Structural Geology

An Introduction to Geometrical Techniques

Second Edition

DONAL M. RAGAN

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Preface

To achieve a high level of understanding in a short time it is necessary to master the essentials of both the traditional approaches and recent advances. In structural geology, the problem of doing this is compounded partly because of the revolutionary character of many of the modern developments and partly because there are few short-cuts to the all-important spatial visualization.

The first steps in the study of geologic structures are largely geometrical. This was true in the historical development of the field, and it is also true in the initial stages of an investigation and in the education of a structural geologist. This concern for geometry includes the basic methods of describing and illustrating the form and orientation of geologic structures, and the solution of various dimensional aspects of structural problems. However, geometry is not the end. The final goal is a full mechanical understanding of the products and processes of rock deformation.

This book attempts to fill a need for a modern introduction to geometrical techniques used in structural geology. The contrast with the more traditional approaches lies in an emphasis on visualization and on those aspects of geometry which yield insights into important new and old problems. Not everything could be included, and it has been necessary to trim some of the material usually covered. Even here, however, I believe that the essence of the older, well-established techniques has been preserved. Where possible, I have tried to bridge the gap between the old and the new by blending the two. I have as well included material not commonly used at the introductory level; in particular, certain fundamental mechanical concepts are applied to the interpretation of simple structures. Not only are these applications important in their own right, but even more they indicate where many of the most challenging problems of structural geology lie. Students who go no further in structural geology should have a working knowledge of the basic geometrical techniques and should be able to follow much of the specialized literature with at least some understanding. At the same time, those who do go on, either in advanced courses or on their own, should have the necessary foundation.

In common with most treatments, the first few chapters apply the methods of orthographic projection to the solution to simple structural problems. For those who feel the need for an introduction or review of descriptive geometry, an outline is given in Appendix A. Use is made in these early chapters, as well as in later ones, of Mackin's powerful method of visualization—the down-structure view of geologic maps.

Fundamental aspects of progressive strain in two dimensions are introduced with the use of card deck models, and the concepts derived from these models are then applied to the analysis of several geologic problems. The difficulties of describing the state of inhomogeneous strain leads to the geometrical description and classification of folds. The properties of ideal parallel and similar folds are explored in some detail, again with the aid of card deck models. The opportunity presented by the shear fold mechanism is used to introduce superposed folding.

The stereographic projection is introduced fairly early, and most of the subsequent problems are solved with it. The use of the stereonet in structural analysis follows naturally, and the method of constructing the various types of diagrams, including contouring, are described.

Faults are described and classified, and problems of displacement are solved by combining orthographic and stereographic methods. The geometrical aspects of stress are developed in much the same terms as the earlier analysis of finite strain in order to emphasize the formal similarity. These concepts, together with the Coulomb criterion of shear failure are then applied to the analysis of the faults.

Finally, methods of presentation and analysis of geologic data, including maps, structure sections, and block diagrams are developed. Throughout, emphasis is given to the geologic map because it is surely the single most important tool in structural geology!

Definitions of a number of important terms are given at the beginning of most of the chapters. Generally, I have followed accepted usage, and for the most part the definitions are taken from the *International Tectonic Dictionary* (Dennis, 1967). However, I have not hesitated to modify these definitions in order to achieve greater clarity. Nor have I attempted to discuss alternative or conflicting usages; these can be found in the Dictionary or in structural geology texts.

A book such as this is by its very nature eclectic, and I hasten to acknowledge my debt to the large number of authors whose material I have adapted. I also thank the various publishers for giving permission to reproduce copyrighted illustrations; these sources are noted at appropriate places throughout the text. I especially thank the Journal of Geological Education for permission to use the material appearing as Chapter 5. If there is a single recurring theme in the book it is the down-structure view of maps, and I owe my gratitude to the late J. H. Mackin for a thorough grounding in the method. A large number of readers and reviewers of the first edition made many important comments, suggestions and corrections; I can not list all their names here but this does not diminish my thanks to them. S. L. Anderson, D. J. Fisher, N. J. Price, J. C. Rosner, and M. F. Sheridan each read one or more of the chapters and their comments lead to noticeable improvements. J. G. Ramsay's influence will be seen on many pages; he also kindly supplied Figure X7.1. I am of course responsible for any remaining shortcomings and inevitable errors. Once again, I should appreciate hearing about them as they are found.

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Note to the Student

The proof of these geometric techniques is in their application. To this end some exercise material is included with each chapter. However, an important part of structural geology is the study of geologic maps. Such maps cannot be included here, but many excellent ones are readily available. U.S. Geological Survey maps, both old and new series, provide a wide variety of examples from many areas. Some of the state geological surveys publish good maps. Occasionally the Geologic Society of America Bulletin contains maps in full color, and numerous black and white maps appear in this and other journals. Two collections of geologic maps with accompanying sections and explanatory text are commercially available (see *Suppliers*). Several books by British authors contain a number of maps and map problems (see *Bibliography of Geometrical Techniques*, p. 201).

The accompanying exercises, and map problems generally, can usually be solved with a minimum of equipment and materials. The required equipment should include a drafting-type compass, a semicircular protractor, an accurate scale, and a straight edge (T-square or large triangle). Those contemplating the purchase of these items or those using drafting equipment for the first time are advised to read the section in Appendix A on maintaining accuracy in drawings. As with all things a better job can be done quicker with more elaborate and specialized equipment. A drafting machine is an especially desirable addition.

Printed stereographic projections, other graphic aids, and some exercise material are grouped at the back of the book on perforated pages. It is convenient to permanently mount the two 15 cm stereonets. One successful method is to glue the printed nets, being careful not to alter their dimensions, to each side of a 20 cm square of pressed sawdust board (also called particle board) which has been well coated with shellac. The surface of the nets can then be protected with a sheet of self-adhesive clear plastic. A small hole is made exactly at the center to accept a map pin.

One important skill that should be cultivated along with an increased understanding of structural geometry is the ability to produce an effective diagram. The requirements are, in varying degrees, both technical and artistic. For many purposes a technically competent diagram is adequate; the literature is full of examples. With care and a little experience, the necessary attributes of clarity and accuracy can be developed. However, an artistic touch invariably raises the quality of an illustration above the merely adequate. Despite disclaimers, at least some of this skill can be acquired and the student is urged to practice by making quick, three-dimensional sketches of various structural features as they are encountered. The importance of developing this habit cannot be overemphasized. By visualizing the three-dimensional form of a structure and then making that visualization concrete by drawing, the ability to do both is greatly strengthened.

SUPPLIERS

Geologic maps available from

Williams and Heintz Map Corporation
8351 Central Avenue
Washington, D. C. 20027

1. Geologic Map Portfolio No. 1, compiled and edited by L. W. Currier.

2. Geologic Map Portfolio No. 2, compiled and edited by Forbes Robertson.

Stereonets

1. Excellent, but expensive 20 cm Wulff and Schmidt nets are available from E. Leitz, Inc., Rockleigh, New Jersey 07647.

2. 10 cm and 20 cm Wulff and Schmidt (both polar and equitorial) nets of very good quality at modest individual and bulk prices are available from the Geological Journal, Department of Geology, The University, Liverpool, England.

3. Very inexpensive 10 cm and 18 cm Wulff nets of good quality are available from the Bookstore, University of Chicago, Chicago, Illinois 60637

Plastic sheets

4. Self-adhesive plastic protecting sheets are commonly available in stationery stores and household departments, including:
1. Cook's Seal-Vu laminating film
2. Stenso Clear Seal
3. Transparent Con-Tact

Contents

1
Attitude of Planes

DEFINITIONS

ATTITUDE	The general term for the orientation of a structural plane or line in space, usually related to geographic coordinates and the horizontal. Both bearing and inclination are components of *attitude*.
BEARING	The horizontal angle between a line and a specified coordinate direction, usually true north or south.
INCLINATION	The general term for the vertical angle, measured downward, between the horizontal and a plane or line.
STRIKE	The bearing of a horizontal line on an inclined plane (Fig. 1.1).
DIP	The inclination of the line of greatest slope of an inclined plane. It is measured perpendicular to strike (Fig. 1.1).
APPARENT DIP	The inclination of a plane measured in a direction *not* perpendicular to the strike (Fig. 1.2).

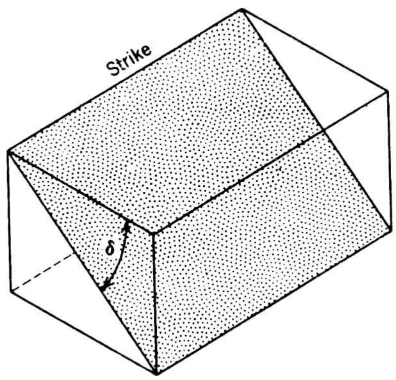

FIGURE 1.1 Angle of true dip δ measured in vertical plane perpendicular to the strike.

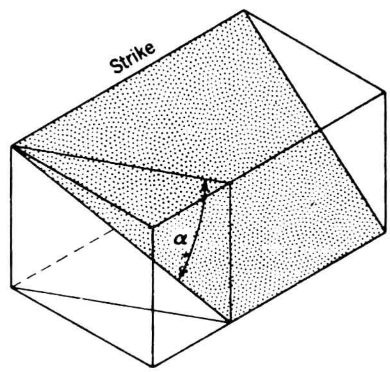

FIGURE 1.2 Angle of apparent dip α measured in vertical plane not perpendicular to the strike.

DIP AND STRIKE

The terms dip and strike apply to any planar structure, and together their values constitute a statement of the attitude of the plane in space. The planar feature most frequently encountered in many areas is the bedding plane; it is also the one dealt with most in beginning structural geology. Other structural planes include cleavage, schistosity, and joints.

Each type of plane has a special map symbol, called a dip and strike symbol, which in general has three parts:

1. *Strike line*, which should be plotted long enough so that the bearing can be accurately measured again from the map.
2. *Dip mark*, at the midpoint of one side of the strike line, indicates the direction of downward inclination of the plane.
3. A number close to the dip mark, and on the same side of the strike line, indicates the dip angle.

The only exceptions are the special cases of horizontal and vertical attitudes. The most common symbols are given in Fig. 1.3, and their use is well established by convention. However, it is sometimes necessary to use these or other symbols in special circumstances, so that their exact meaning should always be made clear in the map legend. The values of dip and strike angles are also often referred to in text. This usage is considerably less standard. Each of the following four examples refers to exactly the same attitude:

1. N 65 W, 25 S: strike is 65° west of north, and dip is 25° in a southerly direction.
2. 295, 25 S: strike is 295° measured clockwise from north, dip is to the south.
3. 25, S 25 W: dip direction has a bearing of 25° west of south, inclination is 25° in this direction.
4. 25, 205: dip direction has a bearing of 205° measured clockwise from north, dip is 25° in this direction.

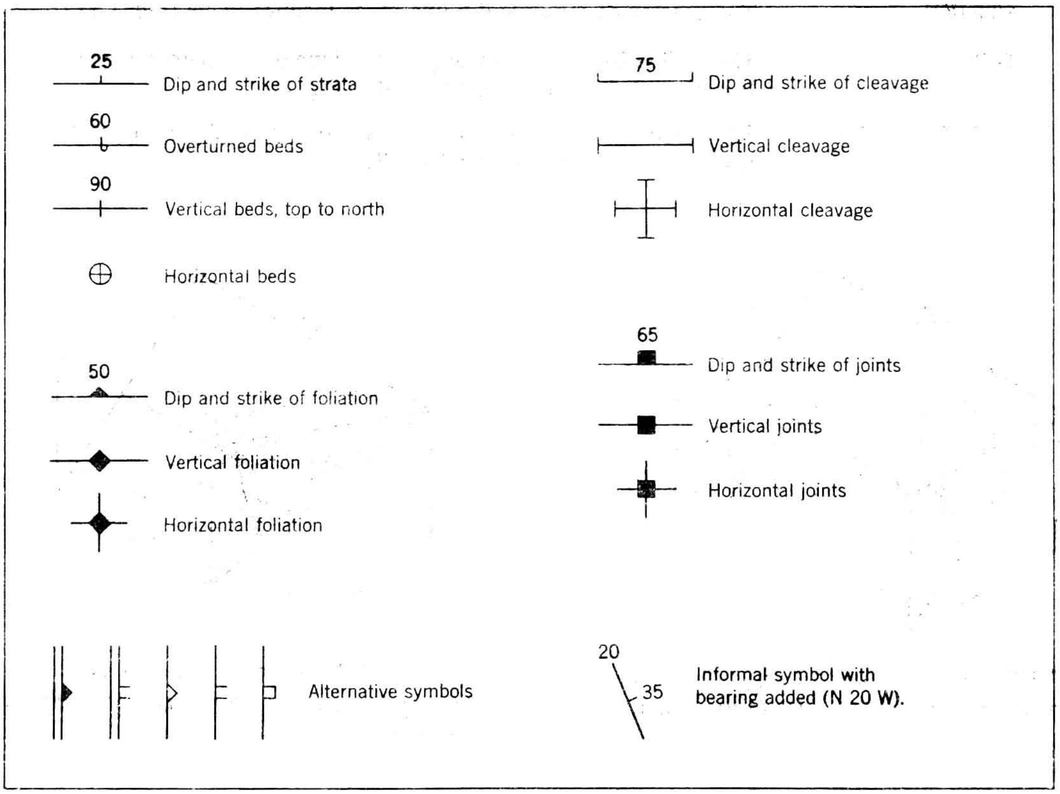

FIGURE 1.3 Map symbols for structural planes.

The first two forms are the most common with the difference usually depending on whether the compass used to make the measurement is divided into quadrants or the full 360°, and on personal preference. The advantage of the quandrant method of presentation is that it is much easier to quickly grasp a mental picture of the attitude, and will therefore be used in this text. The third, and closely related fourth form will be used for the bearing and inclination of lines rather than planes, although sometimes those lines will lie in planes, such as dip lines, in which case both forms may apply. Again the quadrant form will be used here, although the fourth method gives the attitude of the plane unambiguously without need of letters for geographical directions, and is therefore particularly useful in computer treatment of attitude data.

There are a number of ways to determine the attitude of structural planes. All are based on field measurements of one kind or another. The most direct method is to hold the compass directly against the bedding or other plane surface at the outcrop. One edge of the open compass case is placed against the surface and the compass rotated until it is level (Fig. 1.4*a*). The bearing in this position is the strike. Dip is determined by placing one side of the compass box and lid directly on the exposed plane at right angle to the previously measured strike direction. The clinometer bubble is leveled and the dip angle read (Fig. 1.4*b*). While simple to use, this method is subject to rather large errors because of the short compass base and the imperfection of naturally occurring plane surfaces. Other more accurate direct measurement techniques can be found in any field geology text (e.g. Compton, 1962).

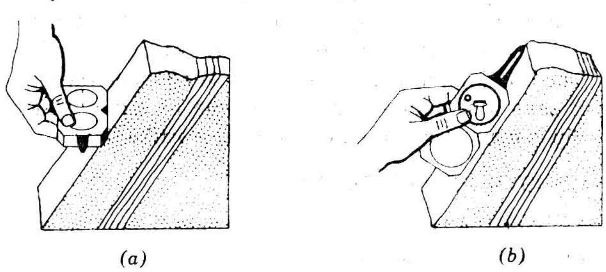

FIGURE 1.4 Measurement of strike (a) and dip (b) with a Brunton compass. (From Compton, 1962, Manual of Field Geology, Wiley, used by permission.)

Indirect methods are also available, and are the subject of this and a later chapter. All the methods dealt with here are concerned with determining the relationship between the components of the attitude—the apparent dip, true dip and strike.

GRAPHIC METHODS

From the point of view of visualizing, and therefore thoroughly understanding the spatial relations of the various angular components, wholly graphic constructions are the most important. Once the ability to visualize is attained, other quicker, more efficient methods can be applied.

The simplest type of problem involves determining one component from the other two.

PROBLEM

Given the attitude of a plane (N 90 E, 30 N), find the apparent dip in the vertical section trending N 45 W.

APPROACH (Fig. 1.5)

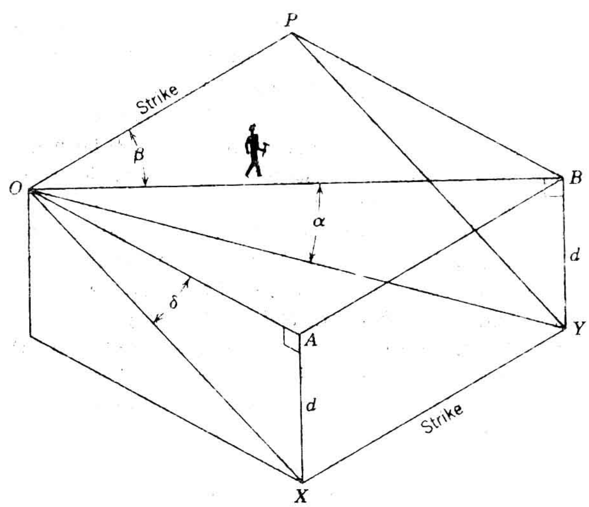

FIGURE 1.5 Block diagram showing the angles involved in problems of true dip and apparent dip.

From one line of strike on the plane (*OP*), and the true dip, a simple triangle (*OAX*) gives the location of a second line of strike (*XY*) with known elevation relative to the first. Such lines on a plane are called structure contours, and the vertical distance between two adjacent contours is the contour interval (here *d*). Moving on a horizontal map surface obliquely from one structure contour to the other (in the example from *O* toward *B*) the depth to the plane steadily increases; at point *B* on the second contour it is exactly *d*. A second triangle can therefore be constructed which gives the inclination of the plane in this direction, that is, the apparent dip in a direction with the specified bearing.

CONSTRUCTION (Fig. 1.6)

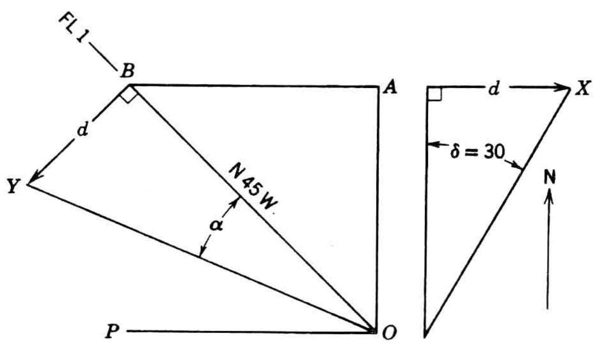

FIGURE 1.6 Graphical determination of apparent dip from known true dip and strike.

1. In map view draw a line of strike (*OP*), and a line of some convenient length perpendicular to it representing the dip direction (*OA*).
2. Draw a second strike line (*AB*) through point *A*.
3. To find the difference in elevation (*d*) between the two contours, construct a right triangle using *OA* as one side and the angle of true dip (*δ*). The other side is then the required *d*, giving point *X* on the second line of strike. Note that this triangle can be constructed independently of the map view.
4. Add the N 45 W line (*OB*) to the map.
5. The second triangle giving the apparent dip (*α*) can now be constructed. In doing this it is always more efficient to use line *OB* as a folding line (FL 1). The side with length *d* is drawn from point *B*, giving point *Y* on the second line of strike. Angle *BOY* is the required apparent dip.

ANSWER

For a plane with attitude N 90 E, 30 N, the apparent dip in the N 45 W direction is 22°.

A similar construction is involved in determining the attitude of a plane from two apparent dip measurements.

PROBLEM

Given two apparent dips (10, N 72 W, and 25, N 35 E) obtain the true dip and strike of the plane.

APPROACH (Fig. 1.7)

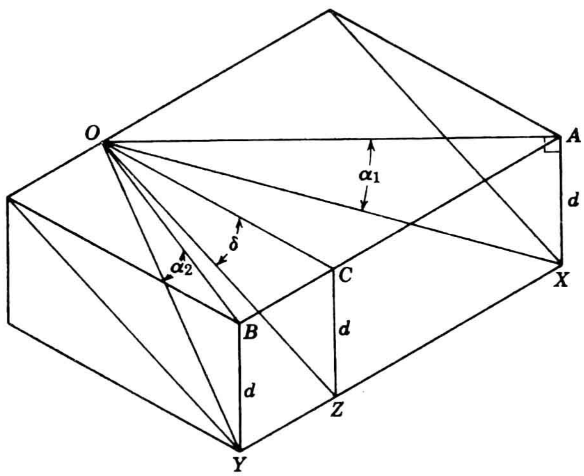

FIGURE 1.7 Block diagram showing the angles involved in the problem of determining dip and strike from two apparent dips.

The apparent dip measurements represent the attitudes of two lines which intersect on the plane of interest. Plotting the bearings of these lines established this point in map view. Since three points determine a plane, two more must be found. A second point is found from a triangle plotted from the information of one apparent dip measurement (*OAX*). Another point, associated with the second apparent dip could be found in like manner. However, it is advantageous to locate this third point at the same relative elevation as the second. The line joining these two points of equal elevation is then a structure contour, or line of strike. The dip is measured perpendicular to this strike line.

CONSTRUCTION (Fig. 1.8)

1. Plot the two apparent dip bearings in map view, intersecting at point *O*.
2. Using one of these lines as a folding line (FL 1) and the associated apparent dip construct triangle *OAZ*. The lengths of *OA* and depth *d* are determined by convenience only, but should be of reasonable length to insure accuracy.

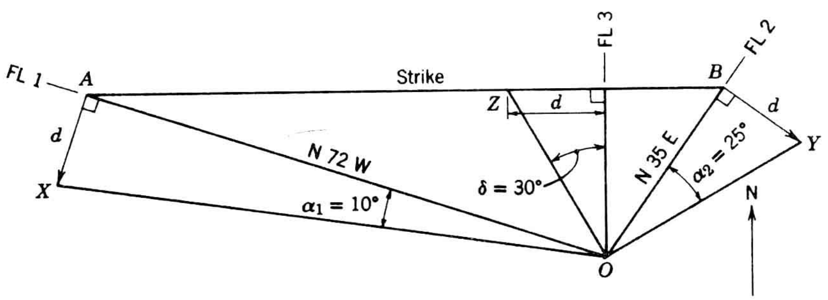

FIGURE 1.8 Graphical construction of dip and strike from two known apparent dips.

3. Using the second of these apparent dip bearings as a folding line (FL 2) and its apparent dip, construct another triangle OBY. This time, however, the depth d muxt be *identical* with that used in step 2.
4. Two points (X and Y) of equal (but unknown) elevation are now located; their positions in map view are A and B. To fix the strike direction join points A and B.
5. A line from point O perpendicular to this strike line (AB) determines the dip direction. With this line as folding line (FL 3) scale off the same depth d, thus establishing point Z on the line of strike.
6. A line joining points O and Z determines the slope of the plane in the direction perpendicular to the strike, that is, the true dip.

ANSWER

The attitude of the plane represented by the two apparent dips is N 90 W, 30 N.

This same type of problem may be solved by a short-cut method which combines the principal features of the full graphic method with trigonometric data.

CONSTRUCTION (Fig. 1.9)

1. As before plot two rays in map view from a single point representing the bearings of the apparent dip measurements.
2. With the use of any convenient scale plot the distances equal to the value of the cotangent of each apparent dip along the respective rays, starting at the point of intersection.
3. A line joining the two points so determined is the line of strike.
4. The perpendicular distance from the intersection to this strike line is equal to the cotangent of the true dip angle.

TRIGONOMETRIC METHODS

The value of the methods of descriptive geometry lies in the practice in visualization that comes with manipulating the elements of a problem in three dimensions. The importance of developing this ability to visualize can not be emphasized enough. It will be obvious, however, that these orthographic constructions have practical limitations. For this reason, alternative methods have been devised to quickly and easily solve the various attitude problems.

Since the graphical solutions of dip and strike problems involve a series of right triangles, it is clear that solutions can also be obtained trigonometrically. The relationship linking true dip δ, apparent dip a, and the

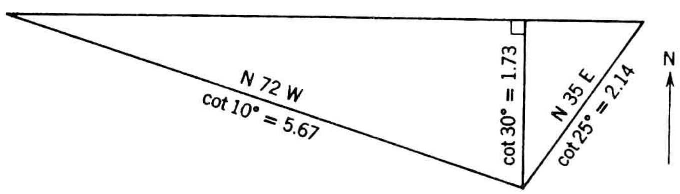

FIGURE 1.9 Graphic-trigonometric method for determining dip and strike from two apparent dips.

angle between the strike and apparent dip direction β, is

$$\tan \alpha = \tan \delta \sin \beta \qquad (1.1)$$

Thus, if only two of the variables are known, the third can be calculated easily. This can be done simply and with sufficient accuracy by slide rule.

Similarly, the true dip and strike can be found from two apparent dips from the following equations (after Earle, 1934, p. 2; Hughes, 1960):

$$\tan \phi = \{|(\tan a_2/\tan a_1) - \cos \theta|\} \operatorname{cosec} \theta$$
$$\tan \delta = \tan a_1 \sec \phi$$

where a_1 and a_2 are the apparent dip angles, θ the angle between the two apparent dip bearings, and ϕ the angle between the bearing of a_1 and the true dip direction (see Fig. 1.7; θ = angle AOB, ϕ = angle AOC).

With the availability of still other techniques there is usually little need to resort to these equations. There are two notable exceptions: first, if very small dip angles are involved, and second, where large numbers of these problems must be solved routinely.

OTHER TECHNIQUES

A variety of graphical and mechanical aids based largely on the trigonometric relationships have been developed. An alignment diagram (Fig. 1.10) is especially easy to use. A simple rule based on cotangent values (White, 1946) and a nomogram (Leney, 1963) may also be used to solve dip problems, as well as a variety of other problems involving angles. Or

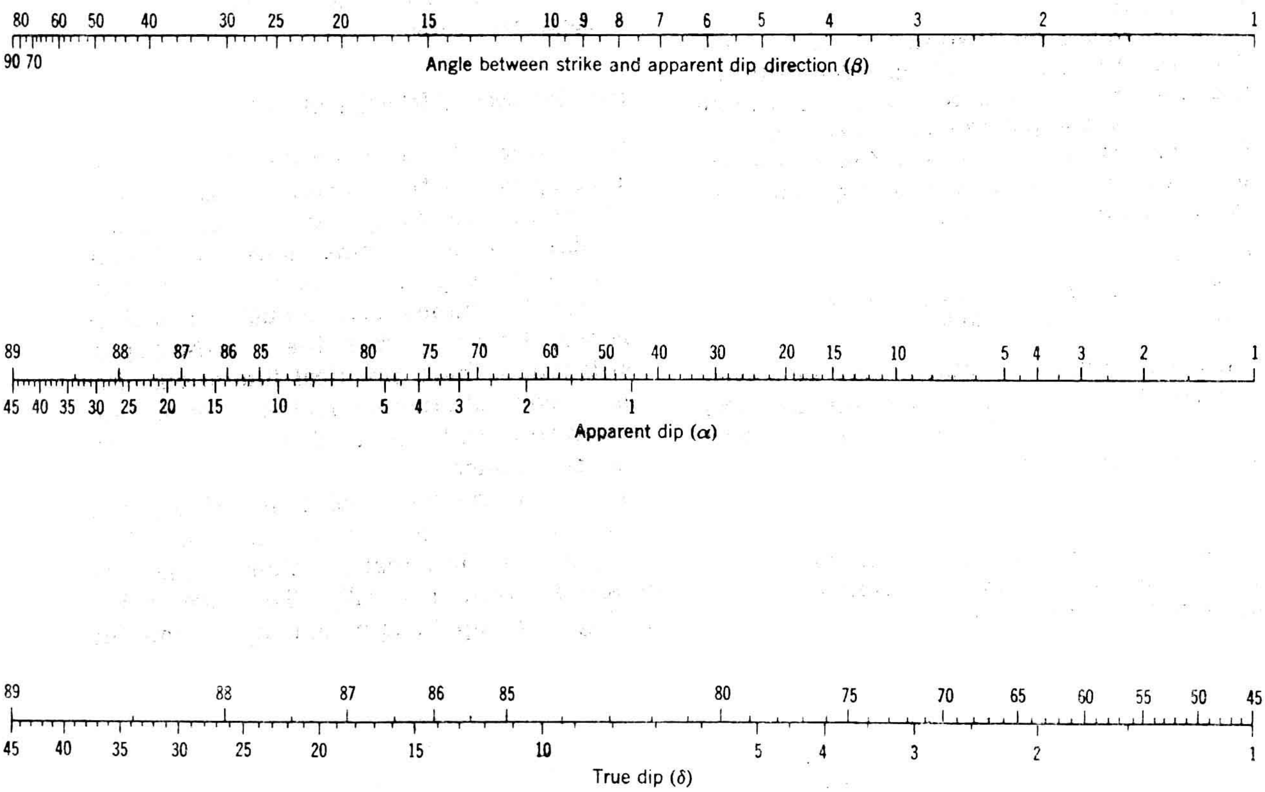

FIGURE 1.10 Alignment diagram for determining apparent dip. (From Nevin, 1949, Principles of Structural Geology, Wiley, used by permission.) Using a straight edge join the points representing the angle between the strike and the apparent dip direction on the first column and the true dip on the third column. The apparent dip is read off the middle column.

a special circular slide rule (Satin, 1960) and a protractor (Ten Haaf, 1967) may be used.

However, the most useful technique of all is based on a completely different type of projection and a specially constructed plotting net. Not only can these, as well as a wide variety of other problems involving even more complex angular relationships be treated, but completely satisfactory numerical solutions can be obtained very quickly, and the entire plotting process checked by visualization, thus making it an exceedingly powerful technique. The details of this method are described at length in Chapter 11.

EXERCISES

A word of advice before you start your first graphical constructions—you will be repaid many times over if you develop the habit of sketching out the main elements of the problem before you attempt an accurate scale drawing. The first advantage is that the sketch will allow you to place the final drawing on the sheet of paper more efficiently. It is a common, but annoying experience to start the drawing on the middle of the sheet only to find that the construction takes you off the page. Even more important, you will find that it is relatively easy, even after considerable experience, to take a wrong turn if you start the full construction first. In concentrating on the accurate plotting, you may measure an angle in the wrong direction from north, or plot the dip on the wrong side of the strike line, or measure a distance along the wrong line. The quick preliminary sketch will encourage you to see the forest, not just the trees.

If you find the use and meaning of folding lines troublesome, it often helps to literally bend the paper around the edge of the table top along the required line of your sketch. You can then examine the map view and vertical section simultaneously. Having seen these views, it is usually an easy matter to decide just how the final drawing should proceed.

1. Become familiar with the use of a Brunton compass. Especially if the dial is divided into quadrants, make sure that you understand how to measure bearings. Because the axis of the compass case is aligned parallel to the structure to be measured, not the needle, the *E* and *W* are reversed from their normal positions, and this may lead to some confusion for the beginner. Note also that the dial can be adjusted so that the compass reads *true* rather than magnetic north.

2. For the following attitude data, determine the unknown component three different ways: (i) graphically, (ii) trigonometrically, and (iii) with the alignment diagram. For one problem, solve graphically using two different scales—the second twice the first. In the field, angles can be measured with a compass and clinometer to an accuracy of no better than one degree, if that. What then can you say about the relationship between the scale of your two constructions and the justifiable accuracy?

   (a) If the attitude of a plane is N 75 E, 22 N, what is the apparent dip in the direction N 50 E?

   (b) An apparent dip is 33, N 47 E; the strike is E-W. What is the true dip?

   (c) The true dip is 40° due north. In what direction will an apparent dip of 30° be found?

3. Graphically determine the true dip and strike from each pair of apparent dip measurements. For one pair also calculate the attitude trigonometrically.

   (a) 20, N 80 W, and 40, N 10 E

   (b) 30, N 60 E, and 50, S 45 E

   (c) 6, N 78 W, and 25, N 36 W

4. A smooth, vertical cliff exposes the traces of uniformly dipping strata. There is no hint of the third dimension. What is the appearance of these inclined traces as viewed from different positions on the ground? What can be said about the true attitude of the beds with no further data?

5. Probably the most important application of the technique for determining the angle of apparent dip from true dip and strike is in the construction of vertical structure sections. Fig. X1.1 shows the boundaries of a proposed trench 10 m deep. The top of a distinctive sandstone unit outcrops at point *A*, and has an attitude of N 60 E, 40 N. The area is also cut by a large number of joints (N 20 W, 65 W). Draw a diagram to scale showing the vertical north wall of the trench as it will appear when excavated. Include point *A* on your section, and show the joints diagrammatically.

6. Three points *A*, *B*, and *C* on an inclined stratum have elevations of 150 m, 75 m, and 100 m, respectively. The distance from *A* to *B* is 1100 m in a dirèction of N 10 W, and from *A* to *C* is 1560 m in a direction N 40 E. What is the dip and strike of the stratum?

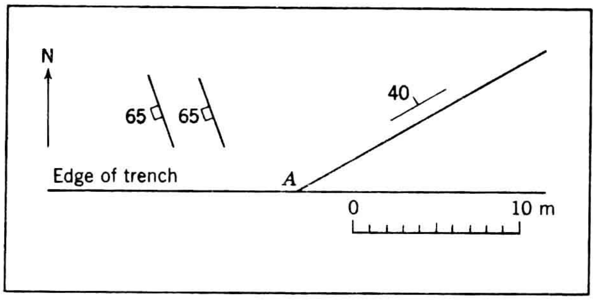

FIGURE X1.1

2 Thickness and Depth

DEFINITIONS

THICKNESS	The perpendicular distance between the two parallel planes bounding a tabular body of rock (Fig. 2.1). Stratigraphic thickness is a special case.
DEPTH	The vertical distance from a specified level (usually the earth's surface) downward to a point, line or plane (Fig. 2.1).

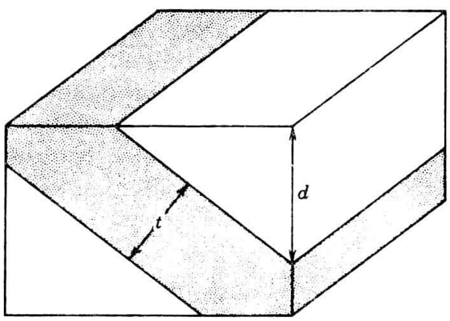

FIGURE 2.1 Block diagram showing thickness *t* and depth *d*.

THICKNESS

The thickness of a layer may be determined in a number of different ways (for a full discussion, see Kottlowski, 1965). In favorable situations it may be possible to obtain thickness by direct measurement; otherwise it must be determined indirectly.