CAMBRIDGE GEOLOGICAL SERIES

THE STUDY OF GEOLOGICAL MAPS

CAMBRIDGE UNIVERSITY PRESS
C. F. CLAY, MANAGER
LONDON : FETTER LANE, E.C. 4

LONDON : H. K. LEWIS & CO., LTD.,
136, GOWER STREET, W.C. 1
NEW YORK : THE MACMILLAN CO.
BOMBAY
CALCUTTA } MACMILLAN AND CO., LTD.
MADRAS
TORONTO : THE MACMILLAN CO. OF CANADA, LTD.
TOKYO : MARUZEN-KABUSHIKI-KAISHA

THE STUDY OF GEOLOGICAL MAPS

BY

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CAMBRIDGE
AT THE UNIVERSITY PRESS
1921

PREFACE

THIS book is based mainly upon the notes for a course of lectures and practical work given to many successive generations of Girton and Newnham students. I was asked to put the subject-matter into the form of a book in order that it might be available for other students of Geology. This I have tried to do, but as my main object has always been to encourage the free use and study of geological maps I have been obliged in the book to assume that access to such maps is possible; an attempt to reproduce any of these maps at the present day would have made the price of the book prohibitive for the very section of the community for whom it is primarily intended.

I acknowledge most gratefully the permission given to reproduce illustrations by the following societies and individuals:

H.M. Stationery Office. Map of the Lake District. Maps and Sections in the publications of the Geological Surveys of England and Wales, and Scotland. Figs. 3, 18, 51, 54, 56, 61, 62.

The Geological Society. Sections and Maps in papers by Prof. O. T. Jones and myself. Figs. 32, 33, 38, 39, 41.

The Geologists' Association. Sections in paper by Mr E. B. Bailey. Figs. 36, 42, 50.

Royal Society of Edinburgh. Figures in papers by Mr Harker, and Prof. Kendall and Mr E. B. Bailey. Figs. 2, 4.

Royal Dublin Society. Figures in paper by Mr Harker. Figs. 21—28, 40, 44, 63, 64.

Yorkshire Geological Society. Figures in paper by late Rev. W. L. Carter. Fig. 5.

I would also express my thanks to Sir A. Geikie, Mr Harker, Prof. Watts, Prof. O. T. Jones, Prof. S. H. Reynolds, and Mr E. B. Bailey for permissions of a similar nature, whilst to Dr Rastall of Christ's College and to Mr J. B. Peace of the University Press I am indebted for much kindly criticism throughout.

Last but not least my thanks are due to my two old pupils, Miss A. B. Taylor and Miss M. Chandler—to Miss Taylor for the clear and artistic drawings from which the plates were made, and to Miss Chandler for copying and drawing many plans and sections in preparation for their reproduction.

G. L. E.

NEWNHAM COLLEGE,
February 1921.

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CHAPTER I

INTRODUCTION

The reading of Geological Maps is one of the most important branches of the study of Geology; every student who reads such a map intelligently can gain a vast amount of information from it, often in a far more convincing form than that acquired by reading an elementary text-book. The subject therefore well repays study, and if this study be supplemented as it always should be by work with maps in the field, a real grasp of it may be obtained, such as could never be acquired by months of hard work in the class-room alone.

There are nevertheless many fundamental principles underlying this geological map-reading which may well be studied in the class-room, in order that their importance may be fully realised in the field; and it is the object of the present book to direct the attention of students to these. It should however be borne in mind that any book dealing with the subject must of necessity be regarded as merely preliminary or complementary to work in the field.

The most cursory glance at almost any geological map shews that the outcrops of strata vary almost indefinitely in form, one and the same outcrop having regular boundaries in one place and irregular in another; the outcrop may be wide here and narrow there; may run straight across country in one part of the map, and may curve about in an amazing fashion in another part.

The first thing then to realise is *why outcrops vary in form.*

Very little study suffices for the conviction that these variants are not haphazard, but are governed by definite circumstances, and as the nature of each circumstance is better understood, the student begins to realise the more or less precise meaning to be attached to each form of outcrop.

It is perfectly possible to draw a fairly correct section across a map without in the least realising the significance of all the features shewn, but when each outcrop has a definite meaning the whole geological history of the area can gradually be made out.

In studying geological maps the student must always try to feel the surface relief and *see solid*, i.e. in three dimensions.

Variation in the Form of Outcrop. The variation in the form of the outcrop is primarily due to

- (*a*) the character of the ground (its slope and irregularities);
- (*b*) the character of the bed (its dip, thickness, and capacity for resisting denudation).

The form assumed by the outcrop of any bed at the surface is so intimately connected with the shape of the ground, that the study of this shape is an all-essential part of the reading of any geological map. Maps upon which the surface relief is depicted are invaluable guides to the physical history of the region, and are full of meaning to the geologist who studies them, even though there be not a single geological line drawn upon them. Such maps are known as *topographical* maps; the surface, on the map, is regarded as a horizontal plane, and the natural features are not imitated, but are represented by significant lines and markings; of the natural features the relief is more important than the drainage, for if the relief be accurately depicted, the lines of drainage appear as it were of themselves.

It is not possible in a work of this kind to do more than refer in general terms to the different ways in which the surface relief can be shewn upon a map; for further details works on Surveying may be consulted[1].

There are three main points that require to be shewn:

(*a*) the height of any point above the datum line in terms of some unit of length;

(*b*) the higher portions of the land as distinguished from those situated at lower levels;

(*c*) the form of each feature as moulded by erosive agencies.

The relief would appear to be most accurately depicted by Contours, but may also be shewn by Hachures, Conventional Hill Shading, and by Hypsometric tints, generally known in this country as the Layer System.

Contours. Contours are lines of level drawn upon the map representing the trace of a fixed level line upon the surface of the country shewn; the most important of all contours is the *datum line*, from which all the other contours are measured; this datum line is also known as the *shore line*, in Britain also as the *ordnance datum* (O.D.). The O.D. of Great Britain is the average height of mean tide at Liverpool, and levels are given in so many feet above it; every point upon a map where an exact height other than a contour level has been taken is noted, and indicated upon the map, and where a permanent structure exists at the spot, the Government broad arrow is marked upon it and such a place noted upon the map by the letters B.M., meaning *Bench Mark*. These heights are in many cases true Spot Heights, but where there is a Bench Mark, the height is usually not the height of the ground at that point, but the height of the B.M. Spot heights are very useful for supplementing the information supplied by contours, but are of little use alone, as they give no indication of the form of the ground.

Every contour line then represents the trace of the cutting of two surfaces; the shore line for instance is the intersection of the surface of the land with that of the sea, and all other contours given on a map represent the intersection of other levels with the relief of the globe. These contour lines are traced and surveyed on the ground and laid down at equal vertical intervals; that is each successive contour represents a fixed rise or fall of so many feet; on any one map the contours may represent a 50 ft., 100 ft., or 200 ft. rise or fall; they should be at a constant interval for any one map, but unfortunately this is only exceptionally the case in the maps in use in the British Isles. In the British Ordnance maps as a rule the vertical interval is 50 ft. up to 100 ft., 100 ft. up to 1000 ft., 250 ft. up to 2000 ft. and 500 ft. above that height. This is apt to be very misleading unless carefully borne in mind, as the spacing of the contours suggests a gentler slope than actually exists. In the maps of Lancashire and Yorkshire and of some of the southern counties of Scotland contours are shewn throughout at intervals of 100 ft., with interpolated contours at 25 ft. intervals. It is much to be regretted that this more detailed contouring has not been more extensively carried out.

[1] Hinks, *Maps and Survey*, 1913, Camb. Univ. Press. Close, *Text-book of Topographical Surveying*, 1913, H.M. Stationery Office.

There are many methods of contouring, and these vary in accuracy from deliberately surveyed contours determined by instrumental levelling, to sketch contours drawn in by eye, and the degree of accuracy is really a measure of the reliance that can be placed upon the map.

The following are the usual methods employed :

(*a*) with theodolite or level,
(*b*) with water level,
(*c*) with clinometer,
(*d*) with aneroid barometer,
(*e*) by eye-sketch.

The accuracy of a map, even if contoured by instrumental levelling, is dependent upon the vertical interval between the lines ; a map with contours at every 25 ft. is clearly more likely to give an accurate picture of the surface relief than one upon which the contours are drawn 200 ft. apart. For instance, in many of our upland valleys the ground is not level, but may be covered with mounds of drift and fragments of moraines, or eskers, or may even be conspicuously terraced, and yet if none of these features rises to an elevation sufficiently high to be shewn on a map contoured on the 100 ft. scale, the map gives no indication of its existence; whereas if the contours had been at the 50 ft. interval, or better still at the 25 ft. interval, the general uneven character of the valley floor must have been made apparent. So too with the moorland surfaces that lie above the 1000 ft. level; since the contours above that height are only inserted at intervals of 250 ft., it is clear that the surface may have many undulations of considerable geological importance without anything upon the map to indicate that such is the case.

It is however obvious that as a result of the method of projecting upon a horizontal plane, the distance between two places upon a map is not shewn with absolute correctness, unless the two places lie at the same height above sea level, and the greater the vertical distance between them the greater the error of the map. Thus a climber ascending a very steep slope must inevitably cover more ground than the map suggests and hence the common use of *time* instead of *space* units in the literature of mountaineering.

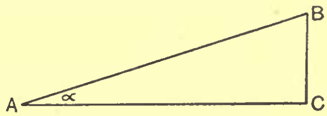


Fig. 1.

Thus if *AC* (Fig. 1) be the distance measured on the map between the two places *A* and *C*, and *CB* be the vertical interval between them as indicated by the contours, then if a triangle be constructed by erecting *CB* at right angles to *AC* and joining *AB*, the angle at *A* (α) is the angle of slope and the

$$\text{Actual Distance} = \frac{\text{Distance on map}}{\text{Cosine of slope of ground } (\alpha)}.$$

The actual steepness of the ground may be noted in two ways:

(1) As a slope of so many degrees, e.g. 3°, 5°, 10°, 20°, etc.;

or (2) As a gradient or rise of so many feet in such and such a horizontal distance, e.g. 1 in 6, meaning a rise of 1 ft. in a horizontal distance of 6 ft.

A slope of 2° = gradient of 1 in 28.
" 5° = " " 1 in 11.
" 10° = " " 1 in 6.

The gradient is commonly used on lines of railway to indicate the steepness of the track, but it is often more useful to have it expressed in degrees when it is desired to emphasise the relation existing between the slope of the ground and the dip of the rocks upon its surface.

The average gradient in degrees between two points which lie on different contours can easily be ascertained by measuring the horizontal distance between the points on the map and converting it into feet (or other unit) by using the scale.

This gives what is known as the *Horizontal Equivalent* for the known vertical interval.

Thus if BC is 50 ft. and AC measures 1430 ft., the average slope, α, between A and B is such that $\cot \alpha = \frac{1430}{50} = 28{\cdot}6$, that is $\alpha = 2°$.

With regard to contours as a whole, the following generalisations may be made:

(*a*) the smaller the horizontal distance between the contour lines the steeper the relief of the ground;

(*b*) the smoother the contour lines are in their flow the smoother and more even the surface of the country;

(*c*) conversely, the more zigzag the contour lines, the more irregular the surface of the country;

(*d*) contours have a more or less V-shaped form where there are valleys and, except in the case of very sharp ridges, contours are U-shaped on projecting spurs.

A contoured map then shews the absolute height of any point above a particular level, usually above O.D.; its relative height with reference to any other point; and in general terms the nature of the slope, whether gentle or steep. The form of the slope can be recognised by the fact that the contours are closer together towards the top in a concave curve, while in a convex curve the distance between the contours decreases towards the bottom.

If contouring be accurate the drainage may be inferred with a high degree of accuracy. In this connection it must be remembered that in a normal drainage system the main rivers run in the direction of the greatest slope, and the tributary streams somewhat obliquely towards the trunk streams.

The contours will be notched for the valleys according to the size and importance of the stream, leaving headlands projecting, as it were, between the different valleys, and since the contours must V up the valleys, the ground being lowered by river action, so the headlands U down the valleys, that is away from the sources of the streams. The perfection to which the drainage is seen is dependent upon the accuracy and completeness of the contouring; in a hilly country where the contouring has been carried out at the 25 ft. interval the drainage is very accurately shewn.

The 1-inch map is probably that in commonest use in the British Isles and is regarded as our standard topographical map, but this scale is too small for any detailed geological work, for which the 6-inch map should always be employed. Occasionally it may be necessary to use the still larger 25-inch map, if available, but the disadvantage of the use of such a map for geological purposes lies in the fact that there are no contours represented, nor any attempt at shewing the form of the surface relief, which must therefore be inserted by the geologist as required.

It is not easy without practice to visualise the relief of a region from contours alone, and partly on this account and partly also to save expense, some method is frequently employed in which the map is made to tell its own story in a manner that more directly appeals to the eye. The more important of these methods are described below: in the first and second of these the *slope* of the ground is emphasised, the height being regarded as of secondary importance; these are the methods of Hachuring and Conventional Hill Shading. In the third the *height* is considered of primary importance, and the slope has to be inferred. This is the method of the Layer System.

Hachuring. As contours stand for horizontality, so Hachures are used to suggest verticality, and are therefore lines representing great changes of level. They are best drawn in the direction of steepest slope, perpendicular to the contour lines; some indeed would confine the term hachure to such lines, but the term has also been used for horizontal lines inserted between the contours at definite intervals, the lesser interval indicating the greater slope; in the case however in which they are drawn perpendicularly to the contour lines, with the slope, they may in a sense be regarded as stream lines since their course is suggestive of the relief, and indicates the possible direction of a stream. Hachures are fixed for one contour, most conveniently for that which has the widest spread upon the map; they may be followed uphill or downhill but *can never cross a ridge.* With increasing steepness they may be drawn closer together and heavier, hence the steeper the relief the blacker the effect upon the hachured map; the main defect of hachures from the point of view of the geologist is that while indicating the slope they fail to shew the degree of slope.

A contoured map which is also hachured gives a very clear picture of the relief of an area, but for the geologist it already has so much upon it, that it is somewhat difficult to insert geological lines which will shew clearly.

Conventional Hill Shading. Hill Shading aims at giving somewhat the same effect as hachuring, at less expense; the hills may be shaded roughly in proportion to the intensity of the slope or an attempt may be made to give an idea of the relief by putting in the shadows at a particular time of day, usually with the sun in the N.W.; in each case the effect is too generalised to be of much real use to the geologist where any detail is concerned.

Layer System. The Layer System is the method employed for many years in the construction of Bartholomew's well-known maps, and more recently in the half-inch Ordnance Survey maps. In this system there is a direct appeal by colour to the eye, the heights above sea level between any two successive contours being indicated by a special colour, the tint deepening with the height, though where more than one colour has to be employed the order of tints must be inverted or the contrast is too great; thus darker green shades give place to paler with increasing height and pale browns are succeeded by those of darker tone.

The small scale of these maps ($\frac{1}{2}$ inch to the mile) and the inconstancy in the scale of contouring present some disadvantages, but they were constructed primarily for use as road maps and have admirably fulfilled their purpose.

CHAPTER II

THE USES OF TOPOGRAPHICAL MAPS IN GEOLOGY

The careful study of an accurate topographical map often directs attention to peculiarities of relief or drainage which may be of the greatest importance in the physical history of the region. These may even be evident upon the small scale layered map, more clearly seen upon the ordinary 1-inch map, and seen with still greater clearness on the map on the scale of 6 inches to the mile or still larger scale.

Coast Lines. The study of the coast line, for instance, may reveal the existence of a flat shelf at a small but approximately constant distance above sea level, suggesting the presence of a raised beach, and denoting the probable emergence of land; if the sea bottom has also been surveyed the continuance of a river valley beneath the sea may be made clear. Should this occur in conjunction with the continuance of practically all the surface features beneath sea level, the submergence of the land at no very distant date is strongly suggested. The continuance of a river valley alone below sea level is however not sufficient proof of submergence, for certain rivers may and do keep in clearly defined channels for some distance from the land. Features such as those just described may be noted in the study of the maps of certain coastal districts of the Western Highlands of Scotland. Again the contours of the coast line may be uniform and the slope of the ground above water continued seaward with a gentler grade; this would seem to shew that the ground has remained stationary for a considerable period.

Mountains. In the inland region, the nature of the mountains and valleys is all-important; if all the summits rise to an approximately constant height, and are all more or less flat-topped, there is at least presumptive evidence in favour of their having been carved out by denudation from a high plateau, which may have been more or less flat, as in the case of the limestone plateau of Yorkshire, where the hills of Ingleborough, Whernside, and Penyghent have clearly been produced by sculpturing from a plateau land probably of greater elevation than any of the present hill tops; or the original plateau may have been more undulating in character, as was probably the once far more complex Highland Plateau from which our Scottish mountains have been carved; in this case denudation has often proceeded so far that the traces of this plateau are hard to detect. Especially is this true in the West Highlands, though somewhat more obvious in the Central Highland Region, where the facts suggested on the map can be verified by a survey of the district from any of the summits of the mountains of the Breadalbane country such as Ben Lawers, or Meall an Tarmachan, whence its remains are strikingly visible.

Valleys. The valleys also may shew many points of interest; they may shew the gentle slopes and overlapping spurs characteristic of water erosion, or at the other extreme they may exhibit wide steep sides, spurless, or with the truncated spurs considered to be characteristic of valleys that have been glaciated (Fig. 2). The tributary streams may enter at grade, with the contours more or less evenly spaced, or the interval between them steadily increasing throughout the course of the stream; again, the contours may be wide apart, in the upper reaches of the tributary, and then suddenly come quite close together where the tributary joins the main stream; this indicates a want of grade

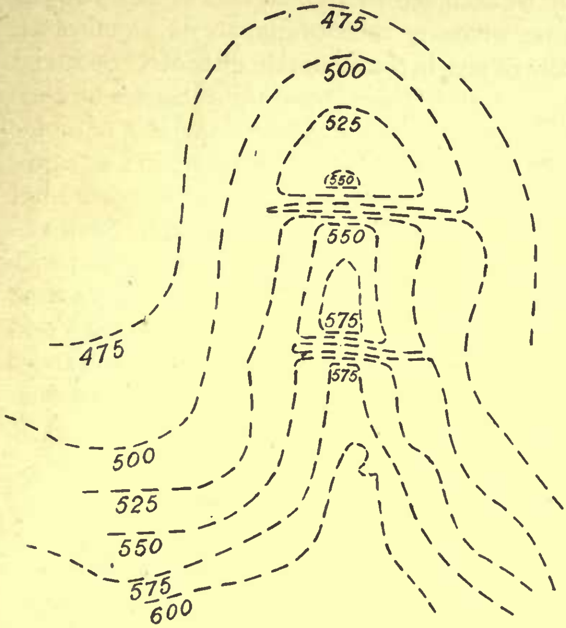


Fig. 2. **Ideal case to illustrate Truncating of a Spur by Overflow Channels.** Shewn by small contour interval. (After Kendall and Bailey, *Trans. Royal Soc. Edinburgh*, Vol. XLVI. Pt 1. No. 1.) Scale ½ inch = 100 ft.

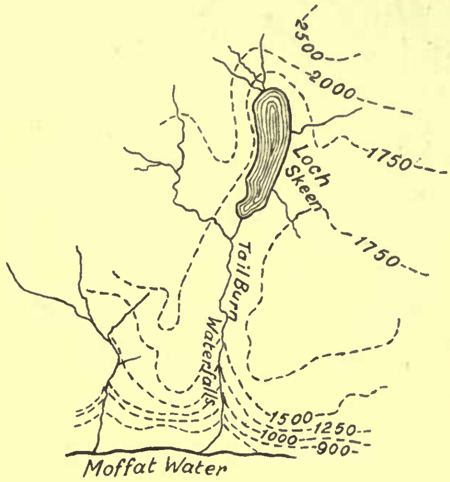


Fig. 3. **Hanging Valley of Tail Burn, Moffat.** Scale 1 inch = 1 mile.

between the main stream and its tributary and shews that the valley is of the type known as a *Hanging Valley*, whatever be the manner in which it has arisen. An excellent example of such a hanging valley is to be seen in the map of the Moffat District of South Scotland in the valley of the stream that comes down from Loch Skeen into Moffat Water and hangs conspicuously at the waterfall known as the Gray Mare's Tail (Fig. 3). Great valleys of the type known as Through Valleys may be seen; these should be recognised not only by the fact that they are often steep-sided, spurless, and shew no great rise in level over a wide area, but chiefly by the fact that they cross the present watersheds. They have almost invariably been occupied by ice during the Glacial Period, and therefore shew many of the characters of glaciated valleys, but as Bailey[1] has pointed out it is by no means certain that they are primarily of glacial origin. There would seem to be at least three possible origins: they may be

(1) structural, when as Marr[2] has shewn in the Lake District they follow the lines of Shatter Belts;

(2) valleys belonging to an ancient river system; such have been described by Bailey in the district round Fort William;

(3) of glacial origin entirely.

[1] Bailey, "Geology of Fort William District," *Proc. Geol. Ass.*, Vol. XXII. 1911, pp. 179—203.

[2] Marr, Pres. Address to Geol. Soc., *Q.J.G.S.*, Vol. LXII. 1906, pp. lxvi—cxxvi.

The heads of the steep-sided valleys usually broaden out their commencement into a wide arm-chair-like hollow known as a Corrie, or Cirque, or Cwm, the bottom of which may be occupied by a small lake or tarn (Fig. 4). These, whatever their origin, are of significance. Many valleys in the mountain districts of Scotland, England and Wales, have these corries at their head. Dry streamless valleys may also be noted and interest as to their origin aroused; as a rule they are either glacial overflows or indicate some permanent diversion of the drainage. Such valleys are but rarely seen distinctly on the 1-inch maps or on any maps with only a 100-ft. contour interval; they are however quite clear in the Yorkshire maps, where the contouring has been carried out at a smaller vertical interval, and also shew well on maps in which contours at 50 or 25 ft. have been specially inserted.

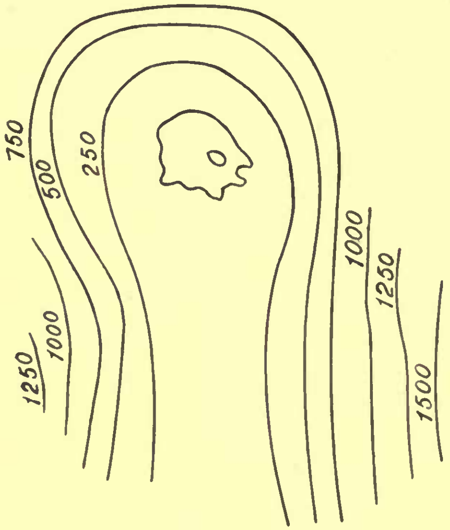


Fig. 4. **Coir a'Ghrunnda, Skye.** Contoured to shew elevations above the neighbouring floor of the valley. (After Harker, "Ice Erosion in the Cuillin Hills," *Trans. Roy. Soc. Edinburgh*, Vol. XII. Pt 2. No. 12.) Scale about 3 inches to a mile.

Rivers. The streams themselves which occupy the valleys, frequently present features of interest; some appear completely to fill their valleys, while others are really misfits. Some shew curious sharp bends, the so-called *Elbows of Capture*, this feature in proximity to another stream and the presence of wind-gaps pointing to river capture having taken place. This should however always be verified on the ground. The capturing stream on the other hand not only receives a number of tributaries flowing toward the trunk of a tree in the normal manner, but may receive others flowing, as it were, against the trunk, in an absolutely anomalous direction, these having belonged to the other stream whose waters have been tapped. The details of such capture are as a rule only clear on a map on which there are at least contours every 50 ft., but some points can be made out in the accompanying diagram maps where the contour interval is 100 ft.

The presence of meanders tells that a stream has reached its base level, while incised meanders indicate rejuvenescence from some cause.

Lakes. The connection of lakes with valleys or their entire independence of valley lines are points of interest in their history; maps too may indicate the stages of their filling up, and shew that in some cases this filling up has gone so far as to separate into two lakes what was once a continuous sheet of water. Such a separation is clearly indicated in the case of Derwentwater and Bassenthwaite Lake[1].

The uses of topographical maps in revealing the story of the physical geology of any district can be made still more convincing by studying the actual maps of a few districts in the British Isles.

Fig. 5 illustrates Carter's suggestion of the steps followed in the evolution of the

[1] Ordnance Survey of England. Map of the Lake District. 1 inch to the mile.

R. Don, whereby the waters of the "Worrall," a powerful feeder of the R. Sheaf, successively captured those of the smaller and slower "Wortley," the "Worrall" eventually becoming the R. Don.

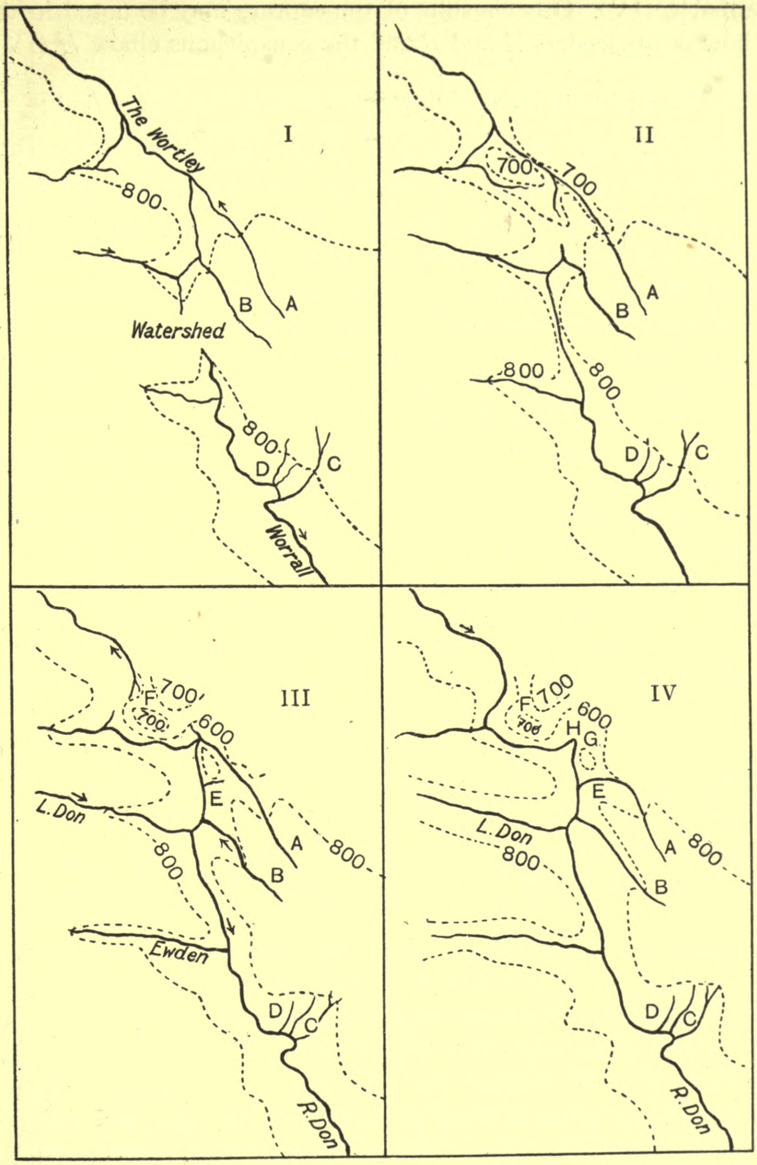


Fig. 5. **Suggested Stages in the Evolution of the River Don illustrating features of River Capture.** (After Carter, *Proc. Yorks. Geol. Soc.*, Vol. xv. Pt 3.) Scale approx. 2 miles to the inch.

The Worrall cutting its way back across the watershed was able to annex successively the feeders of the Wortley, the beginnings of the Little Don at Deepcar, the stream *B* to the north on the opposite bank, and then the eastward feeder *A*, leaving a col between the two 700 ft. contours at *F* (III). The increased power of the southward-flowing river would enable these streams rapidly to deepen their beds and would give such small streams as *E* (III) power to cut through the secondary watershed and tap *A*, leaving another dry col at *G* (IV). Other results of the capture may be noted in the anomalous directions of flow of the feeders *A* and *B* and the conspicuous elbow *H* (IV).

Part of the Lake District[1] (*see Map, at end of book*)

In the Ordnance Survey Map of part of the Lake District, many features of great geological interest may be made out by carefully studying the contour lines.

Mountains. The whole area is clearly a hilly one, the heights in many places exceeding 2500 ft., but the most conspicuous group of elevations lies to the east, where in the Helvellyn range, many of the summits approximate roughly to 3000 ft. Thus along a line running in a general north to south direction, there are: Stybarrow Dod 2756 ft., Raise 2889 ft., the unnamed height west of Keppelcove Tarn 2832 ft., Lower Man 3033 ft., Helvellyn itself 3118 ft., Dollywaggon Pike 2810 ft., Seat Sandal 2415 ft., and then a drop to the comparatively insignificant Stone Arthur 1652 ft.

The line of the watershed however does not exactly coincide with this line of heights all the way, though in the northern part it follows it somewhat closely, with an irregular but nevertheless characteristic zigzag form. After running in an east to west direction the line of water parting turns on Stybarrow Dod and trends in a generally north and south direction. Across the Sticks Pass the line runs a little E. of S., thence S.S.W. up on to the W. shoulder of Raise, S.S.E. to Raise summit and again S.S.W. towards the Keppelcove height; it then becomes less regular, curving somewhat towards Lower Man, and then running S.E. towards the summit of Helvellyn, after which, with some irregularities, its general trend is S. to Dollywaggon Pike; still further S. however, W. of Grisedale Tarn, a noteworthy deflection takes place so that the line of the water parting instead of continuing along the line of high land towards Seat Sandal, descends to the valley and crosses Dunmail Raise. It is therefore clear that this valley watershed requires further investigation. Beyond Dunmail Raise it continues its zigzag course in a general S.W. direction, across Steel Fell, Calf Crag, Sergeant Man, and up on to High Whitestones and so on.

Well developed corries are not a striking feature of the area under description, the most conspicuous being those E. and N.E. of Helvellyn and Dollywaggon Pike, where at the heads of the valleys the contours depart from their usual V-shaped form and curve out to enclose a much wider area; this is especially well seen in the case of the valley of the Red Tarn Beck, E. of Helvellyn; the 1750 and 2000 ft. contours shew the ordinary V-shaped form, the apex of the V lying in the line of the beck, but the 2500 ft. contour turns away from the beck altogether and encloses Red Tarn itself, which is thus seen to be a typical corrie tarn. Precisely similar is the case of the corrie at the head of the Keppelcove Tarn Beck with the Keppelcove corrie tarn at a slightly lower level. Conspicuous corries are also to be seen at the heads of both the two most northerly feeders of Grisedale Beck. These corries are in all cases separated from each other by narrow

[1] Ordnance Survey of England. Map of Lake District, parts of sheets 23, 24, 29, 30, 38, 39, 48, 49, 1 inch to a mile, published as a single sheet.

steep-sided ridges (arêtes), the two best-known in this district being those of Striding Edge, separating the Red Tarn corrie from that of Grisedale Beck, and Swirral Edge, separating the Red Tarn corrie from the Keppelcove corrie to the north. The steepness of these ridges is shewn on the map by special drawing indicating the cliff-like drop.

Valleys. The valleys next attract attention. Most prominent is the great through valley of Dunmail Raise, a steep-sided valley clearly crossing the watershed, since the Raise Beck flows S. and a tributary of the Wyth Burn N. The course of the Raise Beck suggests the presence of a corrom or delta-watershed. A stream with steep grade like the Raise Beck entering a valley like Dunmail Raise will obviously tend to carry into the valley a greater load than it can carry away at the lower grade, hence the certainty that an alluvial cone or delta will be formed where the tributary beck enters the main valley, and though this tributary may originally be able to drain both ways, its course will in the end tend to be confined to one direction only, the delta itself blocking the other.

Hanging Valleys are particularly noticeable in this map; they may be considered as falling into three groups: the Borrowdale group, the Lodore valley group, and the Thirlmere group.

The Borrowdale group[1]. Amongst the many conspicuous hanging valleys that occur in this group, perhaps the most interesting are those which occur along the course of the Styhead Beck; the beck mouths at Taylor Gill Force rather more than 400 ft. above the main valley, a fact which is clearly shewn on the map by the steepness of the ground, as indicated by the closeness of the contour lines between 600 ft. and 1000 ft. respectively; it is most unfortunate that the vertical interval between the contour lines changes at this point, but between Taylor Gill Force and Styhead Tarn it is nevertheless obvious that the grade of the valley has diminished considerably, since only one contour crosses the stream in that distance and that at about one-third of the way along; the 1000 ft. contour on the other hand does not cross the stream till above Styhead Tarn, so that the grade still further diminishes. Continuing up the Gill, however, a rapid rise again takes place as is indicated by the position of the 1750 ft. contour, so that the stream hangs again between Styhead Tarn and Sprinkling Tarn, in which it rises. Sour Milk Gill mouths also very conspicuously above the Seathwaite valley, at an even greater height of 600 ft., and whilst in the lower part of its course the 500, 600, 700, 800, 900, 1000 and 1250 ft. contours are all situated close together there is a wide gap between the 1250 and 1500 ft. levels, at which height the greater portion of the upper course of the Gill runs; the Gill thus commences to hang at about the 1250 ft. contour. Coombe Valley Gill is also a "hanger," the contours of the lower part of the stream's course being conspicuously closer together than those of the middle portion, a wide interval separating the 900, 1000 and 1250 ft. lines. Another valley of this type, though perhaps less conspicuous, is seen in Hause Gill, E. of Seatoller.

The Lodore Valley group. East of Derwentwater the most striking hanging valley is occupied by the Watendlath Beck, which hangs at the well-known Falls of Lodore; here while all the contour lines below 600 ft. are very close together indeed, notably 500 and 600 ft., a very considerable interval separates those of 700 and 800 ft., and 900 ft. The

[1] Marr, Pres. Address to Geol. Soc., *Q.J.G.S.*, 1906.

valley also appears to hang again between Watendlath Tarn and Blea Tarn along the course of the Blea Tarn Gill.

Thirlmere Valley. There appear to be three streams which hang somewhat above the Thirlmere valley at the S.W. end of the lake; these are Launchy Gill, Dob Gill and the Wyth Burn, but they are not nearly such striking examples as those previously noticed.

Lakes. Many lakes have been referred to in dealing with other physical features, but these were for the most part small; some, as has been shewn, are probably true corrie lakes (Red Tarn, Keppelcove Tarn), and Angle Tarn is probably another. The position of others of small size suggests that they may be true rock basins, or otherwise connected with the glaciation of the district, and worth investigation on that account. Such are Stickle Tarn, Sprinkling Tarn, Grisedale Tarn. Of the larger lakes little is seen in this map. Thirlmere lies in the line of the great through valley, whilst the only feature of note in the small portion of Derwentwater that is seen, is that it is being steadily filled up at its S. end by the river Derwent.

Snowdon Mass, North Wales[1]

The district immediately surrounding Snowdon itself forms a very compact area for study, bounded as it is on three sides by the valleys of Llanberis on the N.E., Gwynant on the S.E., and Colwyn-Gwyrfai on the S.W., whilst to the N.W. the mountain land passes gradually down to the low-lying N. Wales coast. Even in this limited mountain mass there are many features worthy of note, the most conspicuous being naturally Snowdon summit 3580 ft., and the high sinuous ridges, veritable arêtes, which radiate from it. Thus, trending N. and E. there is Crib Goch 3023 ft., and to the S.E. Y Lliwedd 2947 ft., curving round so as to run finally E. towards Gallt y Wenallt; Bwlch Main running first S.W., and then S., separated from Yr Aran and its subsidiary ridge by a high-level col lying between the 1500 and 1750 ft. contour lines. These arêtes bound a very striking set of corries or cwms, many of which contain tarns or cwm lakes of some size; the most conspicuous and beautiful of these cwms is Cwm Dyli, and the wide open nature of the head of its valley is clearly revealed by tracing successively the trend of the 1250, 1500, and 2000 ft. contour lines upon the 1-inch map; it contains the three beautiful lakes, Glaslyn, Llyn Llydaw, and Llyn Teyrn, and the stream which flows through it really "hangs" three times before it reaches the main valley, between Glaslyn and Llyn Llydaw below Llydaw, though the contour interval of this map is too great to shew this point, and most conspicuously of all above the Gwynant valley where it mouths nearly 600 ft. above the valley floor. Another noteworthy cwm, though devoid of lakes, is Cwm-y-Llan, in which the cwm-like form of the upper part of the valley is particularly well shewn; the contour lines between 300 and 1000 ft. V up the valley in the usual way, though there is a slight tendency to opening out shewn by those at the level of 900 and 1000 ft. but with the 1250 ft. line broadening-out of the valley head is very conspicuous, and this wide open character is also indicated by the trend of the 1500, 1750, 2000, and 2500 ft. lines. The stream which descends from this cwm commences to hang above the main valley just above Plas Cwm-y-Llan between the 1000 and 900 ft. contour lines. Separated

[1] Ordnance Survey of England, Sheet 30, 1 inch to the mile.

from Cwm-y-Llan by the arête of Bwlch Main lies Cwm Clogwyn, containing some small cwm tarns and occupied by a stream, Afon Treweunydd, which mouths some 500 ft. above the Colwyn-Gwyrfai valley close to Llyn Cwellyn, though here, as indicated by the spacing of the contour lines, the fall of the ground is not so steep as in the valleys of the Cwm Dyli and Cwm-y-Llan streams. About $1\frac{3}{4}$ miles higher up the same valley the Afon Colwyn also hangs above the valley, but less conspicuously, and at an elevation of only 350 ft. or thereabouts, the slope being still gentler than in the Afon Treweunydd valley.

Another cwm lies to the N.W. of Snowdon summit; this is known as Cwm Dur arddu; it contains the little tarn Llyn Dur arddu; the stream which issues from this cwm is the one which hangs above the Llanberis valley close to the Waterfall station on the Snowdon summit railway, not far above the town of Llanberis. The last noteworthy cwm of the group is Cwm Glas, containing the small Llyn Glas, from which flows a small stream to mouth eventually some 400 ft. above the Llanberis valley.

Davis[1] has shewn how much glaciation has had to do with the formation of these features, and hence arises the possibility that like features in other places may have had a similar origin.

Valleys. In addition to the hanging valleys described above in connection with the cwms, there yet remain to be considered the three great main valleys bounding the Snowdon mass on three of its sides. These are all through valleys and hence all cross watersheds. In the Llanberis valley the line of water parting descends from Crib Goch to Pen y Pass 1169 ft., quite near the E. end of the Pass. N.W. of this point the streams drain into the Llanberis valley and the waters are carried N.W. into Llyn Peris 340 ft., and Llyn Padarn 340 ft.; S.E. of Pen y Pass they flow into the Gwynant valley or its continuation the Nant Gwrhyd valley, from which the waters are separated by the valley watershed of Pen y Gwrhyd 900 ft. In the Colwyn-Gwyrfai valley the watershed lies close to Pitt's Head 651 ft., and the streams north of that drain ultimately into Cwellyn and thence N.W. to the coast, while those S. of it run eventually into the Afon Glaslyn at Beddgelert, where they are joined by the waters from the Gwynant valley. These valleys are clearly most important features in the district, and their steep sides and open character shew that they have at any rate been profoundly affected by glaciation.

Lakes. The cwm lakes mentioned above are by no means the only, nor are they the most important, lakes of the district; the larger lakes all lie in the line of the great through valleys, and their situation above points of constriction in the valleys is sometimes very noticeable; it is obvious for instance that the Colwyn-Gwyrfai valley narrows below Cwellyn towards Salem, and again it is noticeable how the high ground comes out towards the valley path immediately below Llyn Dinas in the Gwynant valley; the ground is also steep and high close to the S. side of the Gwynant valley just below Llyn Gwynant, though on the N. side the topography has been considerably modified by the work of the Cwm-y-Llan stream.

It has been suggested that such points of constriction mark the place of most effective work of a glacier descending a valley[2]; if this be so they are most significant in the history

[1] W. M. Davis, *Q.J.G.S.*, Vol. LXV. 1909, pp. 281—344.

[2] Harker, "Ice Erosion in the Cuillin Hills," *Proc. Edin. Roy. Soc.*, Vol. XL. Pt 2 (12). Peach and Horne, *Geog. Journal*, 1900. Geological Appendix to Bathymetrical Survey of the Scottish Lochs.

of the lakes. Another common feature of these larger lakes is the occurrence of large alluvial tracts at their heads; this suggests that they are being steadily filled up. Cwellyn, Llyn Dinas, and Gwynant all shew this conspicuously, while Llyn Peris and Llyn Padarn were probably continuous at no very distant date.

Western Highlands of Scotland. Oban District[1]

This portion of the coast of the Western Highlands shews a great variety of physical features, ranging as it does from sea level to mountain summits between 3000 and 4000 ft. in height, such as Ben Lui, Ben Cruachan, Ben Starav, Stob Ghabhar, and others.

Raised Beaches. With regard to the coastal area, attention is at once directed to the presence of a distinct coastal shelf of low-lying land, coloured the deeper green on the Bartholomew map, extending all round Loch Etive and Loch Creran and away up round Loch Linnhe; in places this shelf is quite broad, as at the Moss of Achnacree, whilst in other places it is a mere ledge carrying the road and railway from Connel Ferry to Ballachulish.

Sea Lochs. The sea lochs are a conspicuous feature of the district, and Loch Etive may be regarded as typical of many others found elsewhere in the country; note first the marked irregularity of outline and its extreme narrowness in proportion to its length, its characteristic shape, bending round almost at a right angle along its course: the hills rise steeply from its sides along its upper waters, as is evidenced by the rapid succession of the contours or the coloured tints on the map. Also if note be taken of the soundings it is clear that the loch does not deepen steadily seawards, but that the deepest water is some way from the coast just above the right-angled bend before mentioned. Here there is an elongated depression exceeding 40 fathoms in depth, and there are also two smaller areas of deep water enclosed by the 30 fathom line, between Bonawe Ferry on the south shore and Kennacraig on the north shore of the loch. Moreover the soundings clearly indicate that both at Bonawe Ferry and at Connel Ferry not only is the loch very narrow but it is also very shallow, the maximum depth lying between the 5 and 10 fathom lines, and most of the bottom being less than 5 fathoms deep.

These features, namely the narrow sinuous outline, irregular shores, and steep bounding hillsides, are all characteristic of the upper part of the valley through which the river Etive now flows, and the inference can hardly be avoided that these are all part of one and the same story and that Loch Etive is merely the lower portion of the Etive valley drowned beneath the waters of the sea. Comparatively slight elevation would in fact restore the valley to its original condition, and the present Loch Etive would be separated into two communicating fresh-water lochs, the one above the Bonawe shelf running N.N.E., the other basin, lying between the Bonawe and Connel Ferry shelves, trending roughly E. and W. Similar elevation would cut off the upper basin of Loch Creran and convert it into a fresh-water loch.

Therefore in this district we seem to have evidence of submergence, as indicated by the sea lochs, followed by a period of re-emergence as indicated by the raised beaches. As a matter of fact in this area the coastal shelf is occupied by two raised beaches at

[1] Ordnance Survey of Scotland, Sheet 45, 1 inch to the mile; *or* Bartholomew's Map, Sheet 11, 2 inches to the mile.

levels of 100 and 50 ft. respectively, but the country is not contoured at a sufficiently small interval to shew this.

Valleys. Inland, notice must be taken of the through valleys of the Pass of Brander, with the hanging valley of the Cruachan Burn on its N. side mouthing at the level of the 1000 ft. contour line; that of Glen Salach, possibly once continuous with the Pass of Brander, the high level valley regarded by some authors as a glacial overflow into Glen Noe, the valleys N. and S. of Beinn Mhic Mhonaidh, and last but by no means least, the most interesting of all, Glen Kinglass. Here as Newbigin[1] has shewn the topography and the course of the Allt Dochard suggest that this burn once flowed into the Kinglass, and thence direct to Loch Etive, whereas now it flows into Loch Dochard, thence into Loch Tulla, through Glen Orchy, Loch Awe, and the Pass of Brander before reaching the sea, a most circuitous route. Here once again the diversion has been effected by the formation of a corrom or delta-watershed, where the more steeply graded stream, the Allt Dochard, enters the flatter main valley and therefore has its carrying power greatly diminished. This corrom at the head of Loch Dochard is clearly indicated on the map.

Corries. The corries are a very conspicuous feature of the area under description; the most striking group are those on the slopes of Ben Cruachan, of which the largest is that at the head of the Cruachan Burn, where the wide open curvature of all the contour lines above the 1250 ft. level is most clearly shewn. Conspicuous also are those on Ben Starav and Ben Oss, the last containing Loch Oss, a small corrie loch. It is doubtful whether the corries cut sufficiently deeply into the mountain mass to form true arêtes, but the dissection of the Cruachan and Ben Lui masses is obviously proceeding rapidly in that direction.

[1] Newbigin, *Ordnance Survey Maps: their Meaning and Use*, p. 66.

CHAPTER III

TOPOGRAPHY AND OUTCROP

In the last chapters a study was made of the way in which the surface relief might be shewn on maps, and the geological lessons that might be learnt from the study of that relief alone. There has now to be considered the effect that such relief may have upon the outcrops of different strata at the surface of the ground. It is not possible to insist too strongly upon the intimate relationship that exists between topography and outcrop. In this connection however there are certain facts that must be clearly understood, and borne in mind.

Every formation has two surfaces, an upper and a lower, and the shortest distance between these surfaces is the *thickness* of a formation. If the thickness is constant the upper and lower surfaces of a formation cut the country relief in lines more or less parallel to each other; these lines are known as the *face traces* (trace) of a formation, and the area included between the two *face traces* is the *outcrop*.

While the thickness of a bed will of necessity affect its outcrop, the width of the outcrop of a bed of constant thickness varies from place to place with two conditions:

(*a*) the slope (inclination of the ground);
(*b*) the dip (inclination of the bed).

If these two conditions remain invariable, as would be the case with a bed of uniform dip cropping out on an absolutely plane surface, the edges of the outcrop will be straight and parallel from end to end (Fig. 6). This from the general nature of things is very rarely attained; usually the ground is undulating, or the dip variable either in amount or direction, or in both together. When the slope of the ground is the same as the dip of the bed, the outcrop will occupy the whole surface of the ground (Fig. 7*a*), but when the surface is horizontal and the bed vertical or, more generally, when the dip of the bed is at right angles to the surface, the outcrop is the narrowest possible (Fig. 7*c*). Hence therefore *as the angle between the dip and the slope increases the outcrop diminishes in width.*

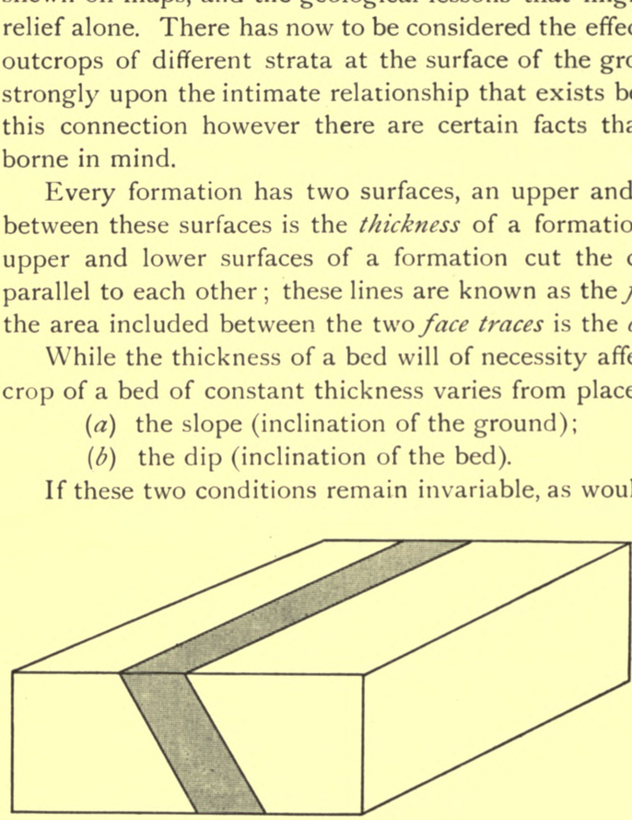


Fig. 6. **Outcrop on flat surface.**

In studying the general relation between topography and outcrop, the following generalizations will soon be made out:

(*a*) the boundary lines of horizontal strata run exactly parallel with the contours;
(*b*) the boundary lines of vertical strata, on the other hand, run in straight lines across country independently of the contours, in the direction of the strike;

(*c*) hence the lower the dip of the strata the more closely will the outcrop approximate in trend to that of the contours, whilst the higher the dip the greater the tendency of the outcrop to run irrespective of the contour lines;

(*d*) the boundary lines of strata dipping into a hill are less winding than the contours.

This should be evident, for if the dip be increased to the vertical the boundary lines of the strata would gradually become parallel straight lines, therefore as the dip of the

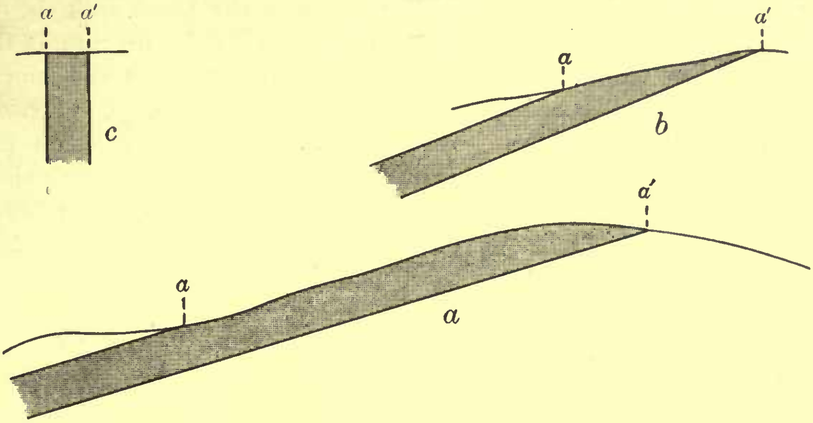


Fig. 7. **Variation in Width of Outcrop, due to relation of dip to slope.** *a—a'* = outcrop.

bed into the hill increases, the boundary lines leave the contours and become more nearly straight lines.

(*e*) the boundary lines of strata dipping out from a hill are more winding than the contours.

This is the reverse of the last generalization, for if the dip be increased till it be equal to that of the slope of the ground the boundary lines would run down the flanks of the hill in parallel lines and until the slope varied they could not meet, but when the dip exceeds the slope, the boundary lines will begin to draw in towards straight lines proportionately to the increase in dip.

The most significant facts of the relationship between topography and outcrop are best brought out by the study of actual examples.

Let it be supposed that a bed of rock 200 ft. in thickness crops out at a certain point on the map with

(*a*) a low dip, e.g. 7°,

(*b*) a higher dip, e.g. 26°,

in (1) an area of simple topography,

(2) an area of complicated topography.

The scale of the map being given and the contour interval known, it is required to put in the outcrop of the bed.

In such cases the variation in the shape of the outcrop will be produced *solely* by *the difference in the amount of dip* as between (*a*) and (*b*) since the direction of dip and the topography are constant,

Or by *the difference in topography* as between (1) and (2), the direction and amount of dip remaining constant.

Example a, 1. Low dip and simple topography. In the map shewn in Fig. 9 the lower trace (face trace) of a bed crops out at A with a dip of 7° S., and the bed has a thickness of 200 ft.; it is required to draw in its outcrop. A line drawn through A at right angles to the direction of the dip, that is from E. to W., represents the strike, and if the ground were level this line would coincide with the outcrop of the lower trace. On the actual surface the outcrop will appear at points on this line where the level is the same as at A. Such points are A_1 and A_2, since A, A_1 and A_2 all lie on the 700 ft. contour.

Through a point a on the line of strike AA_1 draw am in the direction of the dip, that is, perpendicular to AA_1, and an making with am an angle of 7°, the amount of the dip. This line represents the lower trace of the bed in elevation or section. Then marking am on the 700 ft. level, draw parallels above and below it at intervals of 100 ft., using the scale of the map. The points at which an meets these lines of level give points at which the lower trace reaches the lower levels of 600 ft., 500 ft., and so on, on the one side, and the higher levels of 800 ft., 900 ft., and so on, on the other, and lines drawn across the map through these points will give points on the outcrop of the lower face on the corresponding contours. Thus B_1 and B_2 where the line drawn through b cuts the 600 ft. contour are points on this outcrop, and D and E to the north are other points on the 900 ft. and 1000 ft. contours respectively. It will be observed that there is no cutting of the 800 ft. contour on the portion of the map shewn.

When all possible points have been determined in this way, the outcrop of the lower trace can be sketched in from point to point.

To find the line of outcrop of the upper trace, draw the line $a'n'$ parallel to an at a distance above an equal to the thickness of the bed, that is 200 ft. This line represents the elevation of the upper trace, and intersection with the lines of level gives points from which we project across the map exactly as before. The points C_1, C_2, C_3 are points on the 800 ft. contour, found in this way.

The area between the lower and upper traces so sketched is the required outcrop (shaded portion, Fig. 9). In drawing the trace of outcrop through the points determined, careful attention must be paid to the slope and general lie of the land as indicated in the map; there is liable otherwise to be a certain amount of error due to the contour interval, since there is nothing definite to indicate whether the trace runs closer to one contour or another between any two successive points.

By the above method it is possible to put in any number of beds upon the contoured map, whether they form a conformable or unconformable series. In putting in the outcrops of an unconformable series of beds, however, the precaution must be taken of putting in the higher series first, since it is clear that the lower series can only crop out on the ground not already occupied by the higher series, though they may extend everywhere underneath them.

A similar result can be attained by plotting directly on the map, utilising the scale, a value equal to the cotangent of dip. Thus in this first example, as the bed dips at 7° S. and as cot 7° = 8·14 the horizontal distance AM, south of A, which corresponds to a fall, MP,

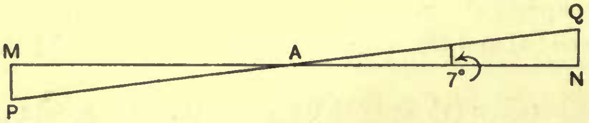


Fig. 8.

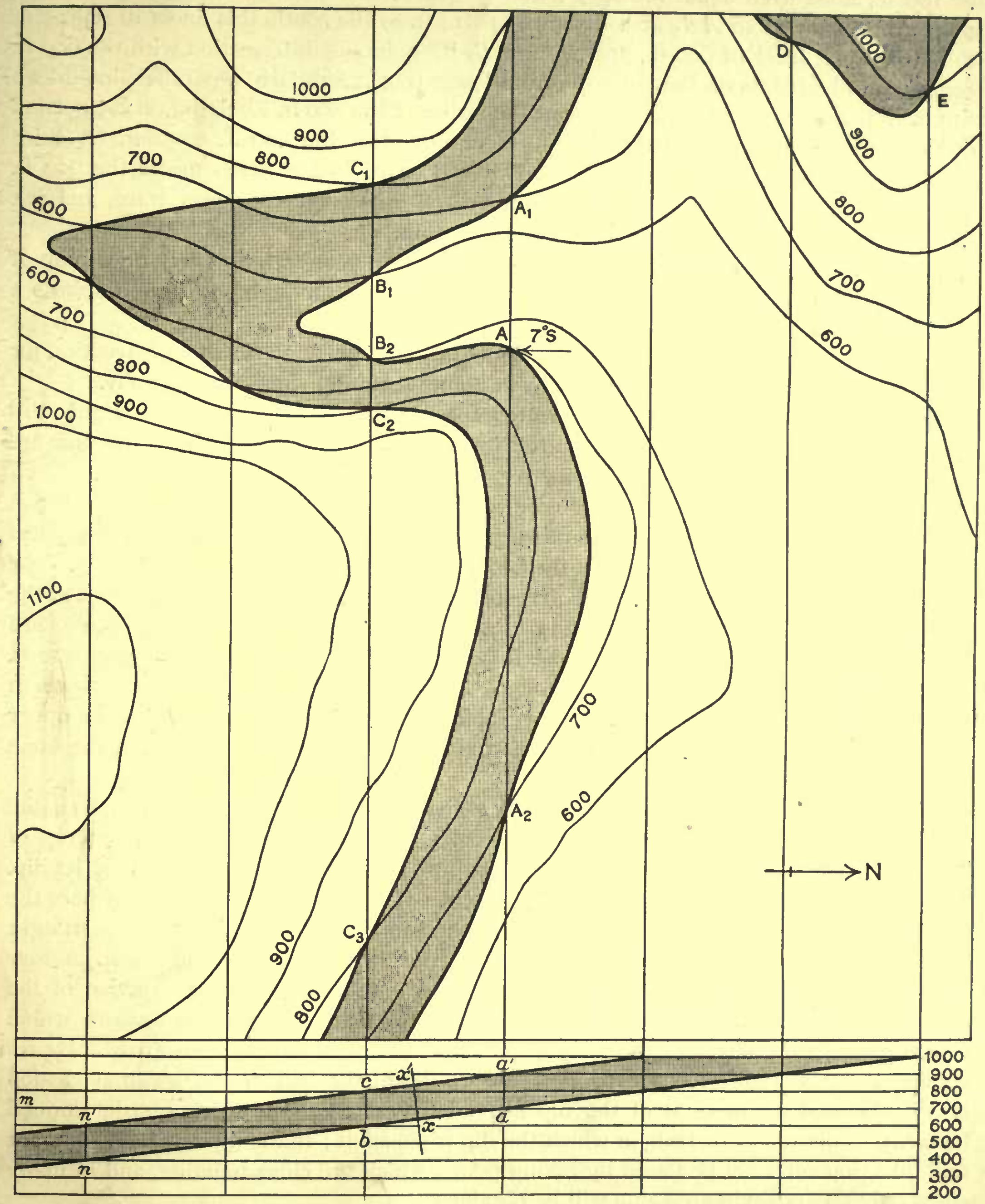


Fig. 9. Example *a*, 1. **Simple Topography and Low Dip.** Dip 7° S. Scale 1 in. = 1000 ft. *xx'* = thickness of bed. *aa'* = depth of bed. Contour interval 100 ft.

of 100 ft., and the horizontal distance *AN*, north of *A*, which corresponds to a rise, *NQ*, of 100 ft., must each equal 100 cot 7°, that is 814 ft. If therefore we draw across the map a line parallel to AA_1 at a distance of 814 ft. to the south, this line will represent the strike at a level of 600 ft., and B_1 and B_2 its points of intersection with the 600 ft. contour will be points on the outcrop of the lower trace. Similarly a parallel line drawn 814 ft. to the north of AA_1 will represent the strike at the 800 ft. level, but on the portion of the map shewn in the figure this line does not meet the 800 ft. contour. A third parallel however drawn at a further interval of 814 ft. to the north meets the 900 ft. contour at *D*, and thus gives another point on the outcrop of the lower trace, and yet another one will be seen at *E* on the 1000 ft. contour.

These distances, especially if small, are not easy to plot with accuracy on a map of small scale, hence the first method is perhaps preferable—though the second affords a valuable check.

Example b, 1. Higher dip and simple topography. Fig. 11 shews the construction for the outcrop of a bed of higher dip, 26°, in the same region of simple topography.

Example a, 2. Low dip and complicated topography, and *Example b*, 2, Higher dip and complicated topography. These are shewn in Figs. 12 and 13 where the dips are respectively 7° E. and 26° E. in the same region of more complicated topography.

It should be noted that, on the scale on which the maps (Figs. 9, 11, 12, 13) are drawn it is almost impossible to shew the difference between the true thickness and the vertical depth of the beds, even when the dip is as great as 26°. The consequence is that the lines of strike of the upper face at the levels of say 1200, 1000, and 800 ft. practically coincide with those of the lower face at levels of 1000, 800, and 600 ft. With a dip of 50° the lines can be distinguished, as is shewn in Fig. 10 where the full lines are the lines of strike of the upper face and the dotted lines those of the lower face, at the same levels.

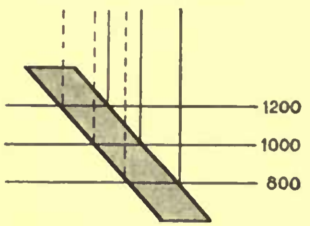


Fig. 10.

The converse of such examples as those given above is a problem with which the student is commonly faced in reading geological maps, namely, given the outcrop of a bed to determine the direction of its strike and the amount and direction of its dip. The shaded area in Fig. 14 represents the outcrop of a bed, and if two points, where the outcrop of one or other of the traces meets the same contour, be joined by a straight line, this line gives the direction of the strike of the bed; A_1, A_2 on the 200 ft. contour are two such points and a line drawn perpendicular to A_1A_2 gives the direction of the dip. The points of intersection on the next contour will shew at once towards which side the bed is dipping and the proper direction can be marked by an arrow. By reversing the procedure given on page 18 the section of the bed can be drawn as shaded in Fig. 14, and the amount of the dip estimated (12°), and the thickness determined (100 ft.). This refers to beds in which the dip is constant; if the dip varies, its amount and direction can only be found by taking points which are close together, and in many cases only an approximate value will be obtained.

In some cases there may only be sufficient data to determine the general *direction* and character of the dip of a bed and not its actual amount; such general conditions may be

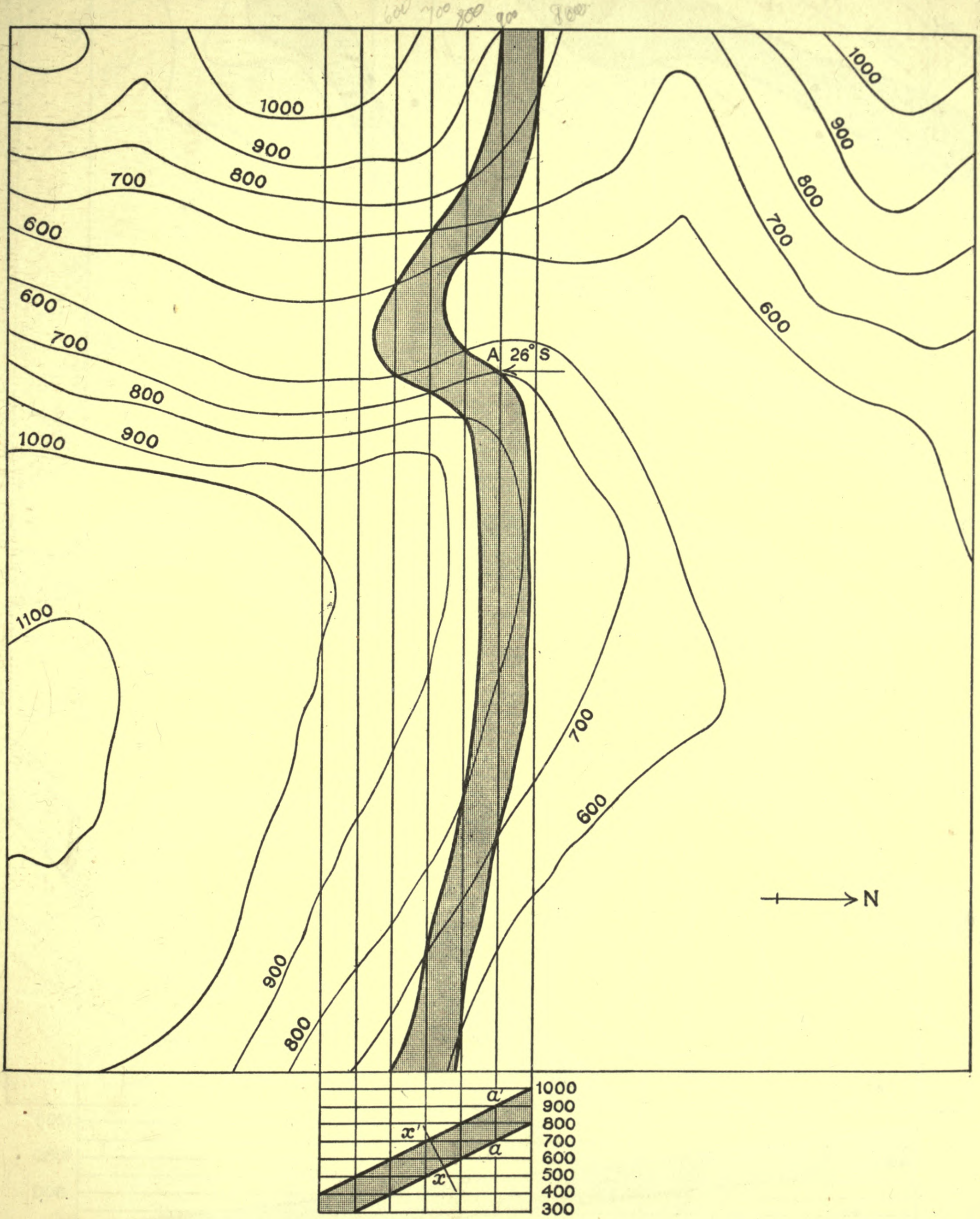


Fig. 11. Example *b*, 1. **Simple Topography and High Dip.** Dip 26° S. Scale 1 in. = 1000 ft. *xx'* = thickness of bed. *aa'* = depth of bed. Contour interval 100 ft.

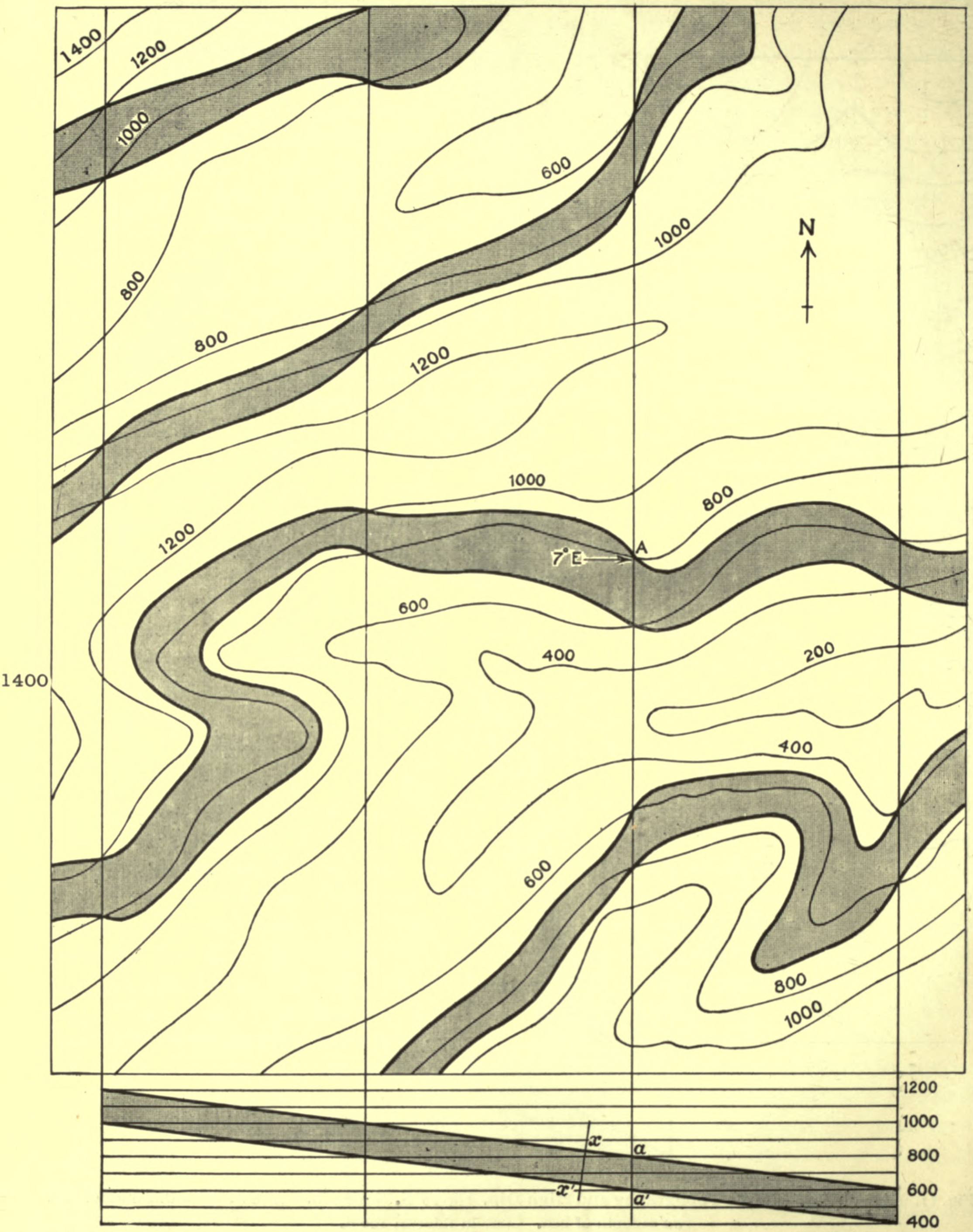


Fig. 12. Example *a*, 2. **Complicated Topography and Low Dip.** Dip 7° E. Scale 1 in. = 1000 ft. *xx'* = thickness of bed. *aa'* = depth of bed. Contour interval 200 ft.

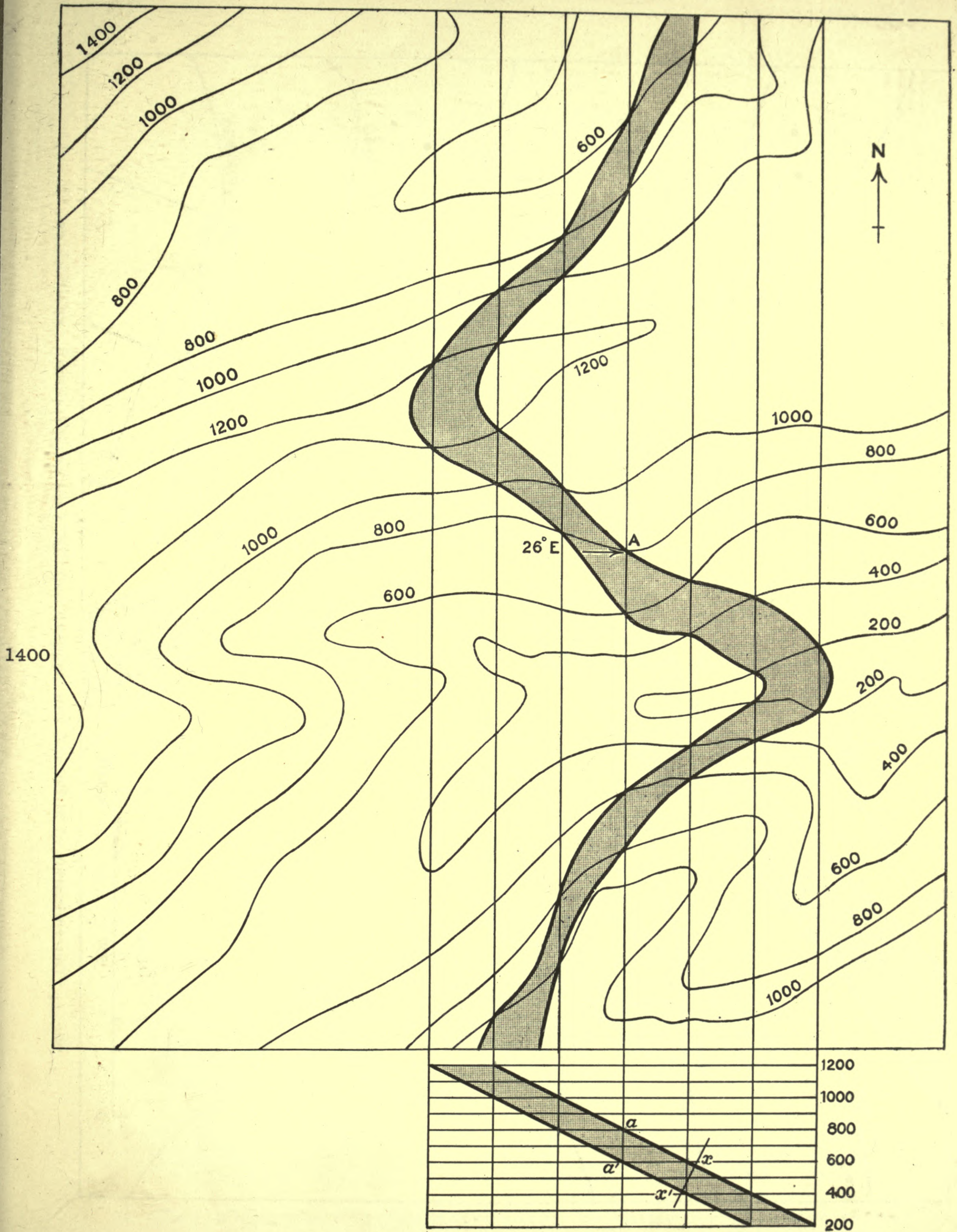


Fig. 13. Example *b*, 2. **Complicated Topography and High Dip.** Dip 26° E. Scale 1 in. = 1000 ft. *xx′* = thickness of bed. *aa′* = depth of bed. Contour interval 200 ft.

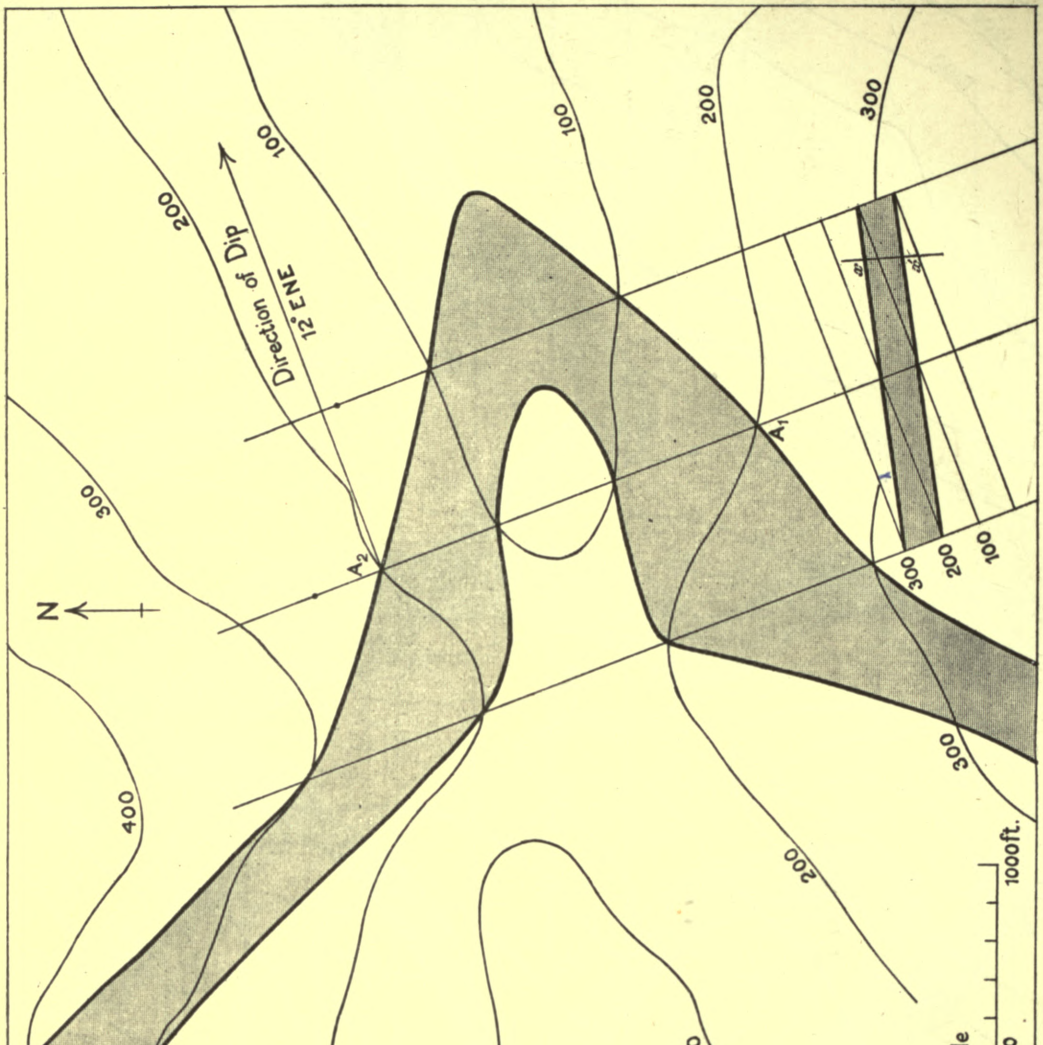
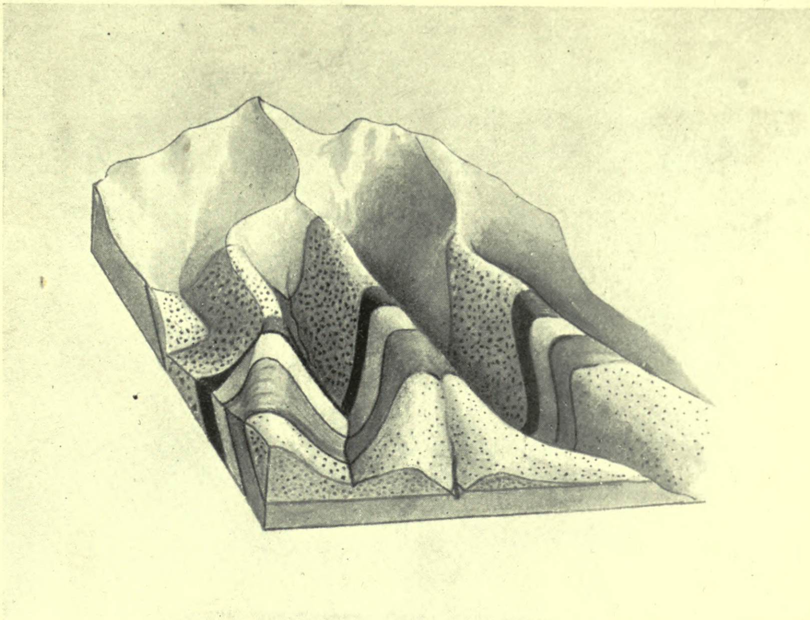
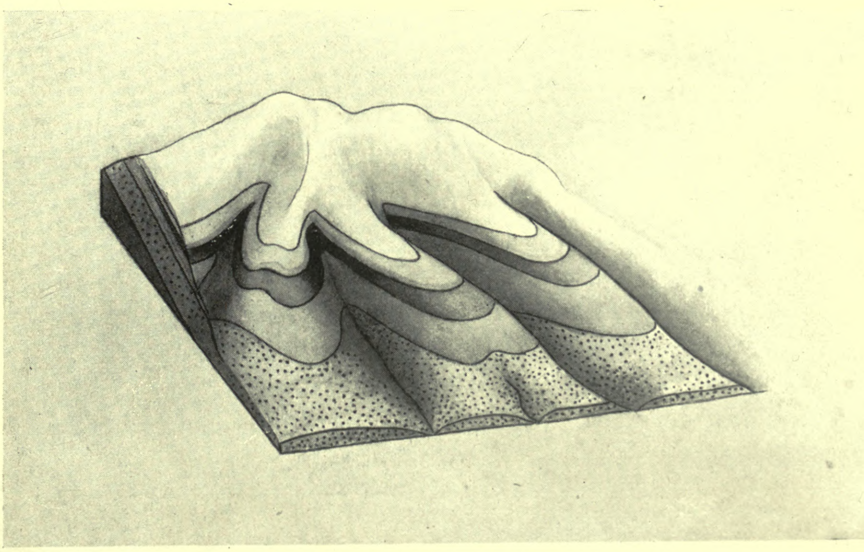


Fig. 14. Determination of Strike and Dip for given outcrop. Contour interval 100 ft. xx' = thickness.



A. Effect on outcrop of beds dipping down a valley more steeply than the slope of the valley.



B. Effect on outcrop of beds dipping down a valley less steeply than the slope of the valley.

PLATE II

Effect on outcrop of beds dipping up a valley.

indicated by a simple long-shafted arrow for a low dip, the shaft decreasing in length with the increase in dip, whilst contorted beds are shewn by an undulating shaft; beds whose outcrop appears to coincide with or run approximately parallel to the contour lines may be assumed to be horizontal, and may be indicated as such by a small rectangular cross (see symbols, p. 68).

Valley Outcrops. The outcrop of any bed dipping in a direction parallel to the trend of a valley will be approximately V-shaped, but the apex of the V may be directed up or down the valley. Let a small portion of the floor of a valley be represented by the three contours marked 400, 500, and 600 respectively in Fig. 15, giving a uniform slope from *A* to *B*. Then the straight line *ab* represents the valley path in section. If the trace of a bed, which slopes down the valley, outcrops at *C*, on the 500 ft. contour, and if the dip be less than the slope of the valley path, the section of the trace will be a straight line such as *kcl*. By the method already used we find the points L_1 and L_2 in which the outcrop meets the 400 ft. contour, and we also see that it cannot meet the 600 ft. contour. The outcrop L_1CL_2 can then be sketched in with its V up the valley.

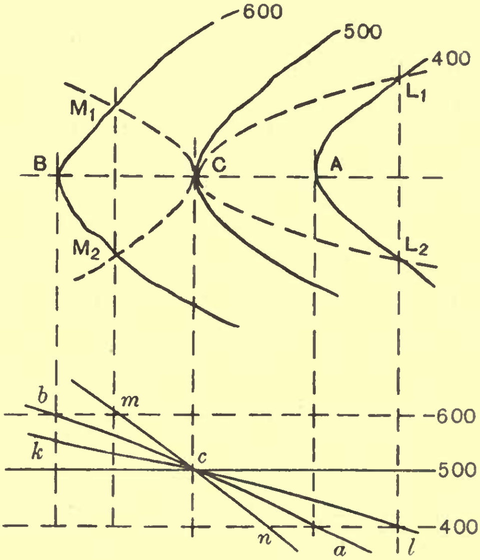


Fig. 15.

But if the dip be greater than the slope of the valley path the line of section of the trace will be such a line as *mcn* and we find the intersection of the outcrop with the 600 ft. contour at M_1 and M_2, and the V M_1CM_2 is found pointing down the valley.

By a similar construction it can be shewn that if the dip is up the valley the V of the outcrop always points up the valley, whether the dip be less or greater than the slope of the valley path.

As Watts[1] has shewn, the outcrop of a bed, which dips obliquely to the trend of a valley path, is still a V but a V with very unsymmetrical arms (Fig. 16).

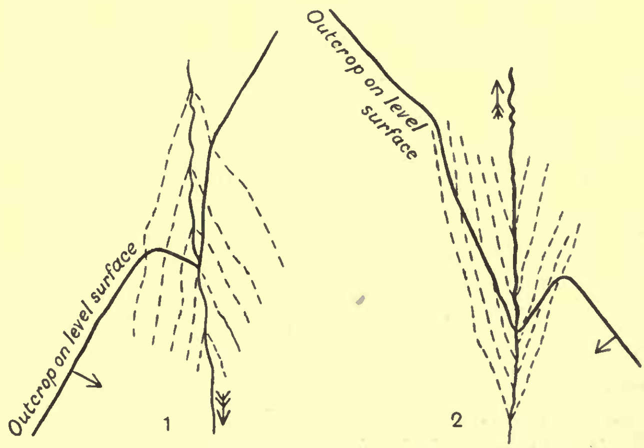


Fig. 16. **Outcrop in Valley. Strike oblique.**
1. Dip with waterway. 2. Dip against waterway. (After Watts.)

By use of the graphic method it is possible, given a contoured map of known scale, to shew the approximate trend of any bed over any area, beneath newer deposits which may overlie it unconformably, or under surface accumulations which may

[1] Watts, *Geol. Mag.*, 1888, p. 356.

conceal it from view, provided that the dip is known and may be assumed to be constant in amount and direction. This might have a practical application in determining the site of a quarry for working a particular stone, or in guiding the purchase of land under which coal or ironstone might be worked, or again in fixing the depth at which a particular water-bearing stratum should occur.

Varying Dip. In the examples treated above the dip has been assumed to be constant both in amount and in direction. This may be true over relatively small areas, or in districts where there has been little earth movement, but in districts where the earth stresses have been considerable, a single bed may change its dip both in amount and in direction, within a comparatively short distance, and this will have a marked effect upon the trend of the outcrop.

When the dip is constant in direction and amount, the lines drawn across a map to represent the strike at different levels will be parallel to each other, since the direction of strike is constant, and evenly spaced because the dip remains unchanged. If however the dip changes in *amount* only the strike remains constant though the lines drawn to represent it while still parallel will be closer together if the dip has increased and further apart if it has decreased in amount; should however the dip have changed both in *amount and direction* the strike will have changed also and the lines drawn across a map to represent it will no longer be parallel, but converging or diverging lines.

An example will make this clear:

A bed crops out at A *on the* 600 *ft. contour* (*see Fig.* 17) *dipping S.E. at* 6°; *it is seen again at* B *on the* 700 *ft. contour dipping S. at* 12°, *and again at* C *on the* 600 *ft. contour dipping S.W. at* 12°. *Required to find its outcrop.*

Through the points A, B, and C draw lines across the map in the direction of the arrow of dip at each point. We shall assume that the dip remains constant in direction and amount along each of these lines. Mark off along each line, on either side of the starting-points A, B, and C, the horizontal distance which corresponds to a rise or fall of 100 ft. determined by either of the methods given on pp. 18, 20; in this case the distances if determined by the second method are respectively 100 cot 6°, 100 cot 12°, and 100 cot 12°. Thus if $AA_1 =$ 100 cot 6°, that is 951 ft., A_1 is a point on the 500 ft. strike line, and if AA_2 also $=$ 951 ft., A_2 is a point on the 700 ft. line of strike. The corresponding intervals along the dip line through B and C will be 100 cot 12°, that is 470 ft. Now join the points on the A line to the like points on the B line, and the points on the B line to the like points on the C line. These joining lines give a series of approximate strike lines for the region between the lines. In the region lying to the S.W. of the A line the lines of strike may be drawn at right angles to the dip line through A, and over the region to the S.E. of the C line they may be drawn at right angles to the dip line through C, since we have no evidence of further variation of dip in these regions. The points of intersection of the strike lines found in this way will give points through which the outcrop can be drawn.

Thus the conviction is gradually acquired that changes in topography may cause many curious windings and straightenings, as well as widenings and narrowings, of the outcrop of a bed of constant thickness and of uniform dip, and that further complications, readily discernible, may be caused by changes in the amount and direction of the dip.

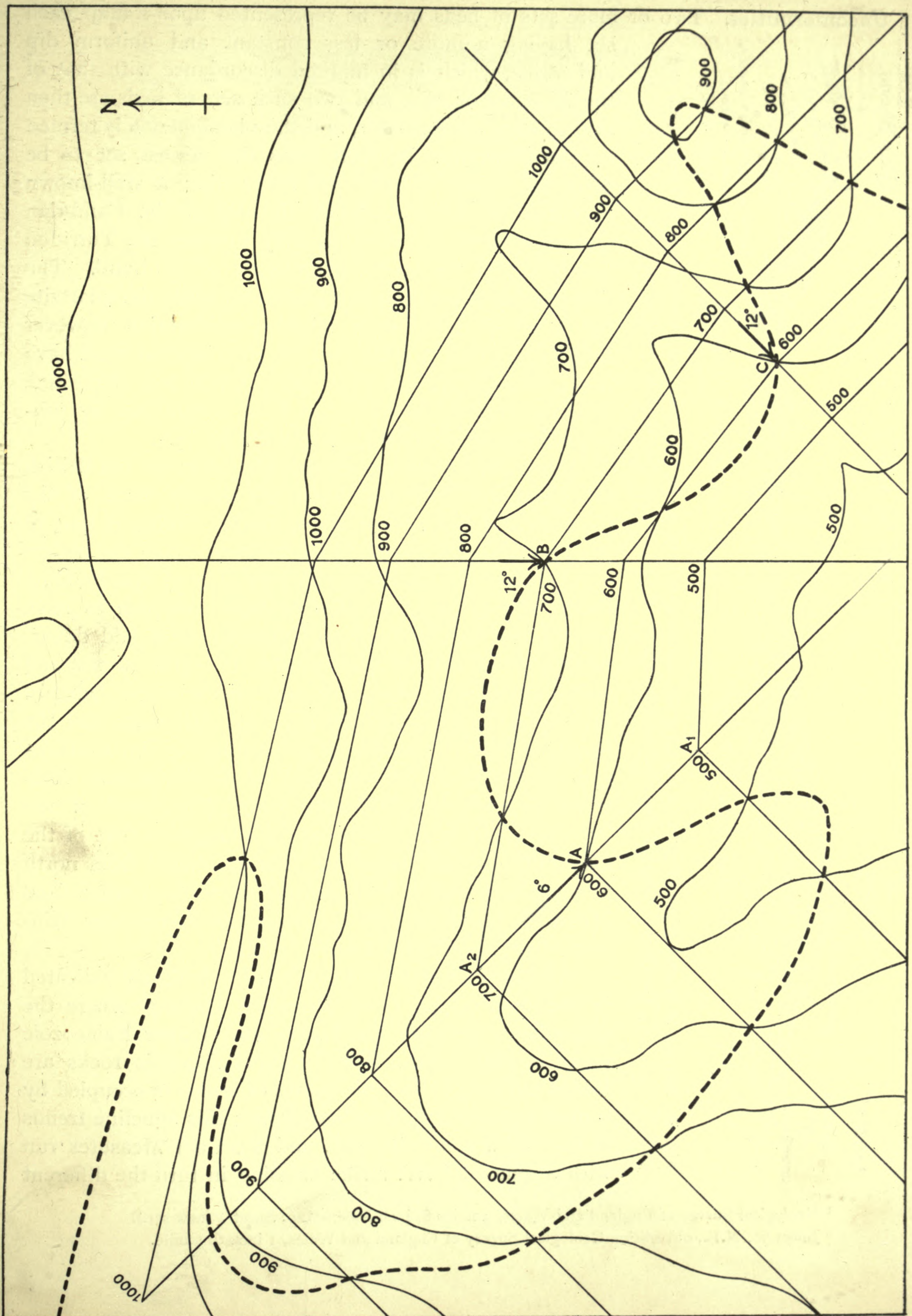


Fig. 17. Outcrop of bed with Varying Dip. Scale 1" = 1000 ft.

Unconformities. Two or more sets of beds may be represented upon a map, each set having a more or less constant and uniform dip and strike, which is in marked discordance with that of the other set or sets, and two such sets of beds are then said to be unconformable, and the phenomenon is termed an unconformity. In such cases the newest set to be deposited usually shews the lower dip; a well-known exception to this rule being the dip of the Cambrian Quartzite where it unconformably overlies the Torridon Sandstone in the N.W. Highlands of Scotland. The Torridonian appears nearly horizontal while the quartzite has a considerable dip; slight consideration however suffices to make it clear that the Torridonian must have had a considerable dip when the quartzite was deposited, and that this original tilt has been neutralised by subsequent earth movement. (Section, Fig. 18.)

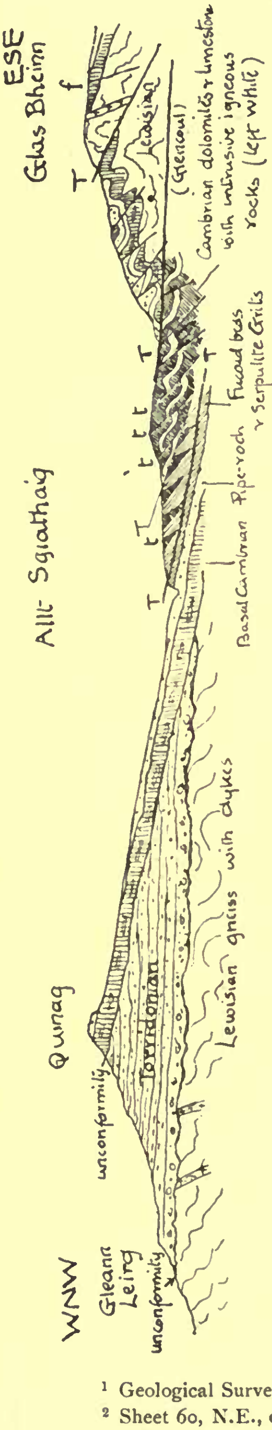


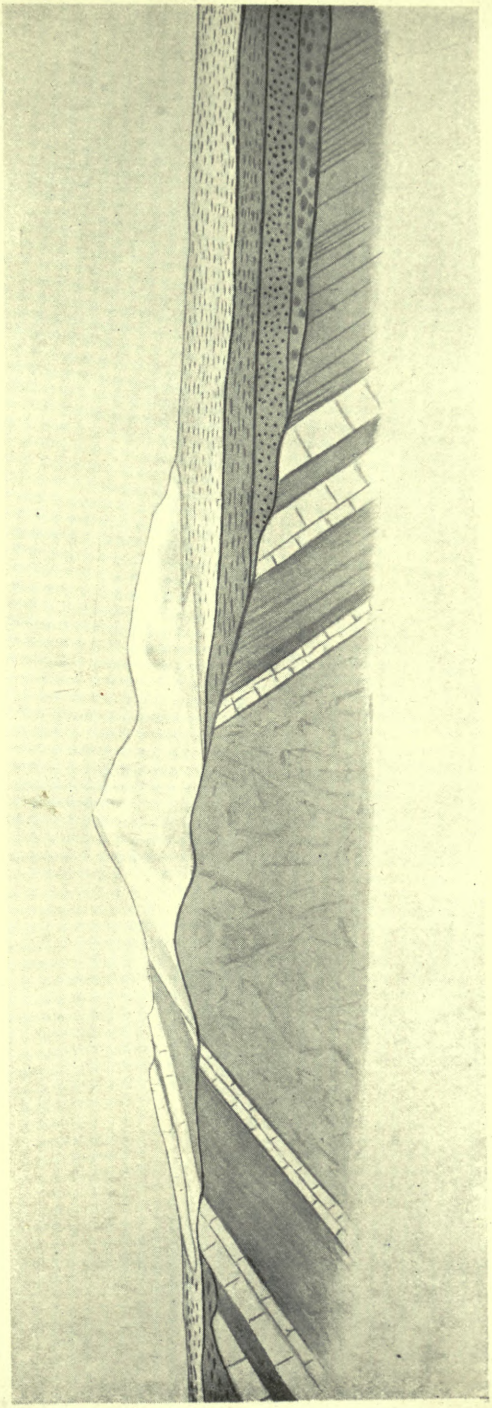
Fig. 18. Section in North-West Highlands shewing Unconformities between (a) Lewisian and Torridonian, (b) Torridonian and Cambrian. Section also shews Imbricate Structure. (From *Memoirs of the Geological Survey*.)

Many unconformities exist in the rocks of the British Isles and are indicated upon the 1-inch maps of the Geological Survey. One of the most striking is that of the Permian beds to the different members of the underlying Carboniferous on the eastern side of the Pennine Chain. Here the Carboniferous rocks are seen to have been folded before the Permian rocks were laid down; these folds have their axes running in a general east and west direction, having the Northumberland and Durham coal basin or syncline at the northern extremity, and the South Yorkshire coal basin or syncline at the southern end, separated by an anticline of Carboniferous limestone overlain by Millstone Grit. The trend of the Permian rocks is practically at right angles to that of the Carboniferous just described, running almost from north to south and resting with marked discordance upon Coal Measures, Millstone Grit, Carboniferous Limestone, Millstone Grit, and Coal Measures in turn[1].

Another conspicuous unconformity is clearly indicated in the map of the Long Mountain District[2] where the discordance between the Lower and Upper Palaeozoic rocks is well shewn. The Lower Palaeozoic rocks are folded into a syncline, the centre of which is occupied by a small patch of Old Red Sandstone; this syncline trends N.E.—S.W., across its N.E. end the Coal Measures run with a general N.W. strike crossing in turn the different

[1] Geological Survey of England and Wales, 4 miles to inch Index-Map, Sheet 4 (new ser.).

[2] Sheet 60, N.E., old edition Geological Survey of England and Wales, 1 inch to a mile.



Unconformable Overlap.

beds composing the older denuded syncline, and these Coal Measures are succeeded with apparent conformity by the Permian and Trias, so that the unconformable relation

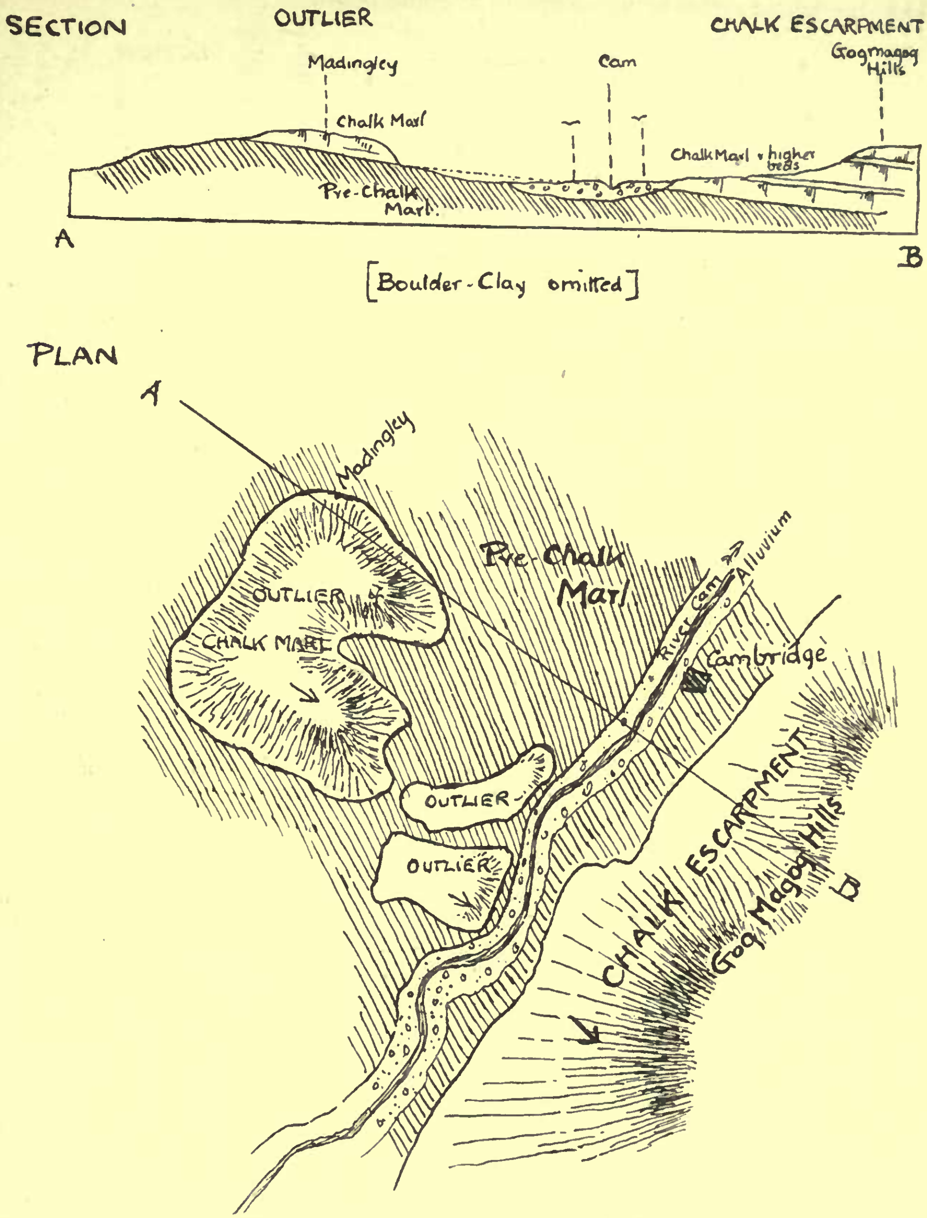


Fig. 19. Diagrammatic Plan and Section of the neighbourhood of Cambridge to shew an Outlier and its relationship to a receding Scarp.

between the two sets of beds is clear. Whilst unconformities suggest the discordant relations between two rock groups, overlap usually refers to the relationship between different members of the same rock group. Thus the Cretaceous is unconformable to the

Jurassic in the neighbourhood of Cambridge and Oxford, while the different members of the Cretaceous tend to overlap each other when traced from E. to W. in the S. of England, the whole series being complete at some point.

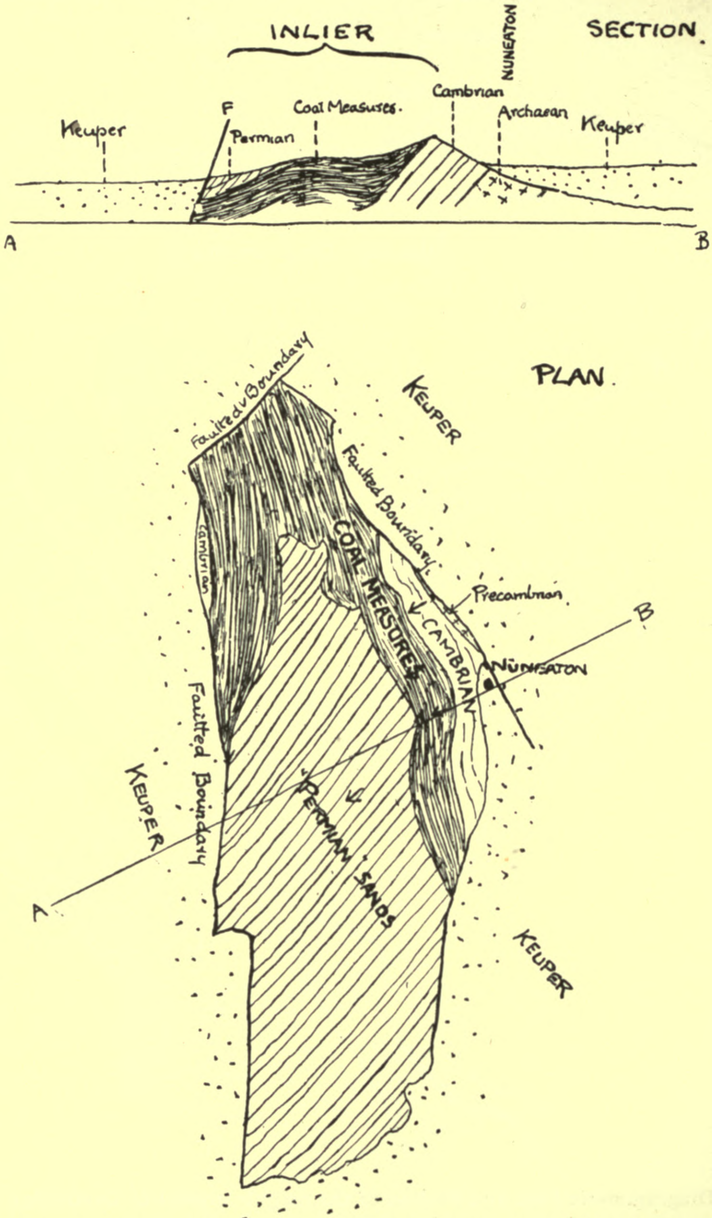


Fig. 20. **Generalized Sketch from Map and Section by Charles Lapworth in the British Association Handbook, 1913.**

The effect of overlap in a map is well seen in Sheet 19 of the 4 miles to an inch Index-Map of the Geological Survey of England and Wales ; here the discontinuous nature of the outcrop of the Lower Greensand in the N.W. and W. of the map is a striking feature. The Wealden itself is only seen in two small patches in the anticline W. of Wilton, and is overlapped to such an extent by the Gault, that the Lower Greensand does not appear, the Gault resting in turn upon Purbeck, Portland, and Kimmeridge Clay. There is however a considerable exposure of Wealden in the S. and S.E. part of the map E. of Haslemere. This overlapping of the Lower Greensand by Gault is characteristic and is displayed all along the edge of the main outcrop, the Gault frequently transgressing on to the Portland or Kimmeridge Clay. In the Index-Map, Sheet 23, this transgression is seen more completely still, for here the Gault, represented by its sandy facies the Upper Greensand, extends far to the W. over the older rocks, Oolites, Lias, and even Trias being successively covered by it.

Here therefore the relation of the Gault to the Lower Greensand and Wealden is one of overlap, but the Gault itself or its Greensand facies lies unconformably upon the Oolitic or Triassic rocks.

Escarpments, Outliers and Inliers. The features termed Escarpments are entirely due to the relation between the beds and the shape of the ground. Where the ground rises steeply forming an escarpment, a succession of beds may be seen, but eventually at the top, one bed is seen with its dip more or less parallel to the surface of the ground (dip slope) and therefore having a wide outcrop. With these escarpments are connected outliers, which are to be regarded as isolated fragments of the escarpment, and a measure of its recession and decay. Hence they are frequently found in front of an escarpment (Fig. 19). In essential characters they consist of newer rocks surrounded by older. Inliers, on the other hand, consisting as they do of older rocks surrounded by newer, are often due to folding (Fig. 20), though in some cases they too are determined by topography.

APPENDIX TO CHAPTER III

GRAPHIC CONSTRUCTIONS

Harker[1] has pointed out, that the problems which arise in connection with the relation between topography and outcrop are those of the intersection of plane surfaces, and many points of practical importance are connected with these. There are three chief methods of solution.

1. By the use of trigonometrical formulae, which can only be applied by the aid of trigonometrical and logarithmic tables. This method has been applied by Green to the determination of the true dip from the apparent dip[2].

2. By the use of special tables originally derived from the trigonometrical formulae by Jukes[3]. By means of these tables the apparent dip in any direction can be found when the true dip is known, and the relation between dip, thickness and depth is also given. Harker[1] gives a clear explanation of the formulae from which these tables of Jukes are calculated.

3. By the use of graphic constructions. In this book prominence is given to graphic methods as tending to make the student realise more clearly the actual state of things which exists on the ground. As elaborated by Harker these methods are capable of being used easily and quickly, for the solution of practically all the important problems with which the student has to deal. Careful and accurate drawing is of course essential.

In the following graphic constructions, as Harker has shewn, it is convenient to use a rectangular protractor (Fig. 21) in which OZ, the width of the protractor, is taken as unity

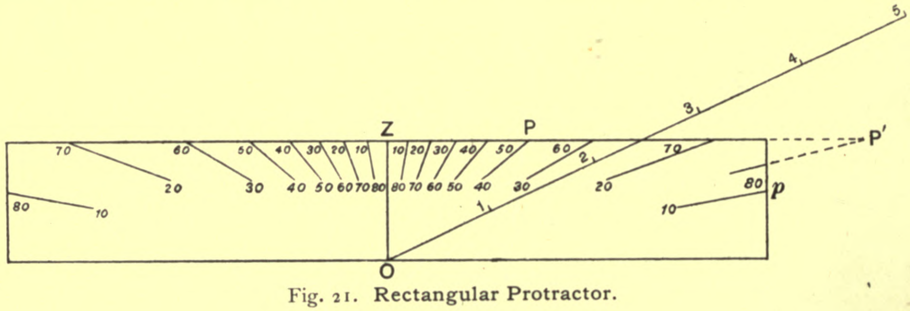


Fig. 21. **Rectangular Protractor.**

so that ZP, the distance from this zero point corresponding to any angle, is equal to the tangent of the angle, and the scale may therefore be referred to as the tangent scale, or, if the figures decrease from the middle, as the cotangent scale. It is also useful sometimes

[1] Harker, *Geological Mag.*, 1884, p. 154, and *Sci. Proc. Roy. Dub. Soc.*, Vol. VIII. (new series), Part 1, No. 3.

[2] Green, *Physical Geology*, ed. 1882, p. 463.

[3] Jukes, *Memoirs of S. Staffordshire Coalfield*, or *Manual of Geology*.

to have an ordinary scale of equal parts graduated so that its unit is equal to the breadth of the protractor. Used in conjunction with the latter it becomes a scale of secants or cosecants according to the scale of the protractor. Such a scale, with graduations 1 to 5, is shewn in Fig. 21. As Harker states, the diagrams used for the solution of the following problems are for the most part of the nature of gnomonic projections, but the required constructions are made with the protractor alone.

The plane of the paper is supposed to be horizontal, and it is evident that the inclination to this of any inclined plane can be completely represented in direction and amount by a straight line drawn from a fixed point Z on the paper. For this purpose we take a fixed point O vertically below Z and such that OZ is equal to the breadth of the protractor. Through O we imagine a straight line drawn perpendicular to the inclined plane

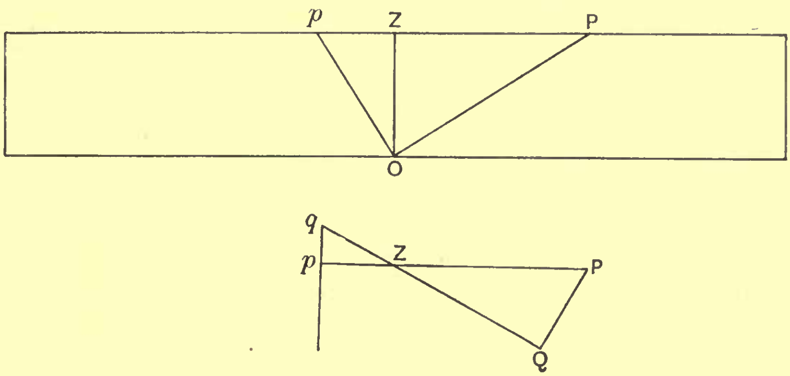


Fig. 22.

and meeting the paper at P, then ZP is equal to OZ tan POZ, that is equal to tan POZ if OZ be taken as unity. Thus ZP can be taken to represent the amount of the inclination of the inclined plane to the horizon, and it also represents it in direction since it is drawn in the direction in which the inclination of the plane is greatest.

In practice the line is laid down on the diagram by simply laying the protractor on the paper, with its zero at Z and its edge in the given direction of inclination. To realise the explanation of this method imagine the protractor placed in a vertical plane beneath the paper, its zero point at Z and its graduated edge along ZP; the centre from which graduations radiate will then be at O. Fig. 22 shews the protractor in this vertical position and, below it, the line ZP as actually drawn on the paper to represent the slope of the surface whose vertical section is Op. If the protractor be turned about OZ into the direction of ZQ, the apparent slope, or apparent dip, in this direction is given by ZQ when PQ is at right angles to ZQ. This will be proved later. In this way such a line as ZP laid down simply by the aid of the protractor may be taken to represent both in direction and amount, the slope of a hillside, the dip of a bed, or the co-hade of a fault or lode. For the inclination of a plane to the vertical instead of to the horizontal, as in the hade of faults, the cotangent instead of the tangent scale must be used.

Note that the inclination of any plane to the horizontal is equal to the inclination of its normal to the vertical and *vice versa*.

Apparent Dips. Many problems both in interpreting geological maps, and in actual field work, depend upon the relation between the *true* or *maximum* dip of a bed, and its inclination in any other direction known as its *apparent* dip. There can be only one value for the true dip; but there may be any value for the apparent dip between the maximum, and the minimum on its line of strike. Harker has dealt with these and other questions of a like nature, and solutions are given below for some of those of commonest occurrence, for the rest Harker's paper may be consulted. In Fig. 23 let ZP, parallel to BK, represent the true dip, α, of the face of a bed which is represented by the inclined plane AKL, and let the vertical line AB be equal to the width of the protractor so that $ZP = AB \tan \alpha$. KL is a horizontal line on the plane AKL so that the apparent dip in the direction BL is the angle β. Let Zq be this direction and let ZQ be the apparent dip, as measured on the tangent scale, so that $ZQ = AB \tan \beta$.

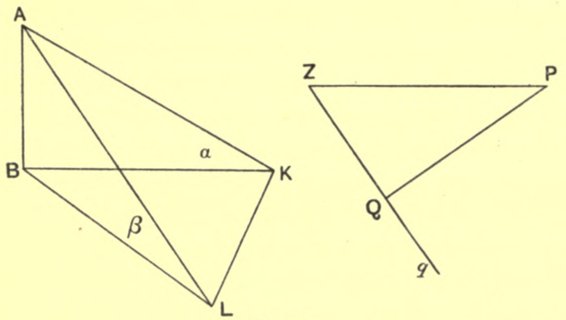


Fig. 23.

$$\text{Then} \quad \frac{ZQ}{ZP} = \frac{AB \tan \beta}{AB \tan \alpha} = \frac{\tan \beta}{\tan \alpha} = \frac{AB}{BL} \Big/ \frac{AB}{BK} = \frac{BK}{BL} = \cos KBL = \cos PZQ.$$

Therefore PQZ is the right angle and we have at once: *Given the direction and amount of the true dip of a bed, to find the apparent dip in any direction.*

Using the protractor set off the true dip ZP in the proper direction and draw a line ZR in the direction in which the apparent dip is required. From P drop a perpendicular PQ on ZR. Then ZQ, read off on the protractor, gives the apparent dip in that direction.

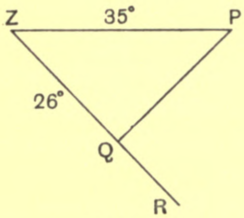


Fig. 24.

Thus if the true dip be 35° E. we find, as in Fig. 24, the apparent dip in the S.E. direction is 26°. A similar result may be obtained from the contoured map by noting the distance in any direction that a bed takes to fall 100 ft. (or the contour interval), and then plotting it according to the scale of the map, when the angle can be read off. The converse of the above problem can be readily solved: *Given the apparent dip in one direction and the direction of the true dip, to find the amount of the true dip.*

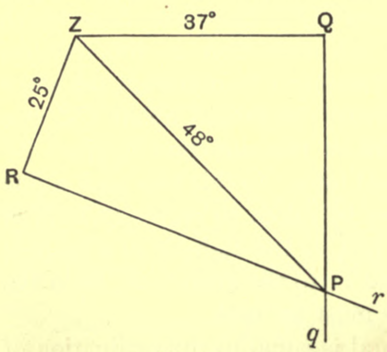


Fig. 25.

Let ZQ represent the apparent dip and let the direction of the true dip be ZP. Draw QP at right angles to ZQ. Then ZP represents the amount of the true dip.

The following problem is closely allied: *Given the apparent dip in two directions, to find the direction and amount of the true dip.*

Let ZQ and ZR in Fig. 25 represent the apparent dips in these directions. By what we have seen, ZP, representing the true dip, must be such that PQ is at right angles to ZQ and PR at right angles to ZR. Therefore the lines Qq, drawn at right angles to ZQ, and Rr, drawn at right angles to ZR, must meet at P and ZP gives the direction and amount of the true dip. If the apparent dips be 37° E. and 25° S.S.W. we shall find, as in Fig. 25, that the true dip is in the direction ZP and is equal to 48°.

When the angle of dip is large, so that it is marked on the end and not on the upper edge of the protractor, the length of the line representing it must be found by production, as shewn by P' in Fig. 21. Thus in the example just given let the apparent dip in the

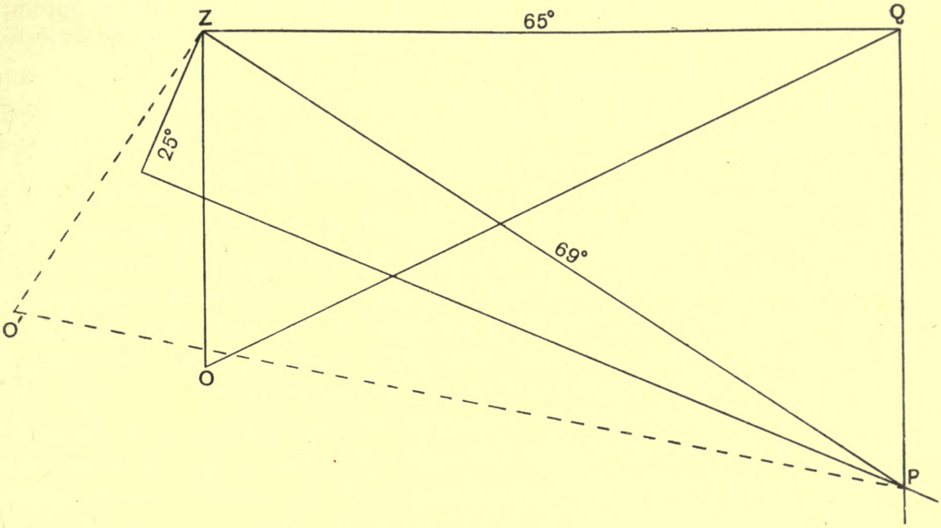


Fig. 26.

direction ZQ be 65°; the construction will be as shewn in Fig. 26, where O is the point on the bottom of the protractor immediately below Z, and O' is the position of this point when the top edge is laid along ZP. In this case the method of production is required both in finding the point Q and in reading off the true dip (69°) along ZP.

In this problem, when both angles are large, it is convenient to use the cotangent scale, that is, we read the angles along the lower scale of the protractor.

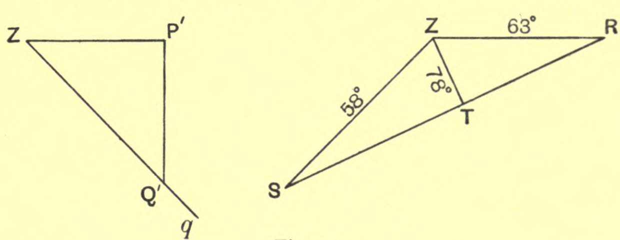


Fig. 27.

Referring to Fig. 23 we see that if the true dip is represented by ZP' (Fig. 27) equal to $AB \cot \alpha$, and the required apparent dip by ZQ' equal to $AB \cot \beta$, we have $\frac{ZP'}{ZQ'} = \frac{\tan \beta}{\tan \alpha} = \cos P'ZQ'$ and therefore the angle $ZP'Q'$ is a right angle. Thus if two apparent dips are given on the cotangent scale by ZR and ZS the true dip must be ZT when ZT is at right angles to RS.

For example, if the apparent dips be 63° E. and 58° S.W., the true dip is found to be 78° in the direction ZT.

As another example we may take the following: *Given the dip of a bed and the slope of the ground, to find the direction of the outcrop.*

As the outcrop is the line in which the trace of the level meets the surface of the ground, its direction must be the direction in which the apparent dip of the bed is equal to the apparent slope of the ground. Using the tangent scale set off ZP to represent the slope of the ground, and ZQ to represent the true dip of the bed, then the required line of outcrop must be such that perpendiculars on it from P and Q cut off equal lengths, representing the apparent dip in the one case and the apparent slope in the other. The direction must therefore be such that ZM is perpendicular to PQ.

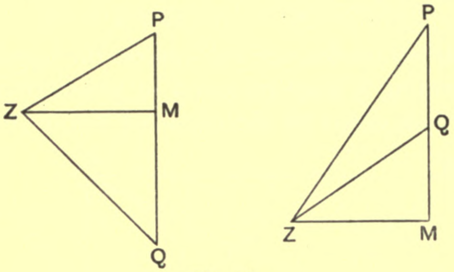


Fig. 28.

CHAPTER IV

OUTCROP AND THICKNESS

In determining the thickness of a bed from its outcrop at the surface of the ground, three considerations must be taken into account:

(i) The angle of dip,
(ii) The angle of slope of the ground,
(iii) The distance across the bed perpendicular to the strike.

There are also three cases to be considered:

(*a*) Surface horizontal,
(*b*) Surface sloping and bed dipping into the slope,
(*c*) Surface sloping and bed dipping with the slope.

In a vertical bed the distance across the bed on a horizontal surface is obviously the true thickness of the bed, and for inclined beds the distance across the bed must be greater than the actual thickness of the bed. When the scale of the map is known and the true dip known or determined as above, the thickness can be estimated by direct measurement on a true scale section, taken perpendicular to the line of strike, as in the example shewn in Fig. 14, where the true thickness of the bed, whose outcrop is shewn on the map, is the distance xx'. This assumes that the dip is constant between the upper and lower limits; if it should change in amount an approximation only will be obtained

By finding the thickness of a bed at any point on a map we can determine the direction in which it thickens or thins out, points which are frequently of significant interest.

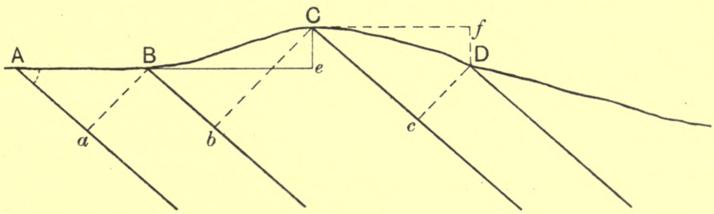


Fig. 29.

Trigonometrical formulae can also be used. Fig. 29 shews a section of the ground and the bed at right angles to the line of strike, and we have the following cases:

(*a*) $A—B$ ground level. Thickness $= aB = AB \sin BAa$

$= \text{distance across bed} \times \text{sine angle of dip.}$

(*b*) $B—C$ bed dipping into slope. The angle CBe is the slope of the ground in the line of the true dip.

$$\text{Thickness} = bC = BC \sin (eBb + CBe)$$

$$= \text{distance across bed} \times \text{sine of sum of angles of dip and of slope.}$$

But Be is the distance across the bed, as shewn on the map, and $BC = Be \div \cos CBe$ so that

$$\text{Thickness} = bC = Be \frac{\sin(CBe + eBb)}{\cos CBe}$$

$$= \text{distance across the bed on map} \times \frac{\text{sine sum of angles of dip and slope}}{\text{cosine angle of slope}}.$$

(*c*) *C—D* bed dipping with slope. The angle fCD is the slope of the ground in the line of true dip.

$$\text{Thickness} = cD = CD \sin(fCc - fCD)$$

$$= \text{distance across bed} \times \text{sine difference of angles of dip and of slope}$$

$$= \text{distance across bed on map} \times \frac{\text{sine difference of angles of dip and of slope}}{\text{cosine angle of slope}}.$$

An approximate formula, given by Charles Maclaren, is that if the apparent thickness of a bed be taken as the width of its outcrop in the direction of true dip, then the true thickness is equal to $\frac{1}{12}$ of the apparent thickness for each 5° of dip. This rule should not be applied for dips above 45°.

Depth. The determination of the depth at which strata may be encountered underground is made by both graphic and trigonometric methods.

The graphic method, from the information given on a map, involves the construction of a true scale vertical section, and the depth can then be estimated by direct reading according to the scale of the map, the dip being assumed to be constant. (Figs. 9, 11, 12, 13, aa' = depth.)

Also if *the thickness of a group of beds be known, and the amount of dip*, the depth they will occupy in a vertical bore can easily be estimated since the ratio of the depth to the thickness is the secant of the angle of dip, which is known.

Also if the width of the outcrop of a group of beds, on a horizontal surface, and their dip be known, the depth they will occupy in a vertical bore can be found, since the ratio of the depth to the width of the outcrop is the tangent of the angle of dip, which is known.

To find the ratio of the width of outcrop to the depth of the boring occupied by the beds proceed similarly but use the cotangent scale.

In the trigonometric method three cases have to be considered:

(1) where the surface is horizontal,

(2) where the surface slopes and the beds dip into the slope,

(3) where the surface slopes and the beds dip with the slope.

1. Depth of bed Aa at B

$$= Ba = AB \times \tan BAa = \text{distance across bed} \times \text{tangent angle of dip.}$$

2. Depth of bed Bb at $C = Cb = BC \dfrac{\sin CBb}{\cos eBb} = \dfrac{BC \sin(eBb + CBe)}{\cos eBb}$.

But Be is the actual distance across the bed on the map, CBe is the angle of slope in the direction of true dip, and Be is equal to $BC \cos CBe$.

$$\therefore\ Cb = \frac{Be}{\cos CBe} \times \frac{\sin(eBb + CBe)}{\cos eBb}$$

$$= \frac{\text{actual distance on map}}{\text{cos angle of slope}} \times \frac{\text{sine (sum of angles of dip and slope)}}{\text{cos angle of dip}}.$$

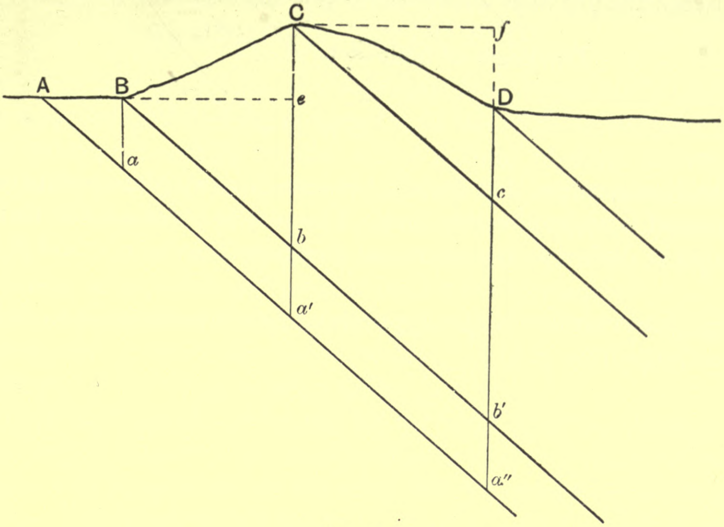


Fig. 30.

(Hayes' *Handbook for Field Geologists*, p. 32.)

3. Depth of bed Cc at $D = Dc = CD\frac{\sin DCc}{\cos fCc} = \frac{CD \sin(fCc - fCD)}{\cos fCc}$

$$= \frac{fC}{\cos fCD} \times \frac{\sin(fCc - fCD)}{\cos fCc}$$

$$= \frac{\text{actual distance on map}}{\text{cos angle of slope}} \times \frac{\text{sin (difference between angles of dip and slope)}}{\text{cos angle of dip}}.$$

The depth of the bed Aa'' at $D = Da'' = Ba + Cb + Dc$.

When the dips vary along the line of a true scale section drawn at right angles to the strike, the following method may be used to find the approximate thickness of the beds.

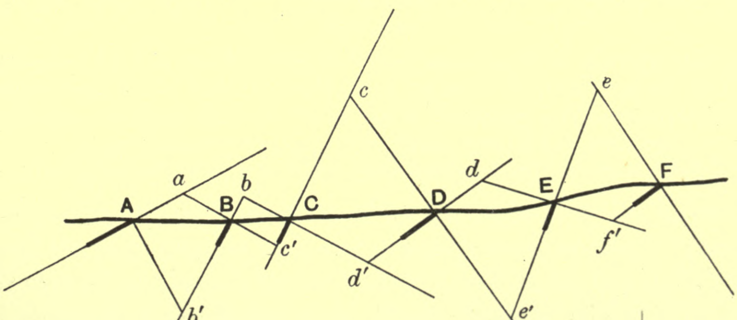


Fig. 31. Diagram illustrating determination of Thickness of Beds by Construction Method on natural section drawn to scale.

Extend the dips in straight lines above and below the line of section; at the intersection of each dip with the surface draw a line at right angles, and continue it till it meets the dip lines on the other side. The thickness of the beds between any two observed dips as A and B will be approximately equal to one-half the sum of the lines intersected between the dip lines above and below the section.

Thus $$\text{Thickness of beds } A \text{ to } B = \frac{Ab' + aB}{2},$$

or $$C \text{ to } D = \frac{Cd' + cD}{2}.$$

This construction assumes that the dip between any two given points varies uniformly and that the ground is approximately level. The results obtained will be too large if the observed dips are at different elevations and converge downwards, and too small if they diverge.

Thus in Fig. 31 the results will be approximately correct from A to D, too small from D to E, and too large from E to F.

CHAPTER V

FOLDS AND SLIDES AND THEIR EFFECT UPON THE OUTCROP OF BEDS

Folds. Assuming that strata are as a rule laid down horizontally, every dip upon a geological map is an indication of the movement of the rocks subsequent to their formation, and every movement usually implies either folding to some extent, or tilting by faulting; rapid changes of dip are however characteristic of countries where there has been considerable folding of the beds, sometimes of every degree and order. These folds, as will be seen, have in general characteristically shaped outcrops, though as has been shewn, the final form in any area will depend upon the topography.

There are two main classes of folds, which are both of the nature of earth waves:

(1) Epeirogenic, or continent-making folds;

(2) Orogenic, or mountain-making folds.

The former have the longer wave-length, but the latter often the greater amplitude, and it is with these orogenic folds that we have chiefly to deal in geological maps of limited areas. These appear to be produced as the result of tangential stresses acting mainly from one direction upon rock sheets which have not free play, but are held in one direction at least, to a greater or less extent, by some resistant rock mass. If the stresses be comparatively slight, the earth waves are simple and reveal themselves in their fundamental form merely as a succession of arches and troughs, known to geologists as anticlines and synclines respectively. In all such folds, while the strike remains constant there must be

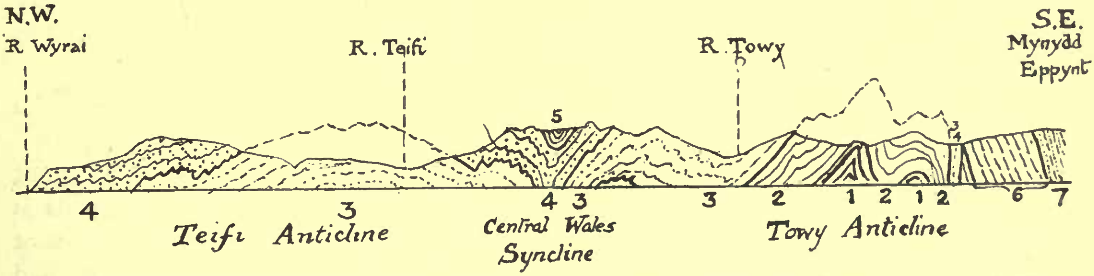


Fig. 32. Diagrammatic Section across Central Wales shewing Teifi Anticlinorium, Central Wales Synclinorium and Towy Anticlinorium. (After O. T. Jones, *Q.J.G.S.* 1912.)

1 = Dicranograptus Shales; 2 = Upper Bala; 3 = Lower part of Valentian; 4 = Aberystwyth Grits; 5 = Purple and Green Beds; 6 = Wenlock-Ludlow Beds; 7 = Old Red Sandstone.

[Horizontal scale: 1 inch = 5 miles; vertical scale: about 5000 feet = 1 inch.]

a progressive change in the amount of dip from the outside to the inside of the fold as the inclination of the beds changes from one direction to its opposite. There must therefore be an area over which there is no inclination or dip at all, this is the *axis* of the fold and the plane in which it lies is the axial plane. Folding of this type is well seen in many sections in the Jura Mountains. This general simplicity may be rendered more complex by the formation of ripples on the waves, i.e. the existence of minor folds or buckles within the larger folds, constituting what are known as anticlinoria and synclinoria; this type of folding is well seen in Central Wales (Fig. 32). The axial planes of the folds may be perpendicular or inclined, so that the fold may be symmetrical, asymmetrical, overturned or recumbent.

Whilst with relatively slight tangential stress the axial planes of the folds lie perpendicular to the direction of stress and the resulting folds are symmetrical, with increasing force, the axial planes of the folds become more and more nearly parallel to the direction of the stress, though in general, they shew a slight dip towards the quarter from which

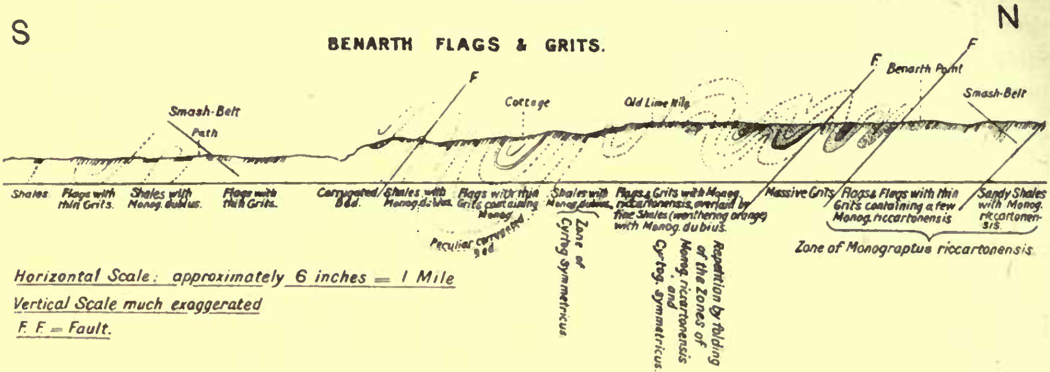


Fig. 33. Isoclinal Folding. W. bank of River Conway, N. Wales.

the tangential force has acted; thus the folding may be symmetrical, and grade almost imperceptibly into asymmetrical folding in which the axial plane of the folds departs but little from the perpendicular, and the dip of the beds is merely steeper on one side of the fold than the other; as the angle of the axial plane still further diminishes, there may be developed the overturned fold or overfold, in which one limb of the fold is, as it were, doubled more or less over the other, so that the beds are in inverted order on the lower limb of the arch, or the upper limb of the trough.

In certain cases of overfolding the wave-length may be very short relatively to the amplitude, the folds being closely packed, and the inclination of the axial planes of successive folds may be considerable and constant in direction, so that the dip of the beds is in the same direction and equal in amount on both sides of the fold; such are termed *isoclinal folds*. They are usually small scale folds in which the dip of the beds is fairly high (Fig. 33).

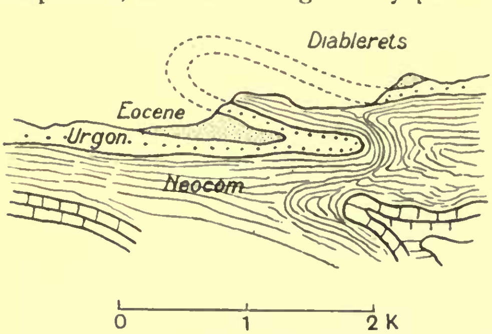
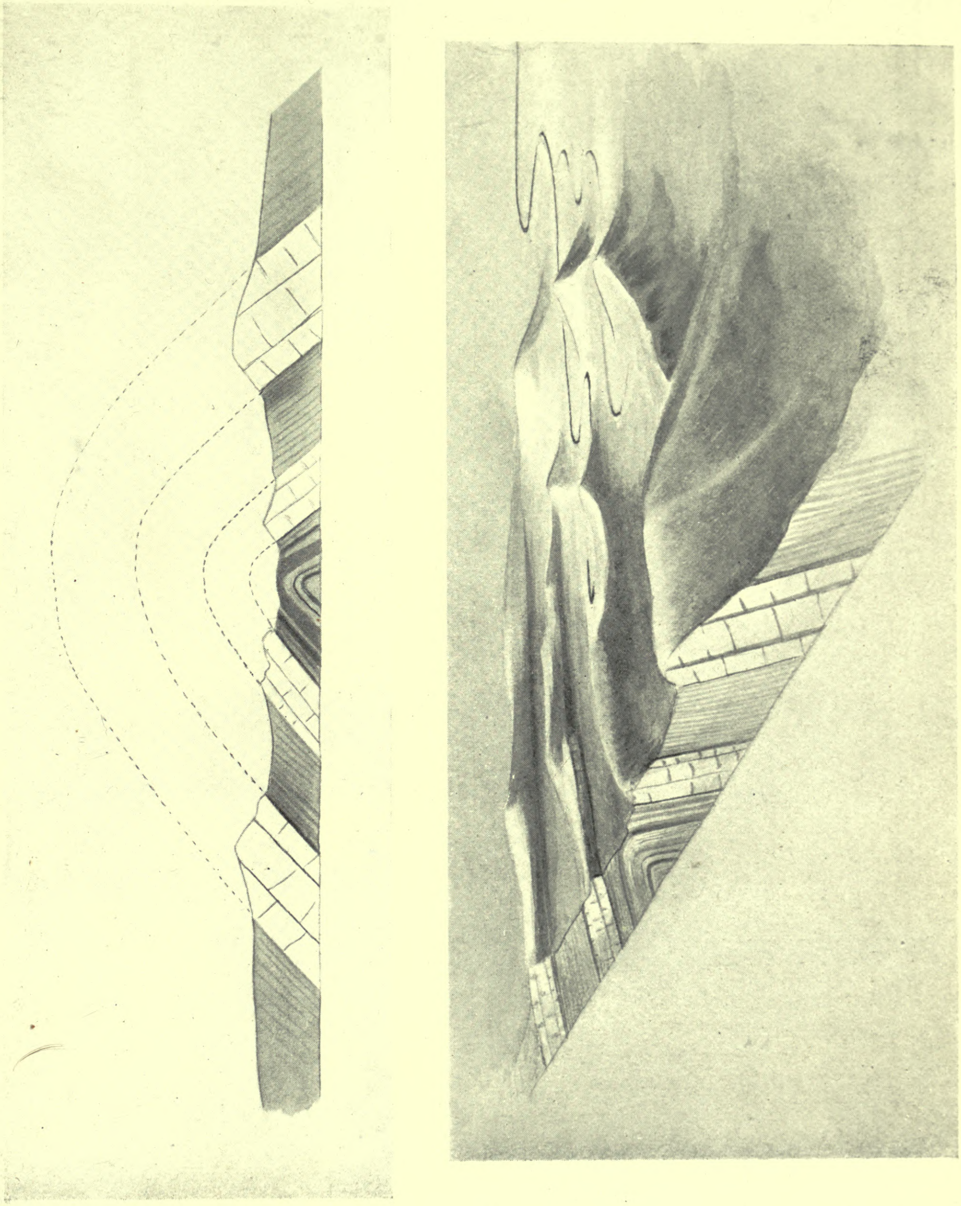


Fig. 34. Overfold of the Diablerets. (After C. Schmidt.)

In other cases of overfolding the axial plane approaches the horizontal and the rock sheets forming the fold are also apparently almost horizontal. Such are termed *recumbent folds*, they are usually regional in character and having often an enormous wave-length occupy considerable tracts of country.

Isoclinal folding is the typical structure of the Southern Uplands of Scotland, whilst



Anticlinal Folding.

PLATE V

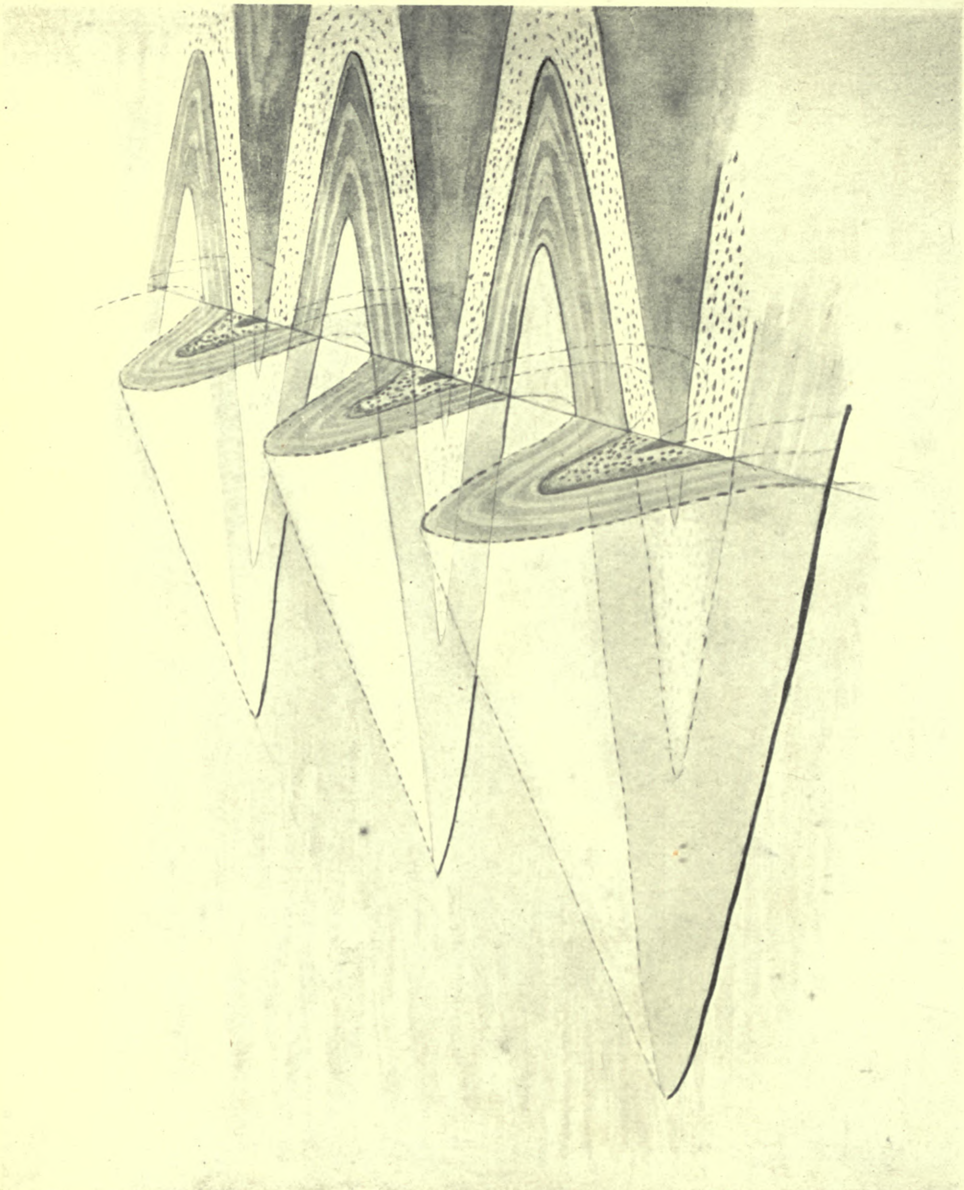


Diagram illustrating Pitching Folds.

the most recent interpretation of the structure of the Alps ascribes many of the complications there seen, to the formation of great recumbent folds; and similar structures, deeply dissected, are to be seen in the Scottish Highlands.

In all cases of overfolding another factor may have to be considered, and that is the bending power of the rocks affected, under the conditions of the formation of the fold; sooner or later the limit of bending or folding may be reached, and the folded rock breaks, with the formation of fold faults; in extreme cases these may constitute veritable *slides* (Bailey) along which, if the tangential force be continued and transmitted, portions of the broken fold may be driven forward for many miles. In their *effects* such faults are similar to *reversed faults* of the *thrust* type, but in their *origin* they represent the highest power of folding. At any subsequent time both fault plane or slide, and its rock burden, may themselves be further folded.

Complications of structure resulting from this extreme type of folding may be studied in the Swiss Alps, where, as Marcel Bertrand, Lugeon, Steinmann and others have shewn,

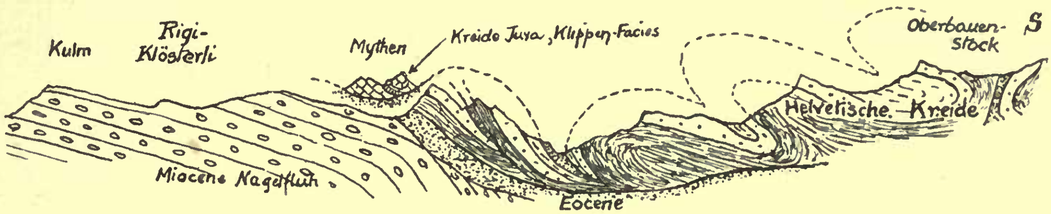


Fig. 35. **Section in the Alps shewing Klippen.** (After Schmidt. Basel, 1907.)

many well-known peaks such as the Matterhorn, the Weisshorn, and the Mythen are mountains "without roots," being carved out of great rock sheets which have been thrust forward an enormous distance from the south, and as the result of denudation they now stand as gigantic erratics in an alien land (Fig. 35). Sometimes all that remains of the overthrust sheet are relatively small detached portions; these differ only in point of size from the mountain masses just mentioned, and all such detached remnants or thrust outliers, as they might be termed, are known as *Klippen* (see Fig. 35 and Fig. 56); they are

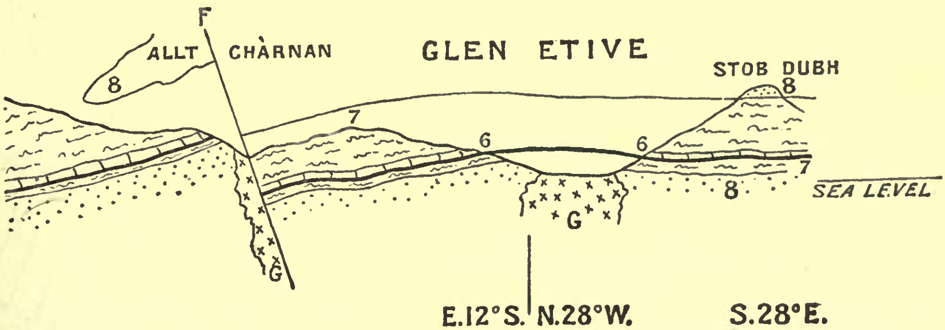


Fig. 36. **"Windows" of Etive the result of Denudation through a Thrust Plane.** (After E. B. Bailey, *Proc. Geol. Assoc.*, 1911.) Scale 1 in. = 1 mile. Lettering as in Fig. 42.

limited downward in all directions by the outcrop of the thrust plane or slide upon which they rest. In other cases denudation may have proceeded sufficiently to wear away the

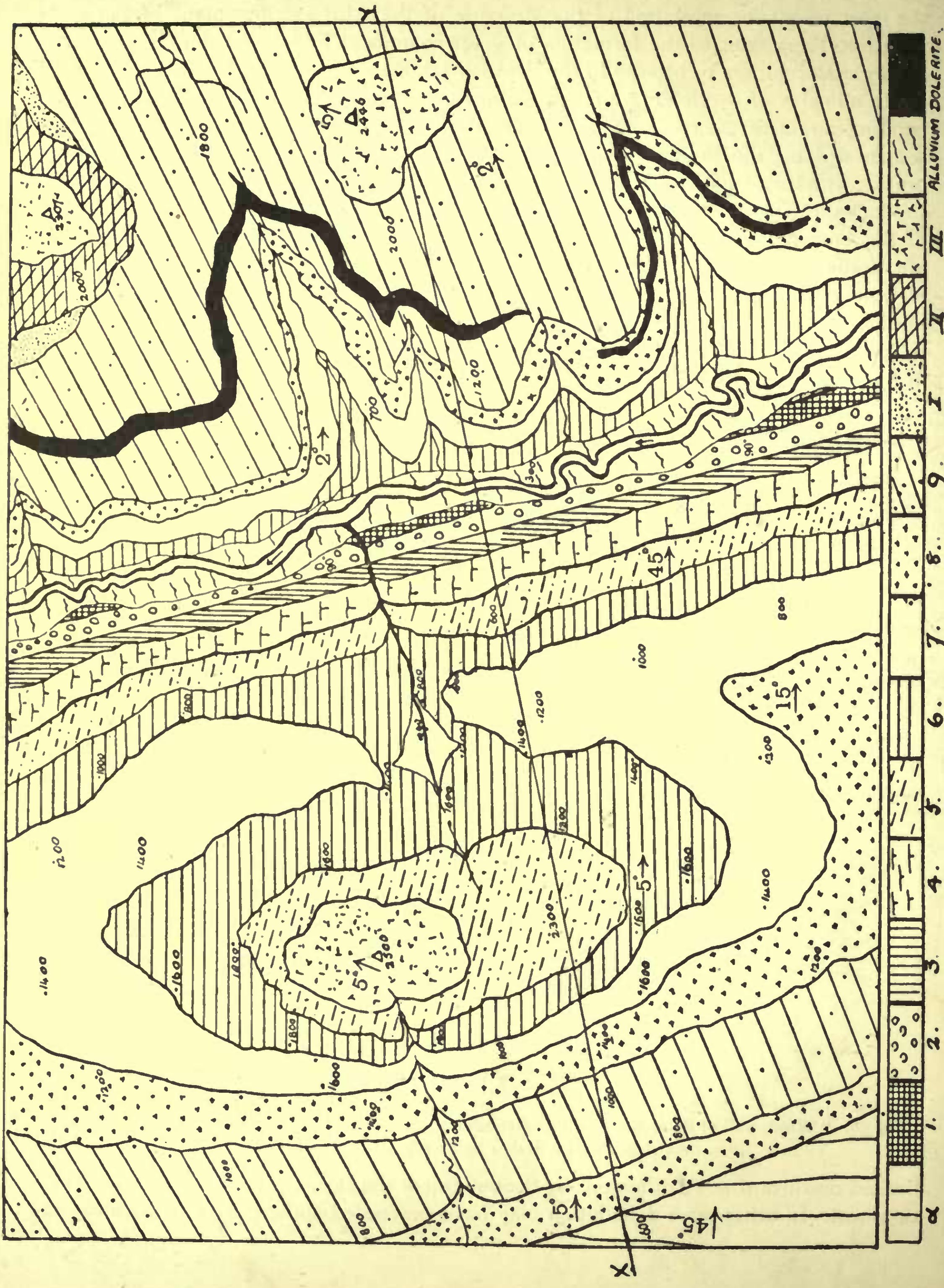


Fig. 37. Map shewing Overfold. Scale 1 inch = 2000 feet.

slide itself so as to reveal a greater or smaller portion of the rocks lying underneath it (see Fig. 36); such apertures in the slide are termed *windows*, and they too are limited by the outcrop of the slide plane which constitutes the framework of the window.

In isoclinal folds the dips are usually high, and the outcrops of the same beds are repeated again and again within a comparatively small area, so that, unless the folding be recognised, an entirely erroneous idea of the thickness of the beds may be obtained.

In recumbent folds on the other hand, the dips are usually very low, unless the apex of the fold be involved, and in consequence the beds concerned generally spread over a considerable tract of country.

Thus in Fig. 37 the most conspicuous feature is a denuded recumbent fold thrust over older rocks (*a*) seen in the extreme S.E. The southern portion is the synclinal limb and the dips which occur in the different beds, 5°, 15°, 45°, 90°, are due to the different portion of the fold revealed by the slope of the ground, its central portion or apex being seen in the middle of the map where the outcrops run in approximately straight lines. Part of the complementary anticlinal limb is replaced by a thrust running along the river valley; this is visible at one locality only, being concealed for the greater part of its course by the alluvium of the river.

Effect of Folds on Outcrop. Now these folds, of whatever type they may be, may run for a greater or lesser distance, but are never continued indefinitely in the same straight line, and more often tend to replace each other fairly rapidly; the axis of the fold may just die away, be replaced by a series of others *en échelon*[1], or succeeded by others in a less regular manner[2], in any case as a unit it disappears, so that it comes about that the common form of outcrop of folded beds is that of an elongated oval or what is known as the *boat-shaped outcrop*; the regularity of such an outcrop is dependent upon the topography, and the amount and uniformity of the dip.

Such oval-shaped outcrops must not be confused with outliers, which might conceivably be done if the fold were of an isoclinal type, otherwise the different direction of the dip upon the two sides would be a distinctive character; but when the fold is of isoclinal type it may be necessary carefully to study the dip of the beds in relation to the topography in order to discriminate between the two. The steep dip of the beds in the isocline implies the necessity of folding in order that the beds should be seen at the surface again within the limited area available.

Pitch. Another element that is partly responsible for the boat-shaped form of the outcrop of folded beds, is the fact that the axis of the fold is very rarely horizontal in the direction of the trend of the fold, but is generally more or less inclined, so that the whole fold shews what is known as *pitch* (Pl. V).

The resulting outcrop is therefore due to two component inclinations acting in different directions, and is best understood by reference to pitching folds seen upon a flat surface. To get a series of boat-shaped outcrops under these circumstances in the same beds, there must be a considerable change of slope in the general direction of pitch, or the folded beds will be lost underground. If, however, the ground be flat, the boat-

[1] Mendip, Map 1, 1 inch, Geological Survey of England and Wales, Sheet 19 (old series).

[2] Moffat, Geological Survey of Scotland Map, Sheet 16, 1 inch.

shaped outcrop disappears, and in its place there is seen a series of zigzag outcrops, the apices of which correspond with the axes of the pitching folds, anticline or syncline alternately ; the anticlines *closing*, the synclines *gaping* in the direction of pitch (Fig. 38). Hence supposing that there is a pitch to S. as indicated along *AB* (Fig. 39), as Jones has shewn, there must always be a component of dip in the direction of pitch, i.e. *pr* for the dip *pq* and *p′r′* for the dip *p′q′*, therefore the outcrop of the beds in either line of the fold or on any slope parallel to *AB* will have an apparent dip in that direction. The value of the apparent dip is in general different from, and bears no simple relation to, the pitch; it affords however a ready means of detecting whether the folds pitch or not, but the actual value of the pitch cannot be deduced from it. Not infrequently pitch combined with marked changes in topography produce peculiar effects as regards the outcrop of beds, these tending to disappear quickly, so that two parallel sections across an area within a comparatively small distance may shew quite a different succession of beds.

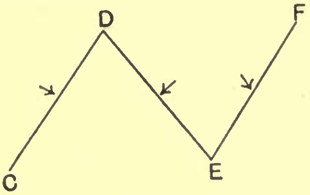


Fig. 38.

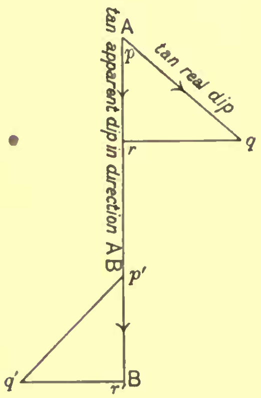


Fig. 39.

Harker (*loc. cit.*) has shewn that, given the direction and amount of the dips on the two sides of an inclined anticlinal axis, it is possible to find the direction and inclination of that axis.

Let *ZA*, *ZB* represent the two dips, then *ZD* the perpendicular to *AB* represents the direction and inclination of the axis. *ZA*, *ZB* are virtually two inclined planes meeting in a line parallel to the axis of the fold. (For Trigonometrical Solution see Harker's paper.)

As Bailey has made clear[1], in a group of recumbent folds it is very likely that the successive anticlines and synclines will overlap each other for a considerable distance, and after such a district has been deeply dissected by erosion, there may be revealed an assemblage of superimposed recumbent anticlines with their complementary recumbent synclines.

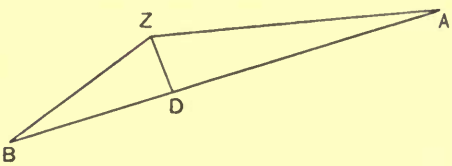


Fig. 40.

Usually a recumbent anticline closes upward and gapes downward, while a syncline does the reverse, but such folds may themselves undulate, and when a recumbent fold dips down towards the direction of its close it will be **Synclinal** in form, and conversely it may be **Anticlinal** in form when it rises in the direction of its close. Thus it is perfectly possible for a recumbent anticline to be of synclinal form (or pseudo-synclinal), and the converse is equally true of recumbent synclines.

A recumbent anticline should have a core of older rocks, and a recumbent syncline a core of newer rocks.

Reference to some maps will probably make clearer the matters here dealt with.

Map of the Mendip Area[2]. Many of the features dealt with in the last few pages are

[1] *Mem. Geol. Survey: The Geology of Ben Nevis and Glen Coe*, p. 25.

[2] Geological Survey of England and Wales, 1 inch to 1 mile, Sheet 19 (old series).

admirably displayed in the 1-inch Geological Survey map, Sheet 19 (old series). In the first place there are the folds of the Mendip Hills; these are seen characteristically *en échelon*, the main lines being (1) the Blackdown anticline, this is succeeded a little further to the south by (2) the North Hill anticline, to the south of which lies (3) the Penn Hill anticline, and beyond this again the (4) Beacon Hill anticline. It is characteristic of all these folds that they are more steeply folded on their northern sides, and are even slightly overfolded as is seen on the N. side of the Beacon Hill anticline where the Coal Measures dip under the Millstone Grit.

In addition to the folding there is the great unconformity of the Triassic rocks upon the different members of the Carboniferous. These Triassic rocks with the overlying cover of Lias stretch out on all sides like a wide sea in which the Carboniferous rocks rise like islands. Further there is the overlap of the Oolites, till they too rest unconformably upon the Carboniferous Limestone. The effect of topography is beautifully seen in the outcrops of all the members of the Oolites, the lower beds cropping out in the valleys by reason of denudation, and since the dip is very slight they may be traced round the various hills like so many contour lines, and the hill tops are occupied by a wide spread of the Great Bath Oolite or else by the Forest Marble. The edge of the main outcrop of these beds forms a well-defined escarpment overlooking the plain of the Lias.

In the S.E. there is evidence of the great Cretaceous transgression seen in the wide spread of the Upper Greensand and base of the Chalk resting in turn upon Kimmeridge Clay, Coral Rag, and finally even upon Oxford Clay.

Small inliers of Carboniferous Limestone are of frequent occurrence, proving the extent of beds of that age under the Trias; they are usually the result of folding, such as those of Worminster, Knowl, and Church Hill on the south side of the Mendip Hills. There is also an inlier of a different type composed of Coal Measures and Triassic rocks near Corston, W. of Bath. This appears to be due entirely to denudation.

Outliers too are also a conspicuous feature, especially those in front of the main Oolitic outcrop. Some of these are quite large, as for instance those of Dundry Hill, Glastonbury Tor, and the ridge running from West to East Pennard; there are also several smaller ones lying nearer to the main outcrop, such as Stantonbury Hill Camp, Willmington, the Barrow Hills and the Sleight, these being all composed of the lower members of the series: there are others in front of the outcrop of the Cornbrash composed of that rock and resting on the Forest Marble.

There is also one marked Cretaceous outlier of Upper Greensand in advance of the main Cretaceous outcrop, forming Roddenbury Hill.

Map of the Moffat Area[1]. This area shews admirably the effect of intense folding; in the first place the boundary between the Llandilo-Caradoc and Llandovery rocks is not a continuous line but broken by incursions of the newer rocks into the older. Such a boundary is highly characteristic of a folded country.

Over the whole area there are shewn numerous elongated boat-shaped folds, sometimes very narrow and of considerable extent, or with irregular broken outline signifying more complicated folding, at others broader, and denuded to shew rocks of many different

[1] Geological Survey of Scotland, Sheet 16, 1 inch to a mile.

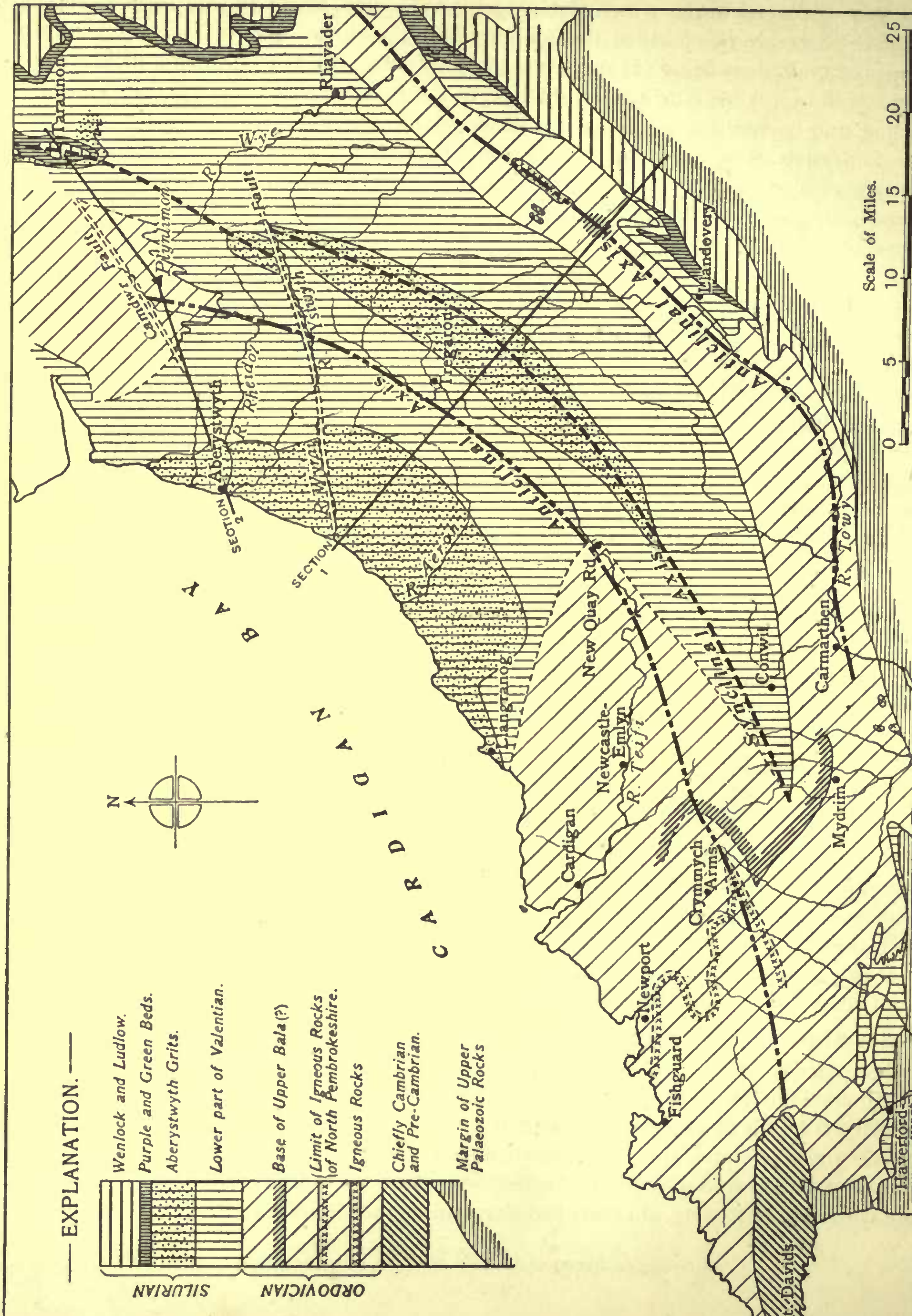


Fig. 41. Geological Map of Central Wales and the adjoining regions. (After Jones, *Q. J. G. S.*, Vol. LXVIII. Pl. 34.)

ages, as for example those in the extreme N.E. of the area, which shew the volcanic rocks and both Glenkiln and Hartfell Shales; or those lying S.W. of St Mary's Loch, where Birkhill, Hartfell, and Glenkiln Shales are all indicated in the heart of the fold; and again on Hartfell itself, where the shape of the outcrop indicates rapid folding of the Birkhill Shales denuded sufficiently to shew the lower Hartfell Shales in the cores of two of the biggest of these folds.

Central Wales. In the excellent little map attached to Jones' paper, and here reproduced, the effect of pitch on folds is particularly clearly shewn.

In this area there are two major anticlinal axes constituting the Towy anticline (or anticlinorium) and the Teifi anticline (or anticlinorium), these being separated by the Central Wales syncline (or synclinorium). In the northern part of the area the boundary lines between the different strata all converge southwards in the limbs of the anticlines and diverge in that direction in the syncline, indicating a pitch to the south; further south, however, the opposite is the case, the synclines converging southwards and the anticlines gaping in that direction. Here therefore the pitch is in a N.E. direction, the beds having swung round so as to run more N.E.—S.W. A region of no pitch should therefore exist somewhere between these two, and its whereabouts is indicated by the parallelism of the rock boundaries and by the relative breadth of outcrop of the anticlinal and synclinal folds in the central part of the district shewn. The synclinal folds will be noted as attaining their greatest breadth at this point, and the anticlinals their minimum; this should also be the region of the greatest depth of the synclinal fold, whilst in the case of the anticlinals the region of change of pitch should mark the greatest elevation of the strata constituting the folds.

Ballachulish Area[1]. The effect of recumbent folding is well seen in the map attached to Bailey's paper on the Ballachulish area, though the area is a complicated one, both the original recumbent folds and their accompanying slides having themselves been further folded. The folds here shewn comprise:

(1) The Appin fold replaced to a great extent by the Fort William slide,
(2) The Ballachulish fold and slide,
(3) The Aonach Beag fold.

There is also the folded slide of Neall a'Bhuirich. The easiest of these to follow is perhaps the *Appin fold*, with its accompanying Fort William slide, extending along the shores of Loch Linnhe in the S.W. part of the map but diverging from the line of the loch to the N.E. This fold is synclinal in form, but in the present state of our knowledge of the stratigraphy of the district it is not possible to state what its original form was.

The *Aonach Beag fold* is of comparatively minor importance. It occupies a structural position midway between the Appin and Ballachulish folds and is seen in the N.E. part of the map where it is clearly indicated by the nature of the outcrop of the Ballachulish limestone.

The *Ballachulish fold and slide* is somewhat more difficult to follow on the map since the foldings are more intricate and the outcrops therefore more sinuous.

[1] Map attached to Bailey's paper, *Q.J.G.S.*, Vol. LXVI. p. 586.

One of its most interesting exposures is in Glen Etive where the denudation of the Lower Schists reveals its existence in veritable windows, the windows of Etive (Fig. 36). The nature of the folding is suggested by the fact that whilst of the beds seen in the area nos. 2—6 enter into the folds; nos. 7—9 are seen in the following relations:

(*a*) Structurally overlying the Ballachulish fold,

(*b*) Structurally intervening between the Ballachulish and Appin folds,

(*c*) Structurally underlying the Appin fold.

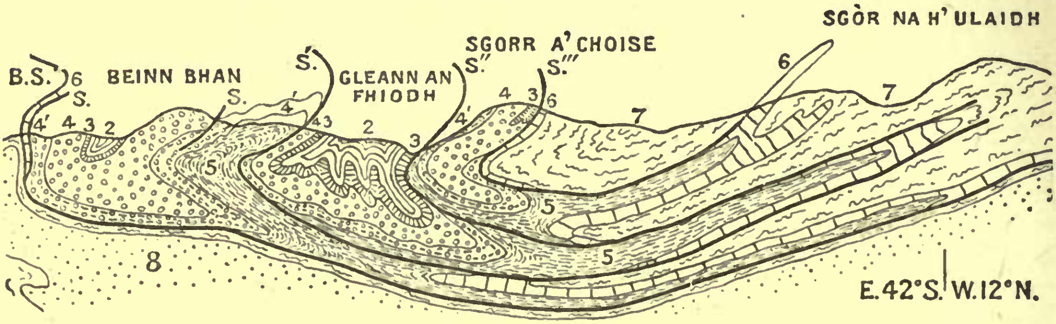


Fig. 42. **Section to shew the Recumbent Fold of Ballachulish and its attendant Slides.** (After E. B. Bailey, *Proc. Geol. Assoc.*, 1911.) Scale 1 in. = 1 mile vert. and hor. 9. Eilde Flags (see Fig. 50). 8. Glencoe Quartzite. 7. Leven Schists. 6. Ballachulish Limestone. 5. Ballachulish Slates. 4. Appin Quartzite. 3. Appin Limestone. 2. Appin Phyllites. B.S. Ballachulish Slide. *S′ S″ S‴* slides.

Denudation of Folds. Though in the case of simple folding into arch and trough the anticline forms originally the higher land and the syncline the lower, it must not be supposed that this is in any way a permanent effect; from the nature of things it follows that the beds in the anticlinal part of the fold are stretched, whilst those in the synclinal portion are compressed; thus the beds in the anticlinal part are weaker towards agents of denudation than those of the synclinal portion, and hence as denudation proceeds the anticline tends to be more quickly destroyed.

Davis has shewn[1] how when beds of original hardness are involved in such structures there may be a gradual but persistent transference of the main drainage lines from the synclinal folds in which they were initiated to the anticlines. This is due to the more rapid work of the tributary streams on the anticlines, with the result that a softer, more easily eroded bed may be reached comparatively quickly, while the hard bed still controls the erosion of the main channel, and then by a series of captures, the head waters of the original synclinal stream are gradually switched off into that of the anticlinal stream running at the lower level.

So that it rarely happens that the tectonic structures are directly responsible for topographic form, as appears, however, still to be the case in the Jura Mountains, which still retain their anticlinal mountains and synclinal valleys, though undoubtedly much material has been removed from the crests of the folds.

In the case of the Appalachians, however, the mountains at the present day are mainly synclines separated by narrow anticlinal valleys, though the general structure is more

[1] Davis, *Geog. Essays*, p. 436.

complicated than it appears at first sight, since Russell has shewn[1] that these mountains preserve within them the records of two well-defined peneplains, the older and higher one the Schooley peneplain, and the lower the Shenandoah peneplain, so that their present

Fig. 43. **Diagrammatic Section of the Appalachian Mountains shewing (a) Erosion cycles, (b) Asymmetric folds.**

form is due to at least two periods of deformation or folding followed by erosion, whilst it is possible that the asymmetric nature of the folds indicates a third[2]. Of our own British mountains which shew a synclinal structure, Snowdon affords perhaps the best example.

Secondary Tilts. Harker (*loc. cit.*) has shewn how by application of graphic methods many problems relating to the secondary tilting of rocks may be solved.

1. *Strata originally inclined receive a new tilt; given the original and final dips, to find the direction and amount of the new tilt.* Let OP and OQ represent the original and final dips, join PQ, this gives the direction of the required tilt. Draw OM perpendicular to PQ (produced if necessary), place the edge of the protractor along PMQ with zero point at M and read off the angle between P and Q, this is the sum or the difference of readings of the tangent scale at PQ according as the points are on opposite sides or the same side of M and it gives the amount of the required tilt. This is obvious if the protractor be imagined to be upright beneath the line PMQ with zero point at M.

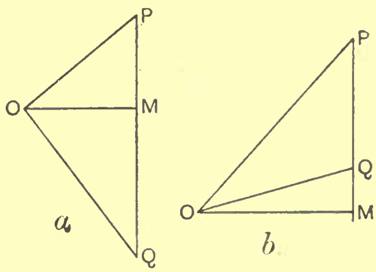


Fig. 44.

Also 2. *Strata originally of known inclination receive a new tilt of given direction and amount, required to find their final dip.* In this case draw OP to represent original dip and a line PQ in direction of given tilt. Then draw OM perpendicular to this line and placing edge of protractor along PM with its zero point at M, take angle from P to Q equal to angle of tilt; line OQ represents final dip.

Similarly it is possible to find the original dip, given the final dip and the new tilt they have received.

[1] Russell, *N. America*, p. 80.

[2] Davis, *Geog. Essays*, p. 424.

CHAPTER VI

FAULTS AND THEIR EFFECT UPON THE OUTCROP OF BEDS

In many natural sections of rocks, strata are found to be broken off apparently abruptly, and adjoining them rocks of a totally different nature may make their appearance; these need not necessarily be of different lithological type, but their fossil contents may be quite distinct, whilst in other cases the lithological type is markedly different. Such lines of break in continuity are known as Faults. At times they are very clearly seen, at others it is very hard to be sure of their exact trend through lack of sufficient exposures, though it is nevertheless certain that the break is there.

The *throw* of a fault is the vertical displacement of the same beds on either side of the fault plane; it is the measure of the amount of displacement that has taken place, this displacement being known as the upthrow, or downthrow, or else in mining as the upcast or downcast. In all faults the downthrow side is that upon which the newer beds are seen, at any point along the fault plane.

Hade or Dip. The inclination of a fault plane from the vertical is usually known as its *hade*, but there is a tendency nowadays, especially amongst mining geologists, to use the term *dip* in this connection precisely in the sense in which it is used in dealing with strata.

Faults may well be classified on a basis of *origin*, i.e. in relation to the nature of the crustal strain which resulted in their production.

1. Tensional (Gravitational) Faults. Mainly vertical movements produced under the influence of gravity.
   - *a.* Normal Faults.
   - *b.* Trough Faults.
   - *c.* Cauldron Subsidences.
2. Compressional (Tangential) Faults. Mainly produced as the result of tangential strains.
   - *a.* Reversed Faults.
   - *b.* Tears.

Tensional Faults.

a. Normal Faults. All normal faults are due to vertical movements under the influence of gravity and the rocks have been stretched and cracked, and have moved so

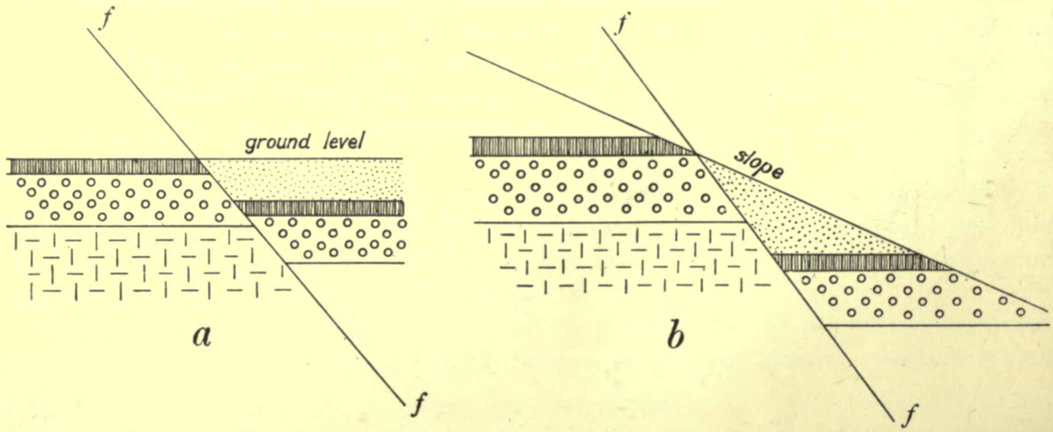


Fig. 45.

as to gain space. The fault plane tends *to dip in the direction of the downthrow*, i.e. *in the direction of the newer beds.*

In the case of horizontal beds, the effects of normal faulting are clearly seen, the fault planes bringing together abruptly strata of very different lithology or fossil contents (Fig. 45 *a*). If on the contrary the slope of the ground be considerable, there may be repetition of the beds, giving much the same effect at the surface of the ground as if the beds were inclined and the ground flat, though in this case the repetition is due to the combined effect of faulting and topography (Fig. 45 *b*).

In the case of *inclined* beds the rocks may be affected more or less in the line of their strike or dip, and these have been termed strike and dip faults respectively. In the case of normal strike faults the outcrops of the rocks tend to be repeated at the surface of the ground as a result of the faulting[1], but there is an exception which is of fairly common occurrence, and this happens when *the angle of dip of the fault plane is in the same direction as that of the beds but at a higher angle*, in such a case there is concealment of beds. (Pl. VI.)

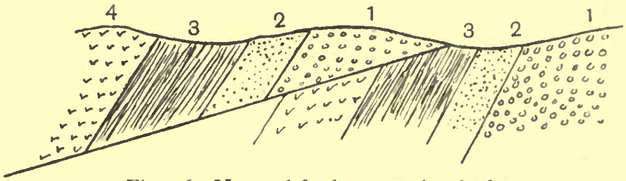


Fig. 46. **Normal fault-repeating beds.**
(Beds 1, 2, 3 are repeated.)

In normal dip faults there is always an apparent shifting of the outcrop in a lateral direction, the effect produced being dependent upon the amount of dip. In general it may be said that the outcrop of the beds on the upthrow side of the fault is thrown forward in the

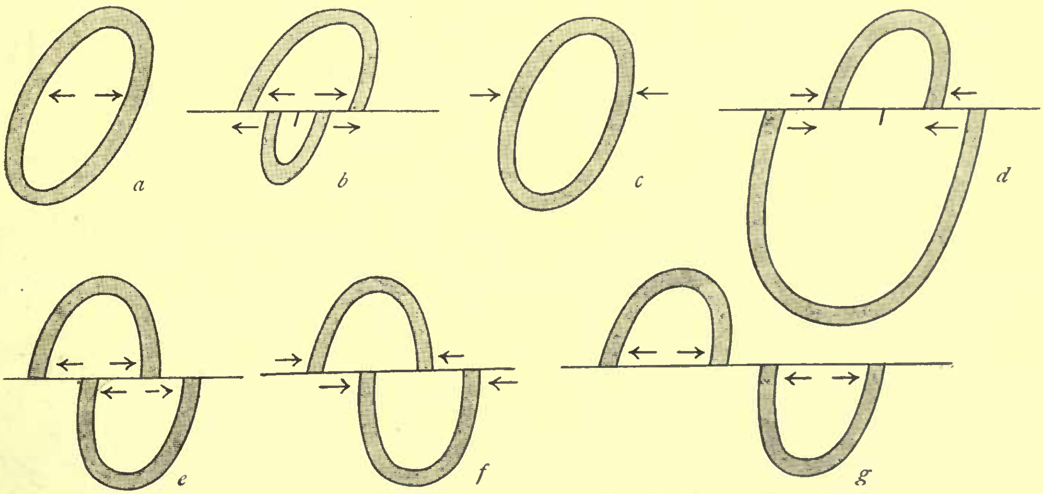


Fig. 47. **Effect of Normal faulting** *a—d*, **compared with effect of Tear faulting** *e—g*.

direction of dip unless *the angle of dip is less than that of the slope of the ground, when the reverse occurs.*

This being so, it follows that as a result of the normal faulting, the outcrops on the downthrow side of an anticline are moved closer together, since the effect is to get nearer

[1] Watts, *Geol. Mag.*, 1888, p. 356.

the top of the arch (Fig. 47 *b*), whereas in the case of a syncline the reverse is the case, the outcrops being further apart on the downthrow side (Fig. 47 *d*).

b. Step Faults may be regarded as a group of normal faults in which the fault planes dip in approximately the same direction and at the same amount, the beds affected being thrown down in a succession of steps, instead of all at one time.

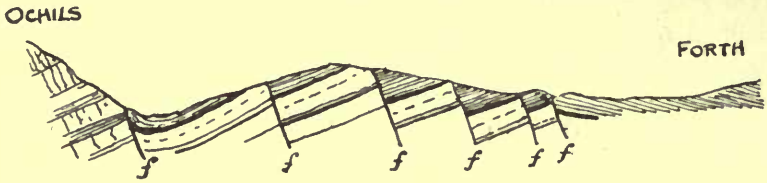


Fig. 48. **Section across Clackmannan Coalfield, shewing Step-faulting.**
(After Sir Archibald Geikie, *Scenery of Scotland.*)

c. Trough Faults may be regarded as a type of tensional fault in which a portion of the earth's crust has been thrown down along two normal faults hading or dipping in opposite directions. Faulting of this kind has been responsible for the formation of some of the most remarkable structural features on the surface of the earth, the so-called Rift Valleys, the most notable example being the Great Rift Valley, which covers over 4000 miles running from the Dead Sea through the Great Lakes of Central Africa.

The Midland Valley of Scotland is also held to be a valley of this type as regards the results of the most recent movements affecting it.

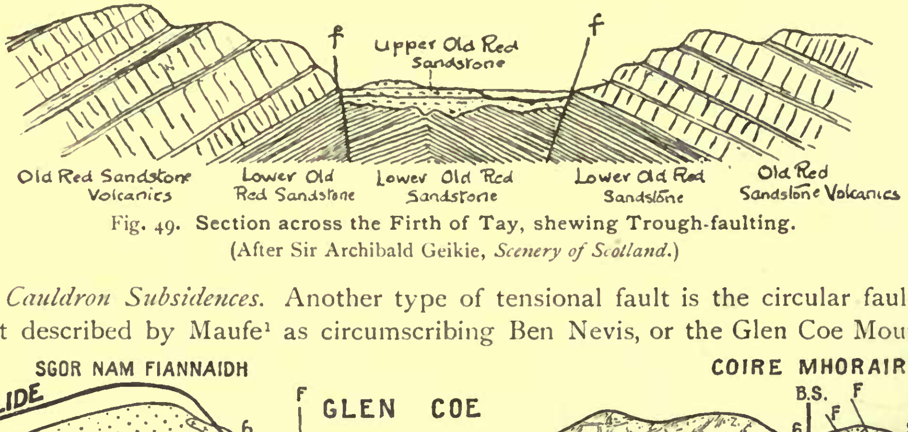


Fig. 49. **Section across the Firth of Tay, shewing Trough-faulting.**
(After Sir Archibald Geikie, *Scenery of Scotland.*)

d. Cauldron Subsidences. Another type of tensional fault is the circular fault such as that described by Maufe[1] as circumscribing Ben Nevis, or the Glen Coe Mountains.

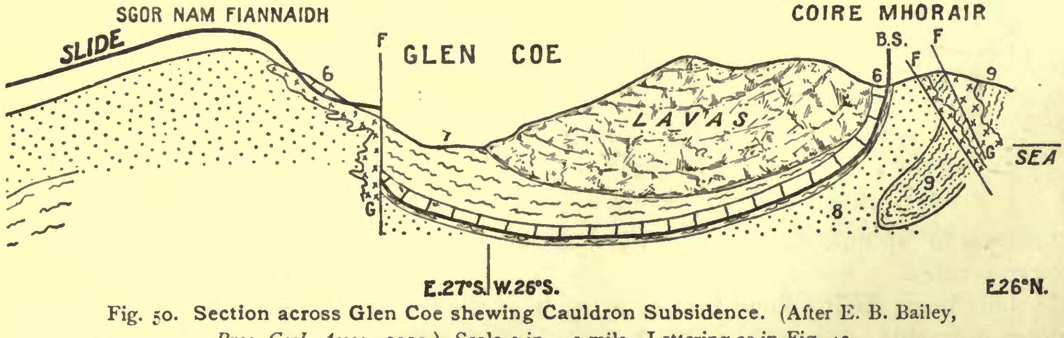
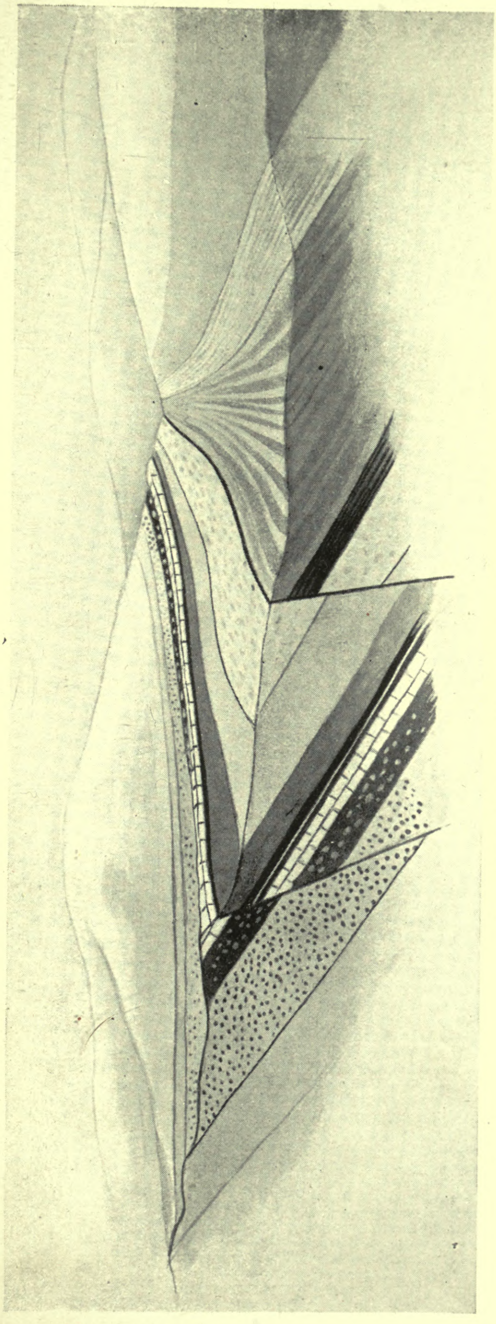


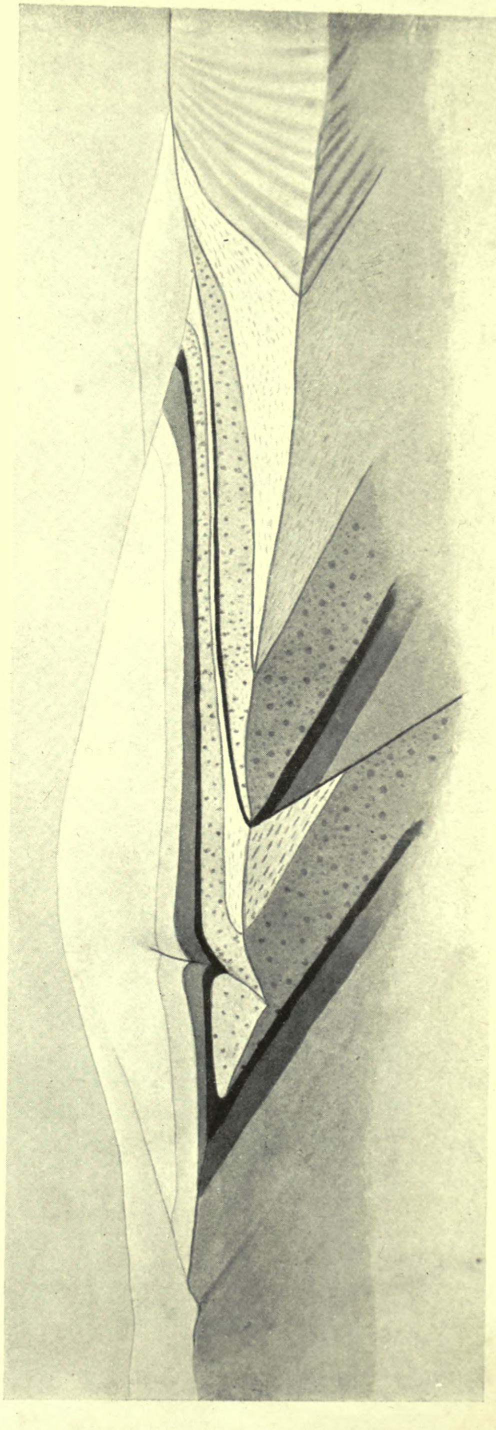
Fig. 50. **Section across Glen Coe shewing Cauldron Subsidence.** (After E. B. Bailey, *Proc. Geol. Assoc.*, 1911.) Scale 1 in. = 1 mile. Lettering as in Fig. 42.

[1] Maufe, *Mem. Geol. Survey: The Geology of Ben Nevis and Glen Coe*, pp. 107, 128.

PLATE VI

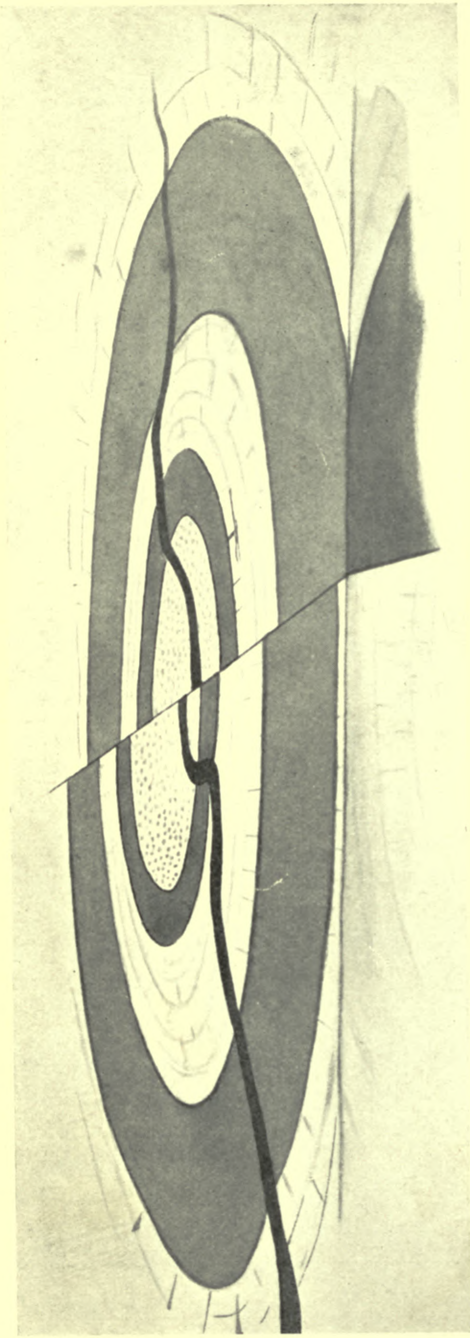


A. Concealment of Outcrop by Normal Faulting.

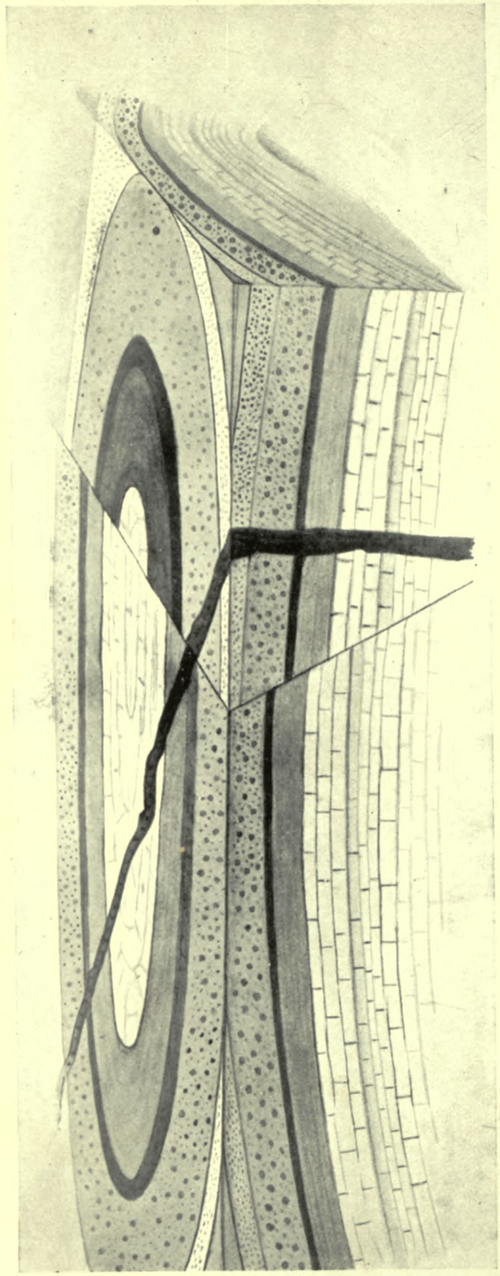


B. Repetition of Outcrop by Reversed Faulting.

PLATE VII



A



B

Effect of a Tear Fault (A) compared with that of a Normal Fault (B).

In faults of this type, a portion of the earth's crust appears to have collapsed bodily into the interior in what are known as Cauldron Subsidences.

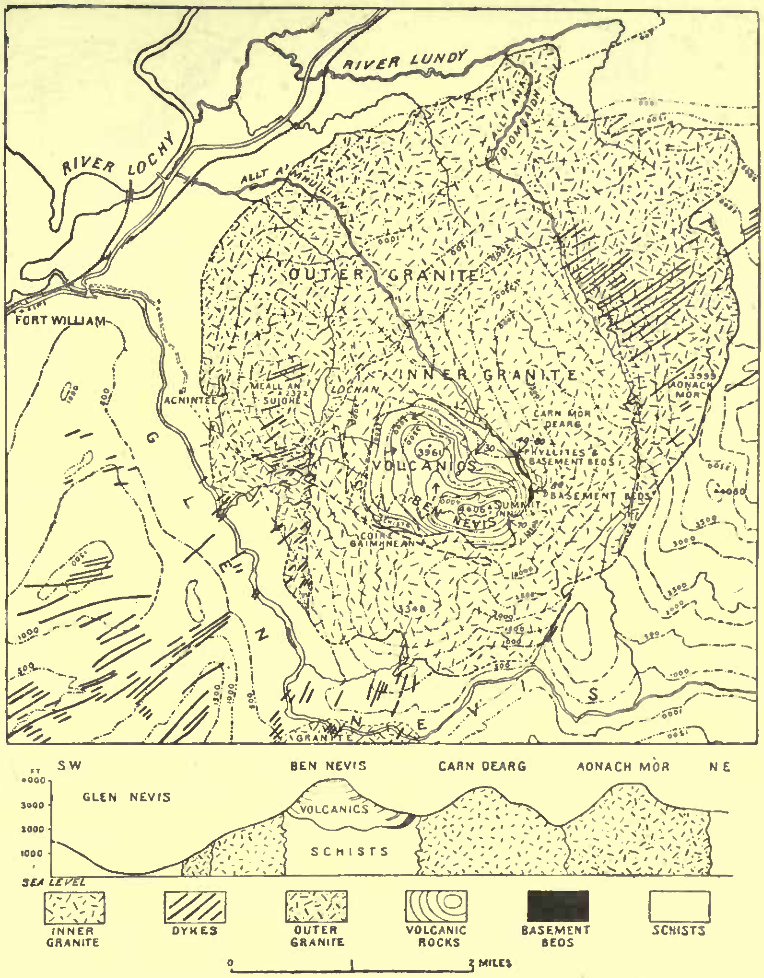


Fig. 51. Geological Map and Section of the Cauldron Subsidence of Ben Nevis. (From the *Memoirs of the Scottish Geological Survey.*)

Compressional Faults.

a. Reversed Faults. Reversed faults, in sharp contrast with normal faults, are those which occur where there has been compression, and space has been saved, the fault plane therefore, *hades or dips in the direction of the upthrow*, i.e. *in the direction of the older beds.*

In inclined beds the effect of such faulting is the concealment of beds[1] (Fig. 53), *unless the dip of the fault plane is in the same direction as that of the beds and at a higher angle*, when repetition occurs. (Pl. VI.)

There are reversed faults of every degree; in some the fault plane is inclined at a high angle, and a rapid succession of such faults developed over a limited area would

[1] Watts, *loc. cit.*

seem to take the place of isoclinal folding in rocks of such a nature that they break

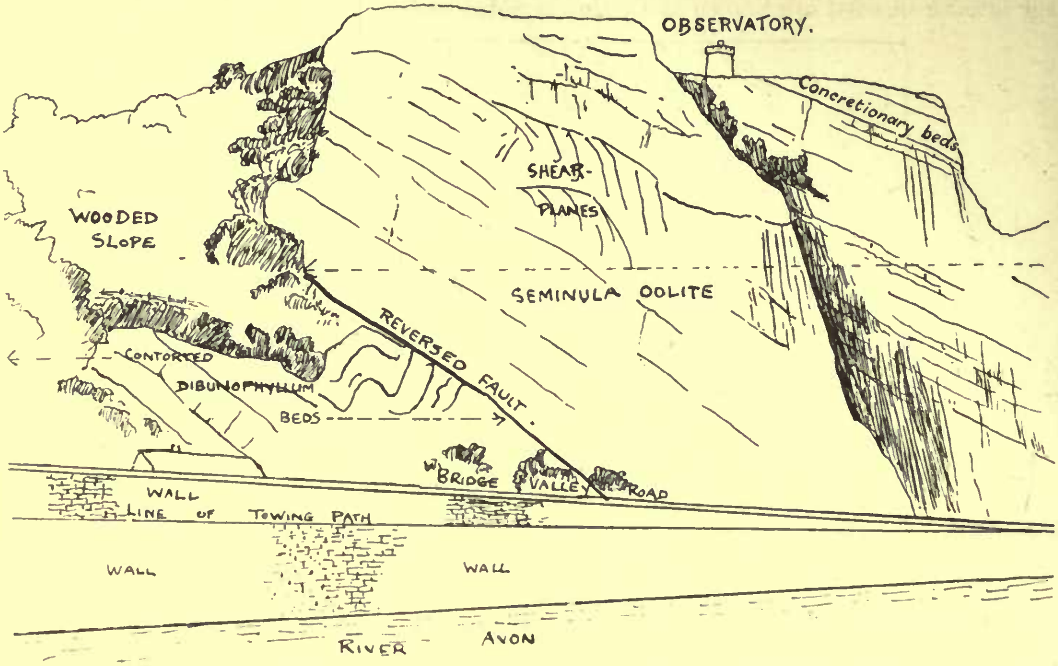


Fig. 52. River Avon. Sketch of section on the right bank of the Avon below the Observatory to shew the Reversed Fault which brings the Seminula beds over the newer Dibunophyllum beds. (Taken from a photograph by S. H. Reynolds in *Proc. Bristol Nat. Soc.* 1906.)

without preliminary folding. The structure thus produced is the well-known *imbricate structure* (Fig. 54) commonly developed in advance of the great lines of disruption[1] in the N.W. Highlands of Scotland. In each case the fault planes dip at a high angle towards the quarter from which the tangential stress has acted. In other reversed faults the dip of the fault plane is very low, and there has frequently been considerable compressional movement along it, so that these planes of dislocation constitute veritable *thrust planes*, along which the strata may have been thrust for many miles. As respects their *effects* there is little or nothing to distinguish them from the fold-faults or slides referred to in connection with folding movements, but as regards their *origin* they appear to have been produced without any preliminary folding, a different resistance to stress on the part of the rocks being implied. Thrust planes occur mainly, as a rule, in the direction of the strike of the rocks.

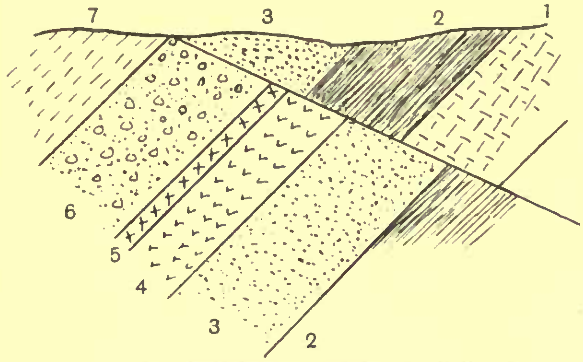


Fig. 53. Reversed Fault concealing beds 4—6.

[1] Survey Memoir on N.W. Highlands.

b. Reversed faults may also occur in the direction of dip, and their effect is perhaps best seen in the case of small anticlines and synclines where, in contrast with the effect produced by pure normal faulting, there will tend to be an alternation of the outcrops along

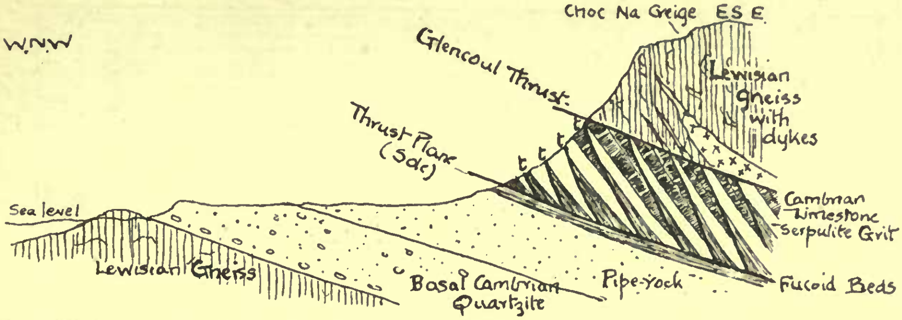


Fig. 54. Section from south shore of Loch Glencoul to Cnoc na Creige shewing Imbricate Structure. (From *Memoirs of Geological Survey*.)

the line of the fault plane as a result of the tangential movement, though should this be combined with some vertical movement, the outcrops in an anticline thus affected will still be closer together on the downthrow side, and those of a syncline further apart.

c. Tears or Flaws. Tear faults are dip faults in which the movement is almost entirely horizontal and the result of tangential strain acting unequally upon different parts of the same rock mass. It is easily seen that the effect of this upon the outcrop of the beds differs from that produced by a movement that is mainly vertical. Tear faults displace all the rocks affected *to the same extent independently of the dip*, whereas in the case of normal faulting the beds are shifted to a degree depending entirely upon their angle of dip; thus in the case of normal faults vertical beds such as dykes, or approximately vertical sediments are scarcely affected at all as the result of the faulting, whereas beds with a low dip will appear to be shifted considerably—in the case of such beds affected by a tear fault all the beds, including the dyke, would appear shifted by the same amount. Good examples of such tear faults are seen in the Geological Survey Map, England and Wales, 1-inch sheet, 98 N.W., where the outcrops of all the Lower Palaeozoic rocks are affected by them. This is especially well shewn at the junction of the Borrowdales with the Coniston limestone series, and the junction of the Bannisdale slates with the Coniston grits and flags.

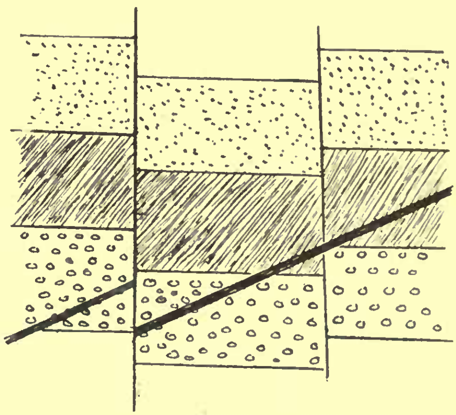


Fig. 55.

Thrust Planes and Unconformities. Unless the relative ages of the beds be known, there may be little on a map to distinguish between an *Overthrust* and an *Unconformity*; if the ages of the bed are known, however, a clue may be given, for by thrusting older beds are frequently placed above newer[1]. Moreover the thrust plane often has an

[1] For exception see Pl. VI, and p. 55.

uneven edge, with wisps of rocks of different ages caught up along it, whilst in the case of an unconformity the edge is usually even, and the rocks always newer than those upon which they lie.

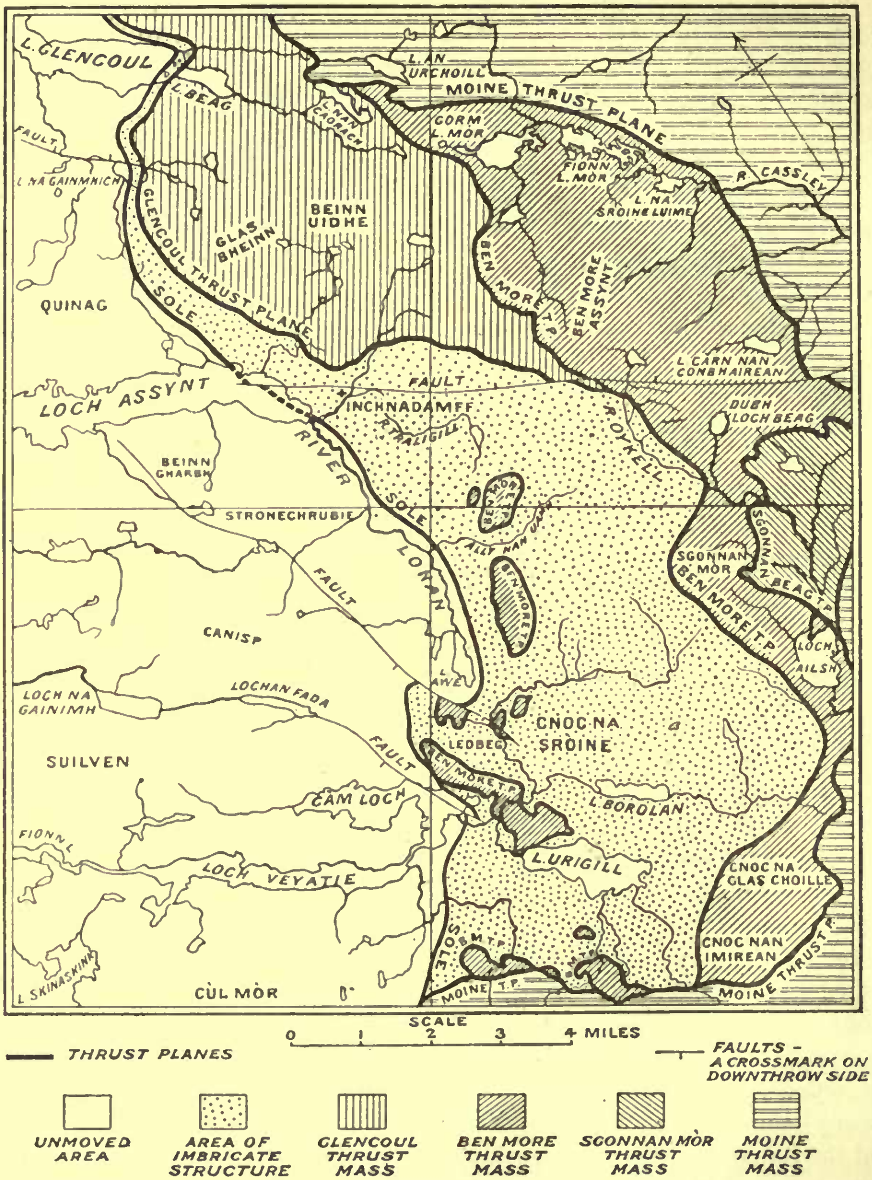


Fig. 56.
(From the *Guide to the Geological Model of the Assynt Mountains.*)

Assynt Country. A map of the Assynt country in the N.W. Highlands (Fig. 56) shews clearly the effects of earth movements of great magnitude and the way that these appear on a geological map. These structures are shewn in the area termed by Messrs Peach and Horne the Belt of Complication; here is seen the sole or incipient thrust plane which limits the belt of complication to the west, while beyond it lie undisturbed Cambrian and Pre-Cambrian strata, and to the east of it lie the three great thrust planes of the region.

In the N. of the area all three are visible in turn from W. to E., namely the Glencoul thrust, the Ben More thrust, and the Moine thrust.

Further S., due E. of Inchnadamff, the Glencoul thrust plane is overlapped by the Ben More thrust plane, so that only two are visible ; in the extreme S. the great overlap of the Moine thrust plane is shewn concealing everything beneath and bringing the Moine thrust mass right over on to undisturbed Cambrian rocks.

The " Klippen " of the Ben More thrust are also seen in the various isolated thrust masses bounded entirely by thrust planes, such as that N. and W. of Loch Urigill, and the masses of Beinn an Fhuarain and Beinn nan Cnaimhseag, S. and N. of the Allt nan Uamh. These last two consist mainly of Torridon sandstone and quartzite, with some gneiss ; the relationships of these are not shewn on the map here figured, but can easily be made out on the 1-inch Survey Maps 101 and 107 (new series, Scotland).

Between the Ben More thrust and the Moine thrust there is a subsidiary line of movement known as the Sgonnan Beag thrust plane.

Additional details can be gathered by further study of the 1-inch maps ; imbricate structure is highly characteristic of the area lying between the great thrusts and the undisturbed country to the west; it is especially well shewn in the area on the north and south shores of Loch Glencoul, the north shore of Loch Assynt, and all round about Inchnadamff. Sometimes these piled-up masses rest upon a well-defined sole in advance of the major thrusts.

In general it may be noted that the different major thrusts are characterised by the nature of the rock burden that they carry ; thus the Glencoul thrust brings forward the Lewisian gneiss, with the Cambrian resting unconformably upon it, the Torridonian being absent. Above the Ben More thrust, however, the Lewisian gneiss is found covered unconformably by the Torridonian, with the double unconformity of the Cambrian quartzites upon the Lewisian gneiss and Torridonian strata. The great Moine thrust bears highly crystalline schists. The minor thrust of Sgonnan Beag bounds a sheet of syenite.

Indication of Faults upon Maps. Faults are indicated upon maps of the Geological Survey by white or blue lines and the direction of downthrow indicated by a special symbol (see p. 68). In black and white maps, they are usually shewn by thick black lines. In the absence of any special indication, the faulted boundary may have to be inferred (it may be hidden under an alluvial tract, or otherwise concealed) from an abrupt change in the dip or the strike of the beds, from the absence of certain strata known to be present close by, or from the abrupt termination of a well-defined lithological band. Caution must, however, be observed in this respect in the case of igneous rocks which may really come to a more or less abrupt end without any faulting at all.

Having then realised that the ground is faulted, it is advisable to determine, if possible, the direction and amount of the throw and the inclination of the fault plane.

Faults are too often indicated upon maps by perfectly straight lines. Very little consideration suffices to shew that this in many cases is probably incorrect; for the trace of the fault is a plane, and it must be affected by the relief of the ground every whit as much as the traces of the outcrop of a bed, and it is only correctly represented as a straight line when its dip approximates to the vertical, which is certainly not always the case. In order to determine the dip of the fault plane, it is sometimes necessary only that it should cut the same contour twice, and another contour once, and it may then be plotted in precisely the same way as was done in the case of finding the dip of strata, provided that the fault is a plane and not a curved surface. If this cannot be done accurately the general hade or dip may be inferred by studying the trend of the fault in relation to the run of the contour lines. If it follows the trend of the hills and runs up the valleys a low dip may be safely inferred, whilst if it run across country independently of all contour lines its inclination must be high, and at the same time the general direction of inclination of the fault plane can be made out.

The *throw*, however, is rather more difficult of determination. This, as has been already stated, is the amount of displacement measured vertically, but it must be borne in mind that the throw of a fault is by no means constant along its length—it may on the contrary throw first in one direction and then in another, alternating as it were from side to side,

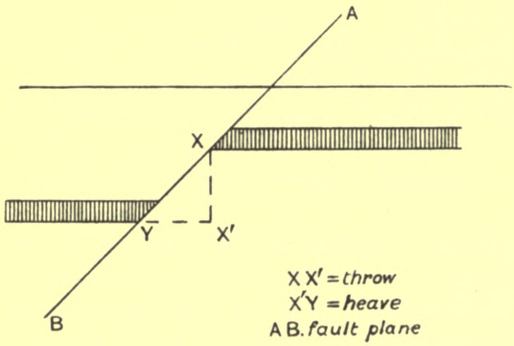


Fig. 57.
Measurement of Throw in horizontal beds.

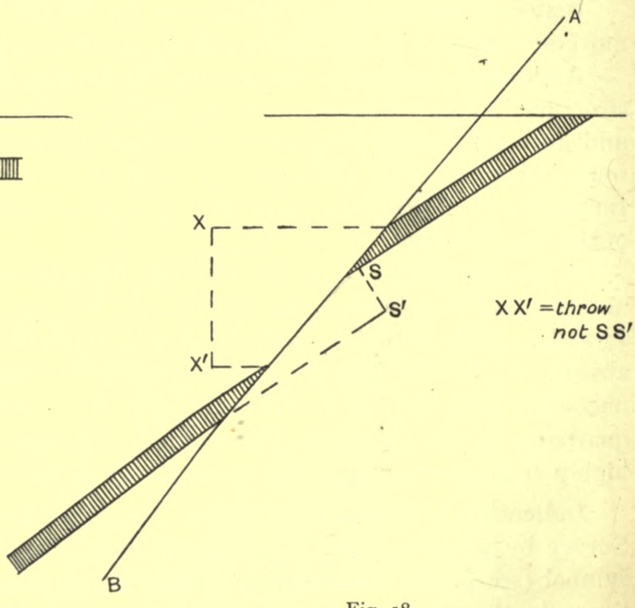


Fig. 58.
Measurement of Throw in inclined beds.

and the amount of throw is almost certain to change along its course, and will in all likelihood disappear altogether in some point. The throw of a fault combined with the inclination of the fault plane, and the dip of the beds, usually results, after denudation, in a considerable amount of horizontal or lateral displacement of the affected beds; if, however, the dip is nearly vertical, practically no lateral movement takes place. This amount of shift is often important in mining operations as determining the amount of ground to be worked through or left before the valuable seam or bed is found again. This horizontal displacement is known as the *heave* of the fault. (See Fig. 57.)

As a general rule, unless there are other indications to the contrary, the plane of the fault dips in the direction of the downthrow, that is in the direction of the newer beds. (Normal faults.)

If the beds be horizontal, or the fault plane vertical, the throw is easily determined in a true scale section.

In other cases the amount of throw will be affected by both the dip of the fault plane and the dip of the strata. (Fig. 58.)

If the fault runs accurately in the direction of dip of the beds, the dip of the fault plane will have little or no effect, and the accompanying diagram shews how the throw may be estimated. (Fig. 59.)

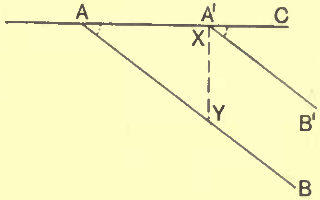


Fig. 59.

Let the angle BAC represent the dip of the bed, mark off the horizontal distance AX equal to the horizontal displacement observed, and make an angle at X to represent the dip of the displaced bed $CA'B'$; the distance XY is the throw of the fault, the section being drawn to scale.

If the fault plane cut obliquely across the strata a similar method can be employed, but apparent and not true dips must be used. (See p. 34.)

If, however, the amount of stratigraphic throw be known, that is if a second bed which from other evidence is known to be a certain distance below or above the first bed is brought by the fault up against it, the following method may be used. (Fig. 60.)

Make an angle BAC to represent the angle of dip of the fault plane, let YX represent the bed dipping in the direction indicated and meeting AC in X; from X draw a perpendicular XZ equal to the amount of the stratigraphic throw, and through Z draw a line ZZ' parallel to XY, representing the shifted bed, meeting AC in Z'. Through Z' draw a horizontal line $Z'X'$ and let a perpendicular from X fall upon it. XX' will represent the throw of the fault, and it differs from the stratigraphic throw by a certain amount due to the inclination of the fault plane.

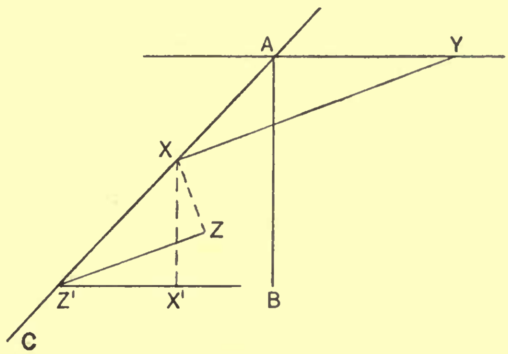


Fig. 60.

Age of Faults. The age of faults is not easy of determination, the most that can sometimes be said is that they are newer than the rocks they affect. In certain cases, however, more accurate information can be made out from a map since a fault may be concealed by newer beds which are unaffected by any such disturbance; the fault is then obviously older than such rocks. A second fault may affect an earlier one also, giving some clue as to relative age, if nothing more.

CHAPTER VII

IGNEOUS ROCKS, METAMORPHIC ROCKS AND MINERAL LODES

In the foregoing chapters the characteristics of the outcrops of sedimentary rocks have been dealt with in some detail; there yet remain to be considered the indications upon maps of Igneous and Metamorphic rocks, and also Mineral Lodes.

Igneous Rocks. Contemporaneous igneous rocks such as Lava flows, Ashes, Tuffs and Agglomerates differ but little from their sedimentary associates as regards their appearance on a map, though as a rule they tend to die out rather more abruptly; in the case of surface flows there may be a conspicuous and rapid thickening towards a centre of eruption, though this is not observable in the case of fissure eruptions when a great area may be covered with a flow of considerable degree of uniformity in thickness and the fissure from which it came may be entirely concealed.

The case of intrusions, however, is somewhat different, and as might be expected their distribution in any area and hence on a map is usually more or less intimately related to the geological structure of such an area. Thus for example the large cake-like granite batholiths of Devon and Cornwall are clearly related in their distribution to the different axes of folding of that area[1].

In ground plan laccoliths may shew an approximation to a circular form, though there is frequently an elongation in the direction of the strike of the invaded rocks, and as a rule unless denudation has proceeded too far, the invaded strata will dip away from the laccolith in all directions. This dip, if shewing, distinguishes the laccolith from the batholith, though in many respects there is no hard and fast line to be drawn between them and it is not always easy to distinguish between them on a map.

Phacoliths, on the other hand, are found in folded strata and are not to be regarded as the *cause*, but the *consequence*, of the folding. They are lenticular masses of rock that tend to occur at the crests of anticlines and the depths of synclines, and their relation to the folds should be fairly easy of detection.

Less obviously related to structure are the Sills; these having a great horizontal extension though often thin, run with the bedding for a shorter or longer distance, but shew a marked tendency to change their horizon sooner or later, and will usually therefore be recognised by this fact, that they will be found at different places on the map at varying distances from the summit or base of any formation.

The behaviour of an intrusive sill is well seen in the Survey Map 102 S.E.[2] In this map the relation of the Great Whin Sill to the different members of the Carboniferous Limestone series is excellently shewn.

Along the edge of the Cross Fell escarpment on the west, the outcrop of the great sill

[1] Geol. Survey of England and Wales, Index-Map, Sheets 21, 22, 25.

[2] Geol. Survey of England and Wales. 1 inch to a mile. Sheet 102 S.E. (old series) or 31 (new series).

is seen with its tendency to run parallel to the bedding, but instead of maintaining a constant horizon, it persistently changes its position in the series; sometimes it lies in the Melmerby Scar Limestone, while at High Cup Nick it gets well up into the Tyne Bottom Limestone. In the upper portion of Teesdale and the valley of Maize Beck it has a wide horizontal spread shewing its sheet-like nature. It is thrown down to the east by the Burtree fault and its outcrop is shifted horizontally by a tear fault two miles further to the east.

Dykes, on the other hand, are often conspicuously related to the structure lines, being merely wall-like masses of rock: they tend to run across country in all directions in more or less straight lines, but these lines are often significant in their trend, as is clearly seen in the distribution of the dykes of the Old Red Sandstone age in the Lorne country of Western Scotland, where they clearly indicate a direction of tensional stress over a wide area (Fig. 61)[1]. Another significant direction is that of the N.W. trend displayed by the pre-Torridonian dykes in the N.W. of Scotland[2].

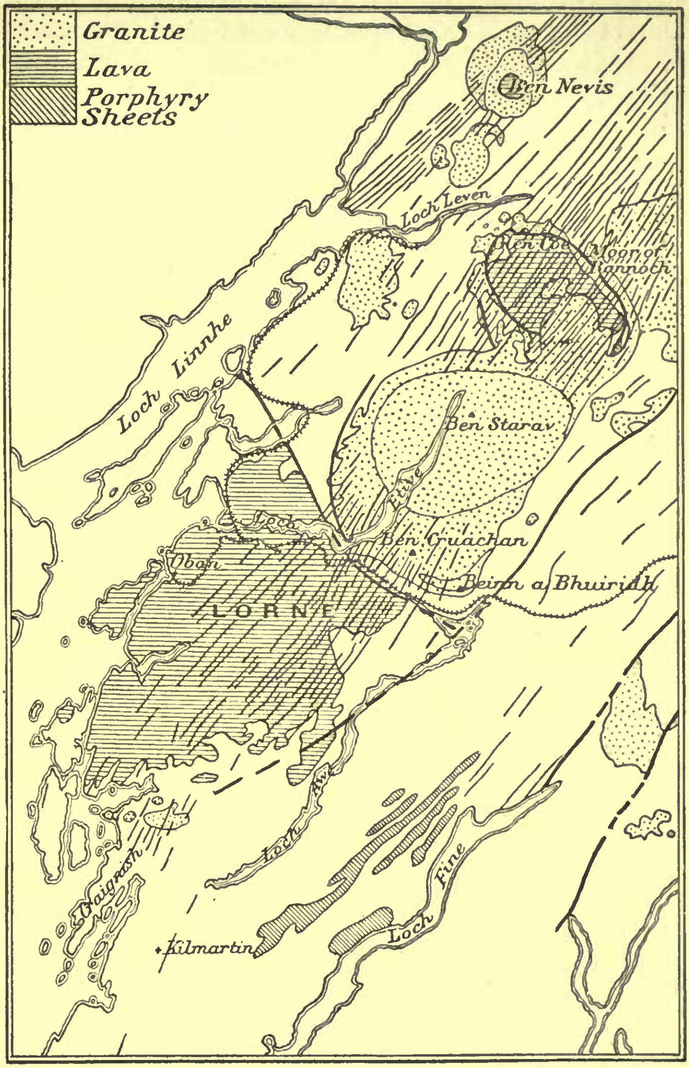


Fig. 61. Sketch Map of Volcanic District of Argyllshire and Inverness-shire, shewing Distribution of Dykes in relation to the Etive and Nevis Granite complexes. Dykes shewn by Light, and Faults by Heavy, Black Lines. (From the *Memoirs of the Scottish Geological Survey.*)

Volcanic necks usually have a more or less circular or elliptical outcrop and are filled with lava, volcanic tuff or agglomerate, and these together with the surrounding strata frequently shew a dip towards the centre of the vent.

Good examples of such necks are to be seen in the maps of E. Fifeshire (see Fig. 62),

[1] Map, p. 90, *Mem. Geol. Survey: The Geology of Ben Nevis and Glen Coe.*

[2] Geol. Survey of Scotland. 1 inch to a mile. Sheet 107.

such for example as Map 41 Scotland (new series), or the index-map attached to the Geological Survey memoir on E. Fife. Here in the Elie district there are numerous volcanic necks of characteristic form lying in the Carboniferous rocks, though in some cases their complete outline is not seen, since it lies beneath the waters of the Firth, or

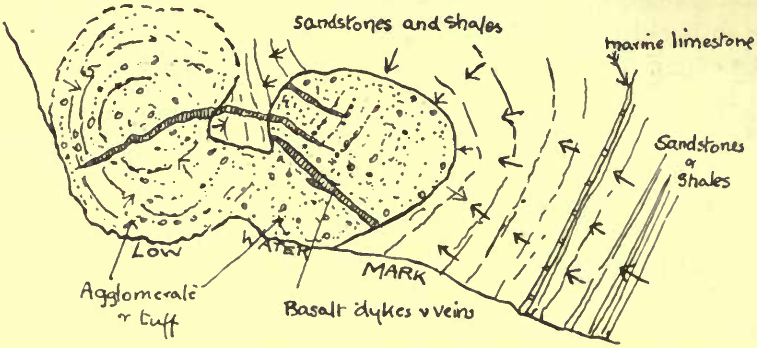


Fig. 62. Ground Plan of two Volcanic Necks at Elie Harbour (Fife).
(From *Memoirs of the Scottish Geological Survey.*)

else is concealed by superficial deposits. The most conspicuous of these necks are those of Largo Law, Kellie Law, Kincraig Hill, and the Boghall Burn, while at Elie Ness the neck is only partially visible since its outcrop is concealed by beach deposits and also by the sea; at Elie Harbour an interesting double neck may be noted (Fig. 62).

Determination of the Age of Igneous Rocks. From the facts shewn upon a map it is not always possible to determine the exact age of all the igneous rocks shewn, especially is this the case in dealing with intrusive rocks; often it is only possible to state that the intrusive rocks are later than the rocks into which they are intruded, but how much later it is not possible to determine. There may occasionally however be indirect evidence of age, such for example as that the intrusion is affected by faulting which does not affect other rocks of known age. In such a case the intrusion is clearly older than the fault, which must itself be older than the beds which are unaffected by it; there may sometimes also be presumptive evidence in favour of a dyke being of about the same age as lines of faulting with similar trend; in fact it may run along a line of fissure or faulting, and should it be possible anywhere on the map to determine the age of the faults, there would be a fair amount of probability in connecting the dyke with the same story.

Lava flows interbedded in strata whose age is known must naturally be of the same age as the strata in which they lie.

Metamorphic Rocks. In metamorphic rocks the structural planes which are indicated upon the map are not those of bedding, but cleavage, or foliation, since all the original structures may be more or less completely obliterated. These structures are indicated by an arrow of special form, which is conspicuously different in character from that which indicates the ordinary dip of rocks.

Mineral Veins and Lodes. Mineral veins and lodes are shewn on the maps of the Geological Survey by gold lines, the nature of the metalliferous material being indicated by a special symbol (see list, p. 68). Like dykes, mineral lodes frequently fill fault lines, cracks or fissures in the country rock, and often have a definite trend connected with earth movements which have been responsible for the production of any folding, faulting or cleavage of which the beds may give indication; in many cases however they are clearly connected with the very latest adjustments of the rocks, what may be termed the final settling movements, and as such are apt to be somewhat more irregular in their trend than those which belong to a definite period of folding and faulting. It is of fairly common occurrence to find lodes that lie parallel to the bedding of the rocks, coincident lodes, and a second set, termed transverse lodes, lying in faults or cracks across the bedding. At other times wholesale shattering of the country rocks may give rise to complex lodes trending in all sorts of irregular directions.

Harker has dealt with the solution of some practical problems affecting lodes, and some of these are given below.

Given hades of two lodes in direction and amount, to find the direction and line of their intersection.

(The two lodes are not supposed to strike in parallel directions.)

Let *OP* and *OQ* represent the respective hades, then *OM* drawn perpendicular to *PQ* will represent in direction and amount the angle of inclination of the line of intersection. In this case the cotangent scale must be employed, but for the *result* the tangent scale.

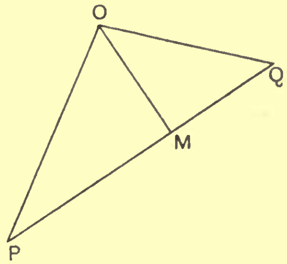


Fig. 63.

A vertical shaft is sunk at a given spot, to find the depth at which it will strike a lode, the position and hade of which are known. The ratio of the depth to the known distance of the shaft from the outcrop of the lode is the cotangent of the hade.

A vertical shaft is sunk at a given spot: find at what depth it will strike the intersection of two known lodes.

The shaft is supposed to be sunk at some point on the line of intersection which can be determined if unknown (see problem above). The distance of the shaft from the point in which the lines of outcrop (produced if necessary) intersect is known. The ratio of the required depth to this distance is the tangent of the angle of inclination of the line of intersection as determined.

This ratio is therefore found as above.

To find the position and depth of intersection of two lodes with parallel strike.

Take *OC* = breadth of protractor and on line at right angles to it lay off *OP*, *OQ* for the hades of two lodes, using the cotangent scale. A diagram is thus obtained drawn to scale representing lodes *PC*, *QC* and the depth of their intersection *OC*, with position of *O* relatively to outcrops at *P* and *Q*. Distance *PQ* between the outcrops being supposed known, the other particulars can be determined by measurement.

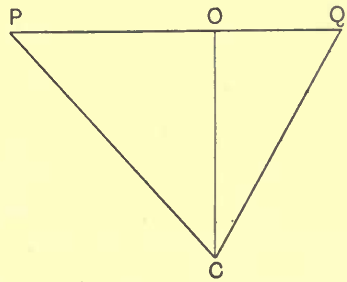


Fig. 64.

CHAPTER VIII

THE INTERPRETATION OF GEOLOGICAL MAPS

The maps issued by the Geological Survey are classed under two heads, as Solid or Drift maps. In the *Drift maps* all superficial accumulations are shewn: thus the map is a faithful representation of what is actually seen and reveals how much of any area is occupied by surface deposits and exactly where the solid rock projects through its superficial cover. This is the map that is of most use to the agriculturalist.

In the so-called *Solid maps*, on the other hand, only the solid rocks are shewn except that the alluvium of rivers is always indicated; each map suggests the extent and nature of the solid rocks if all the surface deposits other than alluvium were removed. In some districts where there are little or no surface accumulations, the difference in the two maps will be hardly noticeable, but in many of the British upland regions where there is a considerable amount of glacial deposits the two maps present widely different appearances. Take for example Sheet 98 N.E. (old series); in the Solid map the outcrops of the various beds are continuous across country except where they are faulted or concealed beneath river alluvium.

In the Drift map, on the other hand, the outcrops of the beds are by no means continuous, being interrupted in many places by glacial drift which occupies all the low ground, and extends far up the hill-sides; note for instance how little of the Basement Conglomerate is really visible at the surface, and how little is actually seen of the shale 'd,' whilst the outcrop of the Bannisdale Slates on the north side of Langdale Fell is very patchy indeed. In some cases it is possible to see that the streams have cut down to the solid rock again in the lower part of their course, whilst they still run over drift in the upper part.

In the interpretation of the geological map of any area, it will be realised from what has already been said that the study of the topography is all-important, and must be the first thing considered by the student; and any interesting facts as regards Physical Geology that may be deduced should be noted. The order of the beds should then be made out, by carefully noticing the dips, when given, or the relation of the traces of the outcrop to the contour lines[1]. In the course of such investigation the main structural features will probably become evident, such as the presence of unconformities, indications of overlap, the existence of folds and their nature, whether simple anticlines, synclines, isoclines, or overfolds; the age of the folding must be made out. If there is any indication of faulting it must be studied carefully, and various facts about the faulting determined, such as the amount of throw, the direction of throw, the dip of the fault plane, and the evidence of the time at which the faulting took place. Then the igneous rocks must be studied, their nature determined, and their age decided so far as possible. These various

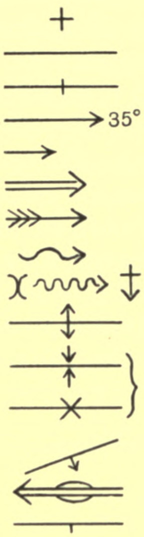
[1] In many cases definite symbols are employed to indicate special facts and these should be noted (see list of symbols, p. 68).

matters having received attention, sections may be drawn across the map, not in any haphazard direction, but with a definite aim in view—that of bringing out the important features in the area shewn, and the structural characters previously noted. It may be possible in some cases to illustrate all the important points in one section, whilst in another case several sections will be required. All sections should be drawn as far as possible to true scale (same horizontal and vertical scale); but should it be necessary to exaggerate the vertical scale in order to bring out some point of special importance, the amount of such exaggeration should be noted in terms of the horizontal scale. This should be avoided, if possible, for in such sections all dips are correspondingly exaggerated[1].

Lastly there is the full account of the geology of the district to be written up, as illustrated by the sections; the beds should be dealt with in definite order, either from top to bottom or else from bottom to top, and all the peculiarities of the outcrop of each should be noted and accounted for, such as the disappearance of a bed by unconformity or by overlap or by merely thinning out, its breadth at various points on the map, or the existence of outliers and what they denote—in fact, any features which are of importance from a geological point of view. Having done this for each of the beds in turn and for the igneous rocks also, the geological history of the area, that is to say the general sequence of events in the district, can be summarised, and the story of the map is complete.

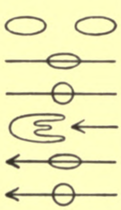
[1] In drawing sections across the ordinary 1-inch Geological Survey maps some exaggeration is unavoidable or little could be shewn, but it should be kept as low as possible.

SYMBOLS ON MAPS



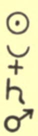
Horizontal beds.
Vertical beds.
" "
Dip at point of arrow } from observation.
Shorter arrow, higher dip } from observation.
Foliation } from observation.
Dip from information, mines etc.
No constant direction of dip, undulated.
Contorted beds.
Anticline.
Syncline.
Cleavage.
Direction of stretch of particles in foliated rock.
Throw of fault (downthrow in direction of vertical line).

Glacial Symbols :



Roches moutonnées } direction of flow not apparent.
Striated surface } direction of flow not apparent.
" flat surface } direction of flow not apparent.
Roches moutonnées } direction of flow apparent.
Striated surface } direction of flow apparent.
" flat surface } direction of flow apparent.

Minerals :



Gold. Copper. Lead. Iron.

Silver. Tin. Manganese. Zinc.

Natural Sines, Cosines, Tangents, and Cotangents.

°	Sine	Tangent	Cosine	Cotangent	°
1	·0175	·0175	·9999	57·2900	89
2	·0349	·0349	·9994	28·6363	88
3	·0523	·0524	·9986	19·0811	87
4	·0698	·0699	·9976	14·3007	86
5	·0872	·0875	·9962	11·4301	85
6	·1045	·1051	·9945	9·5144	84
7	·1219	·1228	·9926	8·1444	83
8	·1392	·1405	·9903	7·1154	82
9	·1564	·1584	·9877	6·3138	81
10	·1737	·1763	·9848	5·6713	80
11	·1908	·1944	·9816	5·1446	79
12	·2079	·2126	·9782	4·7046	78
13	·2250	·2309	·9744	4·3315	77
14	·2419	·2493	·9703	4·0108	76
15	·2588	·2680	·9659	3·7321	75
16	·2756	·2868	·9613	3·4874	74
17	·2924	·3057	·9563	3·2709	73
18	·3090	·3249	·9511	3·0777	72
19	·3256	·3443	·9455	2·9042	71
20	·3420	·3640	·9397	2·7475	70
21	·3584	·3839	·9336	2·6051	69
22	·3746	·4040	·9272	2·4751	68
23	·3907	·4245	·9205	2·3559	67
24	·4067	·4452	·9136	2·2460	66
25	·4226	·4663	·9063	2·1445	65
26	·4384	·4877	·8988	2·0503	64
27	·4540	·5095	·8910	1·9626	63
28	·4695	·5317	·8830	1·8807	62
29	·4848	·5543	·8746	1·8041	61
30	·5000	·5774	·8660	1·7321	60
31	·5150	·6009	·8572	1·6643	59
32	·5300	·6249	·8480	1·6003	58
33	·5446	·6494	·8387	1·5399	57
34	·5592	·6745	·8290	1·4826	56
35	·5736	·7002	·8192	1·4282	55
36	·5878	·7265	·8090	1·3764	54
37	·6018	·7536	·7986	1·3270	53
38	·6157	·7813	·7880	1·2799	52
39	·6293	·8098	·7772	1·2349	51
40	·6428	·8391	·7660	1·1918	50
41	·6560	·8693	·7547	1·1504	49
42	·6691	·9004	·7431	1·1106	48
43	·6820	·9325	·7314	1·0724	47
44	·6947	·9657	·7193	1·0355	46
45	·7071	1·0000	·7071	1·0000	45
°	Cosine	Cotangent	Sine	Tangent	°

Depth to Stratum below Horizontal Surface for various Distances and Dips. (After Hayes.)

Dip angle, degrees	Feet						¼ mile 1320 ft.	½ mile 2640 ft.	¾ mile 3960 ft.	1 mile 5280 ft.
	100	200	300	400	500	1000				
1	1·75	3·50	5·25	7·00	8·75	17·5	23·04	46·08	69·12	92·16
2	3·49	6·98	10·47	13·96	17·45	39·4	46·09	92·18	138·3	184·4
3	5·24	10·48	15·72	20·96	26·20	52·4	69·18	138·4	207·5	276·7
4	6·99	13·98	20·97	27·96	34·95	69·9	92·30	184·6	276·9	369·2
5	8·75	17·50	26·25	35·00	43·75	87·5	115·5	230·5	346·8	461·9
6	10·51	21·02	31·53	42·04	52·55	105·1	138·7	277·4	416·1	555·0
7	12·28	24·56	36·84	49·12	61·40	122·8	162·1	324·2	486·3	448·3
8	14·05	28·10	42·15	56·20	70·20	140·5	185·5	371·0	556·5	742·0
9	15·84	31·68	47·52	63·36	79·20	158·4	209·1	418·2	627·3	836·3
10	17·63	35·26	52·89	70·52	88·15	176·3	232·8	465·6	698·4	931·0
11	19·44	38·88	58·32	77·76	97·20	194·4	256·6	513·2	769·8	1026
12	21·26	42·52	63·78	85·04	106·30	212·6	280·6	561·2	841·8	1123
13	23·09	46·18	69·27	92·36	115·45	230·9	304·7	609·4	914·1	1219
14	24·93	49·86	74·79	99·72	124·65	249·3	329·1	658·2	987·3	1316
15	26·80	53·60	80·40	107·20	134·00	268·0	353·7	707·4	1060	1415
16	28·68	57·36	86·04	114·72	143·40	286·8	378·5	757·0	1136	1514
17	30·57	61·14	91·71	122·28	152·85	305·7	403·6	807·2	1211	1614
18	32·49	64·98	97·47	129·96	162·45	324·9	428·9	857·8	1287	1716
19	34·43	68·86	103·29	137·72	172·15	344·3	454·3	908·6	1363	1817
20	36·40	72·80	109·20	145·60	182·00	364·0	480·4	960·8	1411	1923
21	38·39	76·78	115·17	153·56	191·95	383·9	506·7	1012	1520	2027
22	40·40	80·80	121·20	161·60	202·00	404·0	533·3	1067	1600	2133
23	42·45	84·90	127·35	169·80	212·25	424·8	560·3	1121	1681	2241
24	44·52	89·04	133·56	178·08	222·60	455·2	587·7	1175	1763	2351
25	46·63	93·26	139·89	186·52	233·15	466·3	615·5	1231	1847	2462
26	48·77	97·54	146·31	195·08	243·85	487·7	643·7	1287	1931	2575
27	50·95	101·90	152·85	203·80	254·75	509·5	672·6	1345	2018	2690
28	53·17	106·34	159·51	212·68	265·85	531·7	701·8	1404	2105	2807
29	55·43	110·86	166·29	221·72	277·15	554·3	731·7	1463	2195	2927
30	57·74	115·48	173·22	230·96	288·70	577·4	762·1	1524	2286	3048

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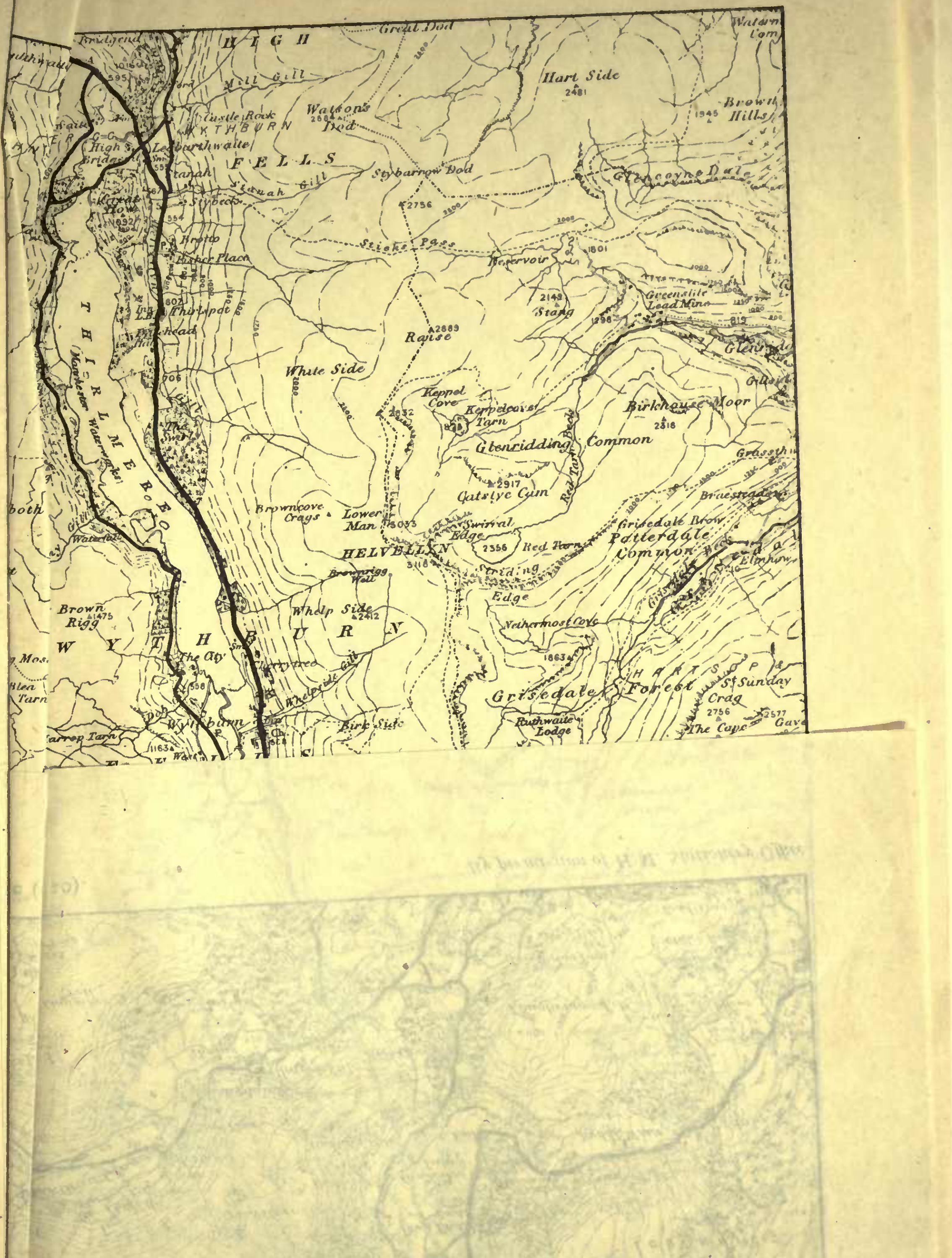

Bridgend
H I G H
Great Dod
Mill Gill
Hart Side
2481
Castle Rock
Watson's Dod
High Bridge
Legburthwaite
F E L L S
Browth Hills
1945
Stybarrow Dod
Glencoyne Dale
Stanah
Stanah Gill
Great How
Stybeck
2756
Sticks Pass
Reservoir
1801
Fisher Place
Greenside Lead Mine
2148
Stang
Thirlspot
Raise
2889
White Side
T H I R L M E R E
Keppel Cove
Keppelcove Tarn
Birkhouse Moor
2318
Glenridding Common
Red Tarn Beck
2917
Catstye Cam
Brownrigg Well
Browncove Crags
Lower Man
3033
Swirral Edge
HELVELLYN
3118
Red Tarn
2356
Striding Edge
Grisedale Brow
Patterdale Common
Brown Rigg
1475
Whelp Side
2412
W Y T H B U R N
Nethermost Cove
1863
The City
Grisedale
Forest
St Sunday Crag
2756
The Cape
Ruthwaite Lodge
Birk Side
Wythburn
Harrop Tarn
Blea Tarn
1163