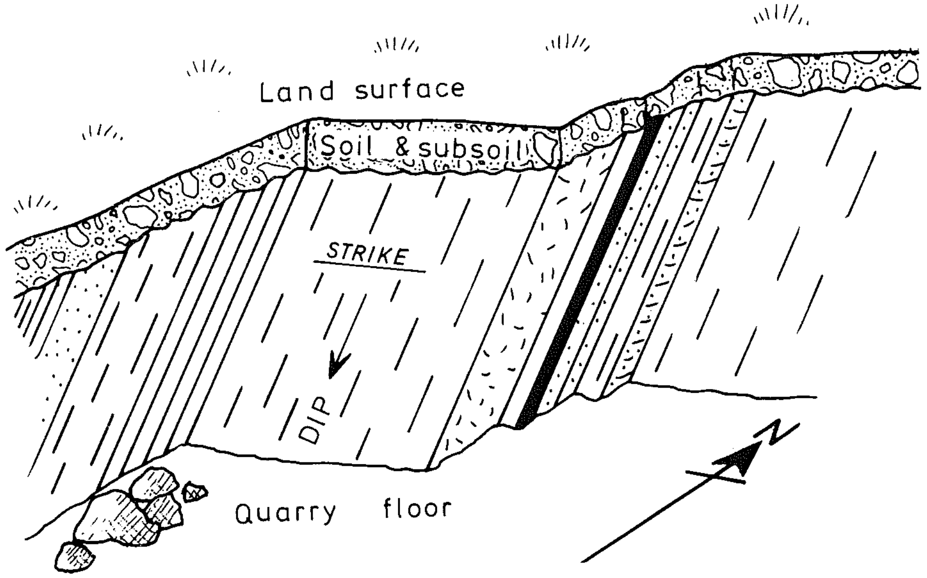


Fig. 3 Southerly dipping strata in a quarry. Note the relationship between the directions of dip and strike.

Map 2 The continuous lines are the geological boundaries separating the outcrops of the dipping strata, beds P, Q, R, S, T and U. Examine the map and note that the geological boundaries are not parallel to the contour lines but, in fact, intersect them. This shows that the beds are dipping. Before constructing structure contours can we deduce the direction of dip of the beds from the fact that their outcrops 'V' down the valley? Can we deduce the direction of dip if we are informed that Bed U is the oldest and Bed P is the youngest bed of the sequence? Draw structure contours for each geological interface* and calculate the direction and amount of dip. (Contours in metres.)

* Some confusion may arise since the term geological boundary is often applied both to the interface (or surface) between two beds also to the outcrop of that interface. It seems a satisfactory term to employ, however, since the two are related and the context generally avoids ambiguity.

Structure contours (= strike lines)

Just as it is possible to define the topography of the ground by means of contour lines, so we can draw contour lines on a bedding plane. These we call structure contours or strike lines, the former since they join points of equal height, the latter since they are parallel to the direction of strike. The terms are synonymous, but for the purposes of this book the term structure contours will be used.

Construction of structure contours

The height of a geological boundary is known where it crosses a topographic contour line. For example, the boundary between beds S and T cuts the 700 m contour at three points. These points lie on the 700 m structure contour which can be drawn through them. Since these early maps portray simply inclined plane surfaces, structure contours will be straight, parallel and - if dips are constant - equally spaced.

Having found the direction of strike we know that the direction of dip is at right angles to this, but we must ascertain whether the dip is 'northerly' or 'southerly'. A second structure contour can be drawn on the same geological boundary S–T through the two points where it cuts the 600 m contour. From the spacing of the structure contours we can calculate the dip or gradient of the beds (Fig. 4a).

Gradient = 700 m - 600 m in 1.25 cm
i.e. = 100 m in 1.25 cm.

As the scale of the map is given as 2.5 cm = 500 m, 100 m in 1.25 cm = 100 in 250 m.

Hence, **the gradient is 1 in 2.5.**

Frequently it is more convenient to utilize gradients, although on geological maps the dip is always given as an angle. By simple trigonometry we see that the angle of dip in the above case is that angle which has a tangent of $\frac{1}{2.5}$ or 0.4, i.e. 22° (Fig. 4b).

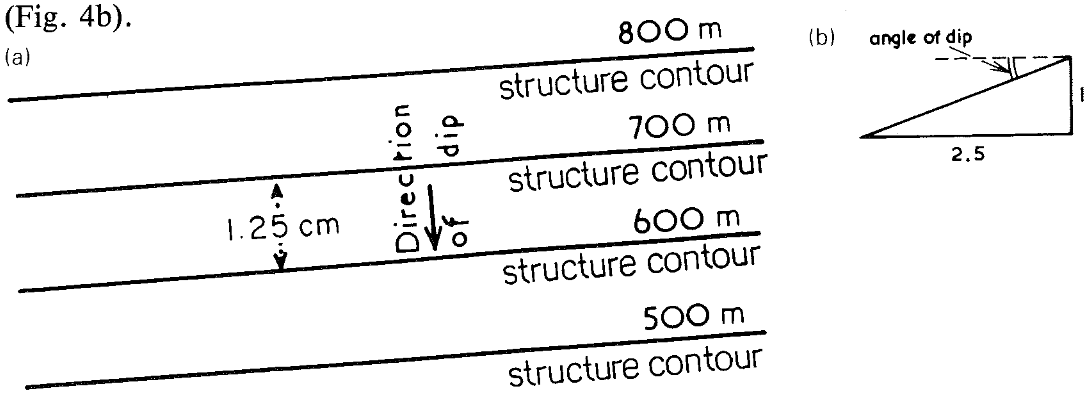


Fig. 4 (a) Plan showing structure contours and (b) section through contours showing the relationship between dip and gradient.

Section drawing The topographic profile is drawn by the method already described on page 7. The geological boundaries (interfaces) can be inserted in an analogous way by marking the points at which the line of section is cut by structure contours. Perpendiculars are then drawn from the base line, of length corresponding to the height of the structure contours (Fig. 5).

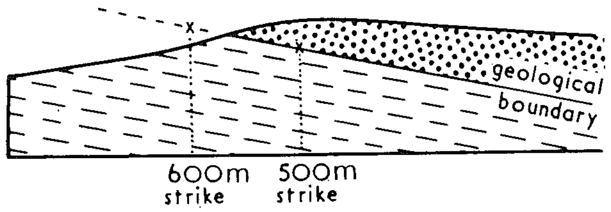


Fig. 5 Section to show the method of accurately inserting geological boundaries.

True and apparent dip

If the slope of a desk lid, or of a geological boundary (interface) or bedding plane, is measured in any direction between the strike direction and the direction of maximum dip, the angle of dip in that direction is known as an apparent dip (Fig. 6a). Its value will lie between 0° and the value of the maximum or true dip. Naturally occurring or man-made sections through geological strata (cliffs, quarry faces, road and rail cuttings) are unlikely to be parallel to the direction of true dip of the strata. What may be observed in these sections, therefore, is the dip of the strata in the direction of the section, i.e. an apparent dip (somewhat less than true dip in angle). The trigonometrical relationship is not simple:

Tangent apparent dip = Tangent true dip × Cosine β (see Fig. 6b; and Table II, p. 64).

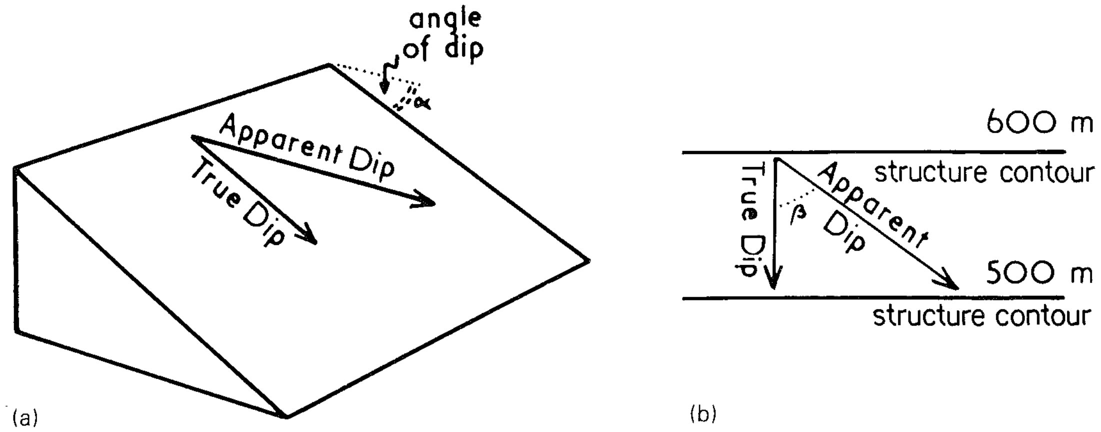
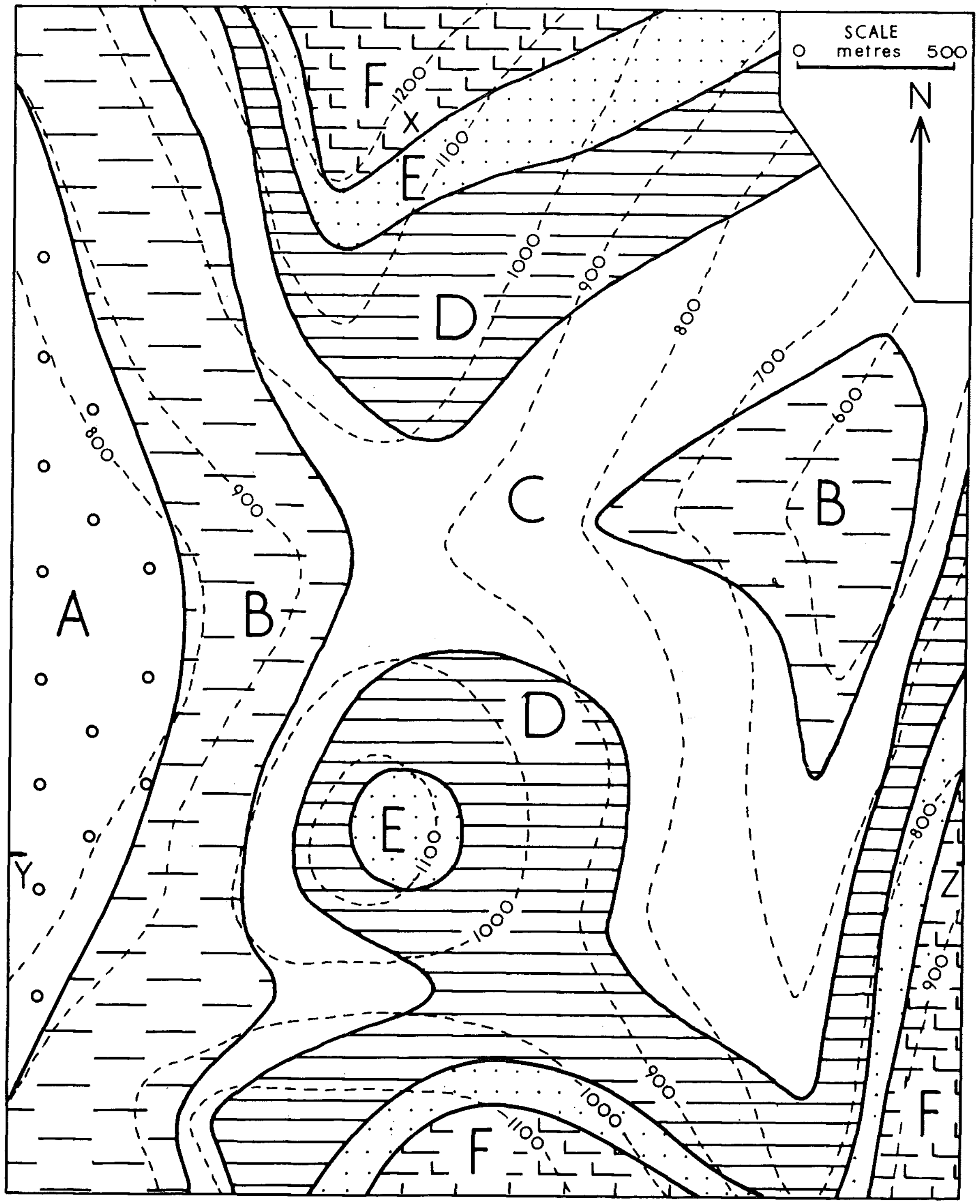


Fig. 6 (a) Diagram and (b) plan or map of structure contours to illustrate the relationship between true and apparent dip.



Map 3 Draw structure contours on the geological boundaries. Give the gradient of the beds (dip). Draw a section along the east–west line Y–Z. Calculate the thicknesses of beds B, C, D and E. Indicate on the map an inlier and an outlier.

However, the problem of apparent dip calculation is much simplified by considering it as a gradient. Just as the gradient of the bed in the direction of maximum dip is given by the spacing of the structure contours (1.9 cm = 380 m in Fig. 6b, representing a gradient of 1 in 3.8, since the scale of the map is 1 cm = 200 m), so the gradient in the direction in which we wish to obtain the apparent dip is given by *the structure contour spacing measured in that direction* (3.25 cm = 650 m in Fig. 6b, representing a gradient of 1 in 6.5).

Calculation of the thickness of a bed

On Map 3 it can be seen that the 1100 m structure contour for the geological boundary D–E coincides with the 1000 m structure contour for boundary C–D. Thus, along this strike direction, the top of bed D is 100 metres higher than its base. It has a vertical thickness of 100 metres. This is the thickness of the bed that would be penetrated by a borehole drilled at point X.

Vertical thickness and true thickness

Since the beds are inclined, the vertical thickness penetrated by a borehole is greater than the true thickness measured perpendicular to the geological boundaries (interfaces) (Fig. 7). The angle α between VT (vertical thickness) and T (true thickness) is equal to the angle of dip.

$$\text{Now Cosine } \alpha = \frac{T}{VT} \quad \therefore \mathbf{T} = \mathbf{VT} \times \mathbf{Cosine}\ \alpha$$

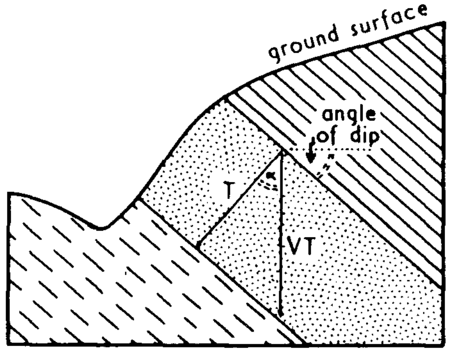


Fig. 7 Section showing the relationship between the vertical thickness (VT) and the true thickness (T) of a dipping bed.

The true thickness of a bed is equal to the vertical thickness multiplied by the cosine of the angle of dip. Where the dip is low (less than 5°) the cosine is high (over 0.99) and true and vertical thicknesses are approximately the same (see Table I, p. 64).

Width of outcrop

If the ground surface is level the width of outcrop of a bed of constant thickness is a measure of the dip (Fig. 8). More generally, beds outcrop on sloping ground and width of outcrop is a function of the dip of the beds and the slope of the ground.

It will be noted that in the case of horizontal strata the geological boundaries are parallel to the topographic contours. In dipping strata the geological boundaries cross the topographic contours, and with irregular topography the steeper the dip the straighter the outcrops. In the limiting case, that of vertical strata, outcrops are straight and unrelated to the topography.

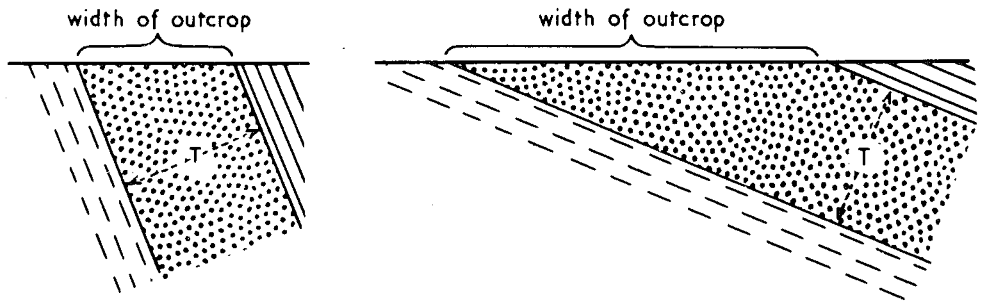


Fig. 8 Sections showing the different widths of outcrop produced by a bed of the same thickness with high dip and low dip.

Inliers and outliers

An outcrop of a bed entirely surrounded by outcrops of younger beds is called an inlier. An outcrop of a bed entirely surrounded by older beds (and so separated from the main outcrop) is called an outlier. In Map 3 these features are the product of erosion on structurally simple strata and are called 'erosional' inliers and outliers. (See p. 30 for details of other inliers and outliers.)

Sections across published Geological Survey Maps

Henley-on-Thames: 1:50 000 (Sheet 254) Solid & Drift Edition Examine the map and section, noting the relationship of topography to geology. (The Chalk is one of the most resistant formations in South East England forming the high ground of the Chilterns, Downs, etc.) Note numerous outliers to the west of the main cuesta.

A structure contour map is included. You will see that the structure contours are approximately parallel but not straight as on most problem maps which cover a smaller area as a rule. What do you conclude from the curvature of the structure contours?

Aylesbury: 1″ (Sheet 238) Excluding the rather extensive Pleistocene and Recent deposits (which form a quite thin superficial cover), the oldest strata are to be found in the north-west of the area with successively younger beds to the south-east. This gives the direction of dip. The amount of dip can best be determined by ensuring that beds are made the appropriate thickness on the section, e.g. Lower Chalk and Middle Chalk should each measure approximately 200 feet if the section has been correctly drawn. Draw a section along a line in a north-west–south-east direction across the map to illustrate the structure of the area.

It is very difficult to make the vertical scale equal to the horizontal scale which on a 1″ to the mile map* is, of course, 1″ = 5280′. It is necessary, therefore, to introduce a vertical exaggeration which, if a vertical scale of 1″ = 1000′ is chosen, will be approximately 5¼ times. (The Geological Survey frequently employs a vertical scale which gives a vertical exaggeration of 3 times.) When dealing with an area of the size of this map it is found that bedding planes are not uniformly dipping but may be slightly flexured. The beds cannot be inserted in a section by constructing structure contours; they must be made the correct thickness, as given in the stratigraphical column in the margin of the map, and given such a dip as will enable them to be 'fitted' to the correct width of outcrop (see above).

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* These maps are being superseded by maps on the scale 1:50 000 with contours at 50 m intervals. A vertical scale of 1 cm = 100 m should be suitable for section drawing and will give a vertical exaggeration of × 5, or in some cases half this scale might be used.
(Some maps on the scale of 1:25 000 are also obtainable.)

2 'Three-point' problems

If the height of a bed is known at three or more points, it is possible to find the direction of strike and to calculate the dip of the bed, provided dip is uniform. This principle has many applications to mining, opencast and borehole problems encountered by applied geologists and engineers but this chapter deals only with the fundamental principle and includes a few simple problem maps.

The height of a bed may be known at points where it outcrops or its height may be calculated from its known depth in boreholes or mine shafts. If the height is known at three points (or more) only one possible solution exists as to the direction and amount of dip, and this can be simply calculated.

Map 4 Deduce the dip and strike of the coal seam which is seen to outcrop at points A, B and C. At what depth would the seam be encountered in a borehole sunk at point D? Complete the outcrops of the seam. Would a seam 200 m below this one also outcrop within the area of the map? Contours in metres.

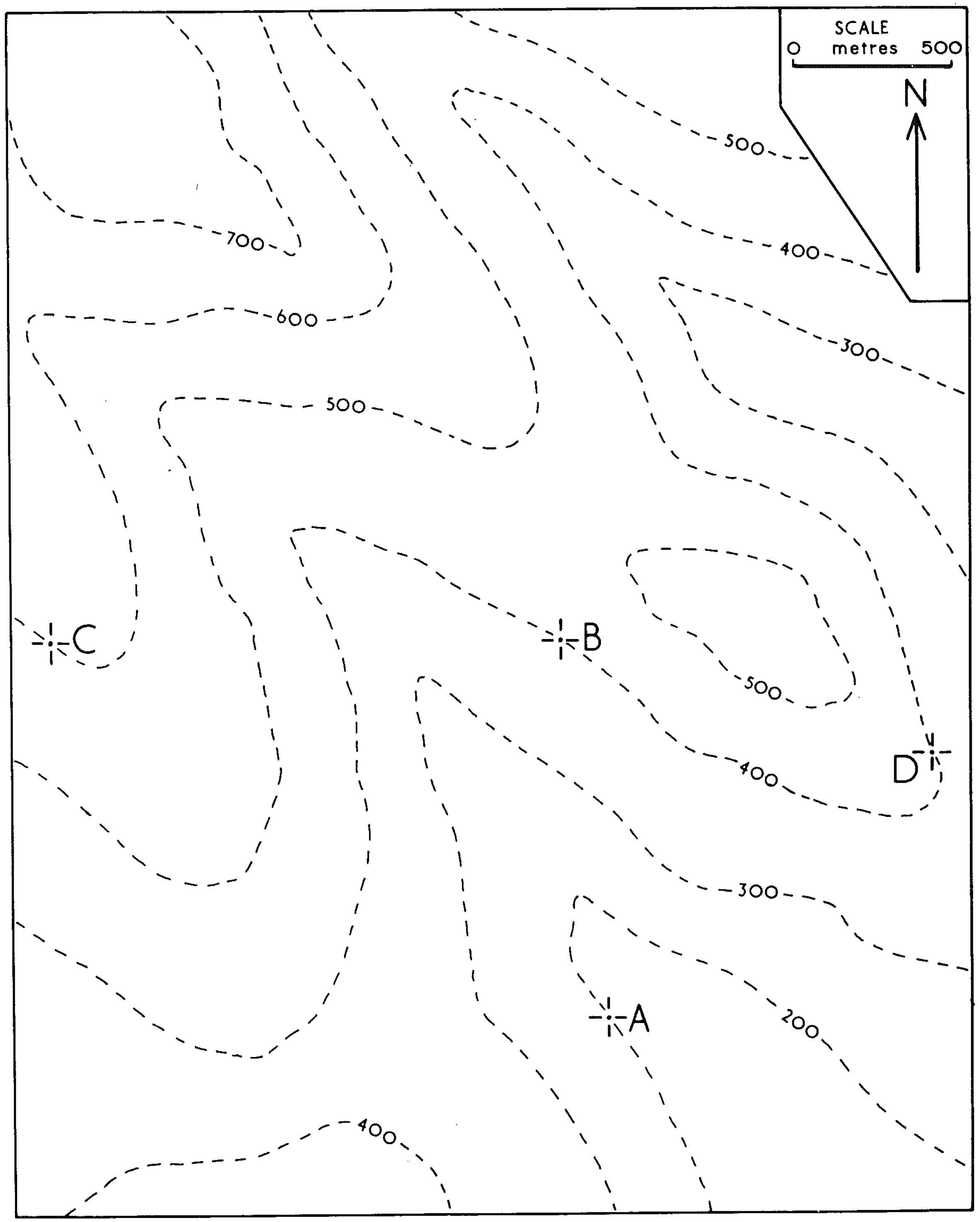
Construction of structure contours

Note: since the map portrays a coal seam, and an average seam is of the order of 2 metres or less in thickness, on the scale of 2.5 cm = 500 m its thickness is such that it can satisfactorily be represented by a single line on the map. There is no need to attempt to draw structure contours for the top and the base of the seam – on this scale they are essentially identical.

Observe the height of the seam at points A, B and C where it outcrops. Join with a straight line the highest point on the coal seam, C (600 m) to the lowest point on the seam, A (200 m). Divide the line A–C into four equal parts (since 600 m – 200 m = 400 m). As the slope of the seam is constant we can find a point on AC where the seam is at a height of 400 m (the mid-point). We also know that the seam is at a height of 400 m at point B. A straight line drawn through these two points is the 400 m structure contour. On a simply dipping stratum such as this, all structure contours are parallel. Construct the 200 m structure contour through point A, the 300 m, the 500 m and the 600 m structure contour – the latter through point C. Having now established both the direction and the spacing of the structure contours, complete the pattern over the whole of the map.

Insertion of outcrops

The structure contours were drawn by ascertaining the height of the coal seam where it outcropped on contour lines. Wherever the seam – defined by its



Map 4

structure contours – is at the same height as the ground surface – defined by topographic contour lines – it will outcrop. We can find on the map a number of intersections at which structure contours and topographic contours are of the same height: the outcrop of the seam must pass through all these points.

Further, these points cannot be joined by straight lines. We must bear in mind that where the seam lies between two structure contours, e.g. the 300 m and 400 m, it can only outcrop where the ground is also at a height of between 300 m and 400 m, i.e. between the 300 m and 400 m topographic contours (Fig. 9). The outcrop of a geological boundary surface cannot, on a map, cross a structure contour or a topographic contour line except where they intersect at the same height.

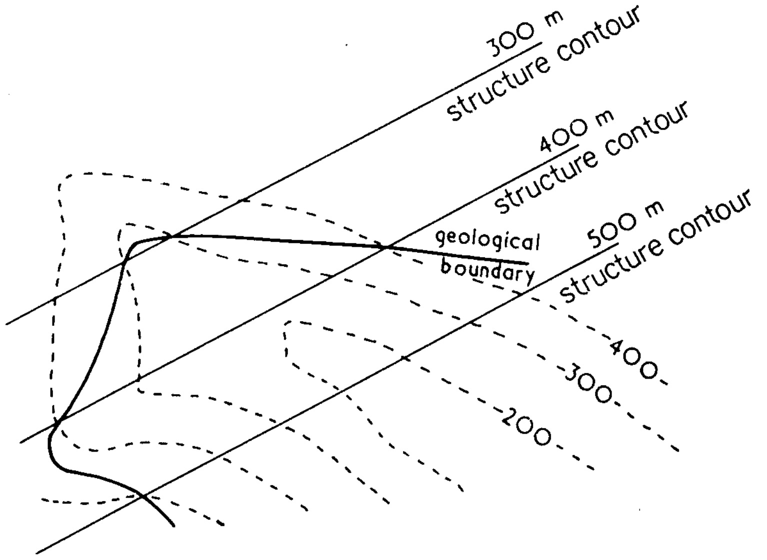
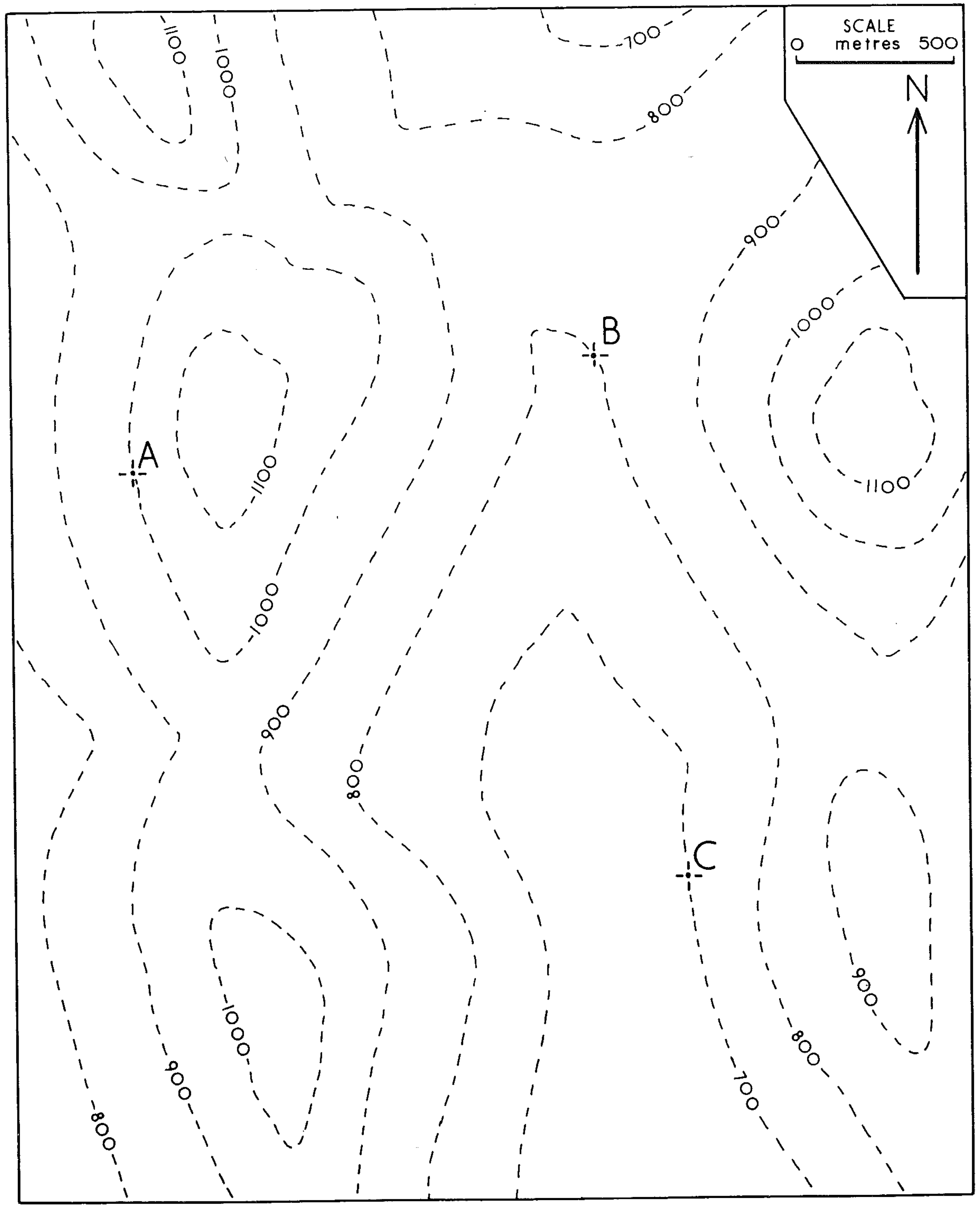


Fig. 9 The insertion of a geological boundary on a map with topographic contours and structure contours.

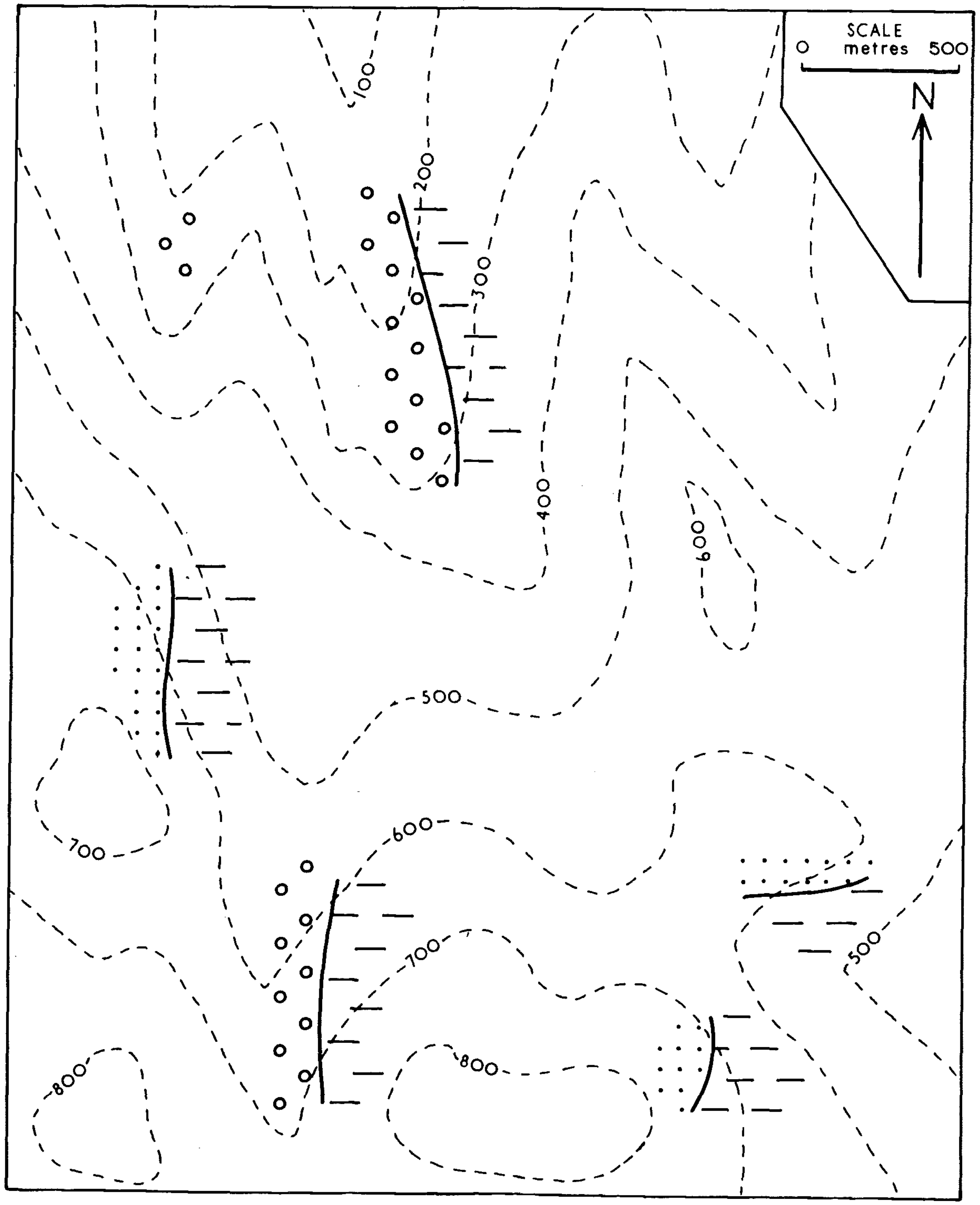
Depth in boreholes

Relative to sea level, the height of the ground at the site of a borehole can be estimated from its proximity to contour lines and that of the coal seam at the same point on the map can be calculated from the structure contours. Quite simply, the difference in height between the ground surface and the seam is the depth to which the borehole must be drilled to reach the seam.

Map 5 Borehole A passes through a coal seam at a depth of 50 m and reaches a lower seam at a depth of 450 m. Boreholes B and C reach the lower seam at depths of 150 m and 250 m respectively. Having determined the dip and strike, map in the outcrops of the two seams (assume that the seams have a constant vertical separation of 400 m). Indicate the areas where the upper seam is at a depth of less than 50 m below the ground surface. It is necessary to first calculate the height (relative to sea level) of the lower coal seam at each of the points A, B and C where boreholes are sited.



Map 5



Map 6 Three beds outcrop – conglomerate, sandstone and shale. Complete the geological boundaries between these beds, assuming that the beds all have the same dip. Indicate on the map an inlier and an outlier.

3 Unconformities

In terms of geological history an unconformity represents a period of time during which strata are not laid down. During this period, strata already formed may be uplifted and tilted by earth-movements which also terminated sedimentation. The uplifted strata, coming under the effects of sub-aerial weathering and erosion, are 'worn down' to a greater or lesser extent before subsidence causes the renewal of sedimentation and the formation of further strata. As a result we find, in the field, one set of strata resting on the eroded surface of an older set of beds (and quite frequently some of the material forming the younger strata was derived by erosion from the older strata).

On a problem map, or on a geological survey map, such an erosion surface cannot be seen, although its presence may be indicated in the stratigraphical column in the margin of the map. However, because of the earth movements producing the uplift of the older strata followed by earth movements causing subsidence and renewed sedimentation, it is rarely that the younger strata have the same dip and strike as the older strata. An exception to this can be found on the margins of the London Basin, where the Lower Tertiary beds rest unconformably on the Chalk with little difference in strike or dip yet, by comparison with successions of strata on the other side of the Channel, we know that this is a major unconformity representing a long period of time since, in Britain, the uppermost stage of the Chalk and the lowest two stages of the Tertiary are absent.

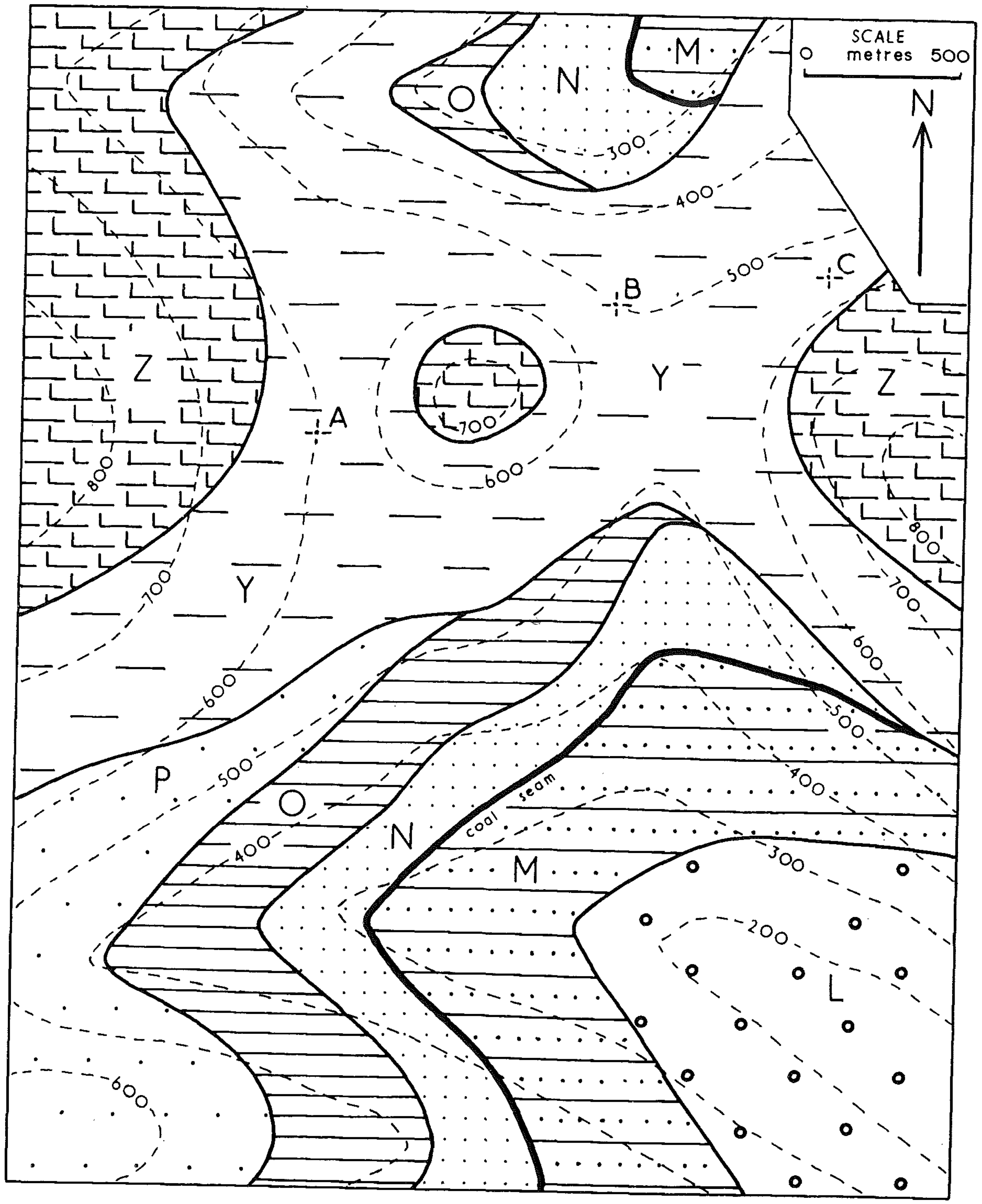
Overstep

Usually the lower bed of the youngest series of strata, having a quite different dip and strike from that of the older strata, rests on beds of different age. This feature (Fig. 10) is called overstep; bed X is said to overstep beds A, B, C, etc.

If the older strata were tilted before erosion took place, they meet the plane of unconformity at an angle, and there is said to be an 'angular unconformity' (Fig. 10).

Overlap

As subsidence continues and the sea for example spreads further on to the old land area, successive beds are laid down, and they may be of greater geographical extent, so that a particular bed spreads beyond, or overlaps, the preceding bed. This feature (Fig. 11) may accompany an unconformity with or without over-



Map 7

step. Bed Y overlaps Bed X. (The converse effect, that of successive beds being laid down over a progressively contracting area of deposition, due to gradual uplift, is known as off-lap. Such a feature is rarely deducible from a geological map and will be discussed no further.)

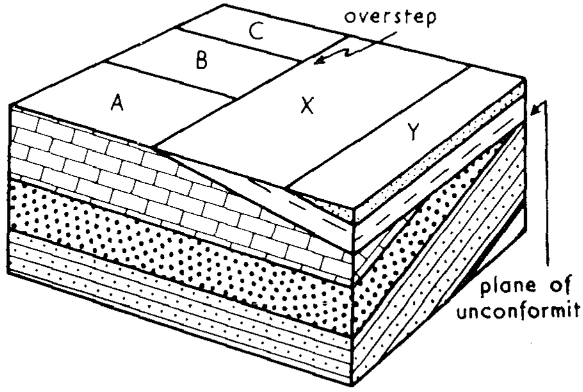


Fig. 10 Block diagram of an angular unconformity.

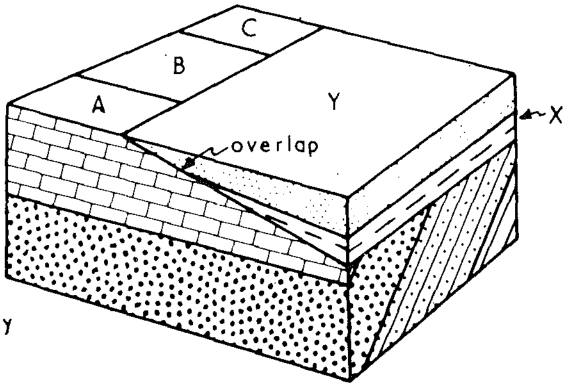


Fig. 11 Block diagram of an unconformity with overlap.

Sections across published Geological Survey Maps

Assynt 1″ Geological Survey special sheet Examine the western part of the map to find the unconformities at the base of the Torridonian and the base of the Cambrian. Draw a section along the north–south grid line 22 to show these unconformities. From your knowledge of the conditions under which the Torridonian and Lower Cambrian were deposited can you explain how and why these unconformities differ.

Shrewsbury 1″ Map No. 152 Examine the map carefully. How many of the unconformities indicated in the geological column in the margins are deducible from the map evidence?

Map 7 *Find the plane of unconformity. Deduce the direction and amount of dip of the two series of* beds. Draw a section along the line from the north-west corner of the map to the south-east corner. Would the coal seam be encountered in boreholes situated at points A, B and C? If the coal is present calculate its depth below the ground surface, if it is absent suggest an explanation for its absence. Indicate the position of the coal seam beneath bed Y.

4 Faults

Faults are fractures which displace the rocks. The strata on one side of a fault may be vertically displaced tens, or even hundreds, of metres relative to the strata on the other side. In another type of fault the rocks may have been displaced horizontally for a distance of many kilometres. While in nature a fault may consist of a plane surface along which slipping has taken place, it may on the other hand be represented by a zone of brecciated (composed of angular fragments) rock. For the purposes of mapping problems it can be treated as a plane surface, usually making an angle with the vertical. This angle (Fig. 12) is called the hade of a fault.

All structural measurements are made with reference to the horizontal, except for the term hade which is measured relative to the vertical. This is confusing but the term is still widely used in Britain and in parts of the world where British influence was or still is considerable. However, it is sometimes simpler to refer also to the dip of a fault plane, i.e. the angle measured between the fault plane and the horizontal (cf. dip of bedding planes, etc.). The vertical displacement of any bedding plane is called the throw of the fault.

Normal and reversed faults

If the hade or slope of a fault is in the direction of the downthrow, the fault is a normal fault (Fig. 12). If, however, the hade or slope of the fault is in the opposite direction to the downthrow, the fault is a reversed fault (Fig. 13). In nature, the angle of hade of a reversed fault is sometimes greater than that of a normal fault, so that in an area of strong relief the outcrop of a reversed fault may be sinuous. If the topography is relatively uniform the outcrop of a fault plane of either type will be virtually straight. It is possible on Maps 8 and 9 to construct structure contours on the fault planes in exactly the same way as we constructed structure contours on bedding planes in Chapter 1. Thus it is possible to find the direction of inclination of the fault planes and to verify whether the faults are normal or reversed. (On some geological maps – such as those produced in Canada and the USA – the direction of dip of fault planes is shown.)

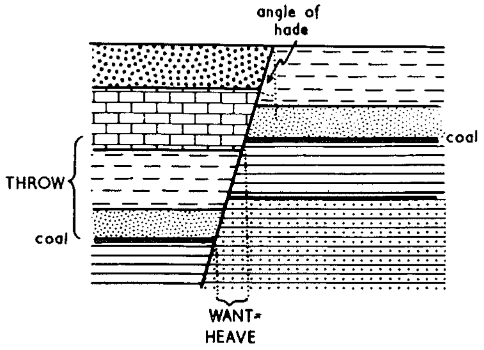


Fig. 12 Section through strata displaced by a normal fault (after erosion has produced a near-level ground surface).

The effects of faulting on outcrops

Consider the effects of faulting on the strata: those on one side of a fault are uplifted, relatively, many metres. Since this uplift is not as a rule a rapid process and the strata will be eroded away continuously, a fault may not make a topographic feature, although temporarily a fault scarp may be present (Fig. 14) especially after sudden uplift resulting from an earthquake. Some faults which bring resistant rocks on the one side into juxtaposition with easily eroded rocks on the other side may be recognized by the presence of a fault line scarp (cf. fault scarp resulting from the actual movement).

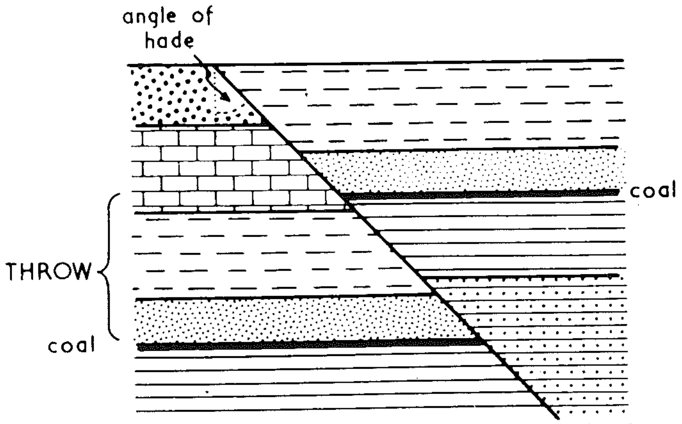


Fig. 13 Section through strata displaced by a reversed fault.

Note that due to erosion the younger beds are removed from the upthrow side of the fault but are preserved on the downthrow side.

A fault dislocates and displaces the strata. The effect of this, in combination with erosion, is to cause discontinuity or displacement in the outcrops of the strata.

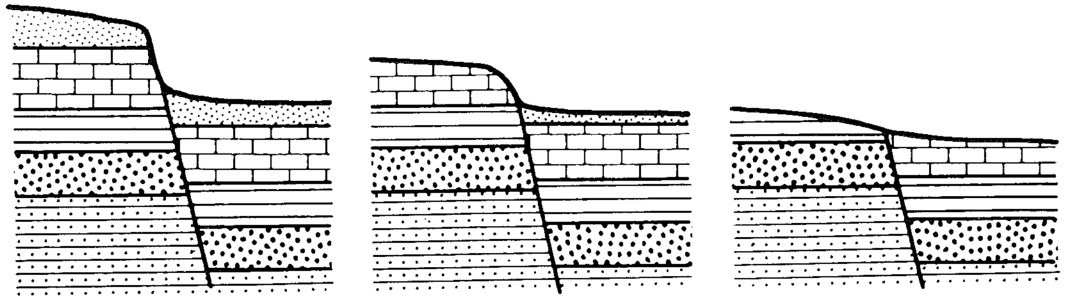


Fig. 14 Sections to show the progressive elimination of a fault scarp by erosion.

Where the fault plane is parallel to the strike of the beds we see either repetition of outcrops (Fig. 15a) where the succession of beds at the surface reads A, B, C, A, B, C or the suppression of outcrops (Fig. 15b) where the succession of beds at the surface reads A, B, C, E, F, G.

Where the fault plane is parallel to the dip direction of the strata (a dip fault), i.e. at right angles to the strike, a lateral shift of the outcrop occurs. This must not be confused with lateral movement of the strata (see p. 50): the transposition of

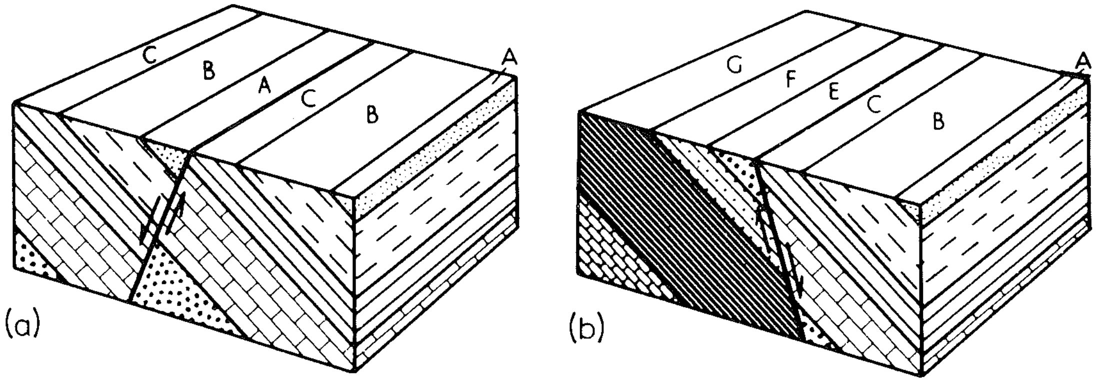
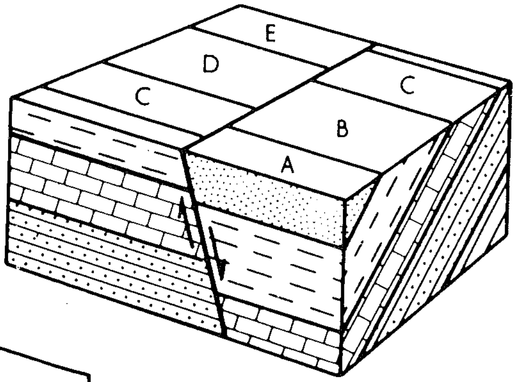


Fig. 15 Block diagrams of a normal strike fault (a) with the direction of dip opposite to the direction of hade, causing repetition of part of the succession of outcrops and (b) with the directions of dip and hade similar, causing a suppression of part of the succession of outcrops.

the outcrops is due to vertical displacement of the beds followed or accompanied by erosion which, because the strata are inclined, causes the outcrops on the upthrow side to be shifted in the direction of dip (Fig. 16).

Fig. 16 (right) Block diagram of a normal dip fault. Note the lateral shift of outcrops although the actual displacement is vertical.



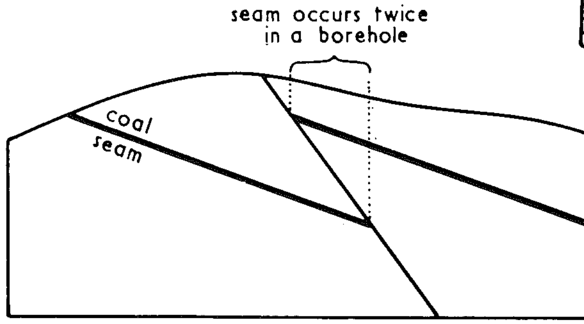
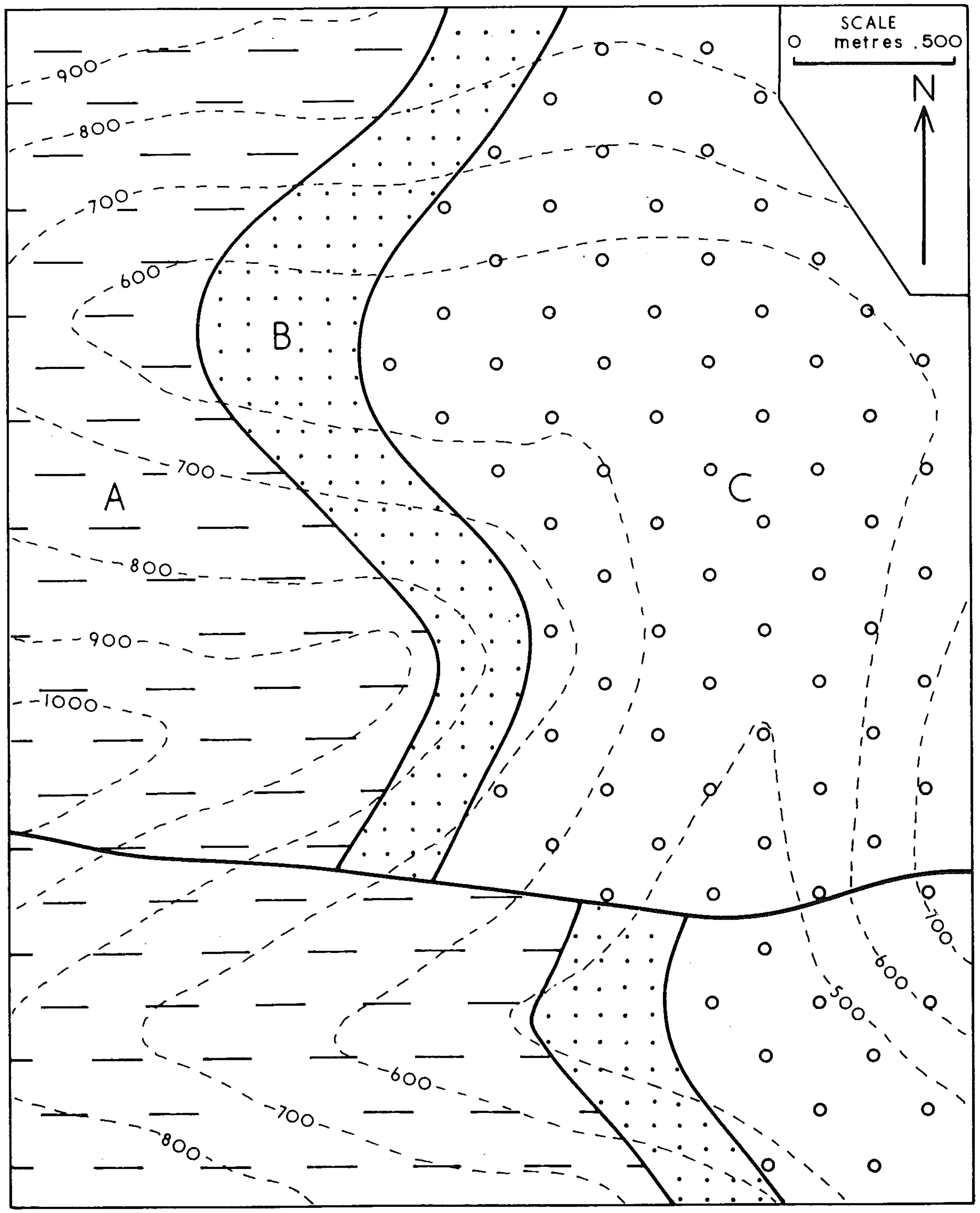


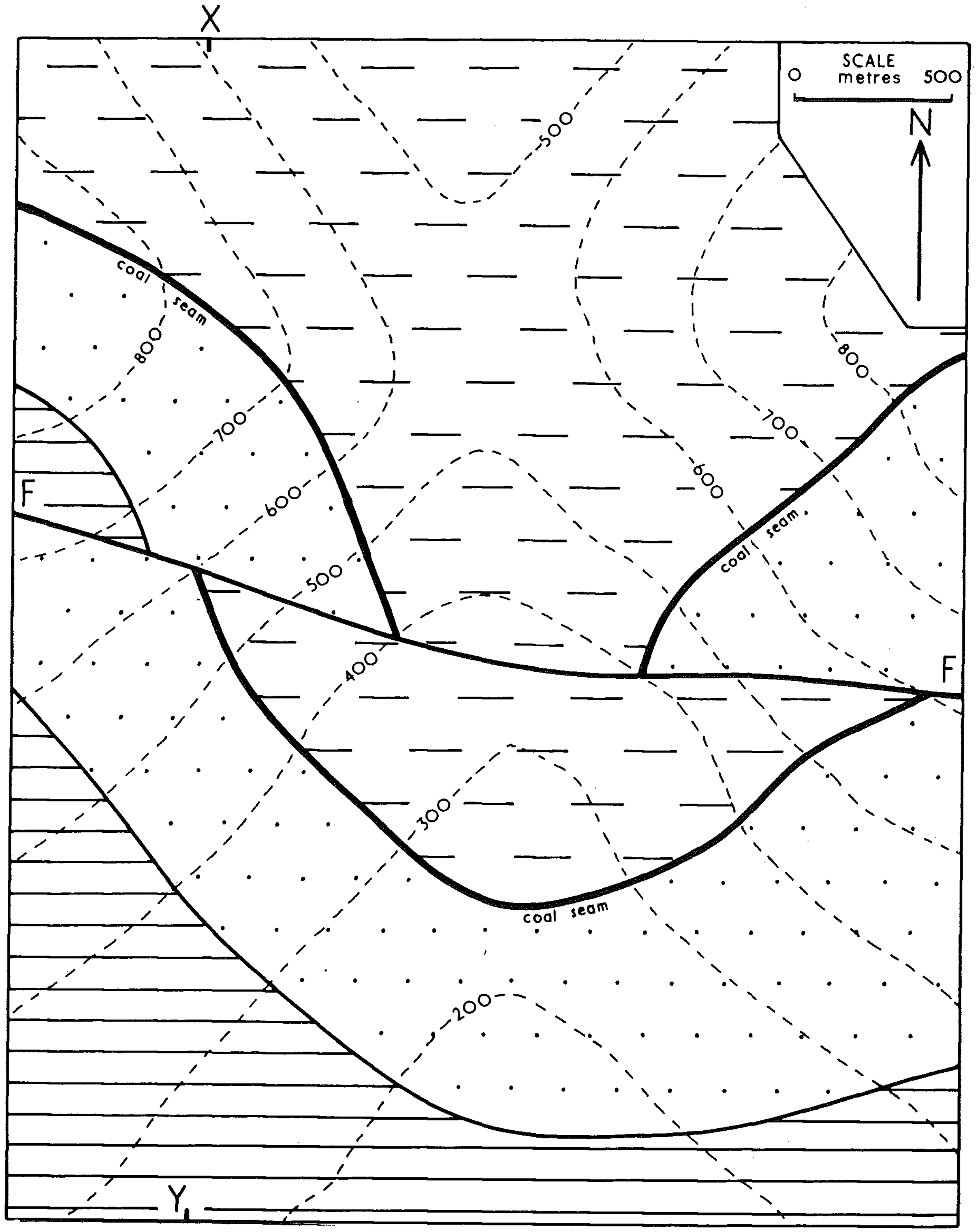
Fig. 17 Section to show a 'low angle' (high hade) reversed fault and its importance in mining problems.

Calculation of the throw of a fault

Note on Map 8 Construct the structure contours on the upper surface of the sandstone bed in the northern part of Map 8. They run north–south and are spaced at 12.5 mm intervals. Follow the same procedure for the upper surface of the sandstone south of the fault plane. The 500 m structure contour drawn on the south side of the fault, if produced beyond the fault, is seen to be coincident with the position of the 1000 m structure contour on the north side of the fault. The stratum on the south side is therefore 500 m lower relatively. The fault has a downthrow to the south of 500 m.



Map 8 Draw structure contours for the upper and lower surfaces of the sandstone (stippled). What is the amount of the throw of the fault? Draw structure contours on the fault plane. Is it a normal or a reversed fault? What is the thickness of the sandstone?



Map 9

Map 9 The line F–F is the outcrop of a fault plane. The other thick line on the map is the outcrop of a coal seam. Shade areas where coal could be penetrated by a borehole (where it has not been removed by erosion). Indicate areas in which any borehole would penetrate the seam twice. What type of fault is this? Draw a section along the line X—Y. Draw the 100 m overburden isopachyte, i.e. a line joining all points where the coal is overlain by 100 m of strata.

Note on Map 9 The zone in which a borehole penetrates the seam twice is defined by the lines of intersection of the fault plane and the coal seam (Fig. 17). The surfaces intersect where they are at the same height (where the coal seam structure contours and the fault plane structure contours of the same height coincide).

Wrench or tear faults

In the case of these faults the strata on either side of the fault plane have been moved laterally relative to each other, i.e. movement has been a horizontal displacement parallel to the fault plane. In the case of simply dipping strata the outcrops are shifted laterally (Fig. 18) so that the effect, *on the outcrops*, is similar to that of a normal dip fault (cf. Fig. 16) - and in this case it is usually impossible to demonstrate strike-slip from the map alone (apparent slip only can be found).

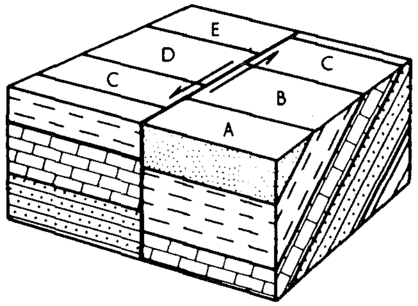


Fig. 18 Block diagram of a wrench (= tear) fault. Note that the effect on the outcrops is similar to that of a normal dip fault (cf. Fig. 16).

Some geologists prefer terminology based on the direction of movement relative to the direction of dip and strike of a fault plane. So faults in which the movement has been in the direction of dip (up or down) of a fault plane are called dip-slip faults (this term would include normal and reversed faults). Faults in which movement has been in the strike direction of the fault plane are called strike-slip faults (these are generally horizontal movements and include wrench faults).

Pre- and post-unconformity faulting

After the deposition of the older set of strata earth movements causing uplift may also give rise to faulting of the strata. The unconformable series (the younger set of beds), not being laid down until a later period, are unaffected by this faulting. Earth movements subsequent to the deposition of the unconformable beds would, if they caused faulting, produce faults which affect both sets of strata. Clearly, it is possible to determine the relative age of a fault from inspection of the geological map which will show whether the fault displaces only the older (pre-unconformity) strata or whether it displaces both sets of strata. A fault is later in age than the youngest beds it cuts.

Structural inliers and outliers

The increased complexity of outcrop patterns due to unconformity and faulting greatly increases the potential for the formation of outliers and inliers (these terms have been defined on p. 14). Indicate on Map 11 inliers and outliers which owe their existence to such structural features and subsequent erosional isolation.

Posthumous faulting

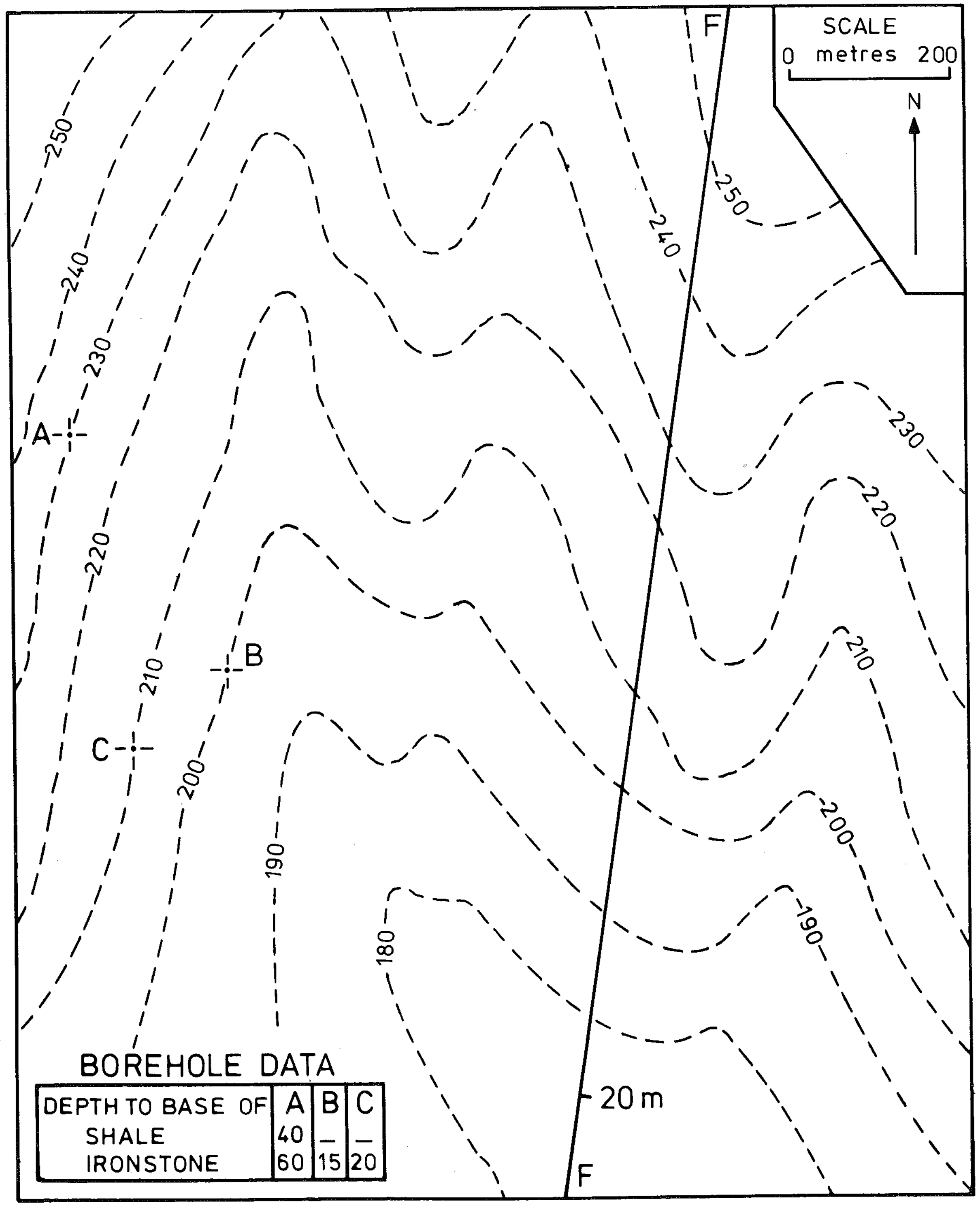
Further movement may take place along an existing fault plane. So the displacement of the strata is attributable to two or more geological periods. It follows that an older series of strata may be displaced by an early movement of the fault which did not affect newer rocks since they were laid down subsequently. The renewed movement along the fault will displace both strata so the older strata will be displaced by a greater amount since they have been displaced twice (the throws are added together).

Isopachytes

Isopachytes (*iso* = equal; *pakhus* = thick) are lines of equal thickness. The simplest use of isopachytes is to show the thickness of cover material overlying a bed of economic importance, such as a coal seam or ironstone. The overlying material - whatever its composition: strata, soil and subsoil - is called the overburden. Its thickness can be determined where the height of the top of an economic bed (ironstone, Map 10) is known from its structure contours, and the height of the ground at the same point is known from the topographic contours. Wherever structure contours and topographic contours intersect on the map we can obtain a figure for the thickness of overburden (by subtracting the height of the top of the ironstone from the height of the ground). Joining up the points of equal thickness gives an isopachyte. Where ironstone and ground are at the same height the thickness of overburden is nil and the bed must outcrop. (Its outcrop would be the 0 m isopachyte.) Bed (or stratum) isopachytes, concerned with beds of varying thickness, are dealt with on p. 44.

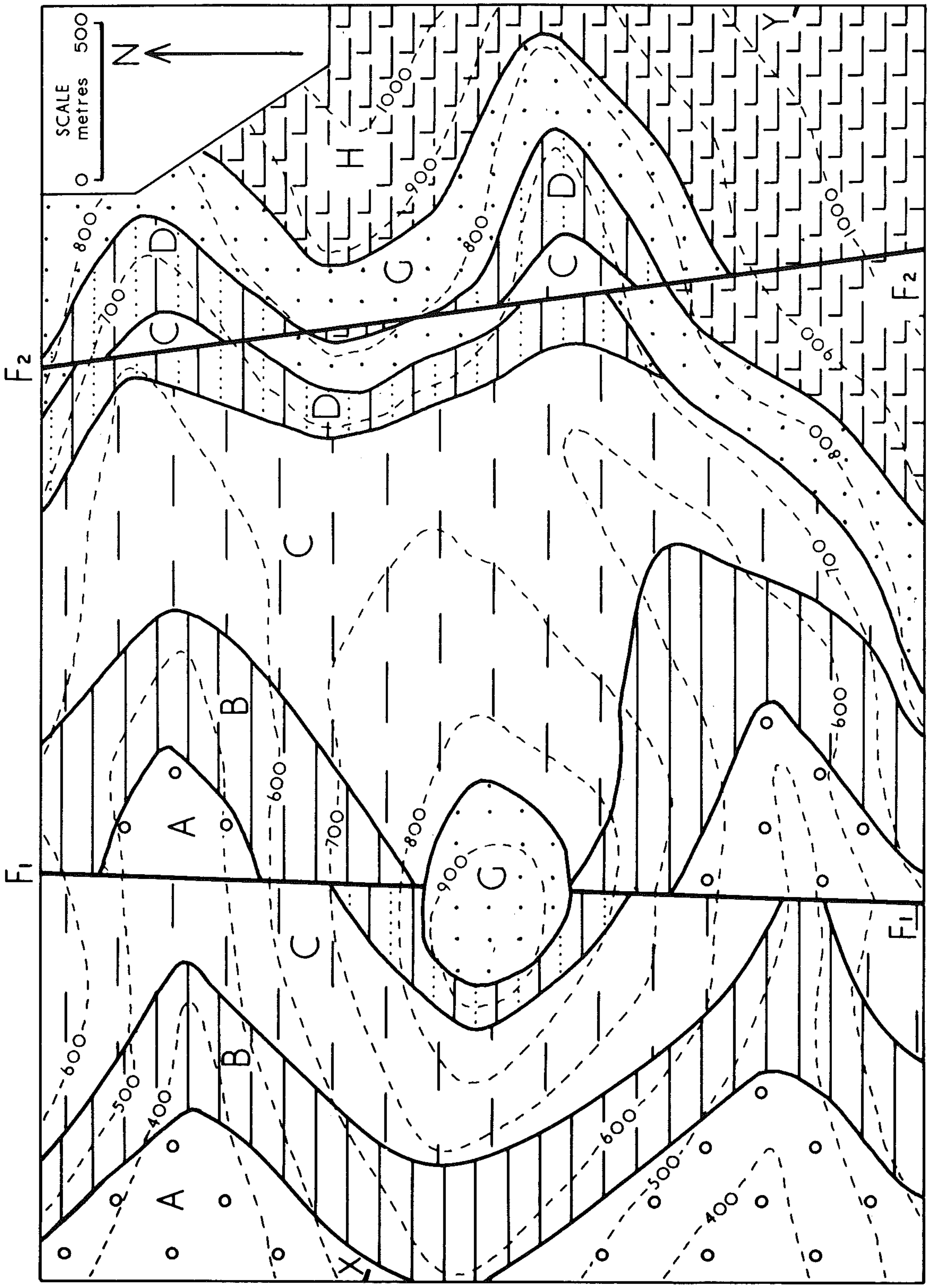
Published Geological Survey Maps
Leeds 1:50 000 Map No. 70 Draw a section along the 'Line of Section' engraved on the map to show the geological structures.

Map 10 The western part of the map comprises a three-point problem enabling us to draw structure contours at 10 m intervals on the base of the ironstone. Assuming the top of the ironstone to be 20 m higher, why does borehole B penetrate only 15 m of ironstone? East of the fault (a normal fault of low hade), produce the structure contours and re-number them 20 m lower (since the fault is shown as having a downthrow of 20 m to the east). Shade outcrops of iron ore on both sides of the fault. Also shade areas where the ironstone could be worked opencast if not more than 40 m of overlying shale is to be removed, i.e. draw the overburden isopachyte for 40 m. Draw a section along a north–south line passing through point B and another section along an east–west line passing through B.



DEPTH TO BASE OF	A	B	C
SHALE	40	–	–
IRONSTONE	60	15	20

Map 10



Map 11 Calculate the direction and amount of dip of the strata below and above the plane of unconformity. Draw a section along the line X–Y. The lines F_1–F_1 and F_2–F_2 are the outcrops of two fault planes. Which fault occurred earlier in geological time?

5 Folding

We have seen that strata are frequently inclined (or dipping). On examining the strata over a wider area it is found that the inclination is not constant and, as a rule, the inclined strata are part of a much greater structure. For example, the Chalk of the South Downs dips generally southwards towards the Channel – as can be determined by examination of the 1″ Geological Survey map of Brighton (Sheet No. 315). We know, however, that in the North Downs the Chalk dips to the north (passing beneath the London Basin); the inclined strata of the South and North Downs are really parts of a great structure which arched up the rocks including the Chalk over the Wealden area. Not all arching of the strata is of this large scale and minor folding of the strata can be seen to occur near the centre of the Brighton sheet.

Anticlines and synclines

Where the beds are bent upwards into an arch the structure is called an anticline (*anti* = opposite: *clino* = slope; the beds dip away from each other on opposite sides of the arch-like structure). Where the beds are bowed downwards the structure is called a syncline (*syn* = together: *clino* = slope; beds dip inwards towards each other) (Fig. 19). In the simplest case the beds on each side of a fold structure, i.e. the limbs of the fold, have the same amount of dip and the fold is symmetrical. In this case a plane bisecting the fold, called the axial plane, is vertical. The fold is called an upright fold whenever the axial plane is vertical or steeply dipping. (Where axial planes have a low dip or are nearly horizontal, see Fig. 36, folds are called flat folds.)

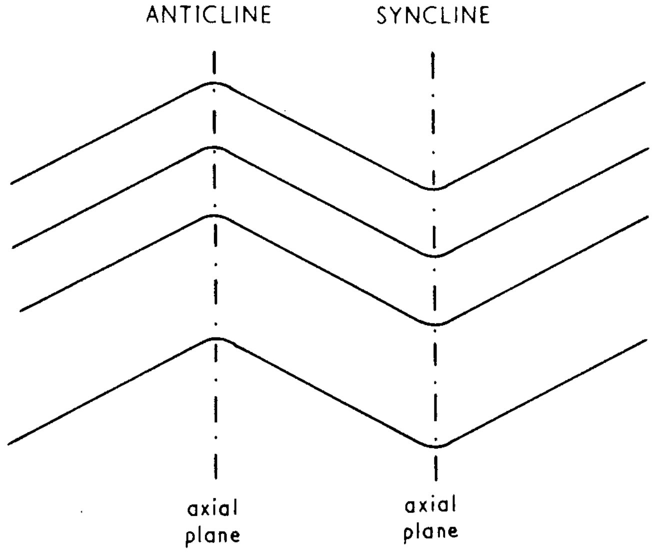


Fig. 19 Diagrammatic section of folded strata.

The effect of erosion on folded strata is to produce outcrops such that the succession of beds of one limb is repeated, though of course in the reverse order, in the other limb. In an eroded anticline the oldest bed outcrops in the centre of the structure and, as we move outwards, successively younger beds are found to outcrop (Fig. 20). In an eroded syncline, conversely, the youngest bed outcrops at the centre of the structure with successively older beds outcropping to either side (Fig. 21).

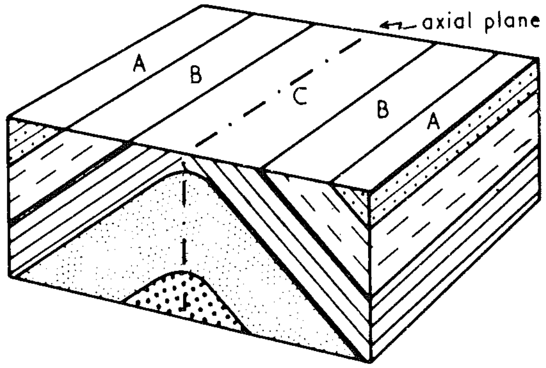


Fig. 20 Block diagram of a symmetrical anticline (an upright fold).

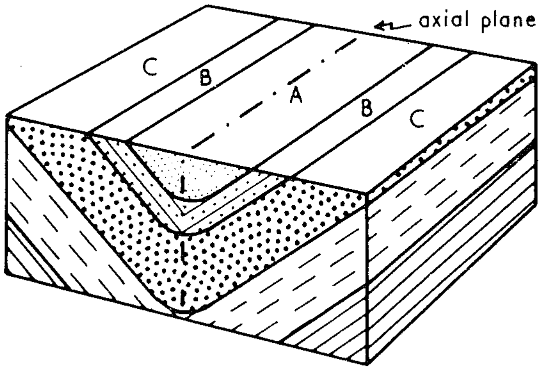


Fig. 21 Block diagram of a symmetrical syncline (an upright fold).

Asymmetrical folds

In many cases the stresses in the earth's crust producing folding are such that the folds are not symmetrical like those described above. If the beds of one limb of a fold dip more steeply than the beds of the other limb, then the fold is asymmetrical. The differences in dip of the beds of the two limbs will be reflected in the widths of their outcrops, which will be narrower in the case of the limb with the steeper dip (Fig. 22). (See also p. 14 and Fig. 8). Now, the axial plane bisecting the fold is no longer vertical but is inclined and the fold is called an inclined fold.

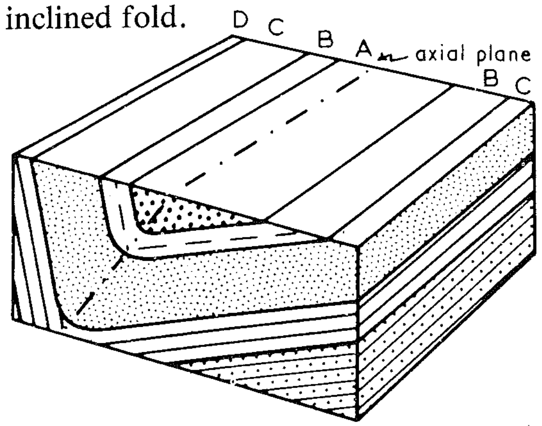


Fig. 22 Block diagram of an asymmetrical syncline (an inclined fold).

Overfolds If the asymmetry of a fold is so great that both limbs dip in the same direction (though with different angles of dip), that is to say the steeply dipping limb of an asymmetrical fold has been pushed beyond the vertical so that it has a reversed – usually steep – dip, the fold is called an overfold (Fig. 23). The strata of the limb with the reversed dip, it should be noted, are upside down, i.e. inverted.

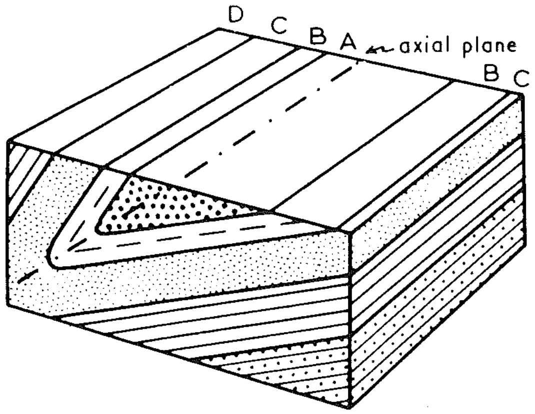


Fig. 23 Block diagram of an overfold (an overfolded syncline).

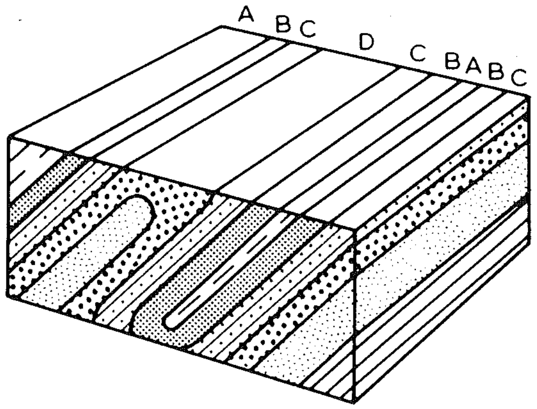


Fig. 24 Block diagram of isoclinal folds, a special case of overfolding in which the limbs of the folds are sub-parallel.

Figures 20 to 24 illustrate fold structures produced in response to increasing tectonic stress. A further terminology should be noted. Where the limbs of a fold dip at only a few degrees it is a gentle fold, with somewhat greater dip (Figs. 20, 21) a fold is described as open, with steeper dipping limbs a fold is described as close and with parallel limbs (Fig. 24) the folding is isoclinal.

Isoclinal folds Isoclinal folds are a special case of over-folding in which the limbs of a fold both dip in the same direction at the same angle (*isos* = equal: *clino* = slope), as the term suggests (Fig. 24). The axial planes of a series of such folds will also be approximately parallel over a small area, but over a larger area extending perhaps forty kilometres (greater than that portrayed in a problem map) they may be seen to form a fan structure.

Similar and concentric folding

When strata, originally horizontal, are folded it is clear that the higher beds of an anticline form a greater arc than the lower beds (and the converse applies in a syncline). Theoretically at least two mechanisms are possible: the beds on the outside of a fold may be relatively stretched while those on the inside are compressed, or the beds on the outside of a fold may slide over the surface of the inner beds (Fig. 25).

The way in which beds will react to stress depends upon their constituent materials (and the level in the crust at which the rocks lie). Competent rocks such as limestone and sandstone do not readily extend under tension or compress under compressive forces but give way by fracturing and buckling while incompetent rocks such as shale or clay can be stretched or squeezed. Thus in an alternating sequence of sandstones and shales the sandstones will fracture and buckle while the shales will squeeze into the available spaces.

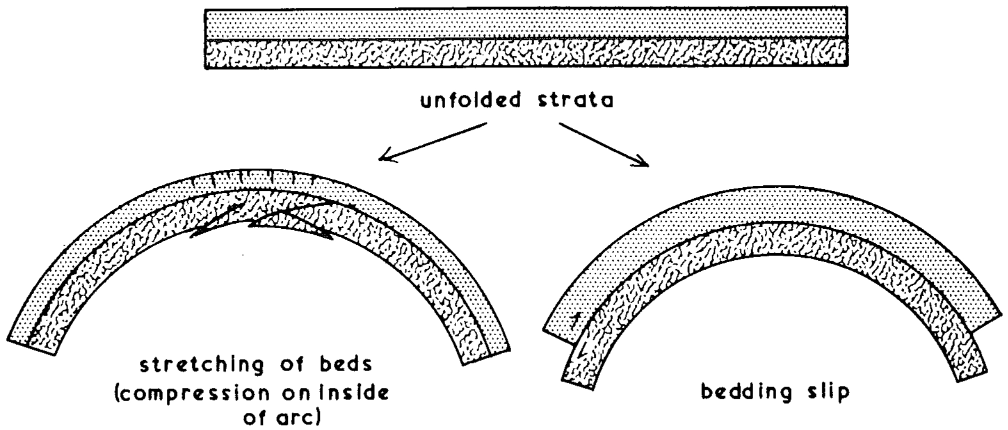


Fig. 25 The response of strata to folding, two possible mechanisms.

Concentric folds The beds of each fold are approximately concentric, i.e. successive beds are bent into arcs having the same centre of curvature. Beds retain their constituent thickness round the curves and there is little thinning or attenuation of beds in the limbs of the folds (Fig. 26a).

Straight limbed folds also maintain the uniformity of thickness of the beds (except in the hinge of the fold) and folding takes place by slip along the bedding planes as it does in the case of concentric folds. Although typically developed in thinly bedded rocks (such as the Culm Measures of North Devon) most of the problem maps in this book which illustrate folding have straight limbed folds since these provide a simple pattern of equally spaced strike lines on each limb of a fold.

Similar folds The shape of successive bedding planes is essentially similar, hence the name (Fig. 26b). Thinning of the beds takes place in the limbs of the folds (and a strong axial plane cleavage is usually developed). This type of folding probably occurs when temperatures and pressures are high.

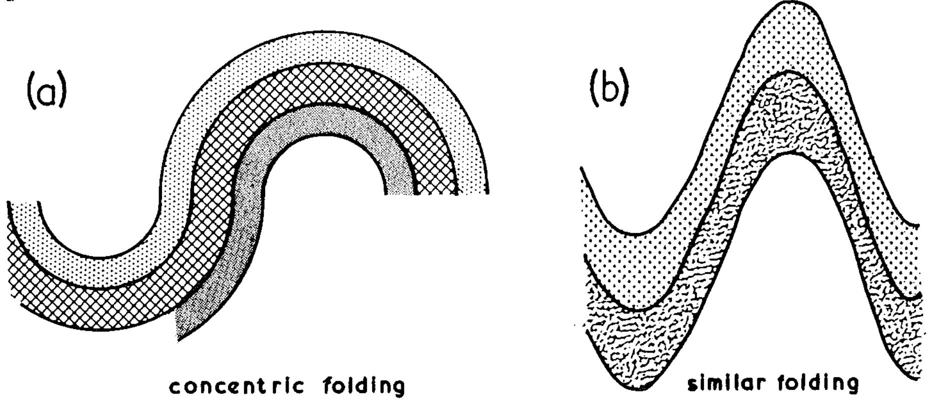
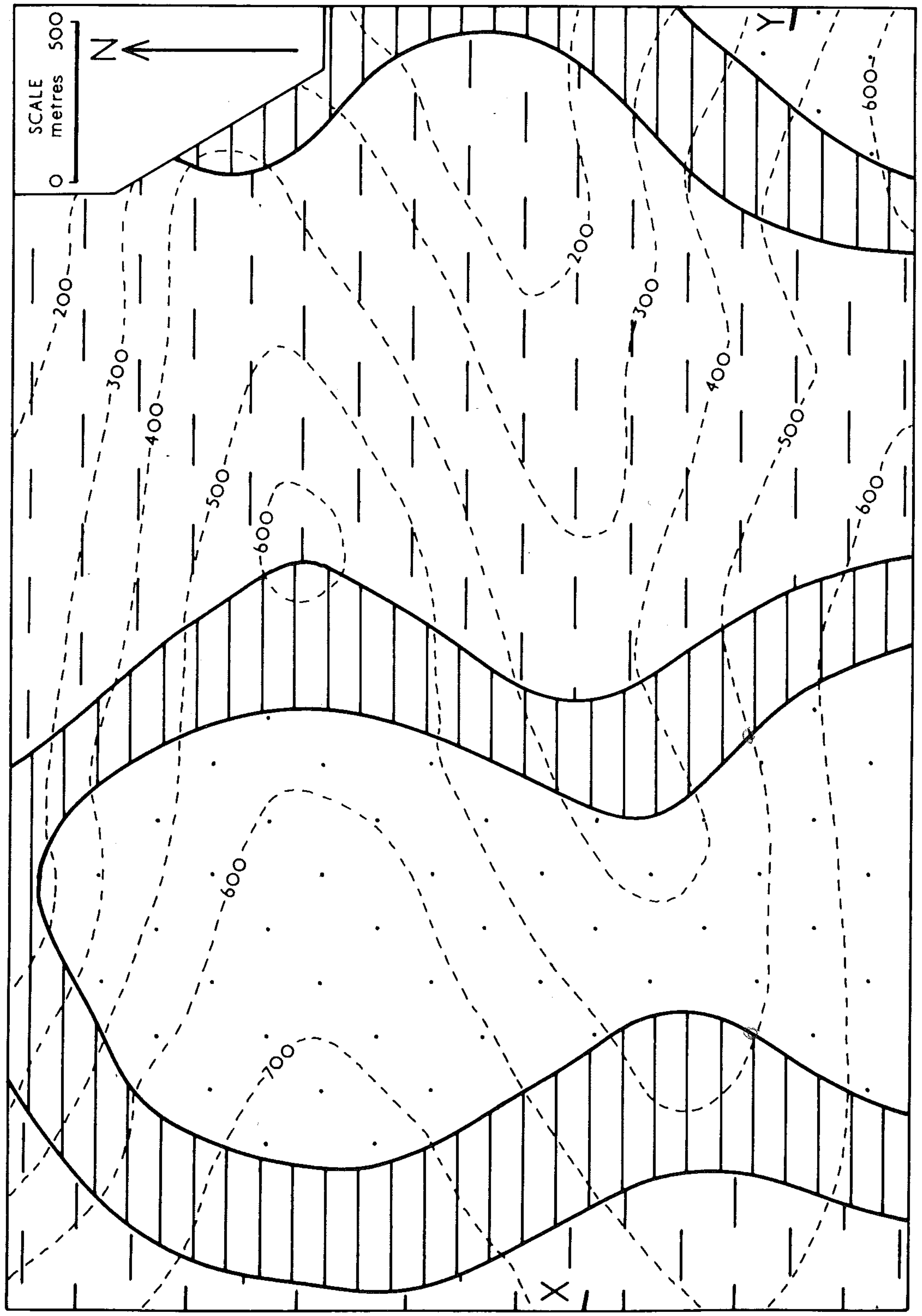


Fig. 26 The shape of concentric and similar folding seen in section.



Map 12 Draw structure contours for the upper and lower surface of the shaded bed of shale. Is the direction of strike approximately north–south or east–west? Indicate on the map the position of an anticlinal axial trace and the position of a synclinal axial trace. Draw a section along the line X–Y. (The axial trace is the outcrop of the axial plane.)

Two possible directions of strike

A structure contour is drawn by joining points at which a geological boundary surface (or bedding plane) is at the same height. By definition this surface is at the same height along the whole length of that structure contour. Clearly, if we join points X and Y (Fig. 27) we are constructing a structure contour for the bedding plane shown, for not only are points X and Y at the same height but the bedding plane is at the same height along the line X–Y. If, however, we join the points W and X, although they are at the same height, we are not constructing a structure contour, for the bedding plane is not at the same height along the line W–X; it is folded downwards into a syncline. Thus, if we attempt to draw a structure contour pattern which proves to be incorrect, we should look for the correct direction approximately at right angles to our first attempt. It should also be noted that an attempt to visualize the structures must be made. For example, in Map 12 the valley sides provide, in essence, a section which suggests the synclinal structure, especially if the map is turned upside down and viewed from the north.

What is the test of whether we have found the correct direction of strike? In these relatively simple maps the structure contours should be parallel and equally spaced (at least for each limb of a fold structure). Furthermore, calculations of true thicknesses of a bed at different points on the map should give the same value.

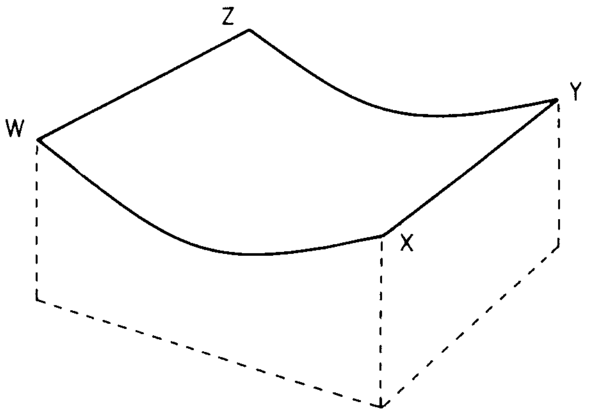
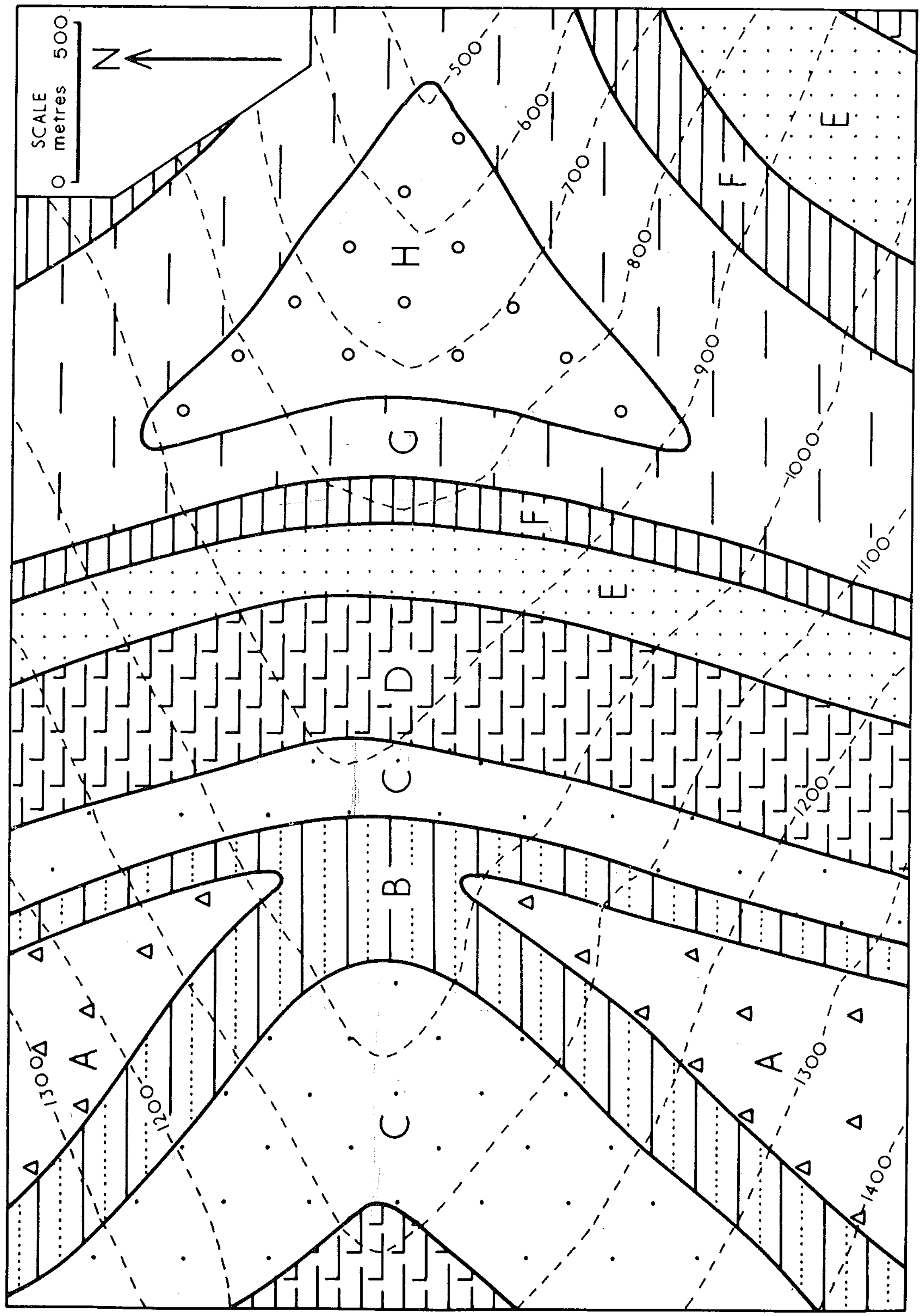


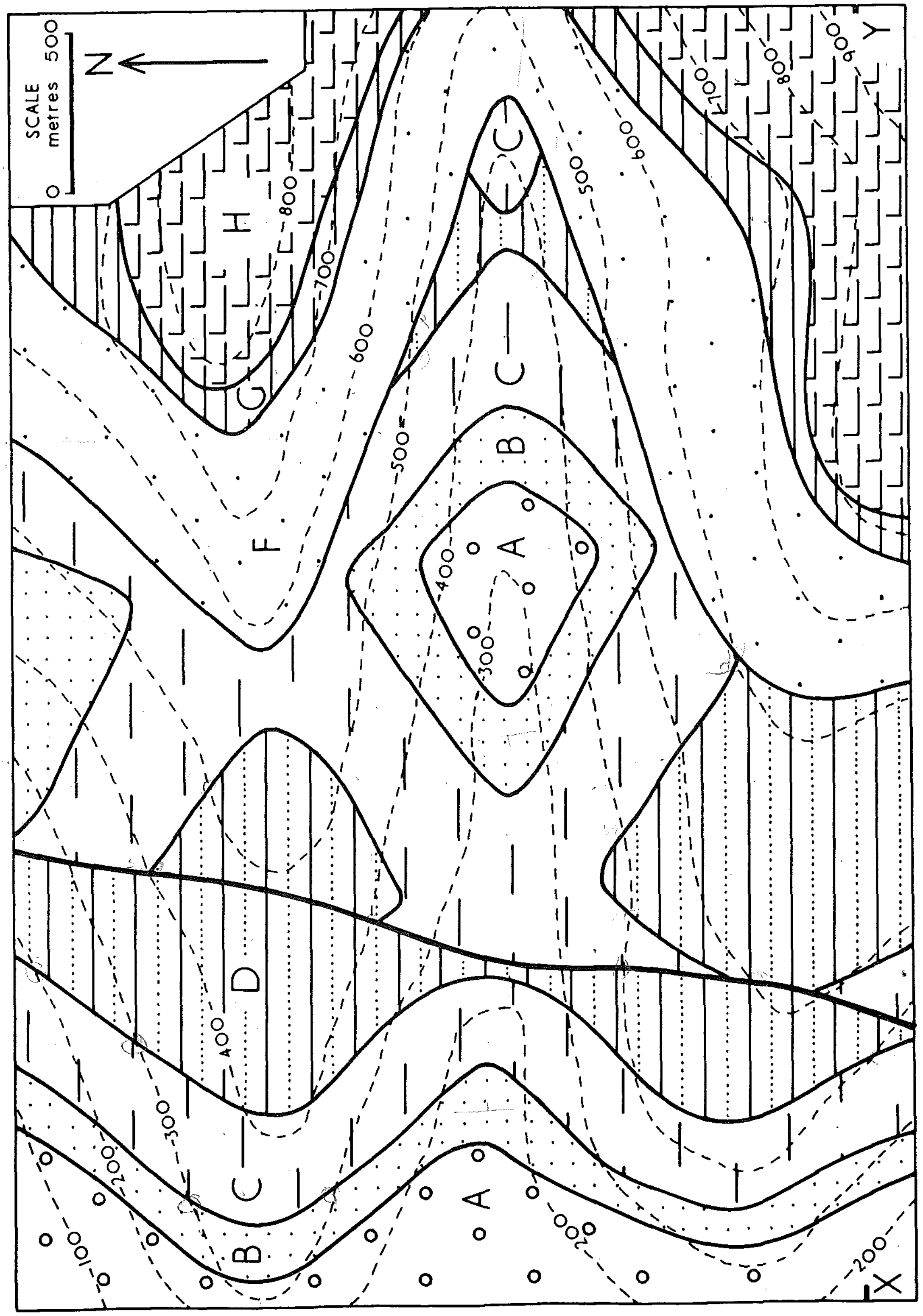
Fig. 27 Block diagram to illustrate the direction of structure contours in folded strata.

Published Geological Survey Maps
Chesterfield: 1″ Geological Survey map (Sheet No. 112) Find the major unconformity on this map. Locate some faults which are older than the Permian beds and some which are younger. Draw a section along a line across the map ensuring that it passes through the Ashover anticline in the south-west.

Note on Map 13 Observe that the northern valley side, read as a section, immediately gives the outline of the structures – an overturned syncline and anticline.



Map 13 Draw structure contours on all the geological boundaries and deduce dips and strikes. What type of folds are these? Draw a section along an east–west line. Draw in the axial traces, i.e. the outcrops of the axial planes of the folds.



Map 14 This map includes all the structural features so far introduced; folds, a fault and an unconformity. Deduce the main structural features of the area from interpretation of the outcrop patterns before attempting to construct structure contours. Write a brief geological history of the area portrayed by the map, giving the order of events producing these structural features. Draw a section along the line X–Y.

6 More folds and faulted folds

Plunging folds

In the folds so far studied the crest of the anticline or the trough of the syncline, i.e. the axis of the fold, has been horizontal and, as a consequence, the structure contours drawn on the beds of one limb have been parallel to the structure contours of the beds of the other limb. (They have, as well, been parallel to the axial plane and, in cases where the axial plane was vertical, parallel to the axial trace (= outcrop of the axial plane).) Clearly, folds are usually of quite limited extent and may plunge at either end before dying out (Fig. 28). Simple folds which have been subsequently tilted by further earth movements will also plunge. This is, furthermore, the simplest way of considering such structures although they may originate in other ways. This type of fold is referred to in some earlier books as a 'pitching' fold, and not infrequently the terms 'pitch' and 'plunge' are used synonymously. The advanced student should consult F. C. Phillips' *The Use of Stereographical Projection in Structural Geology* 3rd edition (London, Edward Arnold, 1971), which clarifies the difference between these terms.

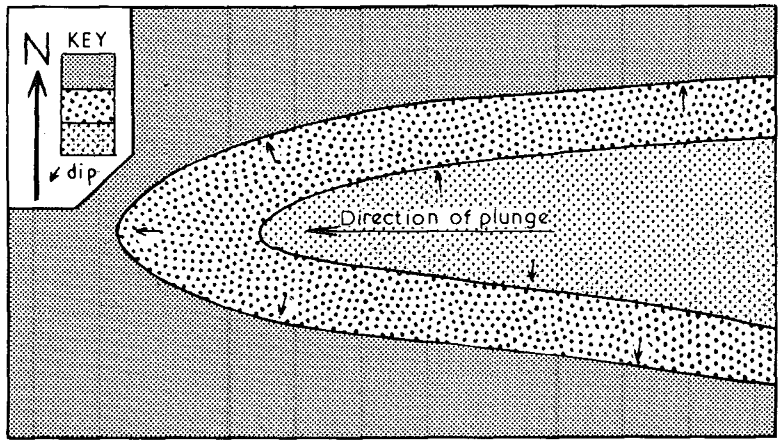


Fig. 28 Map showing the outcrops of anticlinally folded beds, plunging to the west.

The effects of erosion on plunging folds are seen in Figs. 29 and 30. The outcrops of the geological interfaces (on the strike) of the two limbs of a fold are not parallel. While the structure contours are parallel for the beds of each limb, those of the two limbs converge, meeting at the axial plane (Fig. 31).

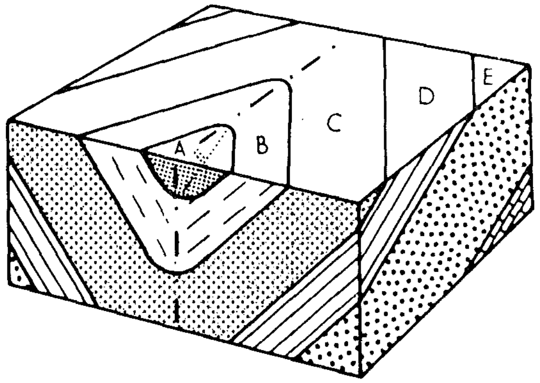


Fig. 29 Block diagram of a plunging syncline.

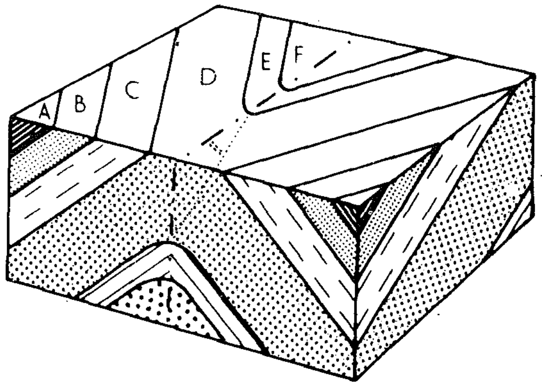


Fig. 30 Block diagram of a plunging anticline.

Calculation of the amount of plunge Just as the inclination of the beds (dip) can be calculated from the spacing of the structure contours (see p. 13) measured in the direction of dip, so can the plunge of the fold be calculated from the spacing of the structure contours measured in the direction of plunge, i.e. along the axis. The plunge of the fold shown in Fig. 31 is, expressed as a gradient, 1 in 3.5, if the scale of the diagram is 1 cm = 200 m, since the structure contour spacing measured along the axis is 1.75 cm. (The dip of the bedding plane of each limb is 1 in 2: check that this is so.)

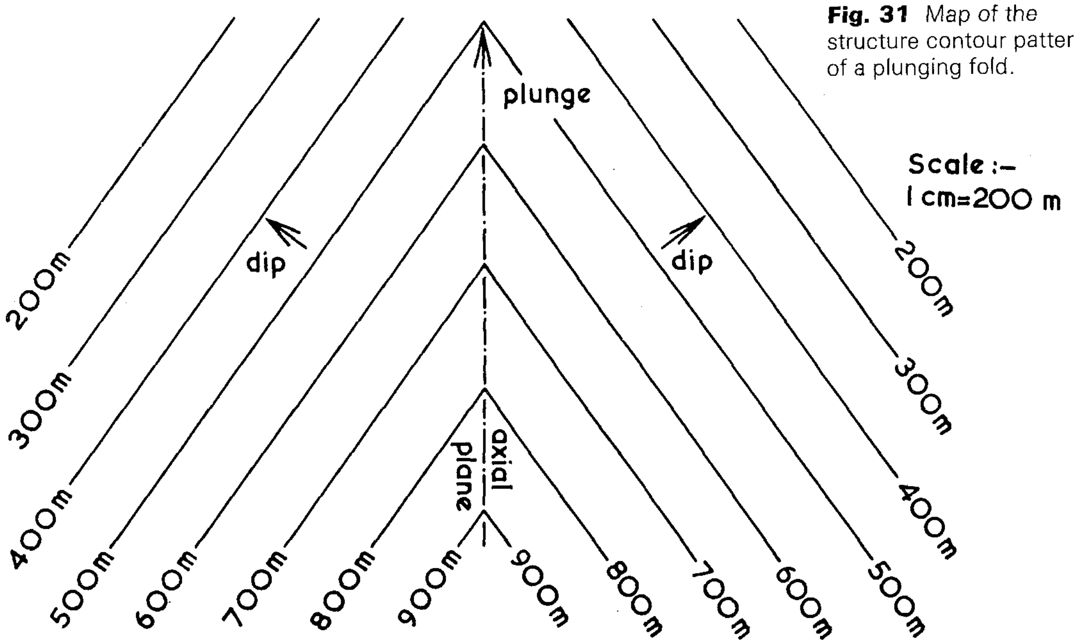
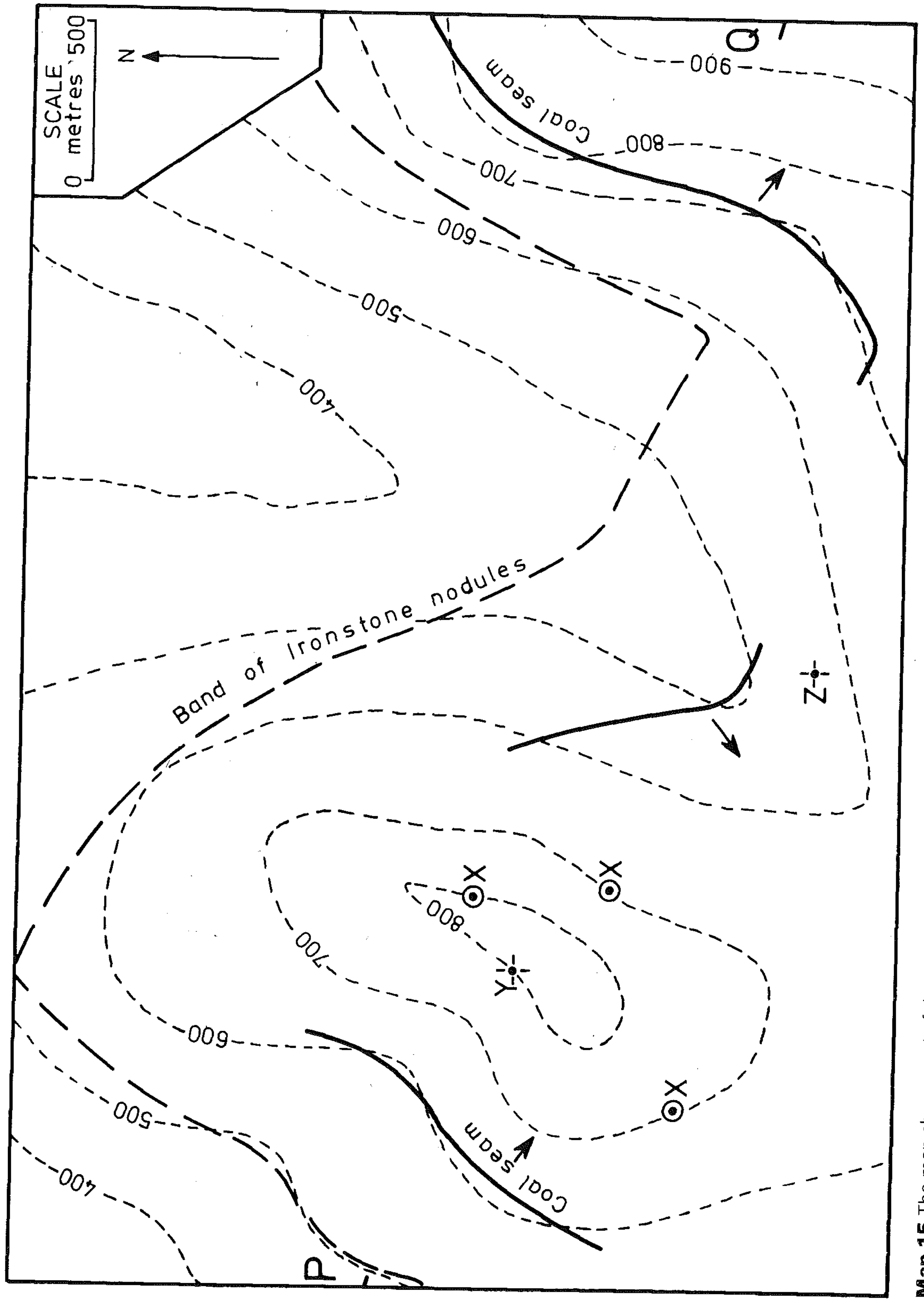


Fig. 31 Map of the structure contour pattern of a plunging fold.

Sub-surface structures

An interesting and important geological consideration is the deduction of the disposition of strata beneath an unconformity. In effect we are considering the



Map 15 The map shows part of the outcrop of a coal seam. It *was also found* at a depth of 300 metres in the boreholes at the several points marked X. Complete the outcrop of the coal seam. Determine the depth at which it would be encountered in shafts put down at Y and Z. Also insert the outcrop of another seam *which lies* 300 m higher (vertically) in the succession. What is the amount of plunge of the fold-axes? Insert outcrops of the fold axial planes on the map. Draw a section along the line P–Q.

'outcrop' pattern on the plane of unconformity. If we could use a bulldozer to remove all strata above that plane we would see the earlier, pre-unconformity strata outcropping.

This problem was touched on briefly in Map 7 where unconformity was introduced. If not already completed, return to Map 7 and insert the sub-unconformity outcrop of the coal seam (remember that topographic contours are now irrelevant; the surface we are considering is the plane of unconformity which is defined by the structure contours drawn on the base of Bed Y. Since both sets of structure contours are in each case straight, parallel and equally spaced – representing constant dips – their intersections giving the sub-Y outcrop of the coal seam should lie on a straight line.)

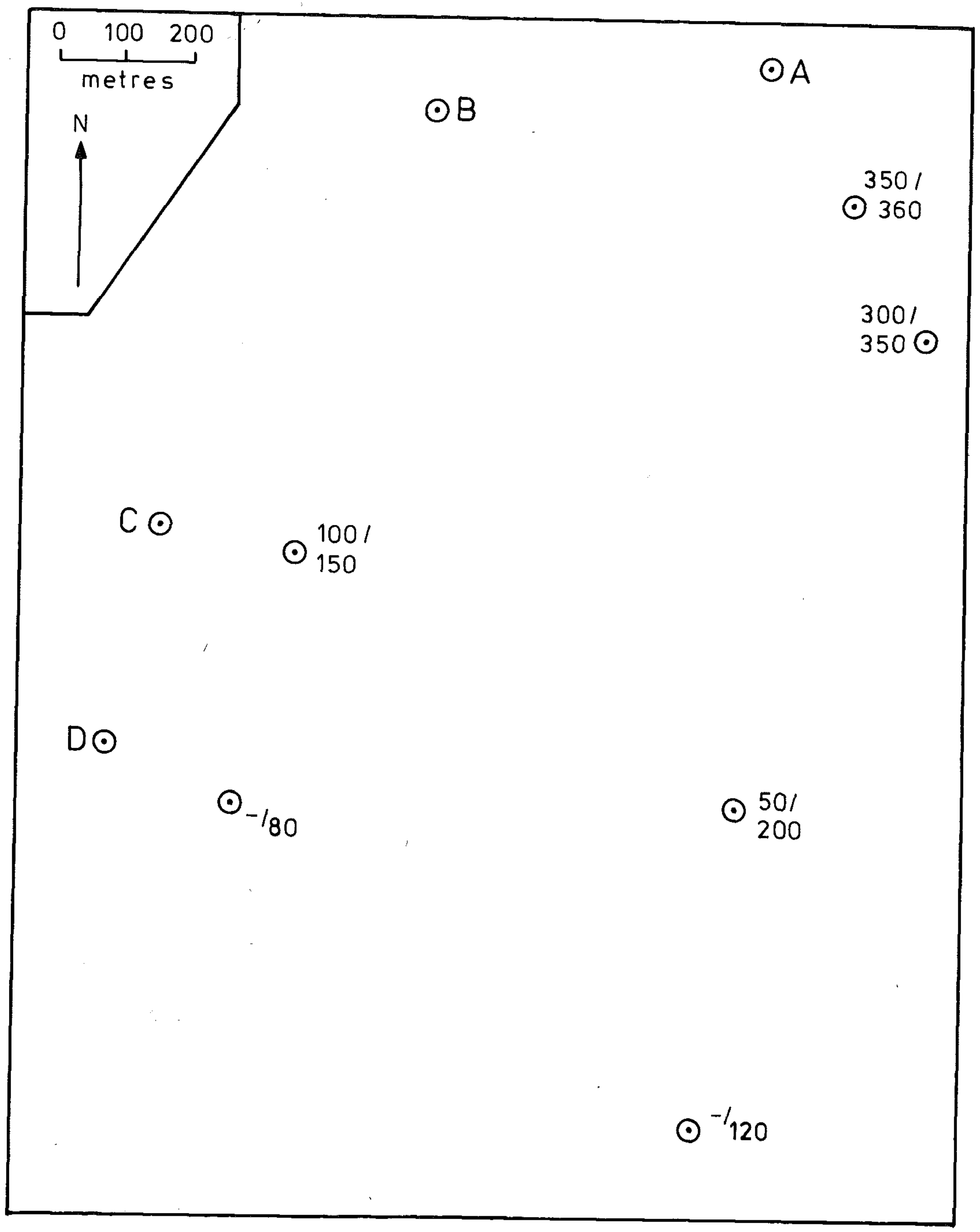
Bed isopachytes

All problems so far have dealt with beds of uniform thickness. However, traced laterally over some distance, strata may be seen to vary in thickness, a function of their mode of deposition. Such variations tend to be gradual and reasonably uniform within the area of a geological map sheet. Variations in the thickness of a bed are usually deduced from borehole data but may be discovered by measuring sections at geological outcrops and are occasionally revealed by variations in width of outcrop on a map.

The way in which a bed varies laterally in thickness can best be shown by constructing a series of bed isopachytes, lines joining points where the bed is known to be of the same thickness. To obtain the maximum number of control points at which the thickness of a bed can be determined it is usually necessary to construct two sets of structure contours, those for the top of the beds and those for its base. Their intersections give the thickness of the bed. Due to the nature of the sedimentary phenomena which produce beds of varying thickness, the isopachytes will tend to be reasonably straight (or curving) and approximately evenly spaced.

Posthumous folding

After the strata in an area have been laid down they may be uplifted, folded and eroded as we have seen in the last chapter. Further subsidence may cause the deposition of strata lying unconformably upon existing beds. Later still the processes of uplift and folding may recur, when this second period of folding is said to be posthumous – if the fold axis in the younger beds is parallel to, and approximately coincident with, the similar fold axis in the older beds. The trend of the two sets of folds may be parallel and the fold axes may coincide, as in Fig. 32, or they may be parallel but not coincident. Since the folding is of two ages, the trends of the two sets of folds may be in quite different directions and it is then called superposed folding or cross-folding and is not included in posthumous folding, but there is usually a tendency for the earlier folding to exercise a 'control' over the later folding so that, more commonly, the trends are parallel or sub-parallel.



Map 18 A wedge-shaped, igneous, sill-like body is encountered in boreholes. The land surface is flat and horizontal over this area and the depths from the surface to the top and base of the sill are given beside each borehole. Construct structure contours for the top of the sill and its base – assuming that both top and bottom are uniformly dipping (but not parallel). Construct isopachytes at 50 m intervals to show how the sill varies in thickness. Shade the area where the sill outcrops. Why is the sill absent in boreholes A and B? If it was not found in boreholes at C and D how would you explain its absence?

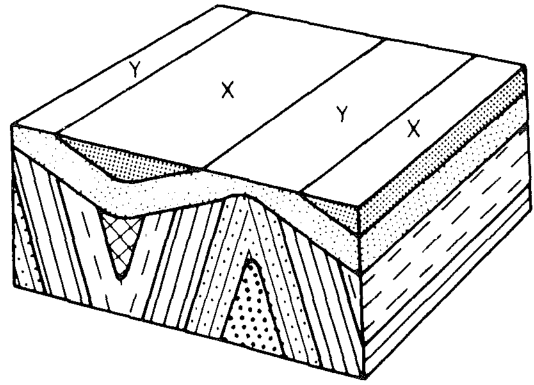


Fig. 32 Block diagram showing the effects of posthumous folding.

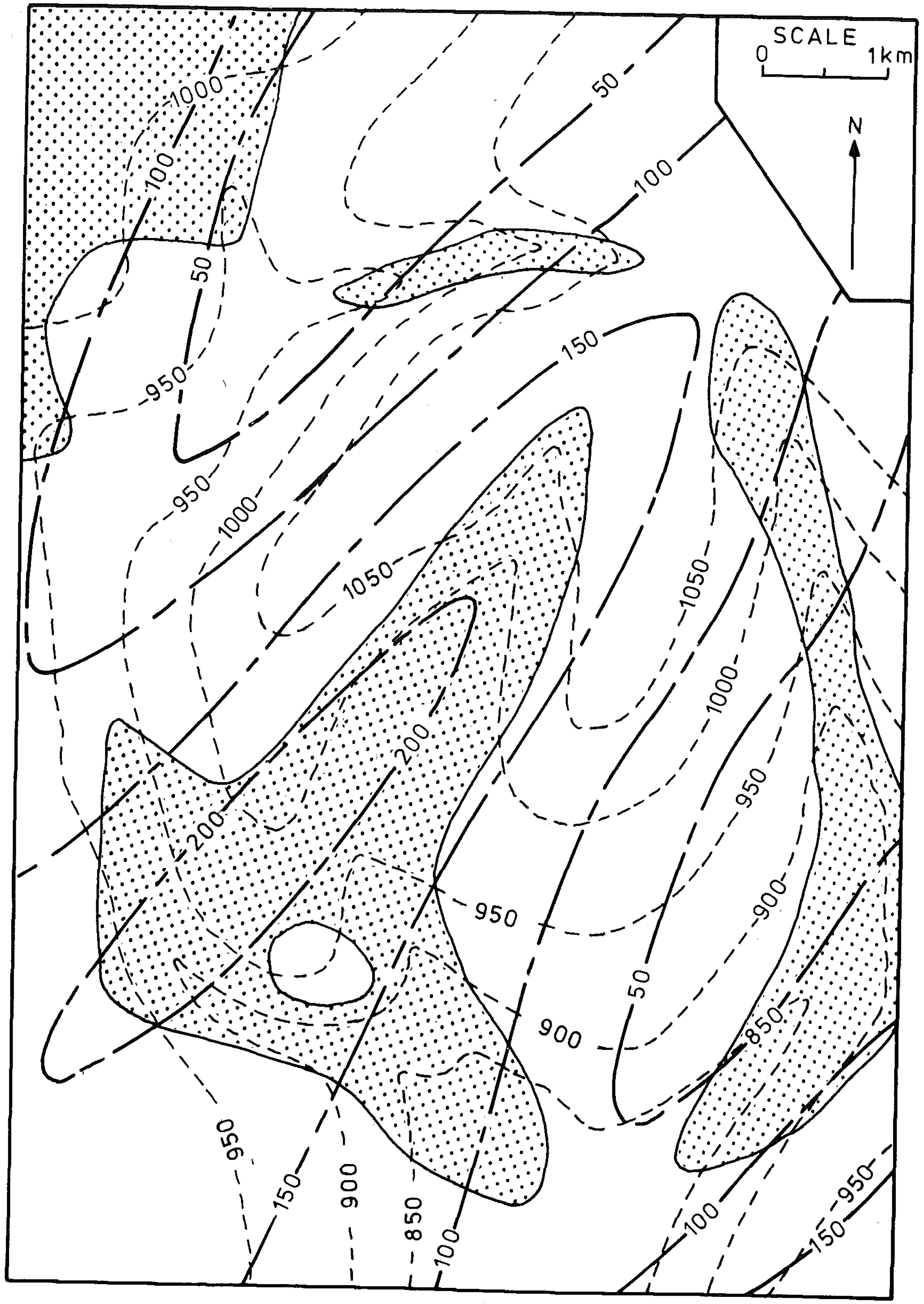
The strata of Pembrokeshire, see the Haverfordwest and Pembroke 1″ Geological Survey maps (sheets 227, 228), were affected by Caledonian folding and later by Variscan (Hercynian) folding. In this area the trend of the folding of both periods is nearly east–west. By contrast, the rocks of the Lake District were gently folded with an east–west strike in Ordovician times and later by the Caledonian orogeny (phase in the mountain folding process) with a north-east–south-west strike, the later folding being of such intensity that it seems to have been independent of the control of the earlier folds.

Where the folds are of different trend it is possible to study the effects of one age of folding by taking a section parallel to the strike of the other folds. This is very neatly shown in the block diagram of a part of the southern Lake District in the 'Northern England' British Regional Geology.

Polyphase folding

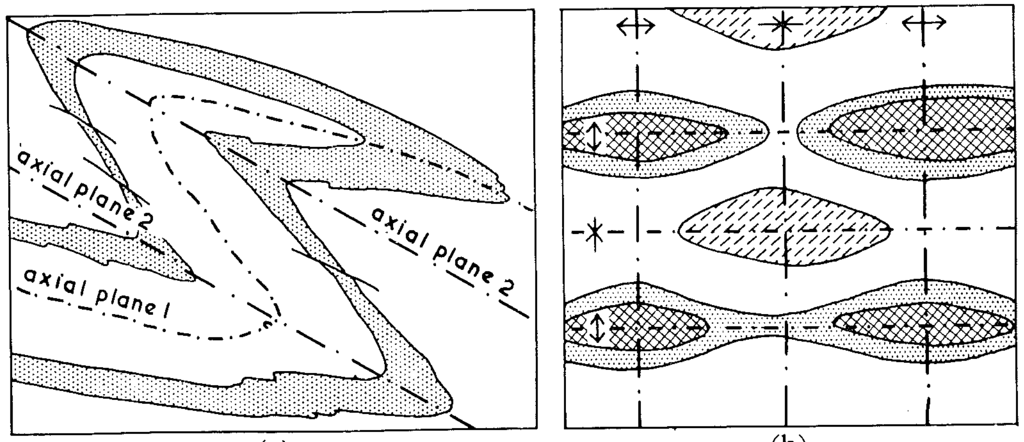
Strata which have already been folded may at a later time be refolded. The stress causing the refolding may be due to a later phase of the same orogeny or even due to a later orogeny. The stress of the later phase of folding may be quite unrelated to the stress direction of the earlier folding (the 'first folds'). As a result of this the trends of the two ages of folding may be quite different.

Map 19 The outcrops of the Middle Coal Measures (white) and the Lower Coal Measures (stippled) are shown. The heavy broken lines are the structure contours drawn on the base of the Lower Coal Measures (and have been deduced from borehole data). Construct structure contours for the Lower Coal Measures/Upper Coal Measures junction using outcrop information. (Note that the base of the Lower Coal Measures is folded, therefore the Lower/Middle Coal Measures boundary will also be folded about the same axial planes. Insert these on the map first). From intersections of the two sets of structure contours deduce the thickness of the Lower Coal Measures at as many points as possible. *Draw isopachytes at 50 m intervals for the Lower Coal Measures.* (Note that neither structure contours nor isopachytes can be drawn with a ruler in this example.) Drawing isopachytes can be done very conveniently on an overlay of tracing paper. Alternatively, different colours may be used for fold-axial traces, structure contours and isopachytes. Draw a section along a north-west–south-east line using a vertical scale of 1 cm = 200 m (a vertical exaggeration of × 2.5).



Map 9

Complex outcrop patterns are produced by the interference of two (or more) phases of folding. Simple examples are illustrated (Fig. 33). In some such simple cases the early folds can be seen to have been refolded since the axial planes of the first folds are themselves folded.



(a) (b)

Fig. 33 Outcrops of refolded folds on flat ground. (a) a refolded isoclinal fold (b) second fold axes crossing first fold axes at right angles.

The effects of faulting on fold structures

We have seen in Chapter 3 that the effect of normal faulting, followed by erosion, is to produce displacement of the outcrops on either side of a fault plane relative to each other. Displacement of the outcrop of all except vertical planes will take place so that, in the case of a symmetrical fold, the outcrops of the two limbs will be displaced but the axial plane will not (Fig. 34).

Since erosion has proceeded to a greater extent on the upthrow side of a fault (necessarily so to achieve a flat land surface as in the figure), and the outcrops move laterally – as a result of erosion – in the direction of dip, the outcrops of the limbs of an anticline will be found to be more widely separated on the upthrow side. Conversely, the same bed outcropping in the limbs of a syncline will be closer together on the upthrow side of a fault than on the downthrow side.

Consider now the effects of faulting and erosion on the outcrops of an asymmetrical fold. Erosion, followed by faulting, causes a more pronounced shift in outcrop of the beds of the less steeply dipping limb. The outcrops of the more steeply dipping beds of the other limb are not shifted to so great an extent (and in the 'limiting case', that of vertical beds, no lateral movement of outcrops would take place). The consequence of this is that in the case of an asymmetrical fold the outcrops of the limb with the lower dip are shifted by the greater amount. Since the axial plane of such a fold is inclined, its outcrop will also be moved laterally by faulting.

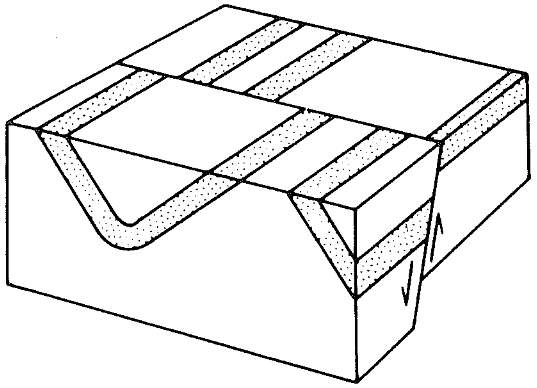


Fig. 34 Block diagram showing folded strata (one bed is stippled for clarity) displaced by a normal fault.

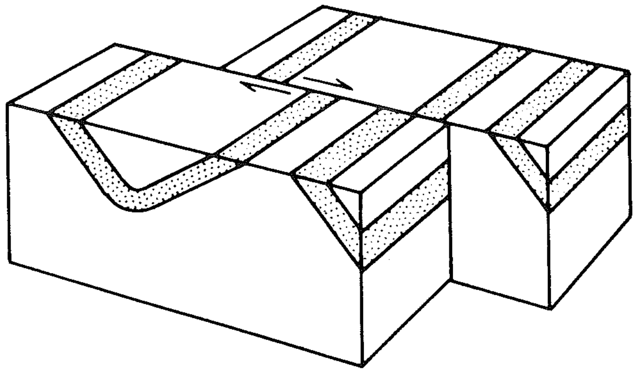


Fig. 35 Block diagram showing similar beds to Fig. 31 displaced by a wrench fault.

Wrench or tear faults

A wrench fault causes a lateral (horizontal) dislocation or displacement of the strata which may in some cases be of many kilometres. The effect of a wrench fault is to displace the outcrops of beds, always in the same direction – and its effect on the outcrops of simply dipping strata in certain circumstances is similar to that of a normal fault: it may not be possible to recognize from the evidence a map can provide whether a fault has a vertical or a lateral displacement (see p. 29). However, the effects of a wrench fault on folded beds is immediately distinguishable from the effects of a normal fault since it will displace the outcrops of both limbs by an equal amount and in the same direction (whether the fold be symmetrical or asymmetrical) and, further, the outcrops of a bed occurring in the limbs of a fold will be the same distance apart on both sides of the fault plane (Fig. 35). The axial plane will, of course, be laterally displaced by the same amount as the outcrops of the beds occurring in the limbs of the fold, and this displacement occurs whether the axial plane is vertical (in a symmetrical fold) or inclined (in an asymmetrical fold). Compare Figs. 34 and 35.

Faults parallel to the limbs of a fold

So far we have considered faults which were perpendicular to the axial planes of the folds or, at least, cut across the axial plane. A fault which is parallel to the strike of the beds forming the limb of a fold is, of course, a strike fault. This will cause either repetition of the outcrops or suppression of the outcrops of part of the succession, in the manner discussed on p. 25.

Published Geological Survey Maps
Haverfordwest: 1:50 000 Map No. 228 Draw a section along the north–south grid line 197. Note the difference in amplitude of the folding in the Lower and Upper Palaeozoic rocks. Tabulate in chronological order the geological events.

7 Complex structures

Nappes

Following the discussion in Chapter 5 in which overfolds were described, structures in which beds are overturned beyond the vertical, we next consider nappe structures. A nappe arises from a very large overfold in which the strata are nearly horizontal over wide areas. The fold structure is referred to as a recumbent fold and has been 'pushed over' so far that both limbs have low angles of dip, and are approximately parallel, although in the case of one limb the beds are actually upside down; i.e. the succession is inverted. Only at the 'nose' of the structure where the strata are folded back on themselves will steep dips be encountered (Fig. 36).

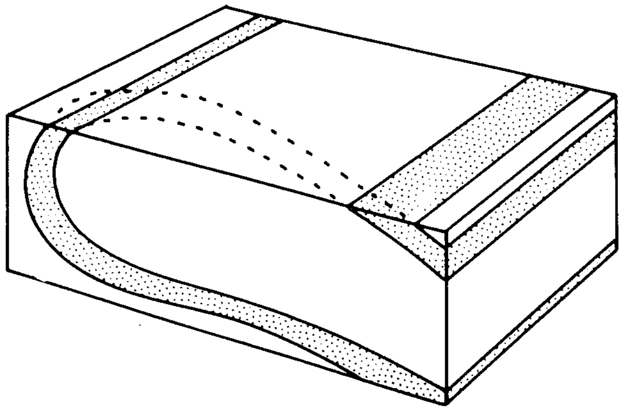
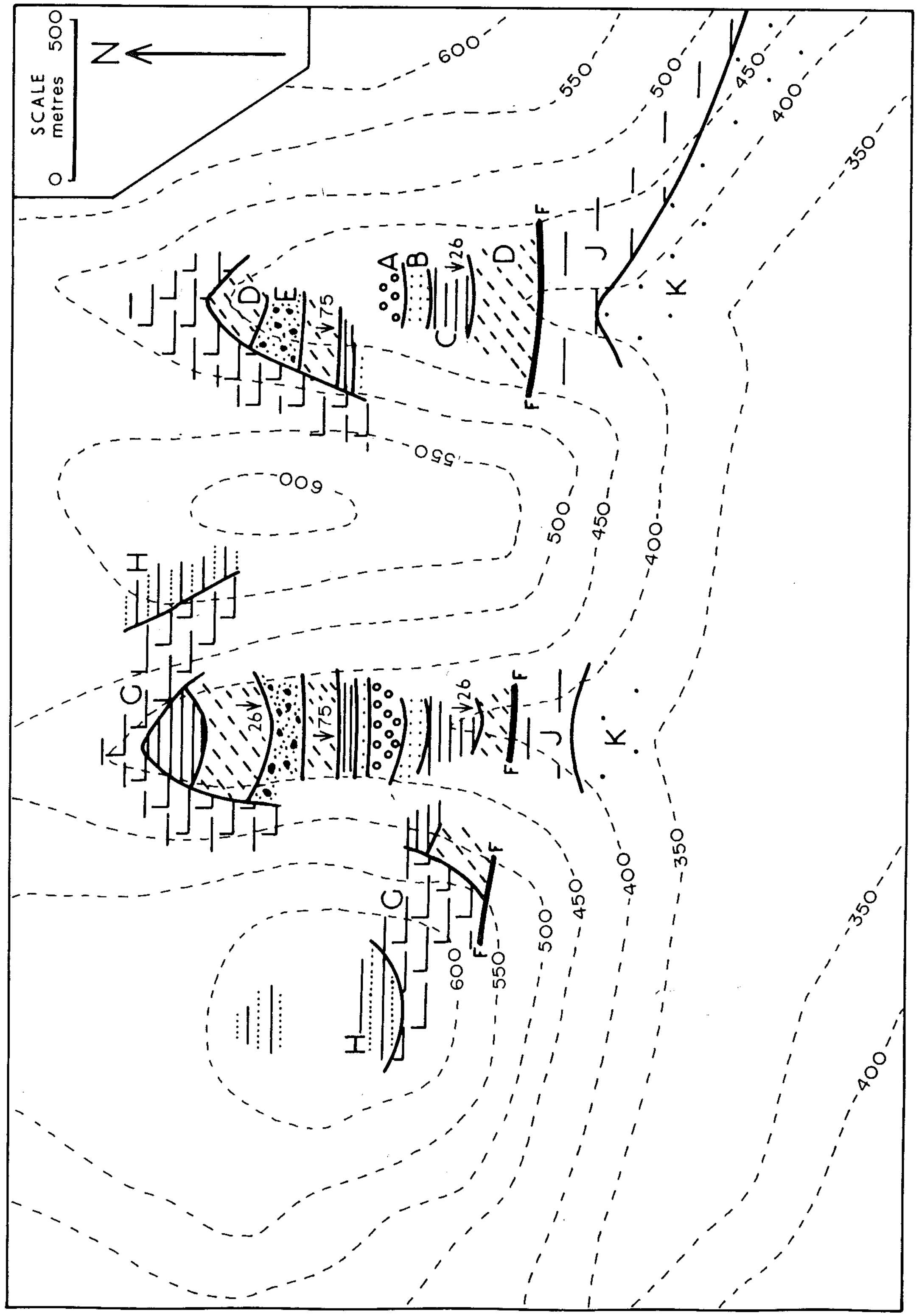


Fig. 36 Block diagram of a recumbent overfold.

The axial plane of such a structure is nearly horizontal, but may be curved as in the above figure. Not infrequently the intense lateral stresses producing recumbent folds also cause rupture of the strata and produce a 'low angle' reversed fault (making a low angle with the horizontal, but actually having a high angle of hade: see definition of hade). The thrust recumbent fold is a nappe structure (Fig. 37a overleaf).

Map 20 Outcrops are few in the area portrayed by the map, but sufficient to enable structure contours to be drawn. Complete the outcrops over the whole map and draw a section along a north–south line. Briefly summarize the geological history.



Map 20

Thrust faults

A thrust is a low angled fault plane along which movement has taken place, the strata above the thrust plane having been carried often for great distances in a near-horizontal direction, by intense earth movements, over the strata beneath. The thrust strata may have been displaced for a distance of many kilometres and may, for example, in the case of the Moinian rocks of Assynt (Sutherland) above the Moine Thrust, be quite different from any of the other rocks in the same district. On the other hand, the strata above the thrust may be similar to those beneath the thrust, but it should be noted that frequently older rocks may be thrust over younger ones. Thus it is possible to find Pre-Cambrian rocks overlying (due to thrusting) Cambrian rocks.

The strata above a thrust plane may be approximately parallel to it but, on the other hand, their dips may be unrelated to the inclination of the thrust plane, a whole block of rocks having been moved *en masse*. Frequently, just above a thrust plane, dips are locally affected by the movement along the thrust, beds being overturned due to the effects of drag of the rocks beneath the thrust.

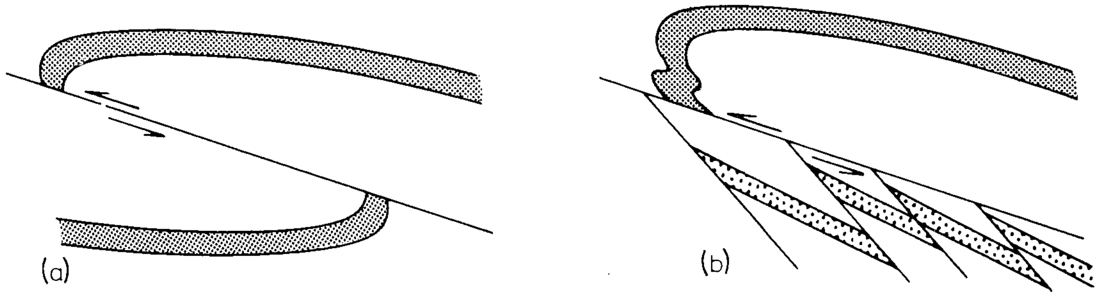


Fig. 37 (a) Section of a recumbent fold which has been thrust (a nappe) and (b) section showing imbricate structures which commonly occur beneath such a thrust plane.

The strata beneath a thrust plane may be very greatly affected by the forces associated with the thrusting. The effect on these beds is to produce imbricate structures. These comprise many parallel or near-parallel faults, sometimes of low hade although they are reversed faults, which divide the unthrust area or foreland into 'slices' (Fig. 37b).

Axial plane cleavage

When rocks which are bedded (possessing what may be termed primary structures) are subjected to pressures – or stresses – they may, as we have discussed, become fractured by faults or they may become crumpled into fold structures. The stress applied to a rock may also cause it to be deformed and new structures are formed such as cleavage and schistosity. Cleavage is developed as a result of shortening of the rock in a direction perpendicular to the cleavage planes with a stretching or extension of the rock in the plane of the cleavage.

Cleavage is often found in rocks which are folded. The greatest shortening of strata due to folding is perpendicular to the fold axial planes and it therefore follows that cleavage planes are parallel to the fold axial planes, hence the cleavage is called axial plane cleavage. (This will not be true for a sequence of beds of different competency nor, of course, in the case of complex refolded folds.)

Cleavage dips, indicated by a symbol such as ⋱ , should not be confused with dips of bedding planes – to which they may not seem at first sight to be an obvious relationship. This information must not, of course, be dismissed as something clouding the issue: if the cleavage is axial plane cleavage (the most frequently found) there will be a consistent relationship between the cleavage direction and the main structural features (folds). The cleavage will be parallel to the axial planes of the folds.

The relationship between the cleavage dip and the dip of the bedding reveals, in overfolds, in which limb the beds are the right way up and in which limb the beds are inverted. Cleavage dip steeper than bedding = right way up: bedding dip steeper than cleavage dip = inverted (Fig. 38). This 'rule' is necessarily true when there has been only one period of folding.

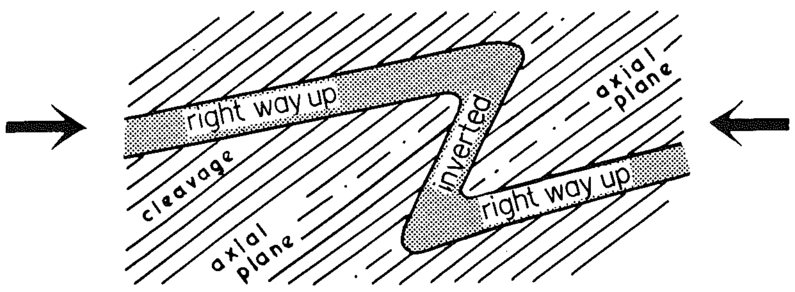


Fig. 38 Section showing cleavage/bedding relationships in an overfold with axial plane cleavage.

Published Geological Survey Maps
Assynt: 1″ Geological Survey map (Special Sheet) How may the thrust planes be distinguished from the unconformities? Find on the map some examples of imbricate structures.

8 Igneous rocks

Igneous rocks may be divided, according to their mode of occurrence, into extrusive and intrusive rocks (lava poured out onto the surface, or injected into existing rock). The intrusive igneous rocks may be further classified according to their form, but they fall from a structural point of view, into two groups, namely, transgressive or discordant intrusions and concordant intrusions.

Concordant intrusions

Sills The chief intrusions of this category are sills, 'beds' ranging in thickness from metres to a few millimetres of igneous material, commonly dolerite or basalt or felsite, which are parallel to the bedding of the sedimentary rocks into which they have been intruded. The intrusion seldom causes any observable disturbance of strata so that a sill behaves structurally as though it were part of the stratigraphical succession: if, subsequent to intrusion, the beds are tilted or folded then the sill is also tilted with the same dip or is folded.

One respect in which a sill is distinguishable from the strata including it, apart from its petrology, is that it is younger than those strata: it has been intruded after they were laid down and consolidated, perhaps long after the sedimentary beds were formed. Consequently, the strata into which a sill is intruded may already have been faulted, so that we may find beds displaced by faults which do not displace the sill. Of course, faulting which occurs after the intrusion of a sill will displace sill and strata alike.

A sill although normally concordant, may change its horizon occurring at one level in the sequence at one locality but at a different horizon at another locality. Often such changes in horizon or stratigraphical position are accomplished in 'steps', i.e. the changes are abrupt, the molten material being intruded taking advantage of lines of weakness such as joints or existing fault planes (Fig. 39).

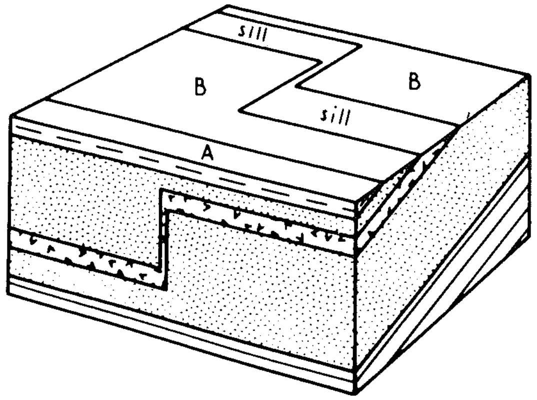
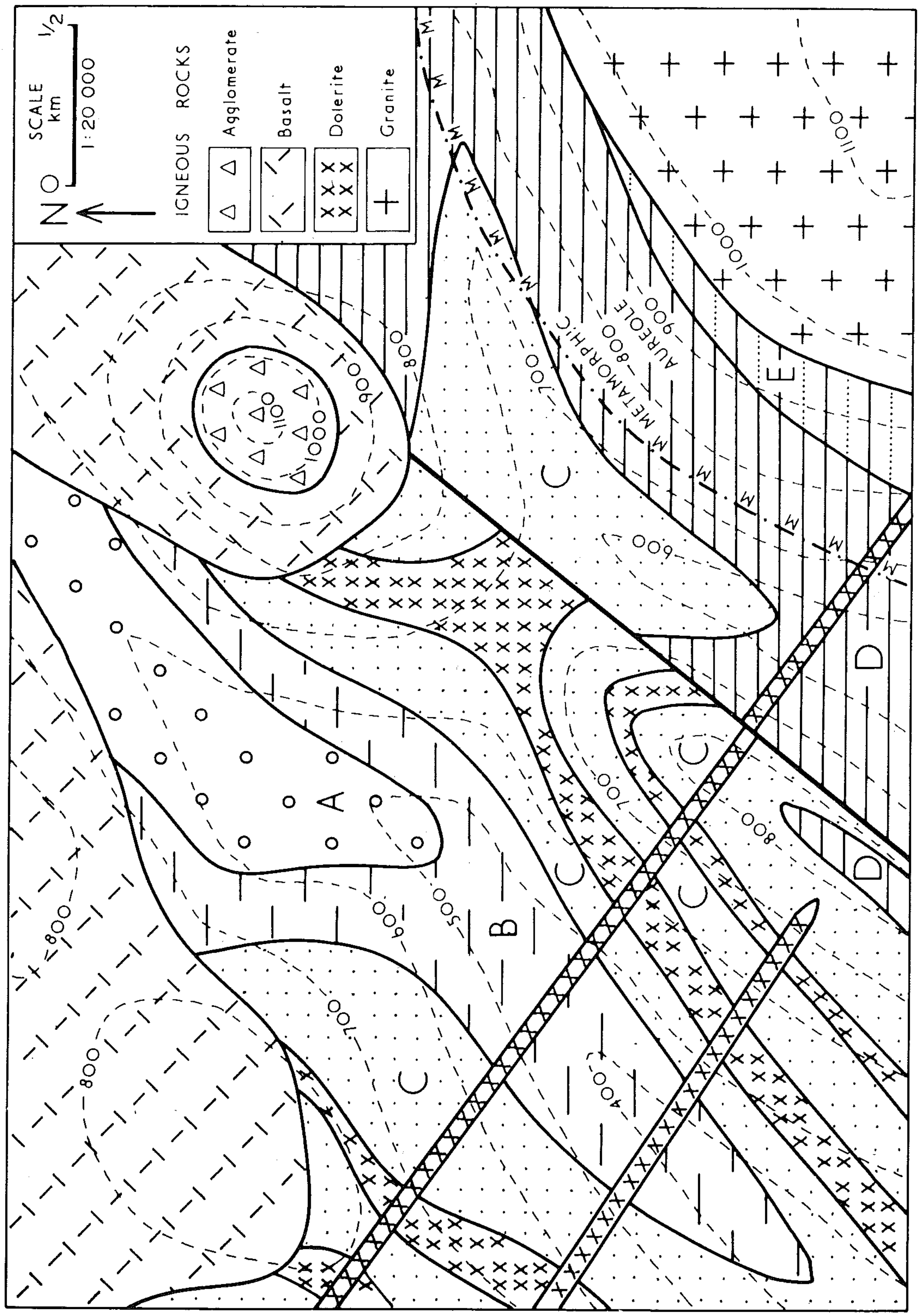


Fig. 39 Block diagram showing a sill intruded into dipping strata. Note that the sill is seen to change horizon abruptly.

Sills, being composed of resistant rock, may often be found capping hills, for example those on the Fife–Kinross border. A sill may form a pronounced



Map 21 Draw sections across the map to show the form of the igneous rocks and the other structural features. Also deduce the relative ages of the igneous rocks as far as this is possible.

escarpment such as the one on which Stirling Castle is built or the one which runs across Northumberland (made by the Great Whin Sill) on which part of Hadrian's Wall is built.

Other concordant intrusions such as laccoliths and lopoliths, the form of which are described and defined in any petrology book, are of much less frequent occurrence and are not dealt with here.

Lava flows and tuffs

These are the products ejected from active volcanoes, but in Britain there are many examples resulting from former periods of vulcanicity. From map information alone a lava flow may be difficult to distinguish from a sill, especially as both may be classed petrologically as basalt: rock type is not a reliable criterion. If a lava is poured out on to an eroded surface it may come to rest on beds of different age, producing in effect an unconformity. If it is poured out on the sea bed or on to recently uplifted un-eroded sediments then it will be 'conformable' and structurally resemble a sill. The field evidence that the upper surface of a lava is frequently weathered whereas that of a sill is not, and the fact that a sill thermally metamorphoses the overlying sediments, cannot be deduced from map evidence.

Tuffs are beds of volcanic ash and they may be interbedded with sediments, and so for structural purposes behave like sedimentary strata despite their volcanic origin.

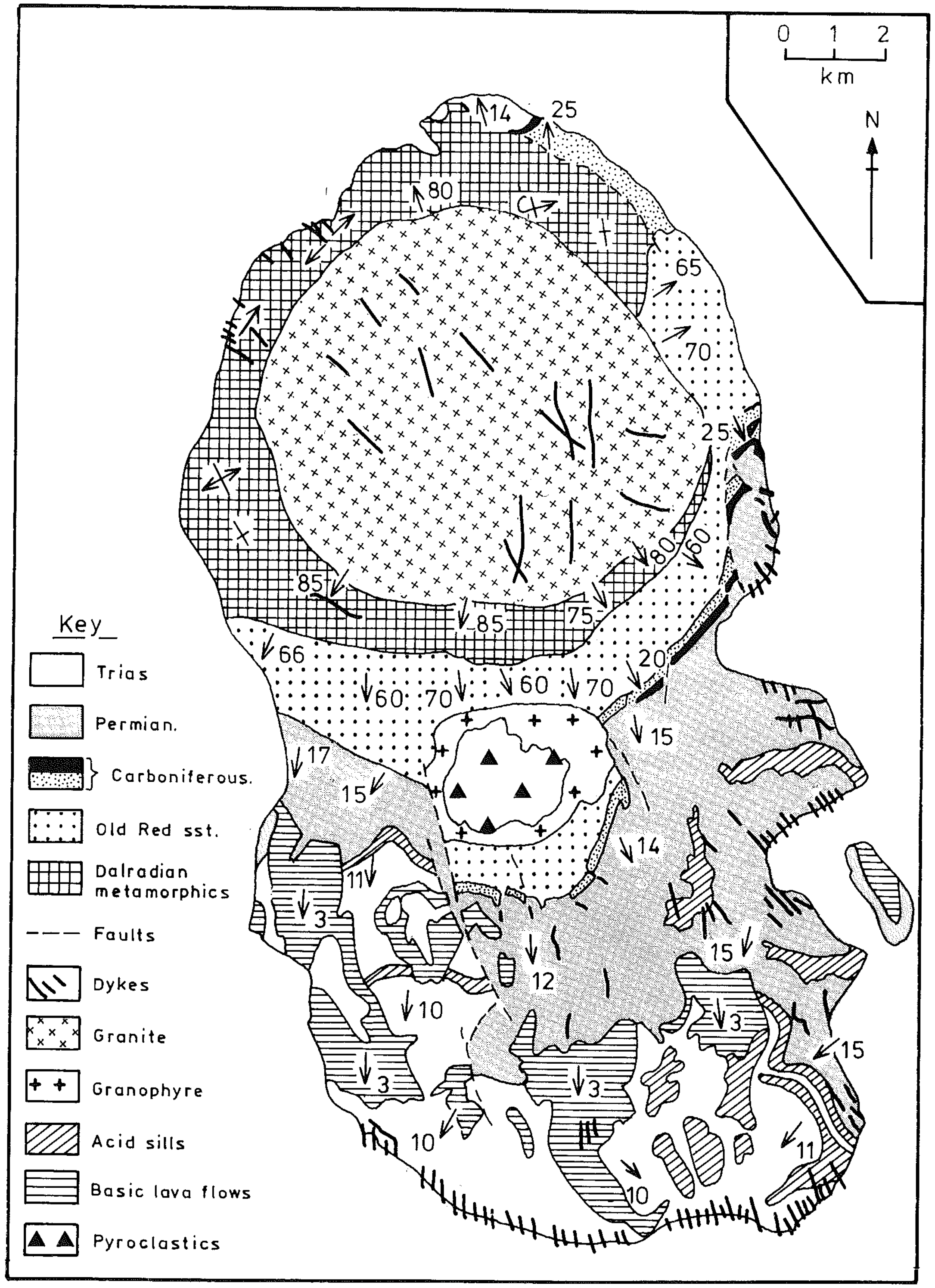
Discordant intrusions

Dykes These are vertical or near vertical intrusions, commonly of dolerite or basalt, varying from a few centimetres in width to several metres (but rare examples are tens of metres wide). They are frequently traceable across country for many kilometres, cutting through the strata into which they have been intruded.

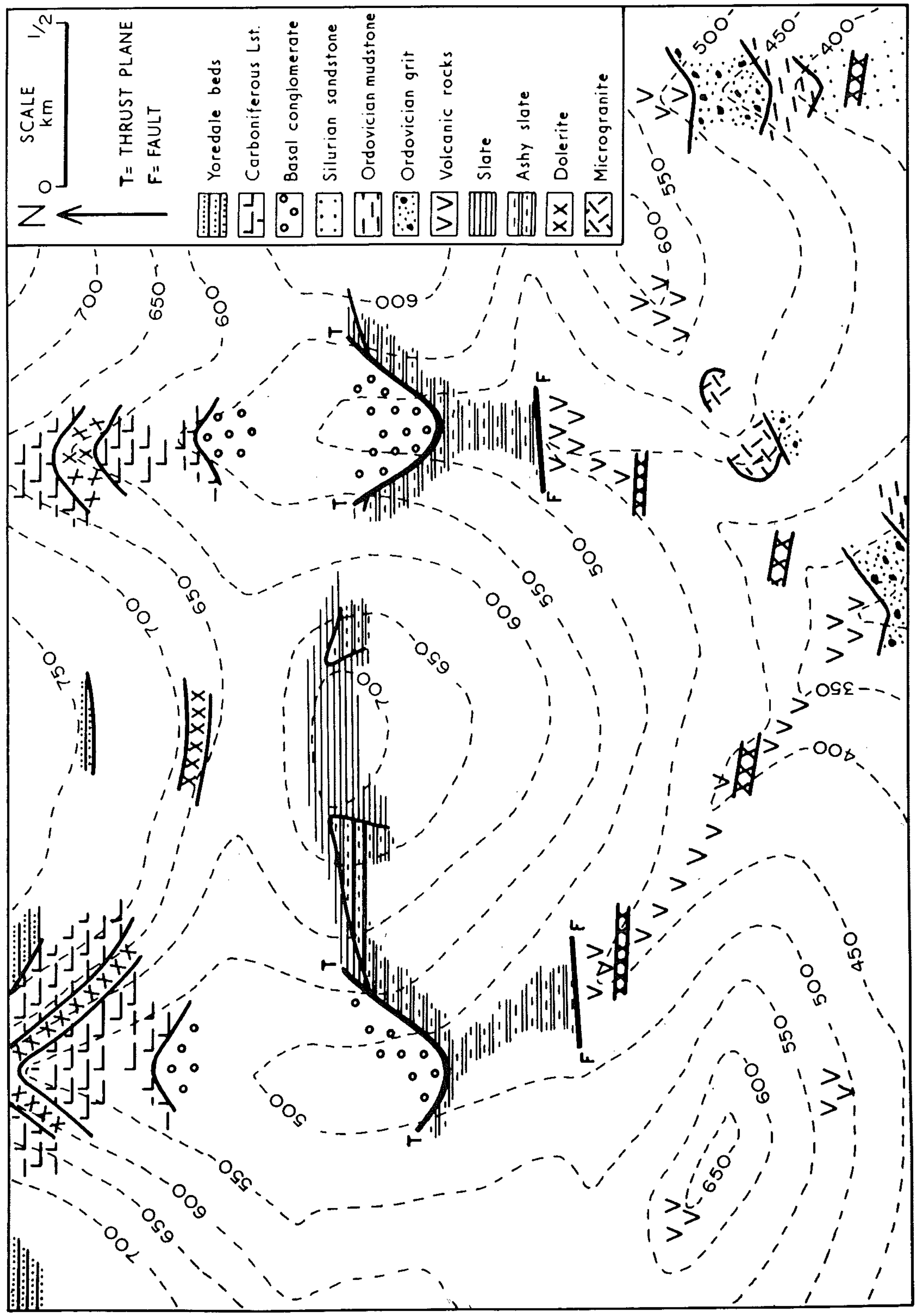
Since they were approximately vertical when intruded their outcrops are usually straight, regardless of variations in topography. It is possible, in certain cases, to date a dyke relative to the sedimentary strata: it must be later in origin than the youngest beds which it cuts and, in addition, where an unconformable series of strata occur it is possible to see whether a dyke cuts both the younger and older series (cf. the dating of faults, p. 29).

Stocks, bosses and batholiths These are larger bodies of intruded material. Of plutonic origin, intruded deep into the earth's crust and now exposed at the

Map 22 This map is broadly adapted from the geological map of the Isle of Arran. Most of the kinds of igneous intrusion shown on the stylized Map 21 can be found here. Write an account of the geology of the area, noting particularly the two major unconformities, the dips of strata of different ages and the distribution and disposition of different igneous rocks. What can you deduce from the general direction of the dykes? It is possible to work out the geological history for this map (however, it will not be identical to that of the one-inch to the mile geological survey sheet).



Map 22 Reproduced by permission of the Director, British Geological Survey (NERC): Crown copyright reserved.



Map 23

surface only through prolonged erosion, they are most commonly of granite. Varying in plan from near circular (bosses) to irregularly shaped masses (stocks) they also vary greatly in size, the larger intrusions (batholiths) being, exceptionally, up to hundreds of kilometres in length. Often these discordant intrusions are longer than they are broad, being elongated parallel to the general strike of folding and other structural features, but in every case their margins are vertical or steeply dipping, cutting discordantly across the sedimentary beds. Made of resistant rock, they commonly form high ground. Areas where the sediments have been baked and altered by the heat from the intrusion occur surrounding the larger igneous intrusions. These are known as metamorphic aureoles.

Volcanic necks These are the infilling of volcanic vents with consolidated lava (basalt, etc.) or pyroclastic material (agglomerate). They cut through existing strata and have vertical or near vertical sides and they are usually nearly circular in plan. A volcanic neck structurally, therefore, resembles a boss, but is normally of much smaller diameter and the rock types encountered are entirely different.

It is sometimes difficult from map evidence alone to distinguish between a basalt capping a rounded hill (a sill or a lava flow), possessing a circular outcrop, from a volcanic neck with a basalt infilling also having a circular outcrop, although in section the two features would be very different (Fig. 40).

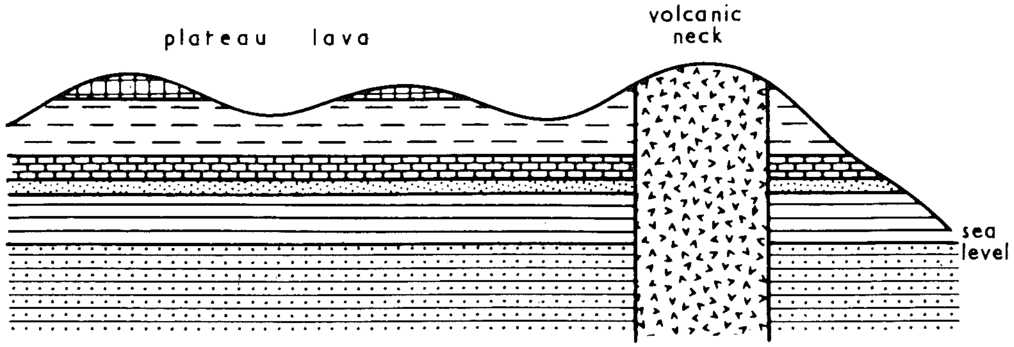
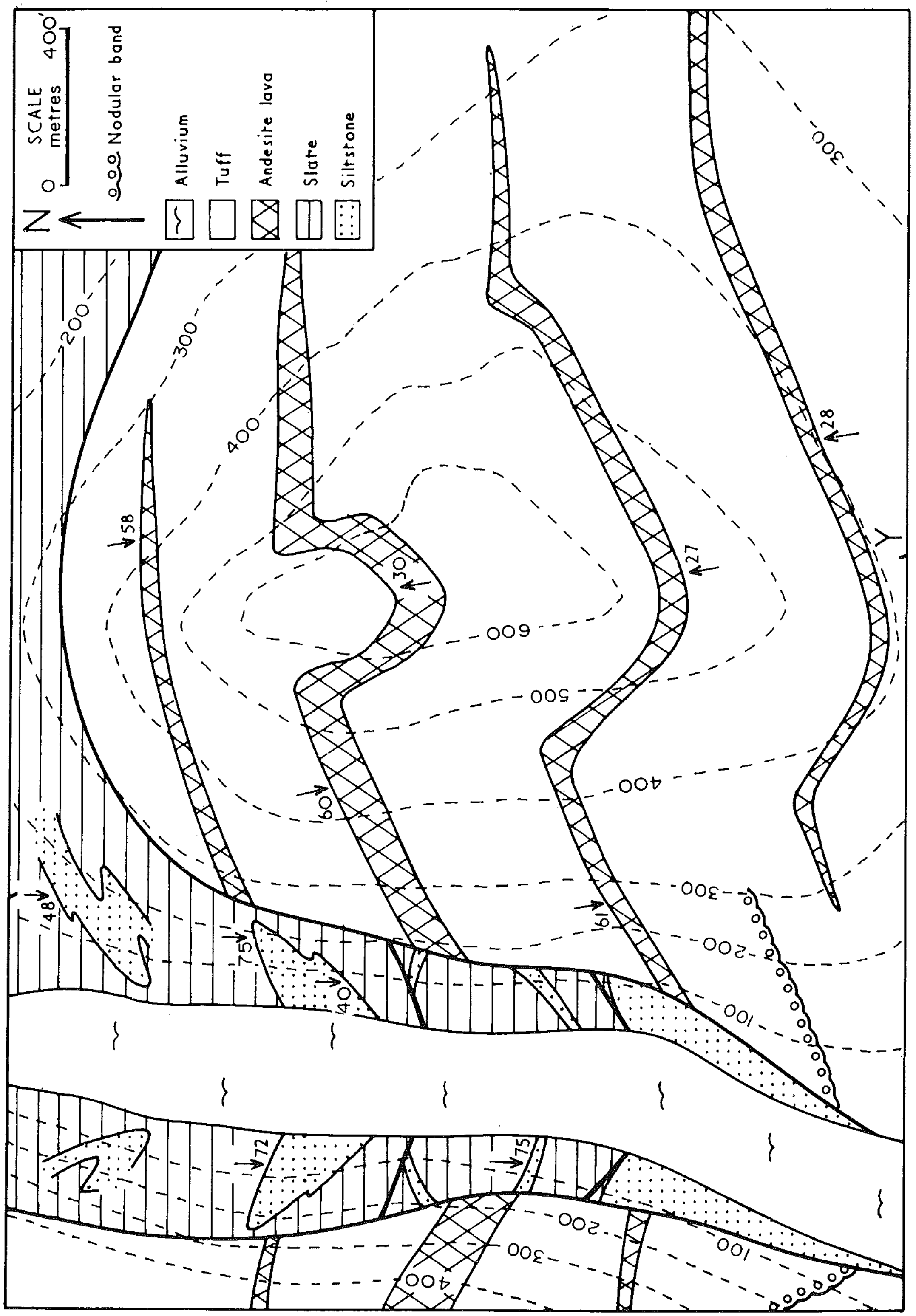


Fig. 40 Geological section showing a volcanic neck and lava-capped hills.

Published Geological Survey Maps

Edinburgh: 1″ Map No. 32 (Scotland) Give the relative ages of the various types of igneous intrusion shown on the map. How can the relative age of an igneous rock be discovered from map evidence and what are the limitations of this method? What other evidence might one expect to find in the field but which cannot be discovered from a map? (This map has now been replaced by 32E Edinburgh and 32W Livingstone on the 1:50 000 scale.)

Map 23 Complete the geological outcrops on the map. Draw a section along a north–south line to illustrate the structures. Write a geological history of the area including notes on the relative ages of the igneous rocks.



Map 24 Describe the geological structure of the area of the map and draw a section along the line X–Y.

Description of a geological map

All sources of information available should be used and coordinated, the information deducible from the map itself, the column of strata usually provided and sections showing the geological structures (the latter if not given on the map, drawn by the student). The description of a map should summarize the strata present. The general structural pattern and the trend of the chief structural features should be deduced from outcrop patterns. The broad relationship of topography to geology should be noted. It is usual to summarize the economic geology. Most important, a geological history of the area should be described. This comprises an attempt to relatively date all geological events, the deposition of sediments, breaks in the succession (unconformities), the intrusion of igneous rocks and the development of faults and folds. The evolution of superficial deposits, the drainage pattern and topography complete the history. In some cases a complete chronology cannot be deduced from map evidence and some events cannot be dated but their possible age and the ambiguity of the evidence must be discussed. An example is given of the main deductions which may be made from Map 23.

The geological history of map 23

The earliest bed present is the ashy slate – formed by tuff falling into a sea in which argillaceous sediment was being deposited. A lull in vulcanicity but with continued deposition accounts for the overlying strata, now slate. The age of both formations is in doubt: they are thrust over Carboniferous Basal Conglomerate (which is clearly younger) and they are faulted against volcanic rocks. Though metamorphism itself is no guide to antiquity of strata, these slates (and ashy slates) may be the oldest strata present, since no other beds have been metamorphosed, and thus older than the volcanics which are earlier than the Ordovician grit. After the volcanic episode, perhaps prolonged although the thickness of volcanic rocks is not deducible since their structure is unknown, a conformable sequence of sediments was laid down. This comprises Ordovician grit and mudstone and Silurian sandstone. The lowest of these appears to rest partly on the microgranite which must therefore have been intruded at an earlier date. The age of the east–west fault must be later than the slates and the volcanics which it cuts, but how much later cannot be established.

Dolerite dykes cut volcanic rocks and beds as young as the Silurian sandstone, and hence were intruded after the deposition of these beds. Although not cutting Carboniferous rocks the dykes *may* be contemporaneous with the post-Carboniferous sill, also of dolerite.

After (probably prolonged) non-deposition (since no Devonian age strata are seen) Carboniferous seas spread into the area depositing initially a basal conglomerate, though its base is not seen and we do not know what it rests on. As the sea became clearer (?deepened) limestone was deposited, followed by the

Yoredale beds – cyclic sediments laid down in shallow marine to terrestial conditions. Two major post-Carboniferous events occurred: the thrusting northwards of older rocks over the Carboniferous, accompanied by overfolding of strata above the thrust plane, and the intrusion of the thick dolerite sill. Neither can be dated precisely. Both may be approximately the same age, referable to the late Carboniferous orogeny (the Variscan) although either could be of much later date. A northerly tilt was imparted to the area since the horizontally deposited Carboniferous strata have a northerly dip.

Mesozoic and Tertiary events are unknown since no strata of this age occur here. However, uplift and subsequent erosion have given rise to the present topography, southwards sloping valleys cutting back into a high east–west escarpment. The topography relates closely to the underlying geology. Superficial deposits are not shown on this map.

Numerical answers

Map 1	Sandstone 2	100 m
	Mudstone	150 m
	Shale	50 m
	Sandstone 1	150 m
Map 2	1 in 2½; Bearing 174° (6° E. of South)	
Map 3	1 in 5; East	
	B	250 m
	C	100 m
	D	100 m
	E	50 m
Map 4	200 m	
Map 7	A	450 m
	B	200 m
	C	absent
Map 8	500 m	
	200 m	
Map 15	Y	400 m
	Z	110 m
	1 in 4 (14°)	

Table I

If vertical thickness of a bed (V.T.) = 100 m

Angle of Dip:	True Thickness of bed:
0	100
10	98.5
20	94.0
40	76.6
60	50.0
80	17.4

Table II

	If angle between line of section and the direction of True Dip is:				
True Dip:	10°	30°	50°	70°	90°
	then Apparent Dip in section is:				
0	0	0	0	0	0
10	10	9	6	3	0
30	30	27	20	11	0
50	50	46	37	22	0
70	70	67	60	43	0
90	90	90	90	90	—

Apparent dips given to the nearest degree

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