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PROBLEMS OF FAULT NOMENCLATURE[1]

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ABSTRACT

The distinction between separation and slip is fundamental to the proper geometric understanding of fault displacements. Ideally geologists strive to find slip: the relative displacement of formerly adjacent points on opposite sides of a fault. In practice we recognize these points where lines formed by geological elements meet the fault plane at piercing points. Such lines are primarily those formed: (1) by intersecting planes, such as dikes transecting strata; (2) by the trace of one plane against another, as where a bed meets an unconformity; (3) by linear geological features, such as attenuated sand lenses, ore shoots, and stream courses; (4) by stratigraphic lines, such as pinch-out lines, lines of facies changes, and fossil shorelines; (5) by constructed lines, such as isopachs, lithofacies lines, and traces of axial surfaces with bedding.

Not always are such data in three-dimensional space available to determine slip. Usually we have only information on displaced planes, such as bedding planes, unconformities, dikes, sills, contacts, etc., and lack recognizable lines lying within these planes. Furthermore, data are commonly given in two dimensions only. More widespread recognition that we must describe the geometry of fault displacements in terms of separation is therefore necessary. Moreover, since separation measures the displacement of traces of displaced planes as shown on a cross section or map, it is as essential to define the orientation of this view as to describe and give the location, amount, and sense of the separation. Where we employ the term apparent in fault definitions, in general we refer to separation.

Geologists must therefore distinguish habitually between geological situations with displaced lines and those with displaced planes. Our fault practice and terminology fail to draw this distinction sharply, so that faults are inadvertently described incorrectly when slip terms are applied carelessly to separation. A qualified committee of geologists should now examine our fault nomenclature and make recommendations that will dispel ambiguities. Precise definitions would also stimulate the search of geological data for clues to slip that alone can reveal significant facts on deformation kinematics.

INTRODUCTION

Recently there has been considerable discussion on the nomenclature and classification of faults. Mason L. Hill (1947; 1958; 1959) especially has pointed to ambiguities in the schemes now in use and has striven to find a classification which will clear up difficulties. Here I would like to emphasize some basic concepts underlying the treatment of faults and to discuss a few problems of fault classification and nomenclature.

To begin with, we can agree that a fault is *a fracture in rocks of the earth's crust along which there has been displacement*. The word *along* is used in order to confine the displacement to directions parallel with the fault surface. It also serves to distinguish faults from the other group of fractures, namely joints, that display very slight rock-displacements normal to the fracture surface. In practice this distinction is difficult to apply rigorously because some joints also show slight displacements parallel with the fracture surface, and thus become faults of small displacement. These usually are not mappable on ordinary scales and accordingly are dismissed from consideration in most field work. Two elements of

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our definition of fault require prime attention. We need to recognize the *fracture* in the rocks and we need to establish that there has been *displacement*. Some ambiguity about faults comes from our failure to recognize the interplay between these two concepts. Depending upon the background or experience of the geologist, and the way he is thinking or writing at the moment, indistinctness may result. A field geologist usually does not recognize that a fault exists until he finds that the geology fails to match along a line or plane. He may therefore feel quite confident that a fault exists, and show it as accurately located on his map, though he is never able to dig out the fault surface itself. It is known to exist and to have displacement although many things about it remain unknown, such as the dip or shape of the fault surface. It can not yet be visualized geometrically. On the other hand, the same geologist, thinking geometrically, or some other geologist, may visualize the fault as a planar fracture first and as possessing displacement second. In one case the fault is thought of as a vague zone where the continuity of the geology is interrupted. In the other it is visualized as a discrete surface within crustal rocks. These concepts emphasize that practical fault terms must allow for situations where data are by necessity incomplete.

This brings us to a discussion of the differences between the way faults are known to exist and the way we visualize them or treat them conventionally. Through long habit and teaching, faults have been dealt with as problems in simplified geometry. We should of course emphasize the differences between faults, beds, rocks, etc., and the geometry of points, lines, and planes in space. But even more important it is essential for geologists to think more clearly in simple geometric terms. In fact, most of our troubles in fault nomenclature stem from careless application of these principles. The geometric difficulties largely arise because in our haste we attempt to force a two-dimensional geometry on a three-dimensional problem. In this paper some fault concepts are therefore discussed in terms of solid geometry, involving relations between points, lines, and planes in space

To begin with, it is appropriate to represent a fault as a plane oriented in space, possessing a strike and dip, although we recognize that most fault surfaces are not planes and that seldom in practice do we know their strike and dip accurately. This stage in our thinking does not often cause trouble. A map shows the trace of the fault plane as a curved line across the topography. Since cross sections are also planes (vertical, horizontal, or inclined), the trace of the fault on them is the line of intersection of the fault and the section.

Difficulties arise when we try to deal with the geometry of displacement, and especially when we try to relate this geometry to geologic practice. This discussion is intended to emphasize the distinction between slip and separation as a useful basis for the description of faults, as Hill (1959) has also done.

Since many faults have significant components of strike-slip, no longer can we assume logically that a fault has only dip-slip until proved otherwise. Underlying assumptions in the discussion here are therefore that formerly adjacent points may move apart in any direction parallel with the fault surface, and that any useful classification needs to allow for such possibilities. Thus, when data at hand are complete enough, slip can be determined and should be employed, but for the majority of situations only separation is applicable. The terms slip and separation are here defined and discussed.

SLIP

Ideally we conceive of slip as the relative displacement of two points away from each other that were formerly adjacent. Here we follow the Geological Society of America committee on fault nomenclature composed of H. F. Reid, W. M. Davis, A. C. Lawson, and F. L. Ransome (1913, p. 168) in defining slip as the relative displacement of *formerly adjacent points* on opposite sides of the fault, *measured in the fault surface.* In Figure 1, point *A* now lies on the foot wall

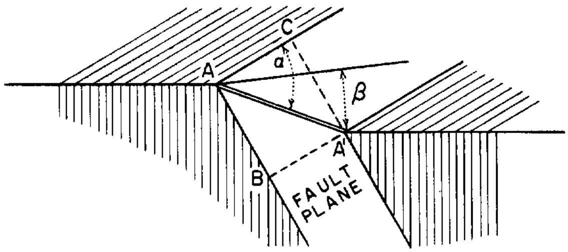

FIG. 1.—Diagram showing definition of slip, a directed line-segment. AA'=slip; AB or CA' = Dip-slip component; AC or BA' = Strike-slip component; α = Pitch or rake angle of slip line-segment (lies in fault plane); β = Plunge of slip line-segment (vertical angle).

of the fault and A' lies on the hanging wall. The displacement can be represented as a line segment oriented in space but we do not know which of the two points remained stationary and which moved, or whether they both moved. It is not worthwhile for us to dwell on this relative aspect of our knowledge since displacements between rock elements are all relative except under unusual conditions, e.g., modern faulting along the seashore or fault displacements determined by geodetic measurements. In fact, it seems cumbersome and unnecessary to include the adjective relative in all fault definitions; it might be treated early in a discussion and then dispensed with. At times we may want to recognize *shift*, defined as the maximum relative displacement of points formerly located on opposite sides of the fault and far enough from it to be outside the dislocated zone (Reid *et al.*, p. 172).

The directed line-segment known as slip possesses orientation and length, and will be a straight line if the fault surface is a plane. If, on the other hand, the fault surface is warped or curved, the line-segment will usually be curved also, since, by definition, it must lie in the fault surface (Reid *et al.*, 1913, p. 168).

It is obvious that we can determine slip in practice only if we can recognize two points which were adjacent previous to faulting. These are the points *A* and

A' in Figure 1. Such points might well be thought of as the two halves of a distinctive crystal which happened to be fractured and moved apart along the fault. Obviously the practicing geologist stands no chance of recognizing such displaced crystals (or points) in the ordinary course of field work, subsurface studies, or even with careful mapping in well exposed mine workings. Fortunately, however, such fruitless searches are not necessary to solve our problem.

Referring again to geometry, where a line pierces a plane, we have a point, the piercing point of this line. Such a line is shown in Figure 2 by the line BA which does not lie in the plane, but intersects it at the piercing point A. If this line is considered as displaced at the plane, its continuation may be recognized as the line $A'C$. *In general, determinations of net-slip are based on the recognition of a displaced line* and where the line is older than the fault. If we grant this fundamental concept we next need to consider: how do we recognize such displaced lines in practice?

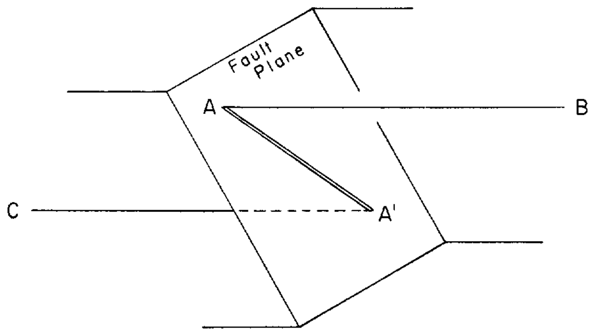

FIG. 2.—Piercing points. A = Piercing point of line BA; A' = Piercing point of line CA'; AA' = Slip.

GEOLOGICAL LINES THAT MAY BE DISPLACED BY FAULTS

According to both their geometric elements and geological occurrence we can treat in turn the kinds of lines that are encountered in geological work. All of these structures form lines which may at places be displaced by faults. In actuality some of these lines may be curved or wobbly; nevertheless, they form piercing points where they meet the fault surface, and if recognizable or correlatable on both sides of the fault, provide a basis for determining net slip.

Lines formed by intersecting planes.—One of the common groups of lines are the lines of intersection of two planes. Campbell (1948, pp. 244–59) successfully applied this kind of feature in working out the net-slip of the West Bay fault in Canada, and in so doing discovered the displaced part of a valuable ore-body. He employed the lines of intersection of non-parallel dikes, as shown here in Figure 3. His calculations give a strike-slip component averaging about 16,100 feet and a dip-slip component of about 1,570 feet, although he actually worked with shift. In stratified rocks, lines of intersection may be recognized where dikes cut strata,

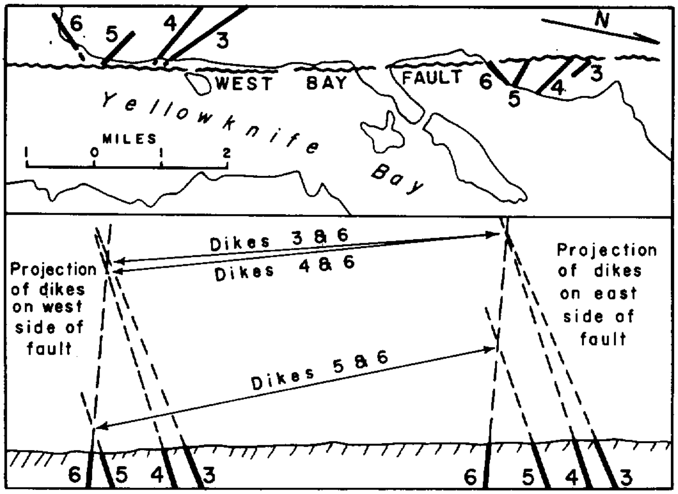

FIG. 3.—Map (above) and cross section (below) of geologic relations along West Bay fault, Great Slave Lake, Canada. (After Campbell, 1948, Fig. 4.)

and where older structures, such as faults, cut strata. These, and other examples are: intersecting dikes or veins; intersecting dikes and sills, sheets, or strata; and intersecting strata, dikes, sills, sheets, veins, etc., with older faults.

Lines formed by trace of one plane against another.—A dipping stratum below an unconformity, for example, forms a line where the stratum meets the unconformity, as shown in Figure 4. Such examples differ from those above in that the planes do not cross, but one terminates against the other. The following examples come to mind.

1. Truncation (overstep), trace of bed *below* an unconformity against the unconformity.
2. Overlap (onlap, offlap, buttressing), trace of bed *above* an unconformity against the unconformity.
3. Older structures terminating against an unconformity. Faults, dikes, sills, veins, sheets, fold axial surfaces, etc., are planar structures that may form traces against an unconformity.

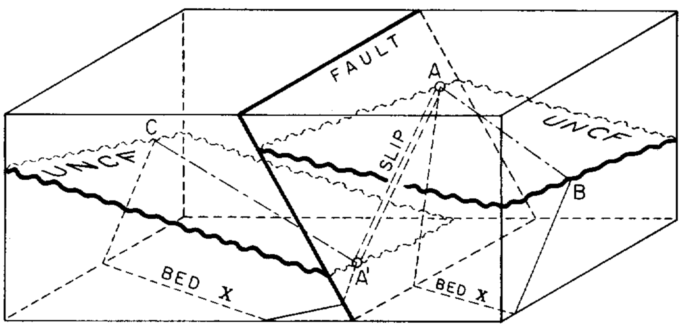

FIG. 4.—Isometric block diagram illustrating fault displacement of line of intersection of bed and unconformity. *BA* and *CA′*=Lines of intersection of Bed *X* and unconformity; *A* and *A′*=Piercing points of these lines; *AA′*=Net-slip line-segment, lying in fault plane.

4. Terminations against old faults. Planar structures, such as beds, dikes, etc., may form traces against an old fault. Where this fault is cut by a younger one, such traces can perhaps be used to determine slip. A possible example might appear similar to that shown in Figure 4, where the unconformity is replaced by a low-angle thrust.

Linear geological features.—Certain geological features, depending on the scale under consideration, may be thought of as "lines" compared with many other features. Such examples are rare and of limited usefulness.

1. Buried river channels, shoestring sands, attenuated sand lenses, etc.
2. Volcanic necks, ore shoots, etc.
3. Physiographic lines, such as stream courses, where cut by recent faulting. Along the San Andreas fault, for example, offset stream channels and terraces, canyons, linear spurs, etc., may indicate slip. Shorelines, older fault scarplets, etc., are additional examples.

Stratigraphic lines.—Another whole group of lines occurs in a conformable

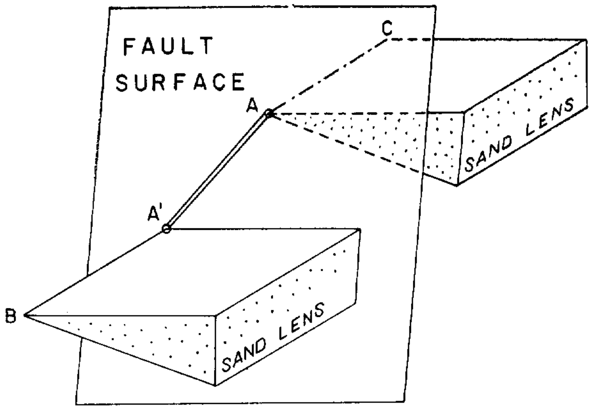

FIG. 5.—Fault displacement of edge-line of sand lens. BA' and AC = Pinch-outs or edge-lines of sand lens; A and A' = Piercing points of these lines; AA' = Net slip.

stratigraphical sequence where there are facies changes. Such lines have been largely ignored in connection with structural analyses.

1. The pinch-out line (zero isopach line) of a sand body, as shown in Figure 5.
2. Lines of facies change, such as from sandstone to shale, marine rocks to non-marine. Many lines of facies change occur in reef areas.
3. Shorelines or margins of depositional basins.
4. Source areas and their derived sediments. In California distinctive rocks in source areas may be matched linearly with sediments derived from them (Wallace, 1949, p. 801; Noble, 1954, pp. 44–47; Hill and Dibblee, 1953; Crowell, 1952).

Constructed lines.—During the geological study of a region we commonly construct special lines which can not be actually traced in the field or recovered in the subsurface but are nevertheless useful in determining slip on faults. Some of these lines are statistical in nature and some result from the intersection of constructed planes (such as axial surfaces) with other surfaces. In many cases, admittedly, the accuracy of location of these lines may not allow their use in this fashion. For example, if a fault has a slip of only a hundred feet, and isopachs are accurate only to two or three hundred feet, the method fails. There must be a nice balance between the scale employed, the rates of change of the quantity being "contoured," and the magnitude of fault displacement.

1. Isopachous lines (and isochores). Lines showing the thickness of a stratigraphic interval, provided the elevation of the top or bottom of the interval is also known, may be used in finding slip. Although isopachs are drawn frequently, seldom are they employed in this fashion. If structure contours are drawn on the same map, the problem is especially simple. In Figure 6 an example is shown where the 620-foot isopach is displaced by a near-vertical fault from a position with an elevation of 1,800 feet on the southeast to one of about 1,080 feet on the northwest, and 1,300 feet to the left.

2. Lithofacies lines. Many lithofacies maps show lithofacies lines where the character of an inter-

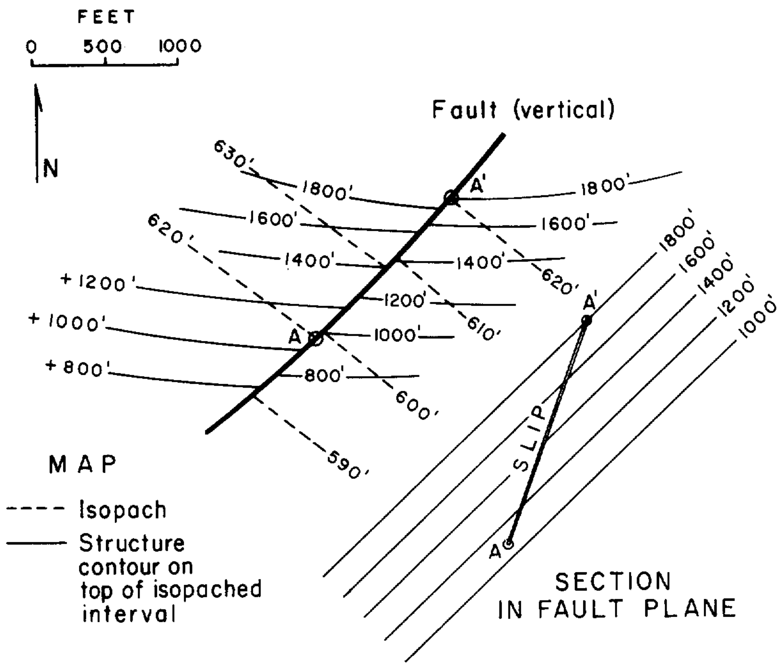

FIG. 6.—Structural and isopachous map showing oblique-slip fault. Map on upper left and cross section drawn in fault plane at lower right. AA' = Slip. A is on northwest side of vertical fault and A' on southeast.

val is represented by a line on a map. Again, if the elevation of a stratum in the section is known, the slip can be determined.

3. Axial and crestal surfaces and axes. The axial and crestal surfaces are commonly shown on maps and cross sections and can usually lead to a determination of slip if data are complete enough. Such surfaces are considered here as "constructed" because they are not commonly observable directly in the field. At best they can be mapped only rarely where folding is tight. Moreover, such surfaces are usually shown on conventional diagrams as traces, and for finding slip they need to be conceived in three dimensions. A "line" in this category is the line of intersection of an axial or crestal surface with a recognizable stratum. Here we must be cautious, in many practical cases, to distinguish this line from the "axis" as shown on the map, which is normally the trace of the crestal surface. Usually the most satisfactory way to find the slip, employing the line of intersection of an axial surface and a reference stratum, is to draw a cross section in the plane of the fault and show the folded beds on both blocks. This has been done for a simple case in Figure 7, utilizing a structure contour map, but it can be done equally as well with a geologic map. In using this method of finding

slip we have to assume that all folding is older than faulting, which of course may not necessarily be true.

In summary, many of the techniques thus described need to be used cautiously and some are far more useful than others. It is especially important to be certain of correlations across faults. In addition, since deformation in blocks on either side of a fault may go on independently as the displacement accumulates, it may not be possible to correlate folds or offset faults. In California, for example, many folds have grown along with movement on some faults so these folds can not of course be used in finding slip. In fact, there is no reason why we should expect determinations of net-slip at different places on one fault to be the same. After all, most faults acquire displacement as the result of deformation of rocks of

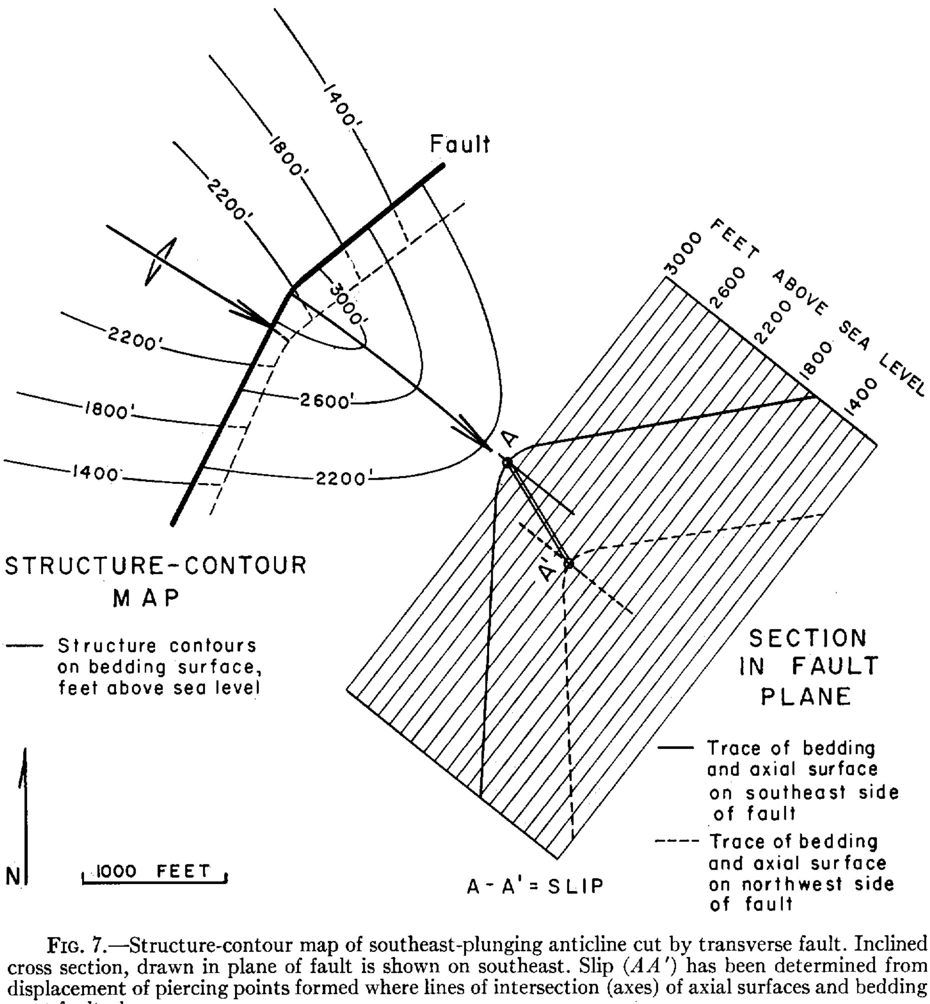

FIG. 7.—Structure-contour map of southeast-plunging anticline cut by transverse fault. Inclined cross section, drawn in plane of fault is shown on southeast. Slip (AA') has been determined from displacement of piercing points formed where lines of intersection (axes) of axial surfaces and bedding meet fault plane.

one wall with respect to the other and are therefore surfaces of discontinuity. Such a concept of faulting implies many different values and orientations of slip.

In striving to find the net-slip of a fault it is therefore essential to visualize the geology in terms so that offset lines occur to the imagination. Certainly one of the most satisfactory ways to expedite such work is to construct cross sections in the plane of the fault, as has been done here for Figures 6, 7, 9, 10, 11, and 13.

Separation

Throughout the preceding discussion emphasis has been placed on the determination of slip in three-dimensional space. We have been concerned with general cases where the slip has any direction within the fault surface and need not be exactly down the dip (dip-slip) or along the strike (strike-slip). It is now clear that at least two major difficulties face us in dealing so precisely with faults in practice.

1. Not always do we have enough data to provide us with "lines." Many of the types of structures dealt with above are uncommon. Too frequently, the best we can hope for is "planes." Perhaps our terrane consists of sedimentary rocks only, in piles of strata of relatively uniform thickness. This is the kind of terrane worked in by most geologists, especially those in the oil industry. The geologic history of the area may be so simple that many of the complicating factors are absent, such as those responsible for the "lines" aforementioned.

2. Most of the data of geology are depicted in two dimensions rather than three. We commonly show our information on maps or sections, and through long practice, our nomenclature has grown up in two-dimensional terms. Here we crash head-on into our antiquated terminology for faults.

In continuing our discussion of faulting in simplified geometric terms, we appreciate immediately that most geologists work with piles of bedding planes cut by a fault plane. Any one of these bedding planes intersects the fault plane as a *trace*. Usually we lack a recognizable line in the plane of the bedding which we can find displaced on the other side of the fault. We have at hand only one plane cut and displaced by another. In fact, we are commonly dealing with three planes: (1) the fault plane, (2) the bedding plane, and (3) the plane of the map or section. Often as not, the displaced bedding plane has a different strike and a different dip on the two sides of the fault, and so we are actually concerned with four planes under these conditions (Fig. 8). And so immediately more difficulties face us, and we can not even define the geometry in simple terms, much less evolve a satisfactory nomenclature.

Reid *et al.* (1913, p. 169) defined the separation as "the distance between the *surfaces* of the two parts of a disrupted bed, vein, or of any recognizable surface, measured in any indicated direction." In geometric terms this is the distance between the traces of the displaced plane on the two sides of the fault and measured on the map or section under consideration. We must designate as well the direction in which we measure the separation. In Figure 8 an example of a general

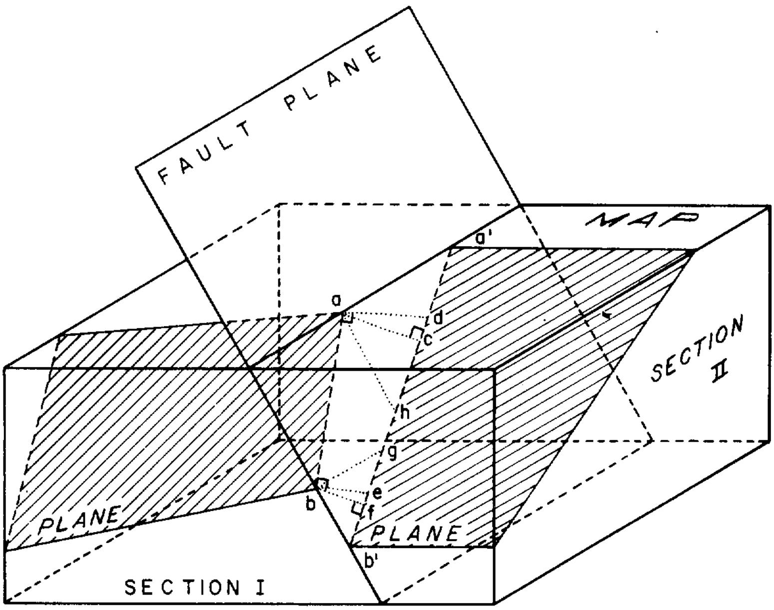

FIG. 8.—Isometric block diagram showing several kinds of separation. Reference bedding plane, cut by fault, has different strike and dip on the two sides of fault. Front surface of block diagram (Section I) is perpendicular to fault strike-line. *aa'* = Strike separation on map level (horizontal surface of block diagram); *bb'* = Dip separation on Section I; *ah* = Dip separation through a ($ah \neq bb'$); *bg* = Strike separation through *b* and *g* ($bg \neq aa'$); *ac, ad, be, bf* = Separations perpendicular to one trace of bedding on fault, but not perpendicular to other (these separations have little, if any, significance).

case is illustrated where there are several "separations," each one of which has to be carefully defined. In this example the dips and strikes of the separated parts of the bedding plane are different. In Figure 9 a special situation is depicted where the dips and strikes of the separated parts of the bedding plane are the same. Here the section is drawn in the plane of the fault, i.e., the plane of the paper is the fault plane. Beds on the distant or far wall of the fault are shown as dotted traces on our section and those on the near wall as solid traces. For this simple case there are three types of separations. 1. cd, the *strike separation*, or the separation between the traces of our plane along a horizontal line. This separation is usually of great significance because it is what first strikes the eye on looking at a geologic map although, as discussed below, the strike separation and the map separation are not strictly the same. It may be the only reliable information available on the fault. 2. ef, the *dip separation*, or the separation between traces of our plane along a line directly down the dip of the fault plane. This is the separation which will appear in a vertical cross section, provided the section is perpendicular to the strike-line of the fault plane. Most cross sections, however, will show the apparent dip of the fault rather than the true dip, so that the separation depicted on the section will be different from the true dip separation. 3. ab, again referring to Figure 9, is the separation between our two traces in a direction perpendicular to them. For this special case, where faulting has displaced our reference bedding plane in such a simple manner that the two parts of the displaced plane are parallel, this kind of separation has some significance. In the general case, as shown in Figure 10, it does not. In Figure 9, a section drawn perpendicular to the fault plane and the two parts of the displaced bedding plane is parallel with the separation ab and is shown at the lower left. This auxiliary section shows the *stratigraphic separation*, a_1s_1, which is defined as the thickness of beds cut out or repeated by the fault. It may be noted that the stratigraphic separation can be shown only in a section which is perpendicular to the bedding and that many cross sections in practical geology are not. Note also that since we are dealing in this case with the distance between two parallel planes (the two parts of our bedding plane), any section perpendicular to both planes will show the *stratigraphic separation*. It is not necessary to select a section perpendicular to the fault plane as well.

But the example depicted in Figure 9 is not the general or ordinary case. As a rule the displaced parts of the bedding plane on the two walls of the fault will not

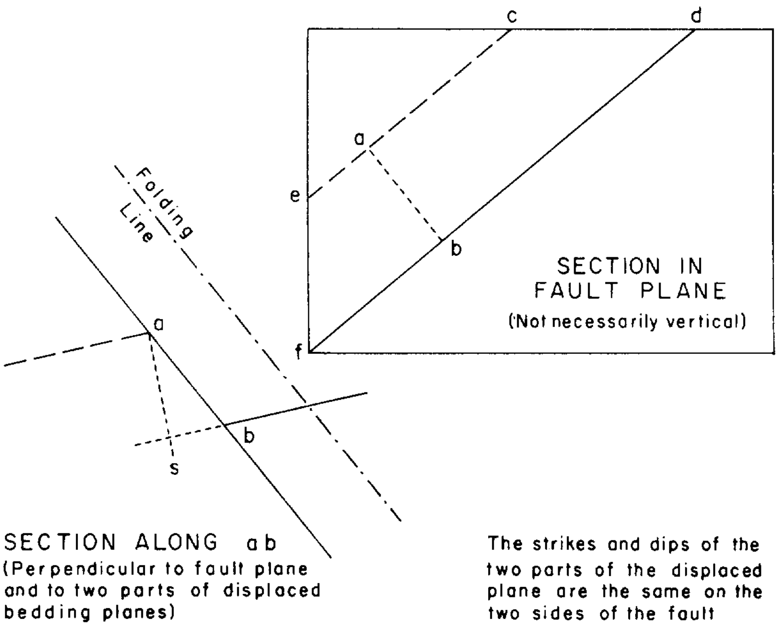

FIG. 9.—Section in fault plane showing separations where strike and dip of displaced plane are same on the two sides of fault. Auxiliary inclined cross section, perpendicular to both fault plane and the two parts of displaced plane is shown at lower left. *cd* = Strike separation; *ef* = Dip separation; *ab* = Perpendicular separation; *as* = Stratigraphic separation (this is defined as thickness of beds cut out or repeated by fault). Note that $ab \neq ef$. (In this fault-plane section the two traces (*ec* and *fd*) of displaced plane are parallel. Although this situation exists where strike and dip of the displaced plane are same on the two sides of fault, it can also exist for some special situations where strike and dip of the two parts differ.)

be parallel. Most faults die out in one direction or another and therefore can not exist, or possess displacement, without having the two parts of the disrupted stratum non-parallel. This means that we will almost always find that the two traces of our reference bedding plane on the fault surface will not be parallel. Such an example is shown in Figure 10, again a section drawn in the plane of the fault.

We note upon examining Figure 10, where the two traces are not parallel, that there are no general ways of defining *strike separation*, *dip separation*, *map separation*, and *stratigraphic separation*. These terms have meaning only if a particular position is first designated. The strike separation has to be tied to a selected level

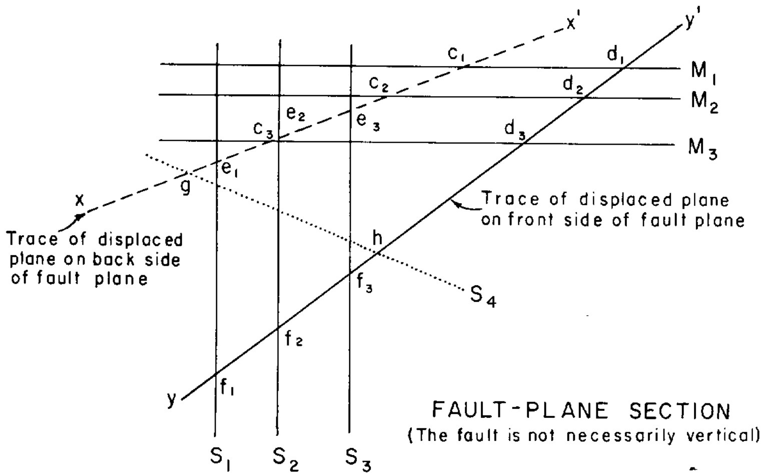

FIG. 10.—Section in fault plane showing separations where strike and dip of parts of displaced plane differ on the two sides of fault. Traces of displaced plane (xx' and yy') on fault plane are not parallel (see text).

to be useful. Hill (1947) has emphasized the use of the *separation shown on the geologic map* in his separation-based fault classification since it is one of the few measurements universally available. In Figure 10, if M_1 is the trace of a level near the level of the present-day geologic map on the fault plane, then the strike separation is c_1d_1. This differs from the separation along a horizontal line at deeper levels, such as those shown on M_2 and M_3 which give separations of c_2d_2 and c_3d_3 respectively. To be clear we need to resort to such phrases as: "strike separation at mine-level-300 feet," etc. Since a geologic map is a projection of an irregular surface, and is not a horizontal section, the map separation is not synonymous with "strike separation as shown on the map." On most maps, the two points separated (where the displaced plane meets the fault plane at the land surface) do not lie at the same elevation and therefore are not along the strike-line of the fault plane.

Reid *et al.* (1913, p. 173) defined other types of separations as follows. The "vertical separation is the separation along a vertical line." This quantity, in that it is not fixed with respect to the fault, would seem to have limited geometric usefulness, but in a well or shaft it is easily recognized. In using the term, therefore, the location of the vertical line needs to be clearly specified. We should see and hear such phrases as "the vertical separation in well so-and-so" more often than we do.

The "normal horizontal separation of a bed or other surface is its horizontal separation measured at right angles to the strike of the bed, etc." If it is determined at the surface of the ground it is usually the *offset* of the bed, and was so employed by Reid *et al.* (1913, p. 173). In the general case, however, where the strike of the displaced bed is different on the two sides of the fault, neither one of these terms has significance. For this reason, *offset*, as so defined, can not be used broadly. The separation shown on the geologic map at the fault, or more briefly the "map separation," is far more useful.

The use of the term *dip separation* poses a similar problem. This quantity will differ depending on what cross section is employed, although each must be perpendicular to the fault strike-line. In Figure 10 the dip separations for cross sections s_1, s_2, and s_3 are e_1f_1, e_2f_2, and e_3f_3, respectively. In these examples, the vertical cross sections S_1, S_2, and S_3 are perpendicular to the fault plane, but in practice many cross sections are not. In the latter cases an apparent vertical separation is shown. In Figure 10, such an example is shown by S_4 which is the trace on the fault plane of a vertical cross section not perpendicular to the fault surface. In the section, gh will appear as the apparent dip separation. It has little direct relation to the true dip separation through g on the one hand or through h on the other.

In view of all of these considerations, the term dip separation has no specific meaning unless we tie it to a particular cross section. And these cross sections will be of two types: those that are perpendicular to the strike-line of the fault-plane and those that are not. Only those vertical sections that are perpendicular to the fault strike-line show the *true* dip separation. For the larger group of cross sections which are not perpendicular to the fault strike-line we will need to use such phrases as: "the apparent dip separation as shown on cross section *B-B′*."

Here we do not describe and illustrate in detail the different kinds of planes or surfaces commonly encountered in geology. These are well known, so they are listed and commented upon briefly.

1. Bedding planes, including the tops and bottoms of sedimentary formations, thin markers or mappable beds, electric and radioactivity log correlation surfaces, etc.
2. Dikes, sills, flows, sheets, veins, etc., and other tabular igneous or volcanic bodies. If these have significant thickness in proportion to the scale of the geologic work, the contact surfaces, or, other reference surfaces, are of course employed.
3. Other rock contacts. Most contact lines on maps, sections, offsets, etc., are actually the traces of contact surfaces. Contacts between plutonic bodies, metamorphic units, metamorphic grades or facies, are examples from other than sedimentary terranes. Isograds are the map-traces of surfaces in metamorphic terranes separating rocks of different metamorphic grade. The displacement of such surfaces has been used by Kennedy (1946) in working out the 65-mile separation on the Great Glen fault in Scotland.

4. Unconformities.

5. Fold surfaces (axial and crestal). Cross sections may show, for example, the traces of the crestal or axial surfaces of folds. The fault separation of such surfaces may show up readily where we are sure of the correlation of the fold across the fault. Such a situation may afford us an opportunity to calculate slip if we can find the displaced line of intersection between the axial surface and some recognizable bedding plane (see foregoing).

6. Other surfaces. In geological work we frequently use lithofacies, mineral grain, paleontological, etc., data during regional analyses. Such features may show a distribution in the rocks with a "contact" surface, which under some circumstances can be used in arriving at fault separation. Boundaries between micropaleontological stages, such as the boundary between Mohnian and Delmontian stages in California Miocene rocks, provide examples. Facies within formations, or zones where distinctive clast-types are recognizable, may also give reference surfaces.

An ordinary geological situation which may bring out the differences in practice between separation and slip is illustrated in Figure 11. A plunging anticline is cut by a transverse fault. To begin with, let us assume that exposures in the field allow us to draw the map as shown and that subsurface data provide us with the dip of the fault. A cross section along *A-A'*, taken perpendicular to the fault strike-line, displays reverse separation. Many geologists would call this a reverse fault, since beds in the hanging wall have *apparently* moved up relative to the footwall. Cross section *B-B'*, on the other hand, displays a normal dip separation, and many geologists, seeing this cross section, would call it a normal fault inasmuch as the hanging wall has apparently moved down relative to the footwall. The trace of the crestal plane on the map shows a strike separation (*PP'*). A section drawn in the plane of the fault, *F-F'*, depicts the trace of beds on the near side as solid lines, and those on the far side as dashed. The two traces of the crestal planes are shown as well and depict the separation of these traces. This section, which is inclined to the vertical, discloses very clearly the way that fault separation of contacts changes from place to place along the fault. The traces of sections *A-A'* and *B-B'* are shown. Vertical cross sections drawn through the points *x*, *y*, *z*, would show no separations at these points, so that a geologist, looking at such a cross section would be hard pressed to justify the fault at all.

With all of these data in hand we can next proceed to determine the net slip. On each wall we have lines of intersection between contact surfaces and the crestal surface. Where three of these lines meet the fault surface we have three piercing points, *r*, *s*, and *t*. The corresponding piercing points, *r'*, *s'*, and *t'* lie on the other wall. Line-segments, drawn between any two of the points, *r* and *r'*, *s* and *s'*, or *t* and *t'*, give us the slip of the fault. Note that the slip has both a a dip-slip and a strike-slip component, and that the fault should properly be called an oblique-slip fault.

The example in Figure 11 serves to emphasize several things. 1. There is no obvious relation between separation and slip. On the map the separation differs in sense along the fault on the two sides of the trace of the crestal surface. In cross sections perpendicular to the fault strike-line the separation changes from place to place and even reverses its sense so that the "apparent displacement" is "normal" on one flank and "reverse" on the other. 2. It is obviously essential to have a system which will allow for clear expression of these relations. In cross sections *A-A′* and *B-B′* we need a terminology to describe these factors. If the geometrical relations observed are called an "apparent displacement" this is tantamount to using "separation," and it would probably be far less confusing to employ the latter.

If this example (Fig. 11) is imagined as a subsurface situation in an oil field under development, the data allowing full interpretation of the geometry will come in piece by piece as wells are drilled. During the period of drilling the extent and strike of the fault, its dip, and its relation to the fold axis may become known only gradually. Perhaps only after the field is fully developed and after many

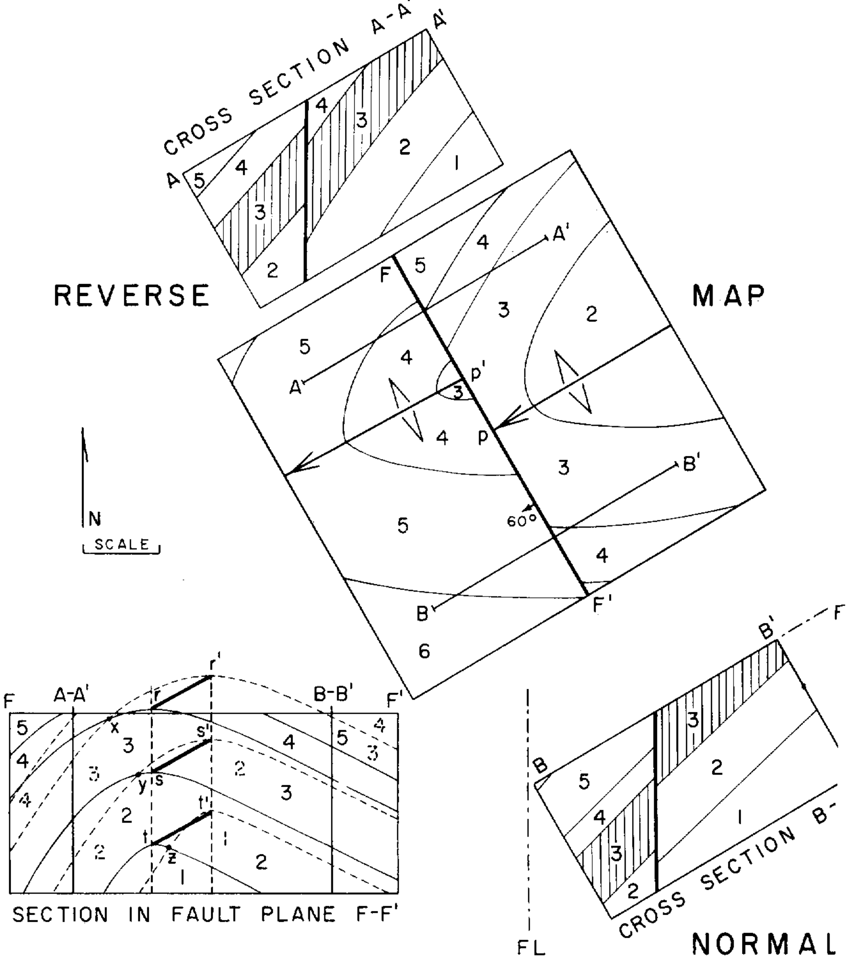

FIG. 11.—In center is simplified geologic map of area with plunging anticline cut by transverse fault. Two cross sections (*AA′* and *BB′*), drawn perpendicular to fault strike-line, are shown along with an inclined section in fault plane at lower left. These are laid out according to principles of descriptive geometry (*FL*=Folding line). See text for discussion.

years will it be possible to determine the slip. Until this time it is obviously desirable to have some useful terms at hand to describe the fault as the data accumulate. The only logical terms are those based on separation.

An intrinsic difficulty faces us in the concept of separation. The planes with which we are dealing are imagined as extending for considerable distances parallel with the fault and away from it. They lack marks or lines on them which show how they matched before they were displaced. In short, when thinking of separation, we imagine semi-infinite planes. Any point on the cut edge of the plane on one side of the fault may match with any point on the other. In dealing

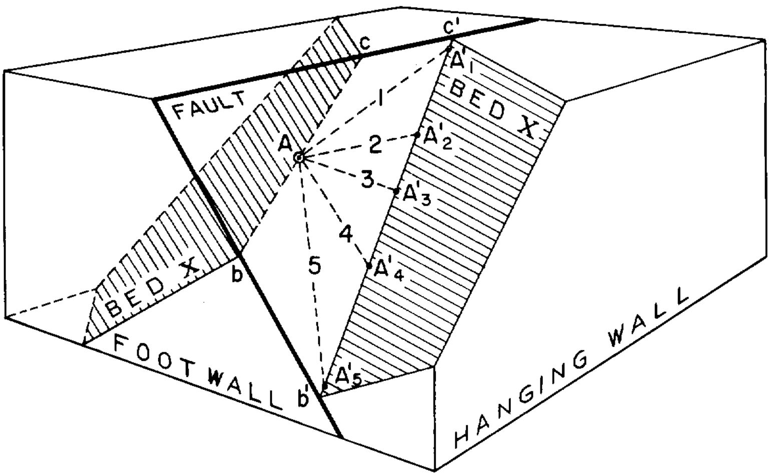

FIG. 12.—Perspective block diagram showing that given separations (*bb'* and *cc'*) can result from many possible slips (*A* to A_1', A_2', A_3', A_4', A_5', etc.). Strike and dip of Bed *X* differ on the two sides of fault. As there are no marks along cut edges of Bed *X*, there is no way to recognize which direction of movement (1, 2, 3, 4, or 5) took place. Note hanging wall had component of up-movement with respect to footwall for movement 1; that it moved laterally with movement 2; and that it moved with down-component for 3, 4, and 5. (Modified from Hill, 1959, diagram.)

with separation, we leave open the fixing of these points whereas in slip they are considered as discrete points whose positions are known. This characteristic of separation is brought out well in Figure 12, based on Hill's diagram (1959).

In our use of the terms, slip and separation contrast in other ways. For slip we visualize the movement of one side of a fault with respect to the other in three-dimensional space, and think in terms of the displacement of discrete points originally adjacent. For separation we see the displacement in two dimensions only as shown on a particular section or map. To use separation it is therefore as essential to define the view at hand as it is to describe the geometry of bedding and the fault. Slip, on the other hand, is independent in concept from the view, map, or section before us. Where we have a particular view only, however, such as a cross section, the displacement of one wall with respect to the other may appear to be reverse, for example, so we employ the adjective *apparent*, and refer to the fault as an *apparent reverse fault*. We must come to realize that in such usage we are dealing with separation. The word apparent means essentially: "in the two-dimensional view at hand the fault displacement appears to be reverse, but in three-dimensional space the displacement may be quite different."

Some geologists have fallen into the careless and incorrect practice of using the term *component* as synonymous with *separation*. The component of a quantity (scalar, vector, or tensor) is less than the whole, whereas many separations are far greater than the net slip (Fig. 12). Such usage of component further involves the mixing of dissimilar concepts, i.e., confusing a displaced plane with a displaced line. We ought to reserve the term for parts of the slip in chosen directions, such as the dip component of slip, or for parts of a particular separation.

In summary, it is clear that geologists must learn to realize instinctively the differences between the solid geometry of slip, where we deal with displaced lines, and that of separation, where we deal with displaced planes and lack recognizable lines lying in these planes. We therefore now must ask ourselves: to what extent do our present terminology and usage allow us to make these distinctions?

Fault Terminology in Use

The Reid *et al.* (1913) report on the nomenclature of faults was the culmination of several years of discussion, and a preliminary version was widely circulated for comments among the profession. The subject came up for consideration when it was realized that many faults had a strike-slip component, and therefore that a classification based on the assumption of dip-slip only was incomplete and illogical. On the whole geologists in this country have followed the recommendations of the Reid report and most textbooks in structural geology phrase their definitions in similar terms (Billings, 1954; Nevin, 1949). In 1941 a Canadian committee under J. E. Gill examined the problem again; some of their recommendations are referred to here.

It is clear throughout the paper by Reid *et al.* (1913), that the differences between slip and separation were in their thinking. On p. 174 they stated:

> "It is extremely important clearly to distinguish between the slip and shift and the separation. The first two refer to the actual relative displacement of the two sides of the fault, the last to the relative displacement of the surfaces of the two branches of a dislocated bed, etc. Movements of one side or of both sides of the fault parallel with the plane of a bed would not alter the separation of the bed, but would materially alter the slip and shift."

However, they did not take a firm position because on pages 177 and 178 they recommended that normal and reverse be retained in their former usage without definite distinction between separation and slip.

The diagram of Hill (1959) modified here as Figure 12, emphasizes these geometric points and clearly shows that many different orientations of slip can result in the same separation. It also demonstrates that an observed separation can be very much greater than the net-slip or any of its components. In fact, it emphasizes that there is no simple relation between separation and slip.

THROW AND HEAVE

Reid *et al.* (1913, p. 175) dealt with the distinctions between slip and separation when they considered definitions of "throw" and "heave." After discussion they advised that the two terms be restricted "to the displacements of the ends of a disrupted stratum." It is therefore clear that they were thinking in terms of disrupted planes, or in terms of separation. They also realized that it was necessary to define the particular vertical section in order to give the terms "heave" and "throw" significance. Paraphrased here, they measured throw in a vertical cross section perpendicular to the fault strike-line and defined it as the vertical distance between the points on the cross section where the disrupted stratum met the fault plane. *Heave,* also paraphrased, was defined as the horizontal distance between these same points and measured in the same cross section. These quantities are shown clearly in their Figure 2.

In the general case, however, where the strike and dip of the displaced stratum differ on the two sides of the fault, the quantities throw and heave differ from

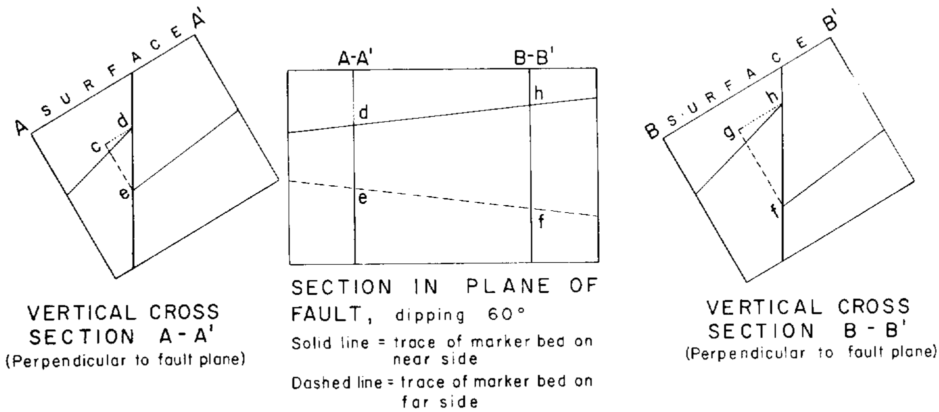

FIG. 13.—Sections showing that throw and heave differ from cross section to cross section where strike and dip of displaced plane differ on the two sides of fault. *ec* and *fg* = Throw; *dc* and *gh* = Heave; *de* and *hf* = Dip separations.

cross section to cross section (Fig. 13). Under these conditions it is essential to designate the vertical cross section in which they are measured. This limitation renders the terms of doubtful usefulness for any faults other than for simple strike faults in relatively flat-lying or uniformly dipping strata. In view of these inherent difficulties with throw and heave, many geologists have abandoned their use. It would seem sensible to follow the recommendation of the Gill committee (Gill, 1941), and drop the terms. If such measurements serve a purpose they may be synonymously expressed as the vertical and horizontal components of the dip separation. This recommendation, where the cross section under consideration is clearly designated, would not lead to ambiguity (Fig. 13), provided the cross section is perpendicular to the fault strike-line.

NORMAL AND REVERSE

Considerable ambiguity clouds the precise meanings and use of the terms *normal* and *reverse* (Reid *et al.*, 1913, pp. 177–78). After pointing out that these terms were originally used for strike faults, Reid *et al.* recommended their extension to diagonal and dip faults as well. Their Figures 7 and 8 demonstrate clearly that slip in one direction may result in an "apparent movement" in another. In short, "reverse" slip may result in "normal" separation, which has been brought out here in Figures 11 and 12. They accordingly recommend that the terms normal and reverse be employed for purely descriptive purposes or "apparent displacements," without indicating extension, contraction, or character of forces, which is usually the same as restricting their use to separation as seen in a vertical section. However, they did not specifically redefine normal and reverse faults according to aspects of separation. Gill (1941, p. 78), on the other hand, states that "one should never describe a fault as normal or reverse unless the direction and sense of the net relative movement between the walls is known positively." Instead, they recommended that the terms be applied as follows (p. 79).

"A faulted body shows a normal dip separation when, in the dip plane of the fault, its hanging-wall trace lies below its footwall trace" . . . and "a *reverse dip separation* when, in the dip plane of the fault, its hanging-wall trace lies above its footwall trace."

They are therefore advocating a dual use of the adjectives normal and reverse: (1) if modifying the fault, then slip is dealt with, and (2) as a modifier of the separation. Billings (1954), p. 143) defines a normal fault as "one in which the hanging wall has apparently gone down relatively to the footwall," and a reverse fault with similar wording. In employing the qualification "apparent," he is dealing with separation and not slip. Hill (1947, p. 1671) has used the terms in the separation sense. It is clear that Billings (1954) and Hill (1947) are defining the terms in essentially the same manner, and are actually following the recommendations of Reid *et al.*, with respect to the extension of the words to diagonal and dip faults.

For clearness, several courses are open to us, short of abandoning the terms and setting up new ones. 1. We can admit that *normal* and *reverse* are separation terms and are not connected with slip. This means that they have no implications as to shortening or extension (as was pointed out by Reid *et al.*, 1913, p. 178). 2. We can follow Gill (1941, pp. 78–79) and use normal and reverse as adjectives to modify faults on the one hand or separation on the other. If applied to faults, that is, a "normal fault," then the slip is known. If the slip is not known, and separation only is observed, they recommend such a construction as "normal separation of the fault." 3. We can follow Hill (1959) and use normal and reverse as separation terms but if we know the slip, add the word with "slip": i.e., normal-slip fault, reverse-slip fault. 4. Another course open to us is to hyphenate the words normal and reverse with both separation and slip depending on which is appropriate. This would result in two groups of terms so that a fault would be a "normal-separation fault" or a "normal-slip fault." Admittedly these word constructions are somewhat cumbersome, and phrases like a "fault with normal-separation" might be more acceptable. This practice would be unambiguous provided one recognizes that a single fault may, for example, possess normal-slip and yet have parts that show both reverse and normal separations (Fig. 11). Under such circumstances, where the slip is known, the slip designation would certainly be employed and stressed.

Hill (1959), to emphasize the distinctions between separation and slip, recommends the adoption of a dual system of fault nomenclature. He suggests that geologists first name faults on the basis of separation. If the data are sufficient, however, these names would be supplanted by slip-based terms that would stand out clearly because of the hyphenation with the word slip, i.e., normal-slip fault. These recommendations are the outgrowth of a suggested classification of faults (1947) based on separation which has not been very widely accepted, presumably because many geologists consider it too much of a departure from prevailing usage or somewhat ambiguous. Perhaps they failed also to grasp the importance of the points that Hill (1947) was emphasizing: (1) in many cases the only data available for naming a fault are the data on separation (apparent relative movement), (2) that it is inaccurate and careless to apply names implying slip (actual relative movement) in many cases, and (3) practicing geologists need honest labels to apply to faults while they are working on them and until slip-based terms can be employed. He stressed as well that ambiguities in fault terms concealed many useful facts concerning fault kinematics.

In setting up his separation-based classification Hill (1947) used in addition to normal and reverse the terms thrust and right and left lateral. He restricted *reverse* to faults which dip more than 45 degrees and applied *thrust* to any fault which dips less than 45 degrees and shows dip-separation and apparent horizontal shortening. He applied the term *lateral* to faults which show a strike separation in map view. These can be grouped into those that are either *right* or *left* depending on the sense of the separation on the block opposite the observer. He further suggested that faults be described in terms of the two views commonly available: the geologic map and a vertical cross section perpendicular to the fault strike-line. By combining words giving the *dip-separation* and the *map-separation* much accurate observational information could be honestly conveyed. Combinations such as "right lateral reverse" and "left lateral normal" are purely descriptive of these two types of separations. Note that the word "lateral," which has been widely adopted, especially in California, applies to separation and not slip. It is therefore not synonymous with "strike-slip" and should not be used interchangeably with it in referring to great faults such as those in the San Andreas system.

The phraseology employed in our fault definitions is unnecessarily complex and appears to place emphasis on points that are seldom confusing. Students tend to concentrate upon simple concepts which rarely cause misunderstanding, and as a consequence, fail to grasp significant differences. Inasmuch as all fault displacements are relative this qualification should perhaps be dispensed with initially and then not allowed to clutter up subsequent definitions. For example, a fault might logically be defined as a fracture along which there has been relative displacement. Perhaps too much emphasis has also been placed on the words actual and apparent, and the phrases "actual relative movement" and "apparent relative movement" may be confusing, especially to students. If the emphasis is placed on the synonymous terms, slip and separation respectively, the cumbersomeness disappears. For example, we need to decide whether a normal fault is one that possesses normal slip or one that displays normal separation in a particular cross section. Definitions of normal fault or reverse fault in such terms would be quite clear, if slip and separation are first adequately defined and comprehended. Indeed, it may even be desirable to introduce new terms in order to prevent ambiguity by re-defining old and well established terms.

An objective classification of faults obviously needs to be based on geometry first. Such a geometric classification need not, however, be considered an end in itself but as fundamental to the clear description of fault relations. Here it seems that our nomenclature has failed us. Geometric information on faults given in terms of separation adds no direct data on the way that crustal blocks have moved inasmuch as there is no relation between separation and slip. We therefore must apply slip-based terms before we can hazard statements concerning kinematics. Such understanding is of course prerequisite to comments on dynamics or genesis. In a logical scientific approach to faulting it is impossible to avoid any of these steps in our analysis. For this reason, it would seem better to avoid terms with a strong genetic implication, like gravity fault (Billings, 1954, p. 195), for a fault with normal slip. Our objective in structural geology is certainly to arrive at a genetic analysis of deformation, but we are delaying our arrival at this high degree of understanding by incorrectly applying genetic labels.

Summary and Recommendations

This discussion has been written primarily to emphasize the necessity for recognizing more widely the fundamental differences between separation and slip. We must habitually distinguish between geological situations where we have displaced lines and can determine slip and those where we have only displaced planes without recognizable lines lying within them and are therefore forced to restrict our observations to separation. Without precise terminology our thinking is confused and we can not describe faults honestly and accurately.

As a rule, the first or only descriptive information on a fault is in terms of separation, and unfortunately this information is often phrased carelessly in terms of slip. All geologists recognize in theory that there is little relationship between separation and slip but in practice many fail to draw the distinction sharply. It is indeed dishonest to apply a slip term carelessly and thereby imply more knowledge than is known about the fault, and it is to our discredit that kinematic and dynamic conclusions concerning tectonics have been based on such erroneous practices. Until slip can be determined, however, which is impossible for most faults in practice, geologists need fault terms. These logically can be based only on separation. Another distressing result of the lack of distinction between separation and slip is that many geologists have failed to determine slip when they had the data before them. Our inadequately defined terms have misled them into thinking erroneously that they had indeed found out how one block had moved with respect to another.

Structural geologists stand before a cross-roads much like that in front of the stratigraphers about two decades ago. Concepts in stratigraphy were confused until rock units, time-rock units, and time units were recognized formally. We should now grasp the opportunity to make progress through the insistence that the fundamental distinctions between slip and separation become basic to our fault descriptions. A qualified committee within the profession should examine our fault terminology, perhaps under the auspices of the A.A.P.G. or the Geological Society of America. The recommendations of such a committee ought to clear up ambiguities in our concepts and definitions and stimulate us toward more precise understanding of faults.

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