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D. K. Norris

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ABSTRACT

A mesoscopic analysis of three extension faults exposed in the roof of Number 4 coal seam, Canmore, Alberta, has revealed that the fault surfaces are manifestly not planes. Moreover, the acute angle between the faults and the layering varies somewhat systematically but does not necessarily increase from the centre line toward the extremities of the faults. The net slip varies erratically along the length of the faults in a manner believed to exist in similar structures on a megascopic scale, and the line of maximum net slip is not necessarily equidistant from the extremities of the faults. The pitch of slickenside striae on a given fault varies systematically from shallow toward the extremities to steep toward the more central regions indicating significant lateral slip and normal slip on one and the same fault surface. A crude mathematical model confirms the need for lateral slip of the relatively active block toward the extremities and normal slip at the centre of even the simplest fault.

STRUCTURAL ANALYSIS OF THREE EXTENSION FAULTS IN NUMBER 4 MINE, CANMORE, ALBERTA

Introduction

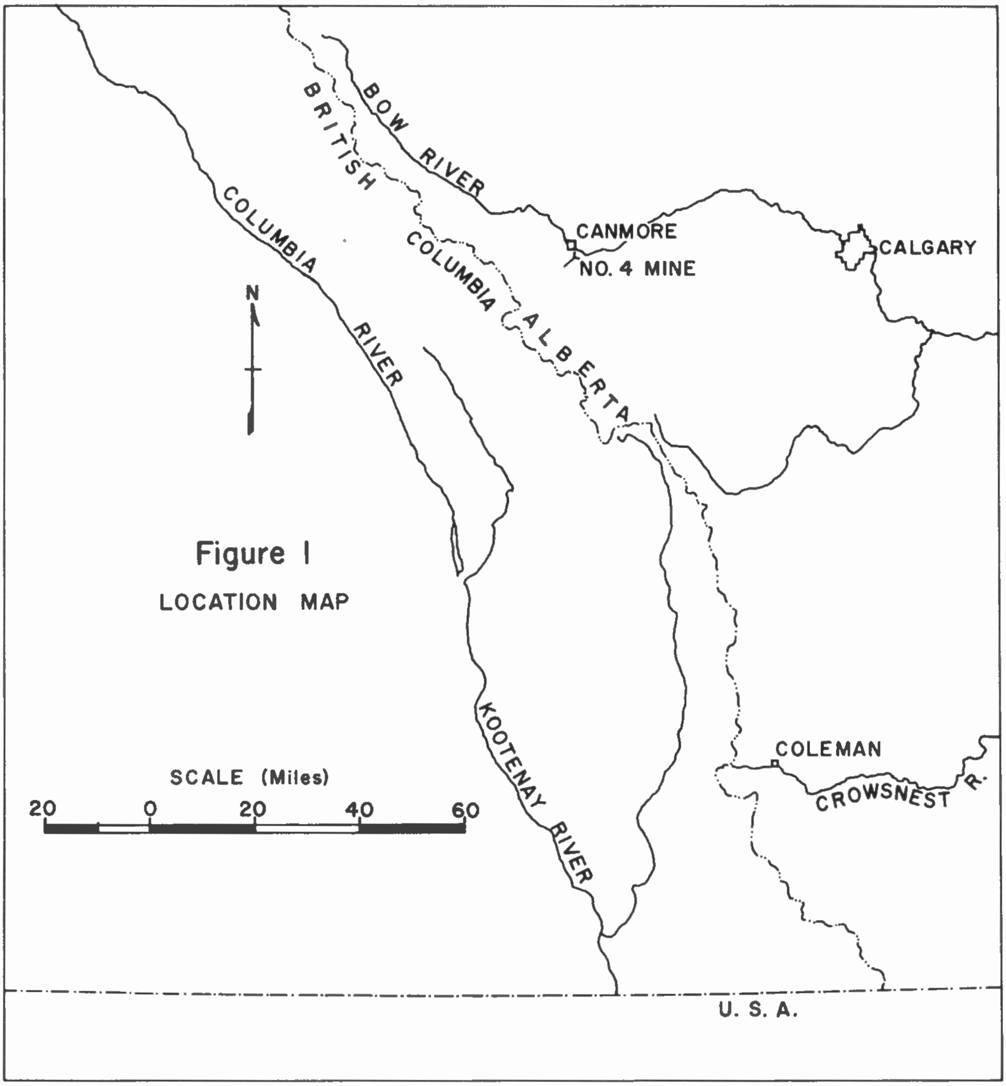
In spite of the increasing number of analyses on the mesoscopic and megascopic scale of geological structures in anisotropic, layered media, there is a dearth of quantitative data on the nature and genesis of many of the structural elements contributing to the various subfabrics. Consequently, kinematic and dynamic analyses based on one or two observations on each occurrence of a given element throughout a structure may lack foundation.

An objective of the present study was to examine in detail one of these elements, extension faults, as they occur in Number 4 Mine, Canmore, Alberta (Fig. 1) in the eastern Cordillera of Canada. There they are occasionally completely exposed at a given stratigraphic level so that one can assess the intrinsic value of one or two observations in relation to the overall geometry, kinematics and dynamics of the fault.

One can then compare the mechanics of extension faulting on the mesoscopic scale with similar small scale phenomena arising in uniaxial and triaxial studies of geological materials and in sand box experiments. The knowledge from these comparative studies may be of value in the mapping, interpretation, and regional relations of such features on the megascopic scale.

The term extension fault as used in this paper is as defined in Norris (1958, p. 14, and 1964, pp. 386, 387). The fundamental reference surface is therefore the layering. In order to compare observations on any given fault surface with those in the same relative position on another fault, the following convention has been arbitrarily adopted: if one were to stand on the relatively depressed block and to face the uplifted block, the left hand extremity of the fault will be to the left and the right hand extremity to the right. Thus, for a north-trending fault with its depressed block to the west, the left hand extremity would be to the north. The intersection of the fault with the layering at some specified stratigraphic level will be referred to as the lips (deSitter, 1961, p. 151). The position of any surface element on the fault is given in terms of the distance along the lip of the fault, measured from left to right from the left extremity or from some specified point and is referred to as the strike distance. The line joining points on the fault equidistant from the extremities will be the centre line.

For convenience in comparing observations on different surface elements along a given fault, a mean planar fault surface may be established. Pitches of slickenside striae are therefore rotated to the values they would assume on this mean surface so that the direction of relative motion at various strike distances can be compared. B.K. Bhattacharyya, of the Geological Survey of Canada, programmed the equations for the solution of the fault model on the computer and assisted in the interpretation of the results. Grateful acknowledgment is made to the management of Canmore Mines Limited, Canmore, Alberta, for making this study possible; their continuing assistance and cooperation are deeply appreciated.


BOW RIVER
BRITISH
COLUMBIA
ALBERTA
CANMORE
NO. 4 MINE
CALGARY
COLUMBIA
RIVER
N
Figure 1
LOCATION MAP
SCALE (Miles)
20 0 20 40 60
KOOTENAY
RIVER
COLEMAN
CROWSNEST R.
U. S. A.

Local Geology

The coal-bearing Jurassic and Lower Cretaceous Kootenay Formation in the Cascade Coal Area (MacKay, 1946) occurs in northwest-trending Mount Allan syncline, a prominent asymmetrical structure in the Lac des Arcs thrust sheet. It is overlain by southwest dipping Mount Rundle fault which has Cambrian, Devonian, and Mississippian formations in its hanging-wall. Coal mining has been limited to the northeast flank of the syncline where dips commonly range from 10 to 30 degrees.

Number 4 Mine is situated in Number 4 seam, approximately 1,400 feet stratigraphically above the base of the Kootenay, and within interbedded sandstone, shale, and conglomerate. This low volatile bituminous to semi-anthracite seam averages about 10 feet thick and where undisturbed by faulting is planar to curviplanar (see Norris, 1956, Fig. 1). Locally, however, the seam is cut by groups of faults with a common trend; some groups parallel the tectonic strike, others trend as much as 90 degrees to it. Most of these are extension faults.

Number 4 seam is virtually unsheared except at the interfaces of the coal with roof and floor rock; the primary depositional features and the fracture fabric are commonly well preserved. Unfortunately, the mine was closed in September, 1964, so that investigations initiated there must now be continued in other mines in the area.

Plate I. Extension Fault No. 2, A Gangway East, Number 4 Mine, Canmore, Alberta.

Figure 2

Poles to Surface Elements of Extension Faults and Sedimentary Layering

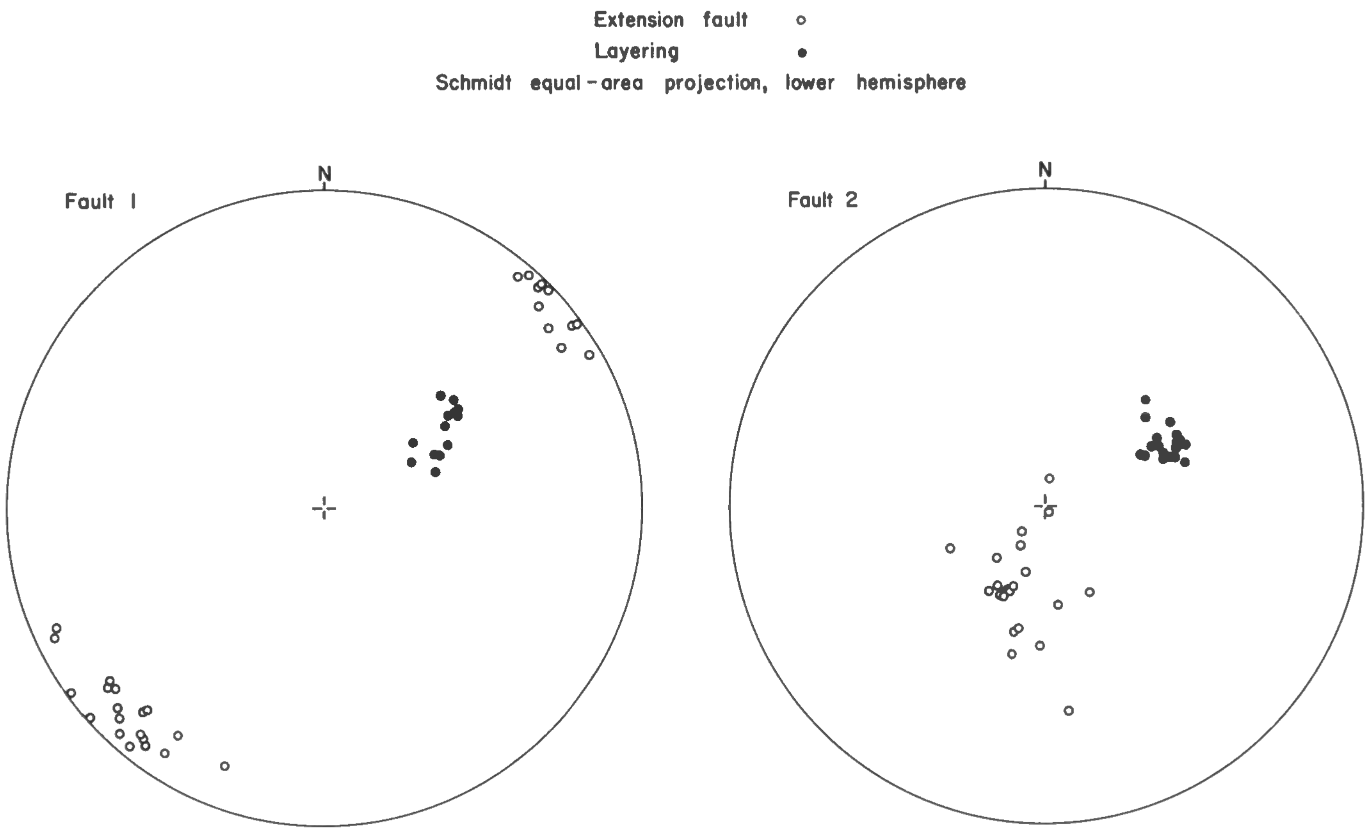
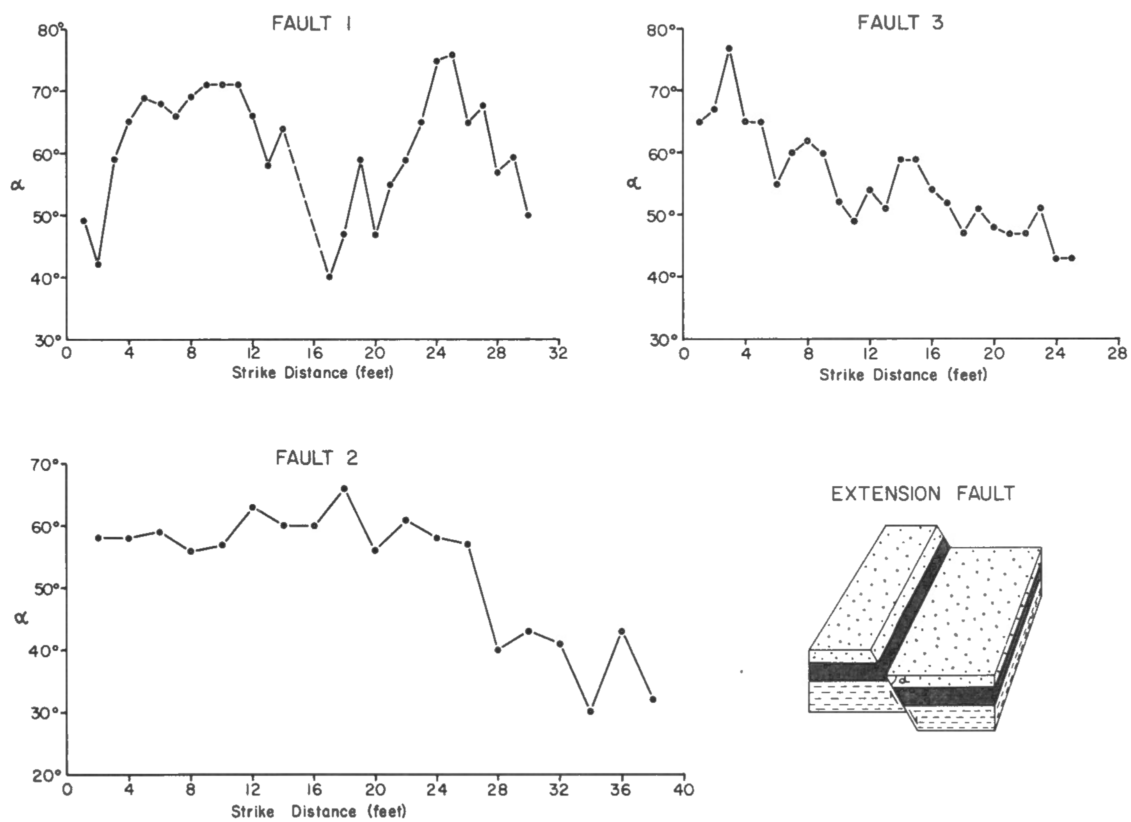


Figure 3

RELATION BETWEEN ACUTE ANGLE OF CUT OFF (α) AND STRIKE DISTANCE FOR EXTENSION FAULTS



Structural Analysis

A detailed structural analysis was carried out on three extension faults exposed in the roof of "A" Gangway immediately southeast of the Main Slope in Number 4 seam. One of these extension faults (Number 2) is shown in Plate 1. Here the relatively depressed block is to the left or northeast. Note the complete exposure of the fault at the stratigraphic level of the interface of the coal and roof rock and the abundance of slickenside striae.

These faults are roughly parallel to "A" Gangway so that in one instance it was possible to study a fault from one extremity to the other and in the other two to study them from one extremity to where they were cut off by other extension faults trending at acute angles to them. The structural continuation of these three faults through the coal and into the floor rock was not evident because the floor rock was largely covered by unmined coal. The roof rock in this part of the mine is a thick-bedded, carbonaceous, silty mudstone which was not observed to change in lithology within the area under examination.

Variations in three principal attributes of the faults were investigated as functions of strike distance: the angle of intersection of the fault with the layering (the cut-off angle), the net slip, and the pitch of slickenside striae. For the purposes of this paper the faults will be referred to respectively as Faults 1, 2, and 3. The depressed blocks in Faults 1 and 3 are to the southwest so that their left hand extremities are toward the northwest; Fault 2, on the other hand, has the depressed block to the northeast so that the left hand extremity is by convention to the southeast. All three attributes were investigated in the case of Faults 1 and 2 whereas only the variation of net slip with strike distance was measured on Fault 3.

The orientation of the bedding and the fault were measured at regular intervals of strike distance for Faults 1 and 2. The poles to these elements, plotted in equal-area projection in Figure 2, indicate the amount of variation in the orientation of the bedding and fault surfaces. Whereas the bedding attitudes range through a solid angle of about 0.05 steradians, the fault attitudes range through a solid angle of 0.15 steradians. The bedding and fault surfaces are therefore not planes, but are moderately to highly irregular in form. By inspection the mean bedding attitude adjacent to Fault 1 was 328°, 36°SW and adjacent to Fault 2, 334°, 35°SW. The mean surface for Fault 1 was estimated to be 316°, 88°NE and for Fault 2, 294°, 22°NE.

The moderately wide variation in attitude of fault surface elements in conjunction with the relatively more constant attitude of corresponding bedding surface elements means that the angle of cut-off of the layering is variable along a fault.

To assess the nature of this variation, the acute angle between the fault and the layering was measured systematically as a function of strike distance at the coal-roof rock lip of the relatively depressed block for the three faults. From the data plotted in Figure 3 it is evident that there is no general relation between angle of cut-off and strike distance applicable to all three faults. For any given fault, however, the angle varies irregularly from point to point but there would appear to be a systematic variation simply because each fault is a physically continuous surface. On Fault 3 for example, there is a progressive decrease in the angle of cut-off from about 70° and 50°. These observations are in contrast to the generalization of deSitter (1961, p. 157) based in part on Lahee's intensive study of the Mexia and Tehuacana fault zones in Texas. There Lahee (1929, p. 352) from abundant subsurface control derived from oil and gas exploration observed that there is a tendency for the normal fault surfaces to steepen towards the ends of the oil fields; but whether the faults end at the limit of mapping is not proved.

Although the acute angle of cut-off is observed to vary between 30 and 77 degrees among the three faults studied in detail in Number 4 Mine, the average is slightly less than 60 degrees and is consistent with the statistical average for that mine and for some 800 faults studied in coal mines in various parts of the eastern Cordillera.

The variations in net slip on the three faults, measured in the direction of slickenside striae between the lips at the coal-roof rock interface are plotted in Figure 4. By convention the measurements are plotted from left to right and the lip of the relatively uplifted block is used as a straight line datum. The net slip of the depressed block is observed to have more than one maximum and to vary erratically along the lengths of the faults. In so far as Faults 1 and 2 are offset by other extension faults, measurements of net slip could only be taken to strike distances of 30 feet in both instances. Only fault 3 had its two extremities exposed. There the net slip increases slowly from left to right and has a maximum value of 14 1/2 inches at a distance of three feet from the right extremity. The maximum displacement is not at or near the centre line of the fault and the change in displacement is not symmetrical about the maximum.

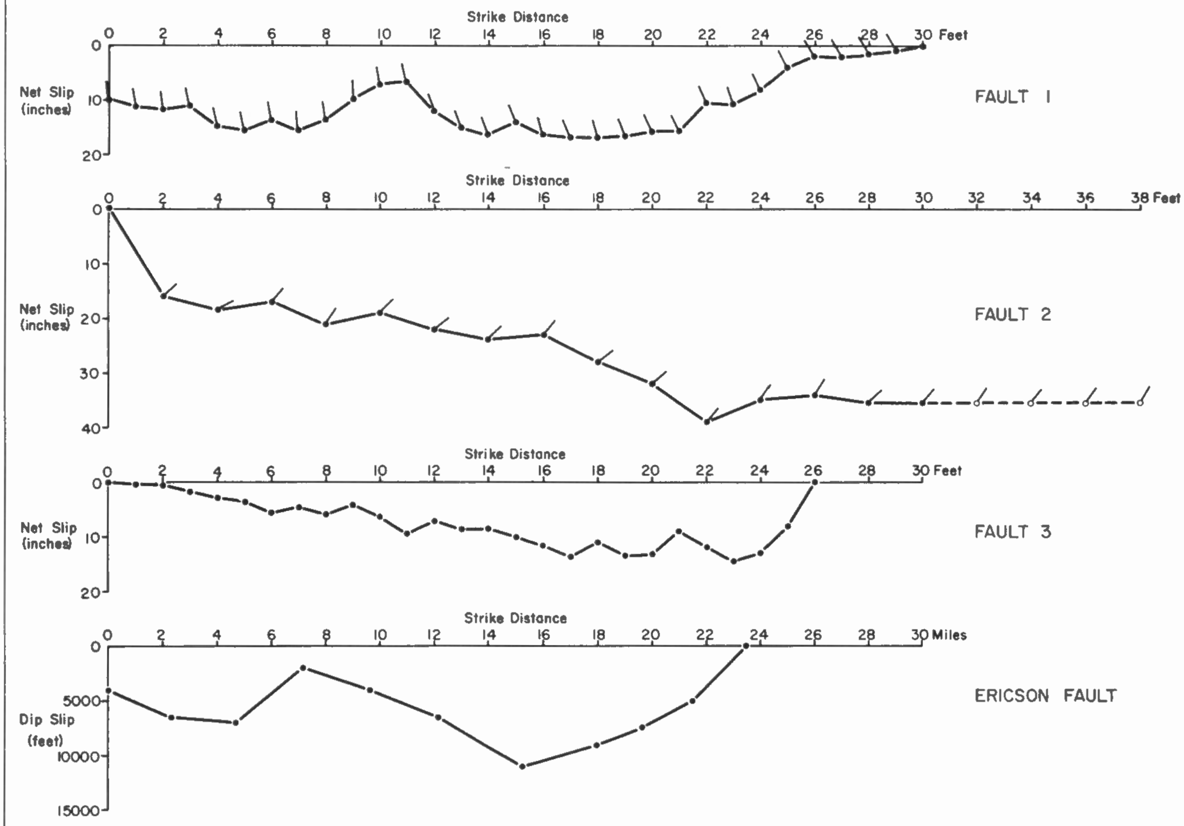
It is not known whether the centre lines were observed in Faults 1 and 2 so that nothing can be deduced about the symmetry of displacement on the faults. It is apparent however that the net slip increases considerably more rapidly from the observed left extremity of Fault 2 than from the right extremity of Fault 1 and that there is more than one point of maximum displacement along the lengths of both faults. A comparison of Figures 3 and 4 indicates moreover that for each of the faults there is no relation between net slip and angle of cut-off of the sedimentary layering.

It is difficult if not impossible to test whether scale is a factor in the variation of net slip with strike distance because little or no published data on net slip are available for megascopic extension faults. In so far as the variation in net and dip slip with strike distance for each of these mesoscopic extension faults was nearly identical, it was deemed feasible to compare these net displacements with dip slip estimates derived from serial sections of Ericson Fault (Price, 1962, Fig. 2), a megascopic, north-trending, 'normal' fault in the Lewis thrust plate of the southeastern Cordillera of Canada. There the relatively depressed block is to the west so that its left extremity is to the north. Although the scale is about five thousand times that of the other three faults, the erratic variation of dip slip with strike distance from the northern limit of mapping is apparent (Fig. 4). There would moreover appear to be two maxima within this distance and the general behaviour of the fault would appear to be not unlike that of features of considerably smaller scale.

Figure 4

RELATION BETWEEN NET OR DIP SLIP AND STRIKE DISTANCE FOR EXTENSION FAULTS

(Direction of Slickenside Striae on Mean Fault Surface /)



Displacement of an extension or normal fault produces an elongation of the layered medium in the direction perpendicular to the strike of the fault. In addition there may be elongation parallel to the strike.

If it may be assumed that the extremities remain a fixed distance apart, changes in shape of the lips of the fault in response to relative motion would require elongation of the layering in the direction parallel to the strike. The fact that the lips at the coal-roof rock interface are demonstrably continuous throughout their length means that the assumed elongation is certainly not accomplished through motion on one or more mesoscopic extension faults perpendicular or subperpendicular to the trend of the main fault. This elongation could be accomplished however through the opening up of fractures pervading the rock mass prior to faulting.

Measurements of the pitch of slickenside striae at regular intervals of strike distance suggest that motion and deformation of the relatively depressed block is accomplished by kinematic activity on bedding surfaces rather than by differential motion on discrete, periodically repeated displacement discontinuities perpendicular and subperpendicular to the trend of the fault. On Faults 1 and 2 there are measurable strike slip components of the relatively depressed block toward their respective extremities and there are progressive decreases in this component as one moves away from the extremities (see Fig. 4)[1]. If displacement and deformation were accomplished in a manner similar to the mechanics of slip folding one would expect all slickenside striae to indicate normal slip; such is not the case. The data would suggest that displacement of the various surface elements of these extension faults are interrelated and the bedding surfaces maintain continuity along the length of the fault. The assumed elongation parallel to the trend of the faults could be accomplished therefore by the opening of joints in existence prior to faulting.

Theoretical Considerations

In view of the above conclusions let us consider an ideal situation of an extension fault developing in a horizontally layered medium with gravity being the greatest principal compressive stress and with the relatively depressed block the active one; the geometry of the uplifted block is therefore considered unmodified by the motion on the fault. A crude, two-dimensional model representing the progressive cumulative strain of the lip of the fault at every instant is a catenary, a curve formed by a cable of uniform weight suspended freely between two points (Fig. 5). If near-equilibrium conditions are maintained at all times during motion on the fault, the shape of the lip will remain constant.

The lip of the depressed block will increase in length as the motion on the fault increases. If it is assumed that this increase in length is spread uniformly along the fault, the kinematic paths of individual elements along the lip of the relatively depressed block can be estimated by dividing the lip

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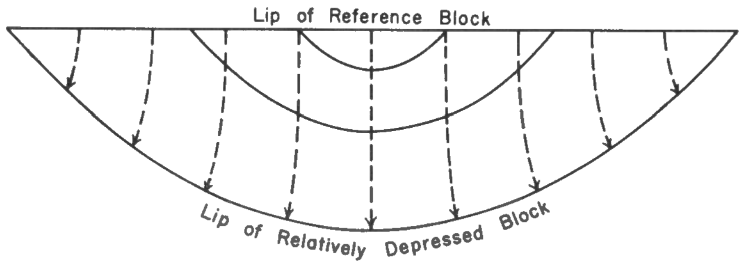
[1] If the relatively uplifted block was considered the active one, the slickenside striae would suggest motion of the active block away from the extremities.

Figure 5

Stages in the Growth of a Planar Extension Fault
with
Assumed Kinematic Paths of Surface Elements



of the reference block and of the depressed block in its final position into the same number of equal parts. Curves joining corresponding points portray the paths of these elements.

These paths are curves of unknown form which degenerate into a straight line for those elements which lie along the centre line of the fault. There is normal slip along the centre line and oblique slip symmetrically disposed about it simulating directions of motion observed on the extension faults.

A comparison of Figures 4 and 5 will emphasize the highly idealized nature of the model, particularly with respect to the lack of symmetry of net slip about the centre line that is observed in the mine. Inherent in the assumptions on which the model is based is that each fault initiates at its centre line and that its growth laterally is intimately associated with the magnitude of dip slip along the centre line. Variations in the elastic parameters and in the spacing of the fractures in existence prior to faulting would contribute to the irregular variation in net slip along strike and to the existence of more than one maximum value of net slip on a given fault.

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