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*STRUCTURAL ANALYSIS OF FEATURES  
ON NATURAL AND ARTIFICIAL FAULTS*

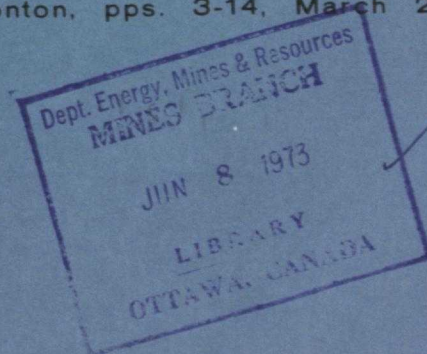
D. K. NORRIS AND K. BARRON

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*IN SITU STRESSES*

H. V. BIELENSTEIN AND K. BARRON

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## STRUCTURAL ANALYSIS OF FEATURES ON NATURAL AND ARTIFICIAL FAULTS

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### Abstract

Many beds in the coal measures of the eastern Cordillera have been detached from one another because of buckling and of differential translation on thrust surfaces. Striae, steps and polish on bedding faults were compared with similar features produced in the laboratory to evaluate their usefulness in kinematic analysis.

Pitches of striae on the same bed at various localities in Upper Marsh seam in the eastern Cordillera approximate a circular normal distribution with a preferred direction of slip essentially perpendicular to the regional strike. This distribution includes a very large number of discrete directions of slip representing some phase of the kinematic activity on bedding. Statistical tests provide reasonable assurance that samples of pitch of striae from one and more slip surfaces are from the same movement picture.

Steps on bedding and on extension faults are of two basic types: those of mineralized gouge plastered on the slip surface (accretion) and those cut into the solid rock (fracture). Both types may be linear or arcuate in projection on the slip surface; they commonly trend about at right angles to the preferred direction of slip and they may be modified or erased by later movement. Accretion steps adjacent to Upper Marsh seam are usually localized at irregularities in surface configuration. In any specimen or locality they characteristically occur on the same flank of depressions. Microscopically they consist of a complex lamination of quartz and carbonate with carbonaceous gouge. Layers of gouge feathered out in the quartz and carbonate, sigmoidal tension gashes, tension fissures filled with mineralization, and fragments of steps plucked from the risers indicate that these steps commonly face in the preferred direction of slip of the opposed wall. The steps are, therefore, plastered in the lee of irregularities in the rock surface. The fine structure, however, suggests modification of some steps of slip in a reversed direction consistent with observations of some faults which have themselves been cut and displaced in the coal seam. Fracture steps may originate in at least three ways in and adjacent to Upper Marsh seam: by inheritance from the initial fracture configuration of the slip surface, by plucking of platy fragments, and by faulting of the slip surface.

Polish on and within beds is widespread adjacent to Upper Marsh seam. It may be due to relatively large shear displacement over considerable area on individual beds or to microscopic shear on a multitude of slip surfaces of limited area within beds.

Steps and striae were created in the laboratory on prepared and induced slip surfaces in cylindrical specimens of soapstone, mudstone and siltstone loaded axially under confining pressures up to 9,000 psi. The steps were similar to the two basic types observed in the field. Both were oriented more or less perpendicular to the direction of the striae. Risers on accretion steps were observed to face in opposing directions depending largely on whether the fragments of compressed gouge stuck to one side or other of the specimen when the slip surfaces were separated for viewing. The directions in which the risers faced, therefore, were not consistent with the known sense of slip. Prominent fracture steps were observed to be due to faulting of the principal slip surface on the conjugate shear set. They consequently opposed motion on the principal surface.

Both field and laboratory data, therefore, indicate that accretion steps are formed as slip surfaces are parted, and depending on which wall retains the gouge, the steps will face in the one direction or other. Because the gouge is more readily bonded to the lee flank of irregularities, however, it commonly sticks there so that risers face preferentially in the direction of motion of the opposed block. Fracture steps on the other hand can face in either direction and therefore cannot be used indiscriminately as a definitive criterion for sense of slip. Where their nature and origin are understood, however, both kinds of steps may be used with meaningful samples of pitch measurements to establish directions of slip and therefore to document at least part of the kinematic history of faulting and folding in orogenesis.

## INTRODUCTION

With increasing knowledge of the structural geometry of orogenic belts there is a proportionate demand for reliable criteria for assessing the direction and magnitude of relative displacement on detachment surfaces, whether parallel or at an angle to bedding. Only when reliable and meaningful data are available, can an accurate analysis be made of the kinematics and perhaps also of the dynamics of orogeny.

The acquisition of meaningful samples of data is more often than not fraught with difficulties because of limited, accessible outcrop in structural positions critical to the analysis. It may be difficult, moreover, to sample adequately the fabric of a given surface in a specific structural position. Fortunately in the eastern Cordillera of Canada some of these sampling difficulties are overcome through the existence of underground mines, locally extending a few miles along strike and as much as a mile down dip, in one and the same bed. Exposures are fresh and extensive; they reveal in minute detail some of the Laramide deformational history as it may have been recorded in the coal measures of the eastern Cordillera.

The coal measures there are intimately involved in the thrusting and folding and unquestionably play a fundamental role in the style of the deformation. Thrust faults, both major and minor, are commonly localized in the coal seams; bedding thrusts at these and other preferred horizons (Norris, 1961, p. 184) lead to the fault habit first outlined by McConnell (1887, p. 33D) who not only documented that thrusts parallel the layering along strike and down dip, but also recognized the fundamental similarity between the structure of the southern Rocky Mountains and that in the southern Appalachians (idem, p. 32D).

Of the number of fabric elements which have been used in qualitative evaluations of the kinematics and dynamics of orogenesis (see, for example Roder, 1960; Lindstrom, 1962; Price, 1967), slickensides<sup>1</sup> and steps on slip surfaces are of prime importance in an objective analysis. The pitch of striae defines the orientation of the kinematic axis. Steps commonly face in one direction or other in a given structural position, and according to most textbooks the sense of relative motion along the slip surface may be determined from them. According to Billings (op. cit., p. 149) for example, "These rough surfaces can be used . . . in much the same way that roches moutonnées indicate the direction in which glacial ice was moving". The steep faces or risers of the steps would, therefore, face in the direction of relative motion of the opposed block.

The first to challenge the textbook description of sense of slip was, to the writers' knowledge, Dzulynski (1953, p. 332) who provided field evidence to support the thesis that the risers more commonly face the oncoming, opposed block. His argument was supported, moreover, by Paterson (1958, p. 469) who, from laboratory studies of faulting in Wombeyan marble, demonstrated the unequivocal existence of steps with their risers facing in the manner described by Dzulynski. He concluded (idem, p. 474) that "the sense of shearing should not be inferred from the appearance of a slickensided surface only, but should be confirmed by mapping". Additional field evidence was supplied by Tjia (1964) and laboratory evidence by Riecker (1965) to support the views of Dzulynski and Paterson. However, in a discussion of Riecker's and Tjia's papers, Rod (1966, p. 1163) writes "it seems that steplike breaks of very different origin have been lumped together" and points out that steplike breaks on well preserved, slickensided faults in Northern Australia appear to be secondary faults "the majority of which belong to a shear system having a sense of movement opposite to the one along the master fault". He emphasized that the rule of thumb (or finger) for roughness and consequently for sense of slip is still valid because "it never applied to the steps caused by secondary faulting". Like Paterson, he states "only mapping can give certainty". In a detailed account of directional indicators on faults Tjia (1967, p. 394) confirmed Rod's suggestion that the large step on the fault, cited to strengthen Paterson's arguments, was in fact a secondary fault. He maintained (idem, p. 396), however, his earlier stand "that the smoothness criterion for detecting fault displacements should be discarded".

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<sup>1</sup>"Slickensides are polished and striated surfaces . . . along the fault plane".  
Billings, 1954, p. 149.

It would seem from the preceeding discussion that incontrovertible evidence on the kinematic significance of steps must come, ideally, from a situation where there has been one and only one direction of motion, and where the magnitude of displacement can be measured from the rupture and offset of features known to have been in existence prior to displacement. In reality, however, it may be difficult if not impossible to ascertain the true nature of the movement picture. In the coal mines of the eastern Cordillera, for example, striae on faults vary widely in pitch (Norris, 1966a, p. 194) and the direction of motion on bedding has been up- as well as down-dip (Norris, 1966b, p. 115). It is therefore impossible to identify steps on bedding with one particular direction of slip and hence impossible to relate the orientation of risers to a specific sense of motion. Under these circumstances, it was found necessary to examine critically the micro-structure of the steps in search of criteria useful in determining sense of slip.

## UPPER MARSH SEAM

### Geological Setting

The coal measures of the southeastern Canadian Cordillera are Jurassic and (?) Lower Cretaceous in age. They make up the Kootenay Formation, a succession of non-marine shale, siltstone, sandstone, and conglomerate. The formation rests with gradational contact on the marine, Jurassic Fernie Group and is overlain disconformably by Lower Cretaceous Cadomin Formation in Cascade Coal Area (Fig. 1). The outcrop thickness of the Kootenay ranges from 230 feet a few miles south of Crowsnest Pass (Norris, 1959, p. 233) to 3,070 feet near Canmore (Norris, 1957, p. 5).

Upper Marsh seam lies 1,600 feet stratigraphically above the base of the Kootenay Formation. It ranges in thickness from 3 to 12 feet in the area mined, averaging about 9 feet. The coal is low volatile bituminous in rank. Although commonly sheared, it is locally bright and blocky, in spite of considerable Laramide kinematic activity in and adjacent to the coal.

The structural position of Upper Marsh seam is the gently dipping east flank of the asymmetrical to overturned Mount Allan syncline (Plate 1), which extends throughout the length of the Cascade Coal Area. The measures are bounded on the west by Mount Rundle thrust (Norris, 1957, p. 6) and are underlain conformably by the Jurassic Fernie Group of the Lac des Arcs thrust plate.

The Cascade Coal Area lies in a series of overlapping plates (see Fig. 1). The major thrust faults with their associated splays and folds impart a north to north-west trending structural grain to the east-central Cordillera. Vertical to west-dipping axial surfaces characterize the folds and in conjunction with the thrust faults impart a strong asymmetry to the deformation. Wrench faults, occurring singly or in swarms, commonly trend subperpendicularly to the structural grain, are vertical to steeply dipping and locally have large displacement. The bulk shortening arising from the thrusting and folding does not appear to vary appreciably within the region so that an increase or decrease in horizontal displacement on any one thrust is apparently compensated by corresponding changes in displacement on faults lying en echelon to it (Norris, 1966a, p. 193),

## Structural Fabric

The principal mesoscopic elements contributing to the structural fabric in and adjacent to Upper Marsh seam are bedding, slickensides and steps, joints and cleats, and extension and contraction faults. Bedding is abundantly polished, commonly striated and locally stepped as a consequence of kinematic activity during the Laramide orogeny. Successive beds have been detached from one another as a consequence of interbed slip (Plate 2) caused by differential translation on thrust surfaces and by

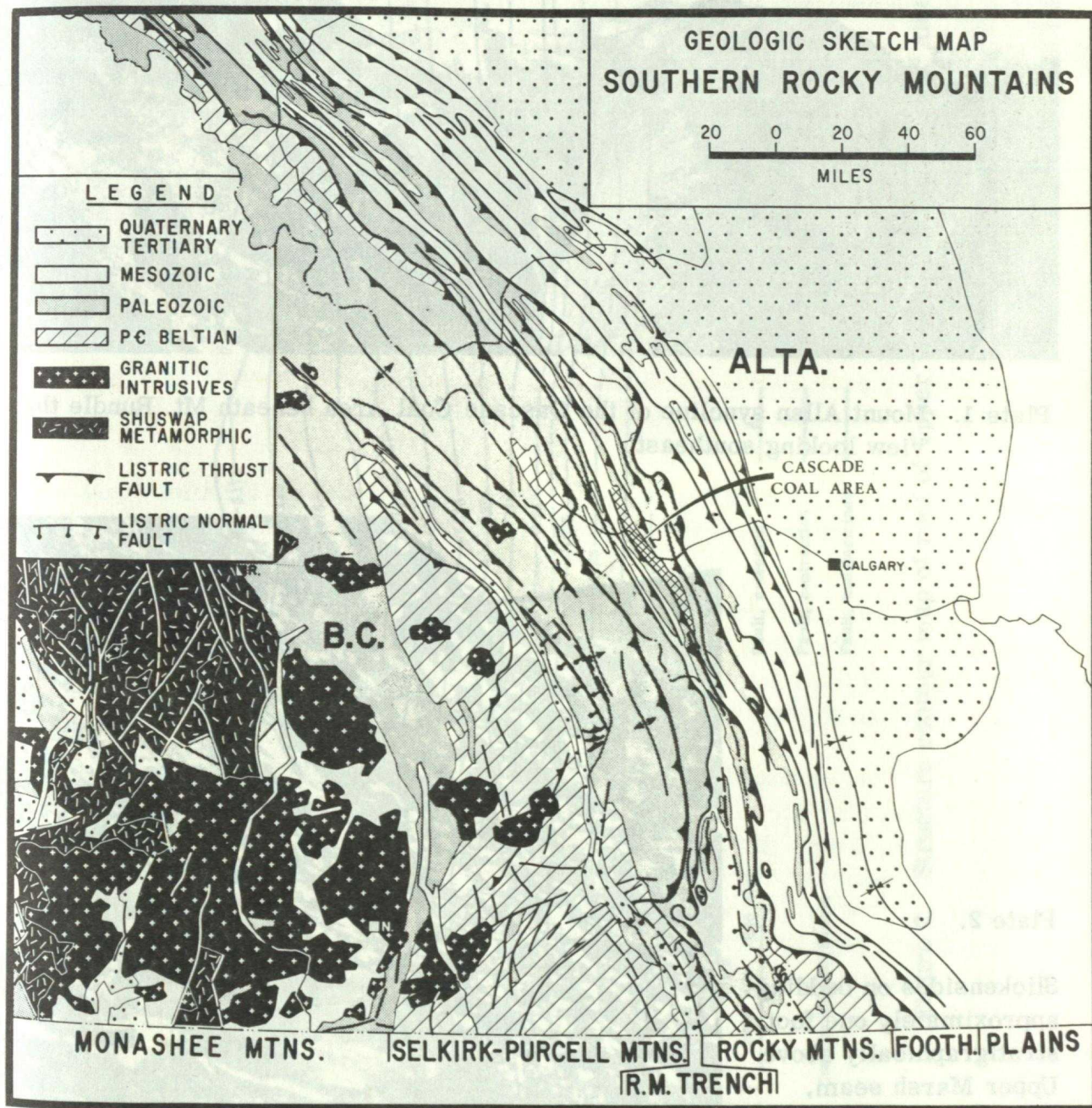


Figure 1. Geologic map of the southeastern Cordillera of Canada. Cascade Coal Area contains band of Mesozoic rocks beneath Mt. Rundle thrust in the vicinity of Canmore, Alberta. (After Bailey et al., 1966)

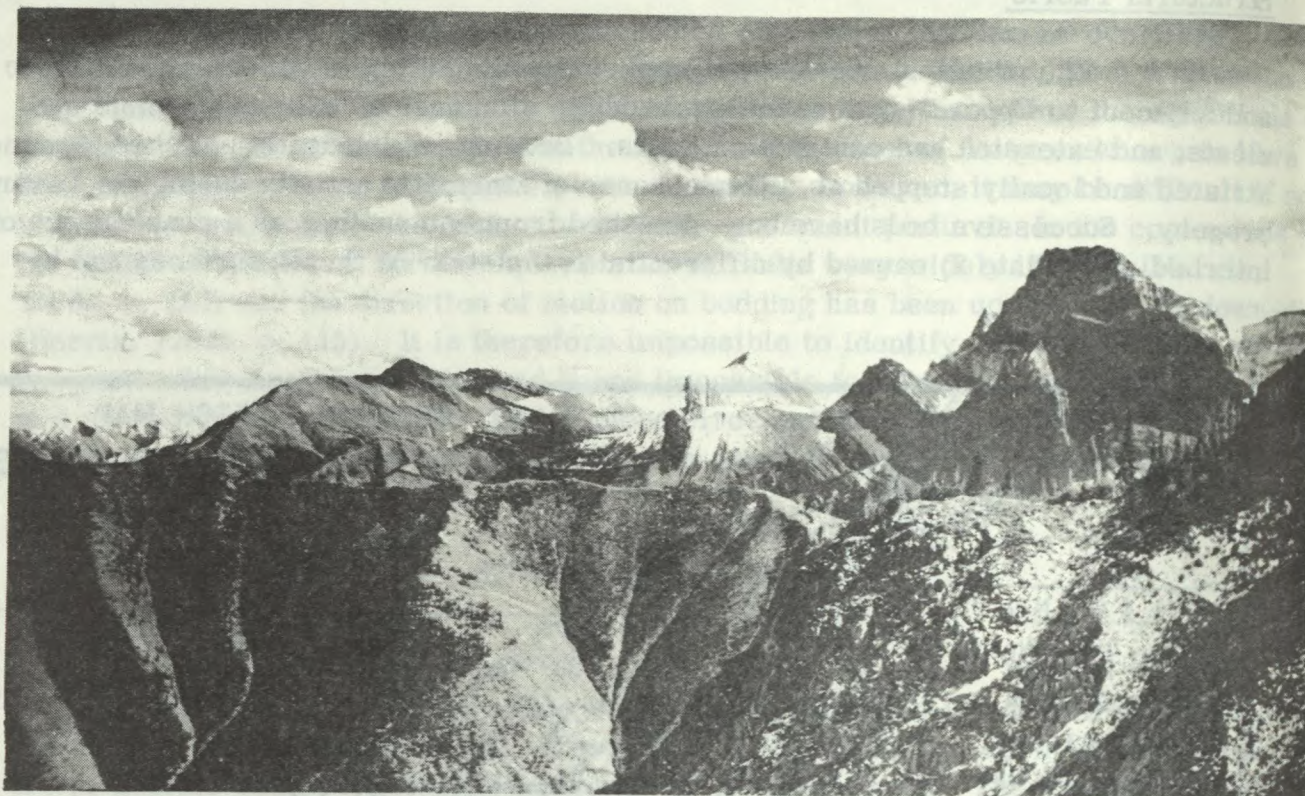


Plate 1. Mount Allan syncline of the Cascade Coal Area beneath Mt. Rundle thrust. View looking southeast.

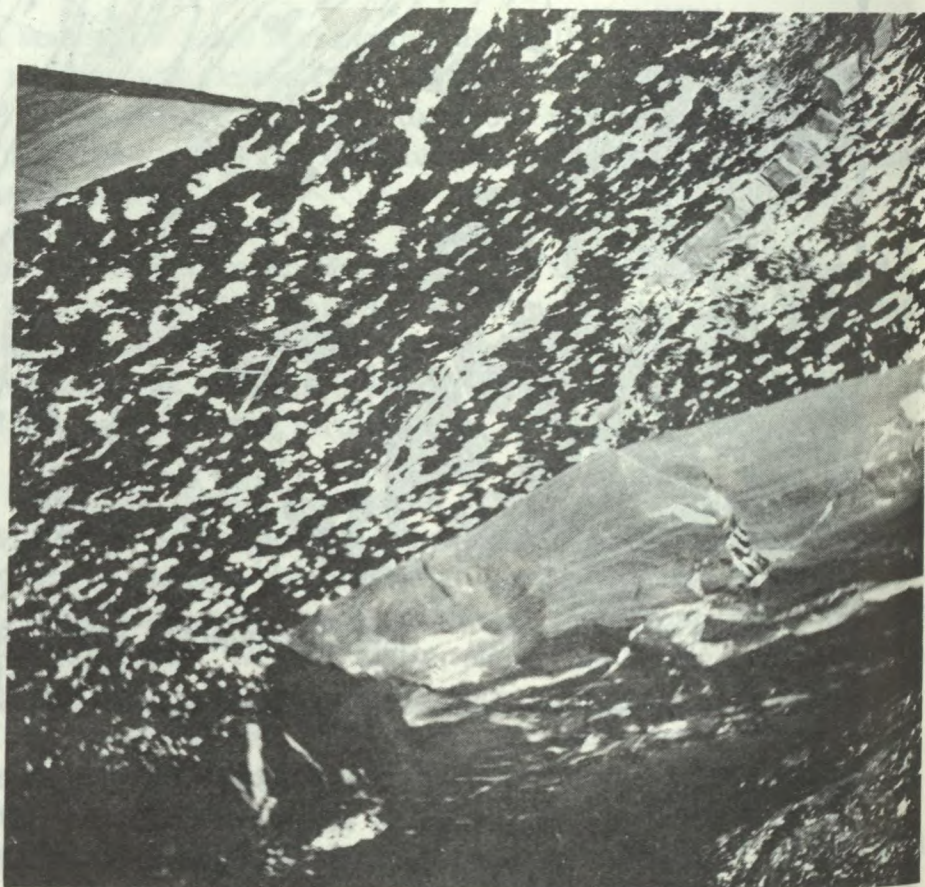


Plate 2.

Slickensides on bedding approximately one foot stratigraphically above Upper Marsh seam, Canmore, Alberta. Striae pitch of  $86^{\circ}$  from North arrow. Accretion steps face down-dip. Arrow is one foot long.

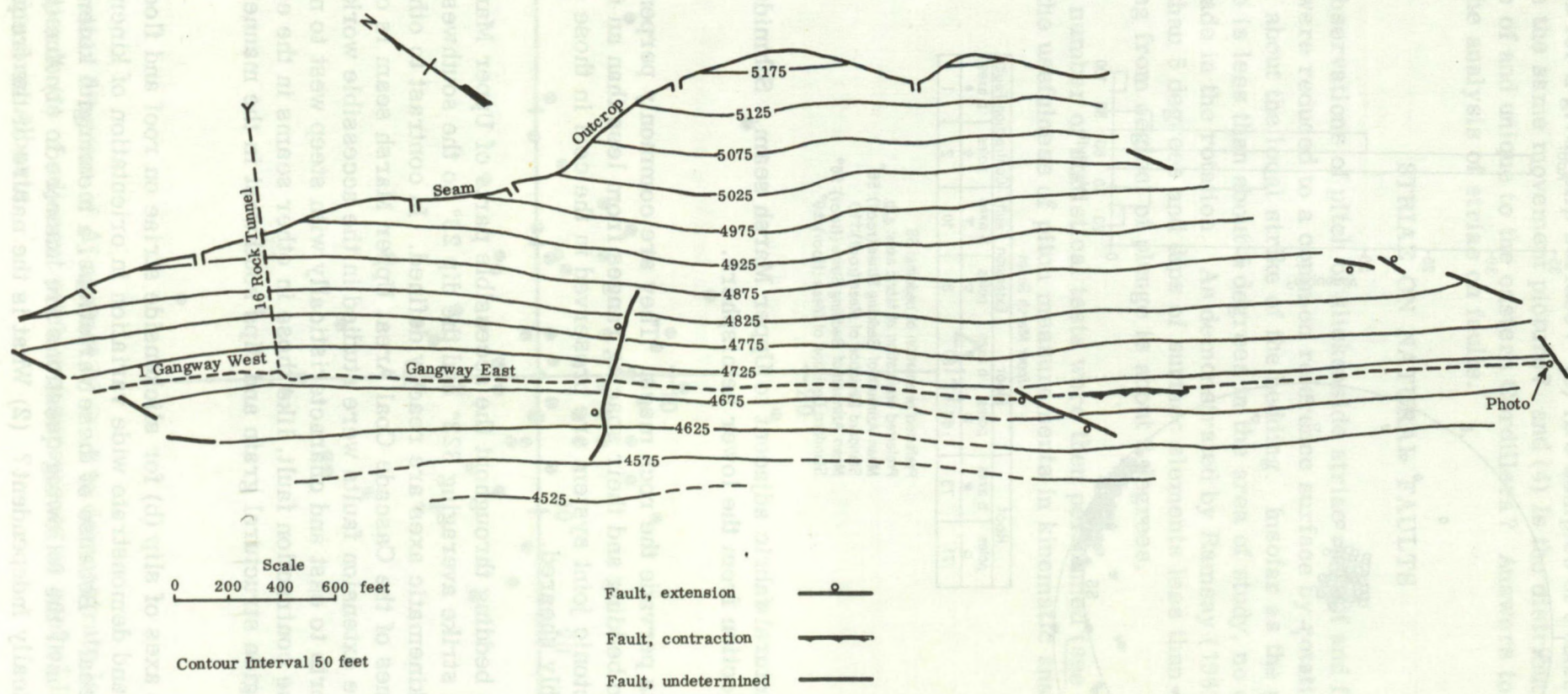


Figure 2. Structure contour map of roof of Upper Marsh seam, Canmore, Alberta.

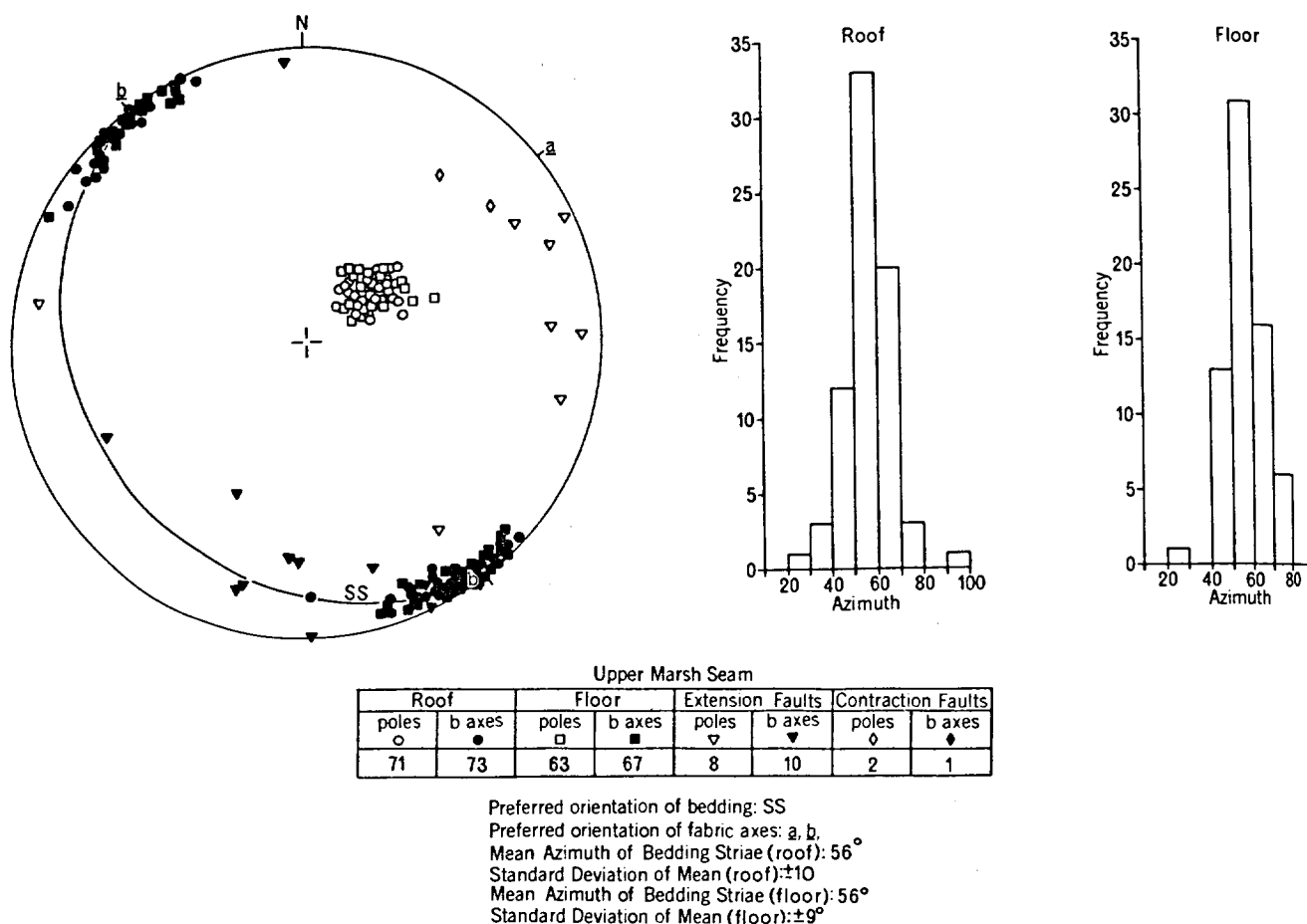


Figure 3. Structural fabric adjacent to Upper Marsh seam. Schmidt equal area projection from the lower hemisphere.

buckling. Joints pervade the rock mass. They are commonly perpendicular and sub-perpendicular to bedding and their spacing ranges from less than an inch to a few feet. Cleats and a tectonic joint system are preserved in the coal in those areas where the seam is not highly sheared.

The bedding throughout the accessible parts of Upper Marsh seam is quite planar, with the strike averaging 323° and the dip 23° to the southwest (see Fig. 2). The fabric and kinematic axes are readily defined. In contrast to other seams examined in mines of the Cascade Coal Area, Upper Marsh seam is cut by relatively few faults. Five extension faults were studied in the accessible workings, with strikes ranging from north to east and characteristically with steep west to north dips (see Fig. 3). The one contraction fault, like those in other seams in the eastern Cordillera, parallels the region structural grain and dips southwest in the manner of the major thrusts.

The axes of slip (b) for slickenside striae on roof and floor range through an angle of 62° and demonstrate wide variation in orientation of kinematic a axes adjacent to the coal. Because of these variations, a meaningful kinematic analysis cannot be made until the following questions are answered: (1) Are these kinematic a axes stochastically independent? (2) What is the nature of the frequency distribution

of these  $\Delta$  axes for a given slip surface? (3) Are samples of  $\Delta$  axes from two or more surfaces from the same movement picture? and (4) Is the distribution of  $\Delta$  axes characteristic of and unique to the eastern Cordillera? Answers to these questions are found in the analysis of striae on faults.

### STRIAE ON NATURAL FAULTS

Observations of pitch of slickenside striae on roof and floor of Upper Marsh seam were reduced to a common reference surface by rotation of striae into the horizontal about the local strike of the bedding. Insofar as the plunge of Mount Allan syncline is less than about 5 degrees in the area of study, no correction for plunge was made in the rotation. As demonstrated by Ramsay (1961, p. 89, Fig. 5) for plunges less than 5 degrees and dips of surface elements less than  $40^\circ$ , the angular error resulting from neglect of plunge is about 2 degrees.

A number of statistical tests were then performed (see Appendix) to demonstrate the usefulness of pitch measurements in kinematic analysis. The mutual

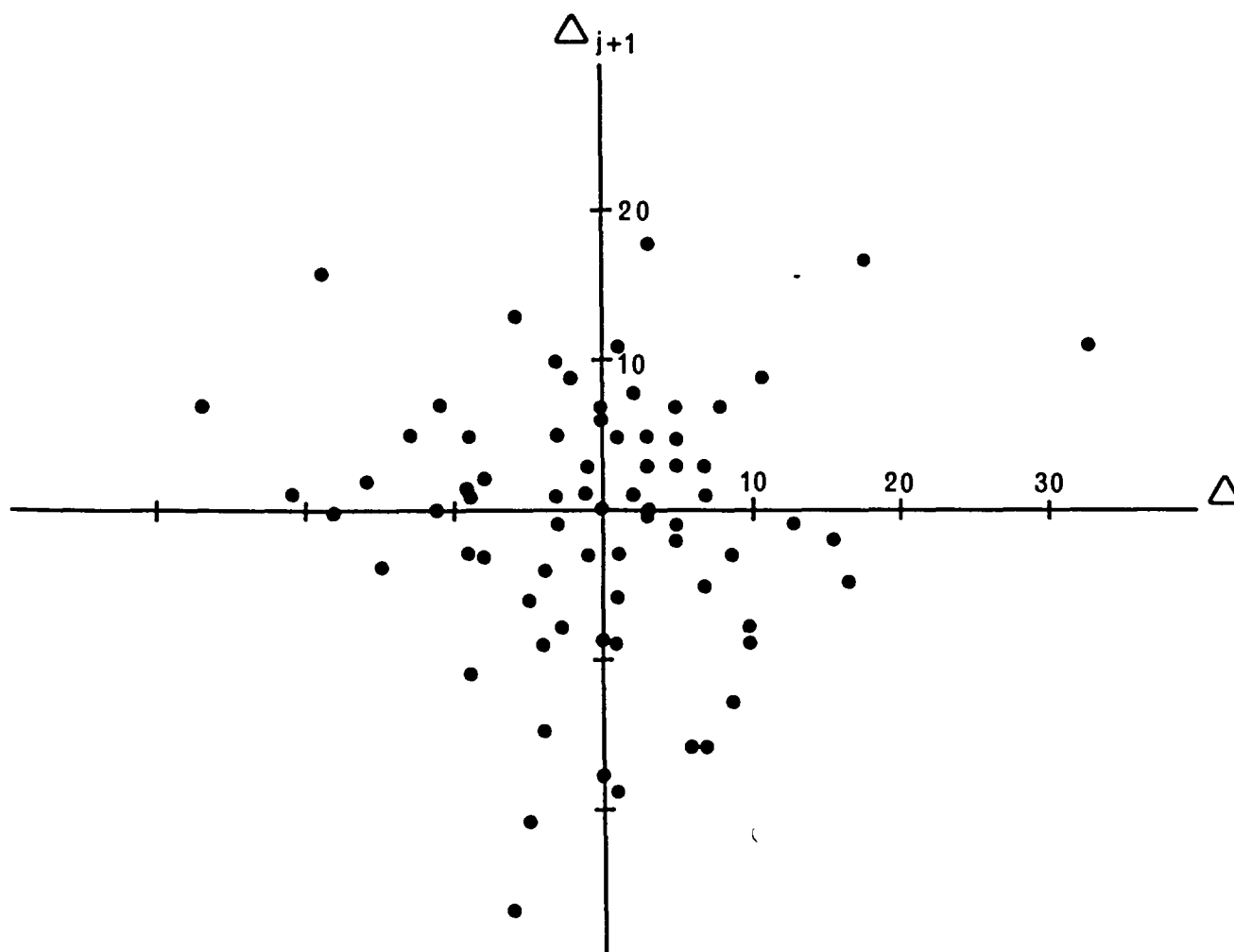


Figure 4. Scatter diagram of  $\Delta_j$  against  $\Delta_j + 1$  to demonstrate lack of mutual dependence of adjacent pitch measurements on roof of Upper Marsh seam, Canmore, Alberta.

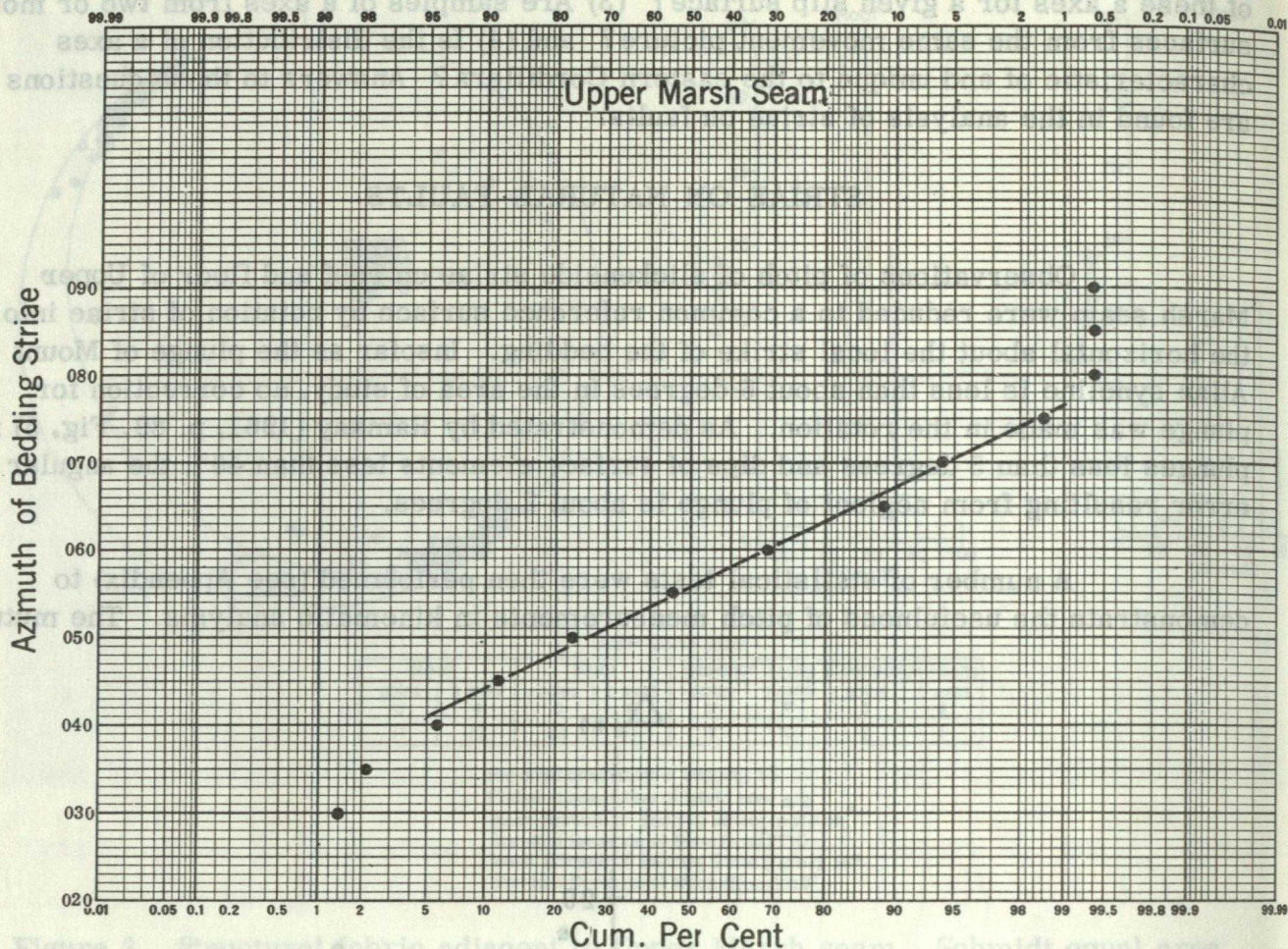


Figure 5. Distribution of azimuths of striae on bedding adjacent to Upper Marsh seam, Canmore, Alberta.

independence of adjacent measurements of the a kinematic direction on a given bed was tested (Fig. 4) because it is impossible to conduct meaningful significance tests on measurements unless stochastic independence is fulfilled. The arithmetic means and standard deviations were calculated for the a kinematic directions for roof and floor of Upper Marsh seam and statistical tests performed to demonstrate reasonable assurance that roof and floor samples of pitch measurements are from the same normally distributed population of striae (Fig. 5). A sample of intersecting sets of striae on roof and floor were then shown to confirm the assumption that interbed slip adjacent to Upper Marsh seam may be represented by a single movement picture (Fig. 6). It includes a very large number of discrete, temporally distinct, randomly used axes of slip with a circular normal distribution representing at least in part the latest kinematic activity of the surfaces.

Of fundamental importance, moreover, is the fact that the mean orientation of the (ac) deformation plane ( $056^\circ$ ) is subparallel to the mean counterdip direction ( $053^\circ$ ) and is therefore in near coincidence with the presumed direction of relative transport of thrust plates in this part of the Cordillera.

The circular normal distribution of pitches of striae with a preferred direction of slip perpendicular to the regional strike defines the basic structure of the kinematic pattern for bedding slip in the east-central Cordillera.

In the preceeding discussion care has been taken to imply nothing regarding direction of slip because a given set of striae simply define the (time-dependent) a kinematic axis. The problem now at hand is, therefore, to find definitive criteria which may be used to establish direction of slip. It may be argued that if a fault cuts

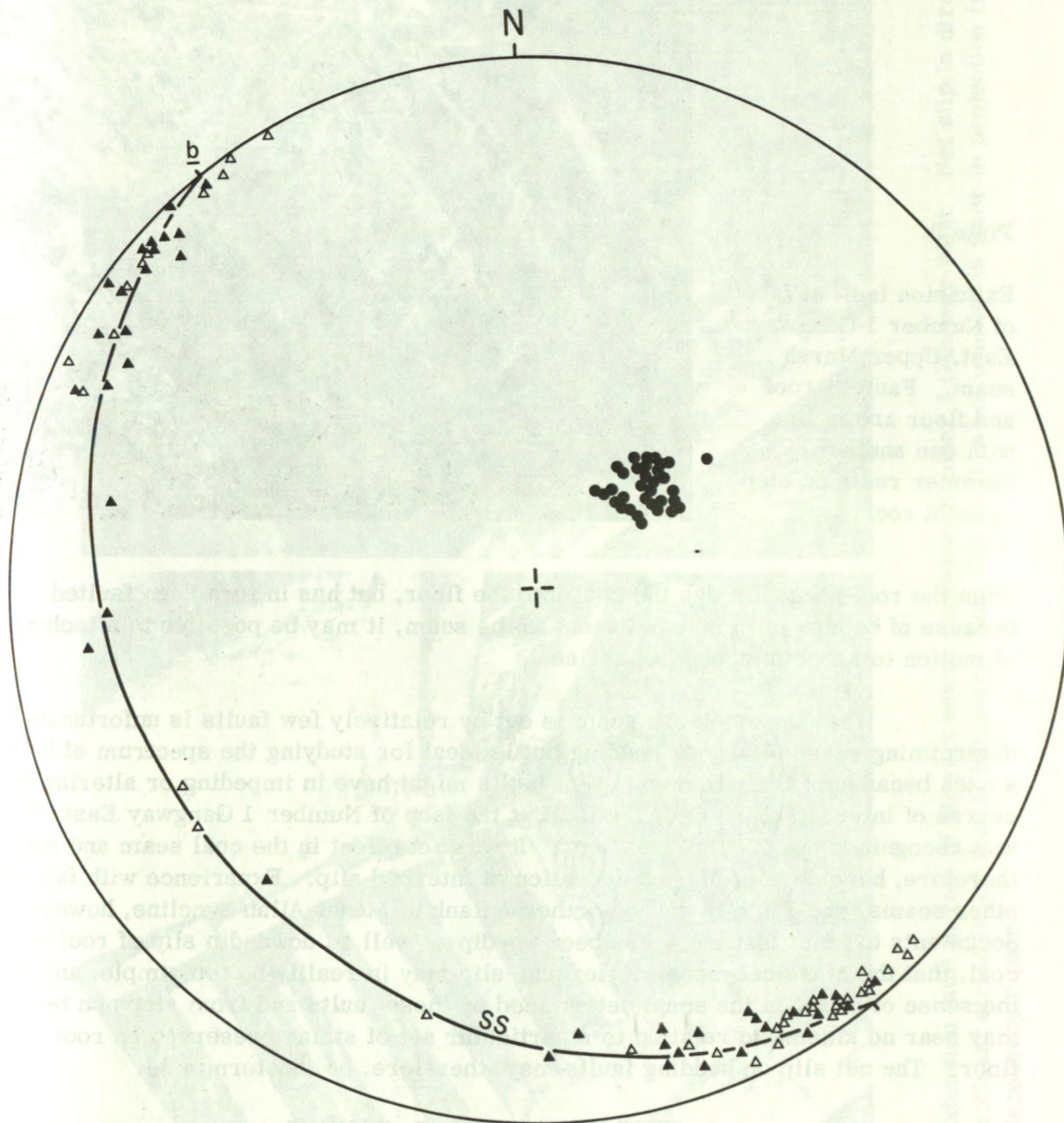


Figure 6. Axes of slip (b) for relatively younger (▲) and older (△) striae on roof and floor of Upper Marsh seam. Schmidt equal area projection from the lower hemisphere.



Plate 3.

Extension fault at face of Number 1 Gangway East, Upper Marsh seam. Fault in roof and floor are in line with one another. Hammer rests on step in solid rock.

from the roof rock, through the coal into the floor, but has in turn been faulted because of bedding slip in or adjacent to the seam, it may be possible to attach a sense of motion to associated bedding striae.

That Upper Marsh seam is cut by relatively few faults is unfortunate for determining sense of slip on bedding but is ideal for studying the spectrum of kinematic axes because of the minimum effect faults might have in impeding or altering the course of interbed slip. Only the fault at the face of Number 1 Gangway East (Plate 3) was recognized in both roof and floor. It was not offset in the coal seam and may, therefore, have developed upon cessation of interbed slip. Experience with faults in other seams (see Plate 4) on the northeast flank of Mount Allan syncline, however, documents the fact that there has been up-dip as well as down-dip slip of roof over coal, that the classical model of flexural-slip may in reality be too simple, and that the sense of offset in the seam determined by these faults and from steps on bedding may bear no kinematic relation to a particular set of striae preserved on roof and floor. The net slip on bedding faults may, therefore, be indeterminate.

#### STEPS ON NATURAL FAULTS

Because bedding striae define only the orientation of the a kinematic axis for interbed slip, and offset faults indicate both up- and down-slip motion on bedding, an analysis was made of steps as a criterion for sense of slip. It is apparent,

Plate 4. Extension fault in roof of Stewart seam, Canmore, Number 1 Gangway West. Net slip in direction of dominant striae is 4.0 feet at hammer. Note that fault is not present in floor in projection from roof. Stereoscopic pair.

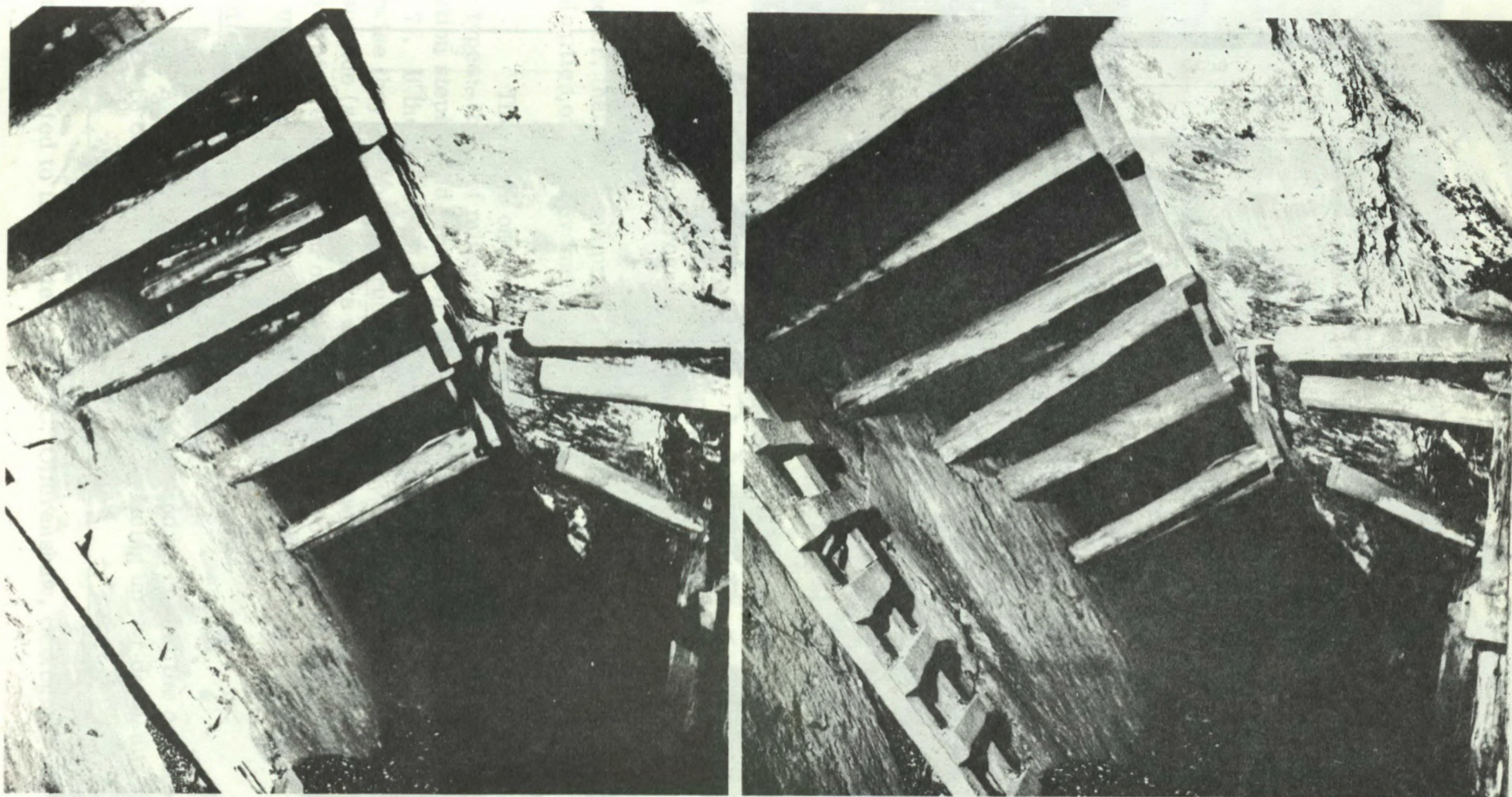


Plate 4. Extension fault in roof of Stewart seam, Canmore, Number 1 Gangway West. Net slip in direction of dominant striae is 4.0 feet at hammer. Note that fault is not present in floor in projection from roof. Stereoscopic pair.

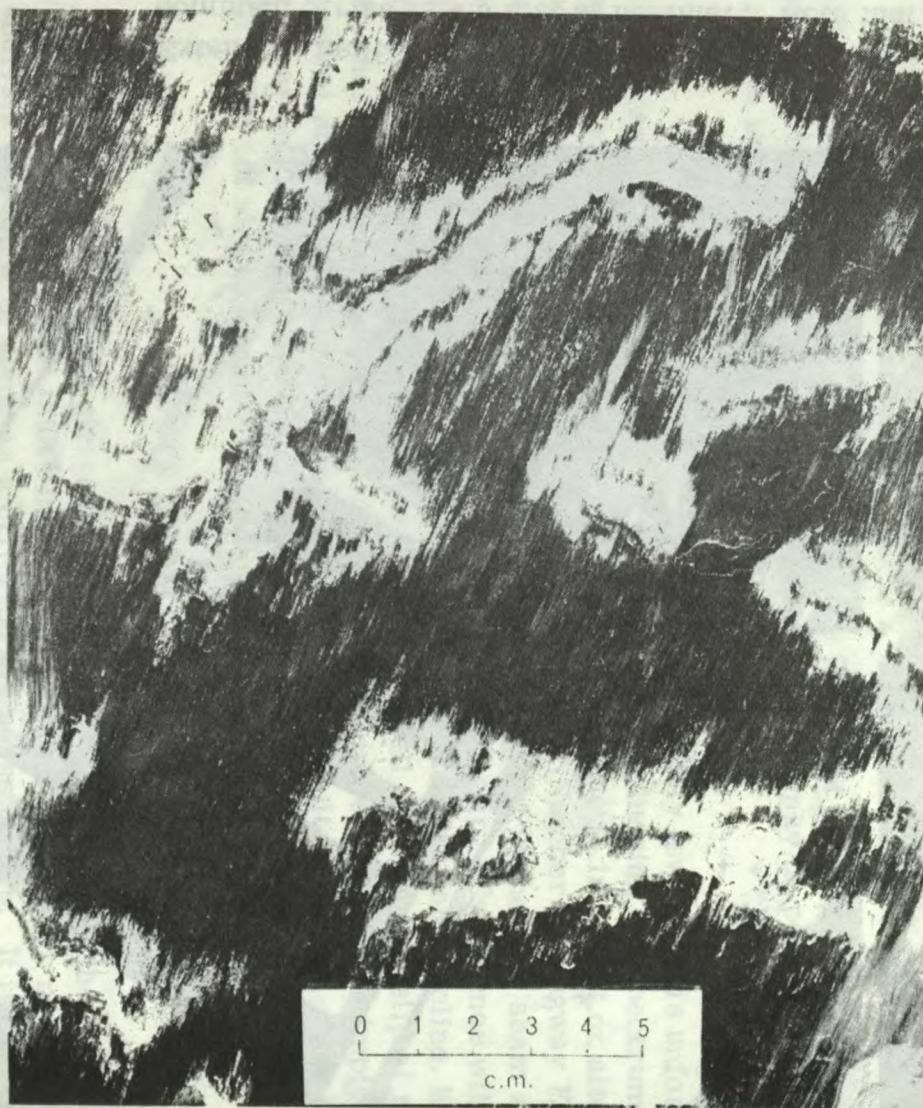


Plate 5. Details of steps and striae in roof of Upper Marsh seam shown in Plate 2.

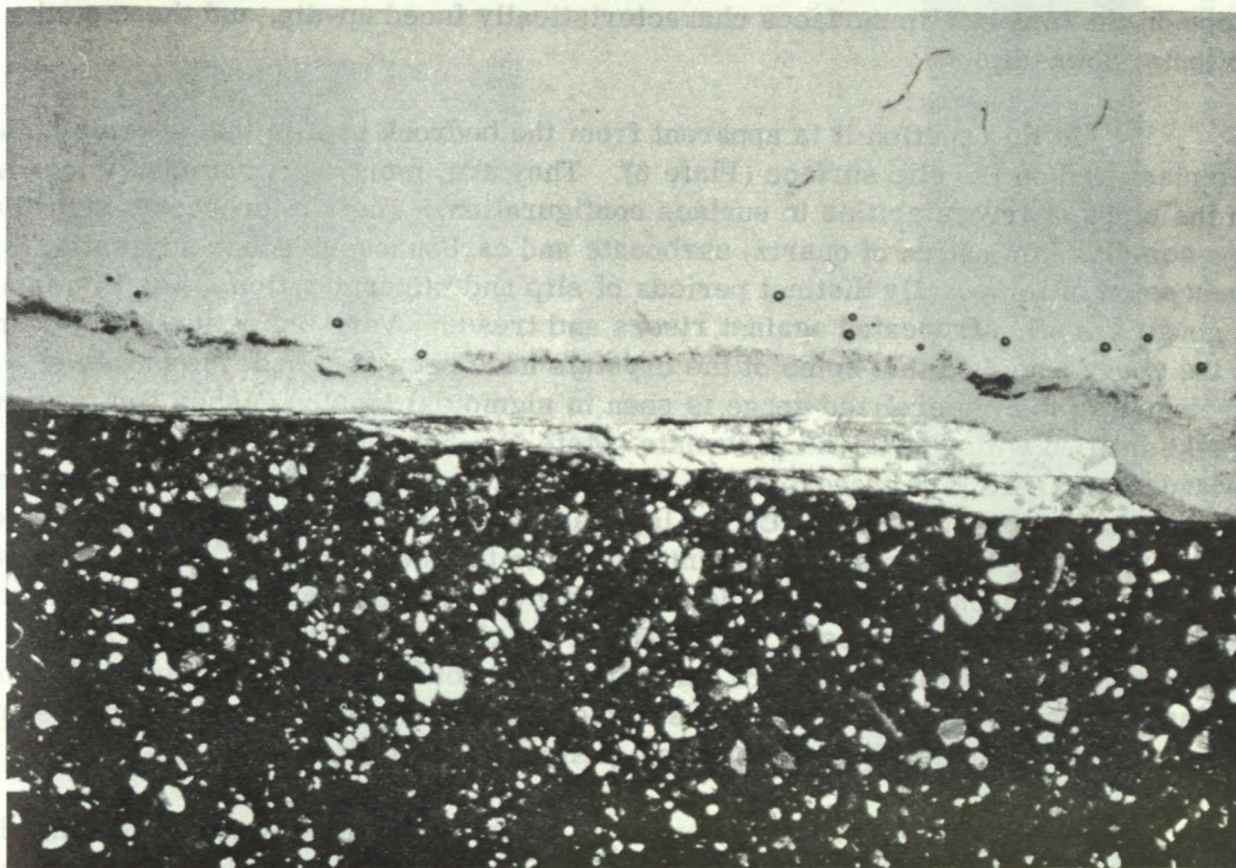


Plate 6. Thin section of step on sedimentary rock from southwestern Alberta. Note laminae and cross laminae of gouge in carbonate and quartz.

moreover, that steps, as products of slip, may provide further documentation of the complexities of the movement picture during orogenesis.

The steps on bedding and on faults cutting the bedding appear to be of two basic types: those of mineralized gouge plastered on the surface, herein termed accretion steps<sup>1</sup>, and those cut into the solid rock, herein termed fracture steps (Fig. 7). If the steps are oriented to oppose shear, they will be said to be incongruous, otherwise they will be congruous. They may be linear or arcuate in projection on the slip surface (see Plate 5), are commonly in swarms, trend more or less at right angles to the preferred direction of slip, and may be rounded off, worn down or erased by later movement.

#### Accretion Steps

Accretion steps composed of ground up coal at the contacts between coal and rock were observed to have their risers facing up- or down-dip, depending upon

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<sup>1</sup> Term suggested to the writers by N. C. Ollerenshaw, Geological Survey of Canada.

whether or not the coal stuck to the rock. They were, therefore, of no value in determining sense of slip. Steps of mineralized gouge up to one-eighth inch high were observed on slip surfaces in the mudstone or siltstone above and below the coal. Those steps on the tops of slip surfaces characteristically faced up-dip, and those on the bottoms, down-dip.

In this section it is apparent from the bedrock profile that accretion steps are plastered on the slip surface (Plate 6). They are, moreover, commonly localized on the sides of irregularities in surface configuration. Their microscopic structure is a complex lamination of quartz, carbonate and carbonaceous gouge suggesting a succession of temporally distinct periods of slip and mineralization. The thin laminae of gouge are often truncated against risers and treads. Variable extinction of quartz in the gouge suggests that some of the crystals have been strained. Evidence of stretching in the mineralized gouge is seen in sigmoidal tension gashes and tension cracks infilled with quartz and carbonate (Plate 7). Some tension cracks, inclined towards the risers, are traceable into the rock mass and indicate that the stretching was not confined to the gouge. Cross-laminae dip away from the risers and towards them, suggesting that the gouge was introduced to the steps because of both forward and reversed senses of motion. The feathering out of this gouge, the sigmoidal tension gashes, the tension fractures in the steps and the plucking from the risers support the hypothesis that accretion steps are generally congruous. They are, therefore, commonly plastered in the lee of irregularities in the rock surface although the micro-structure of some of the laminae suggest instances of slip in a reversed sense.

No voids or cavities are apparent between adjoining walls of bedding slip surfaces in the coal measures. Patches of mineralized gouge fill the spaces caused by mismatch in slip surface configuration. It is apparent, therefore, that accretion steps must be formed as the walls are parted, and depending upon which wall the gouge sticks to, the risers may face in the one direction or other.

In the lee of irregularities there is opportunity for mineral matter to bond itself to the fresh surface of the rock, whereas on the forward side there is active shear, and gouge may be introduced between the mineral matter and the adjoining slip surface. The one extremity of a patch sticks more readily to the one wall where it is protected from shearing motion of the adjoining surface, and the other extremity to the opposite wall, as the surfaces are parted (see Fig. 8). The probability is, therefore, that accretion steps oriented in the manner described in most textbooks are formed, their risers facing in the direction of relative motion of the adjoining wall. The slopes of the risers are, moreover, simply the fracture angles of the gouge and have no direct relation to slip on the fault.

The sense of slip determined from the orientation of the risers as well as from the micro-structure of accretion steps is generally consistent with the flexural slip model for growth of the Mount Allan syncline and with the differential eastward motion of progressively higher beds in the Lac des Arcs thrust plate.

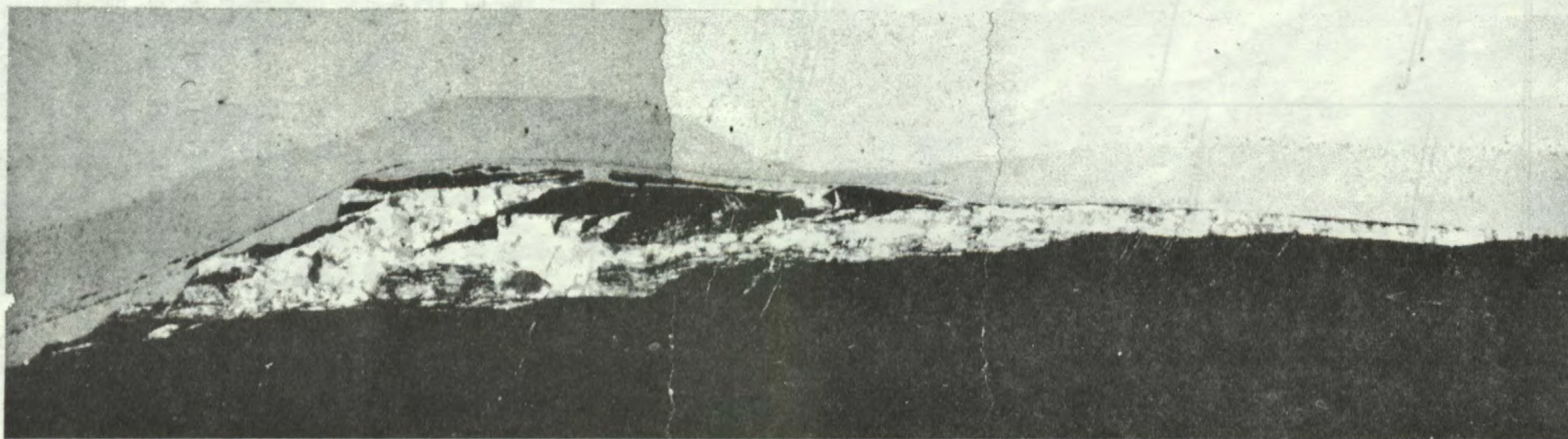
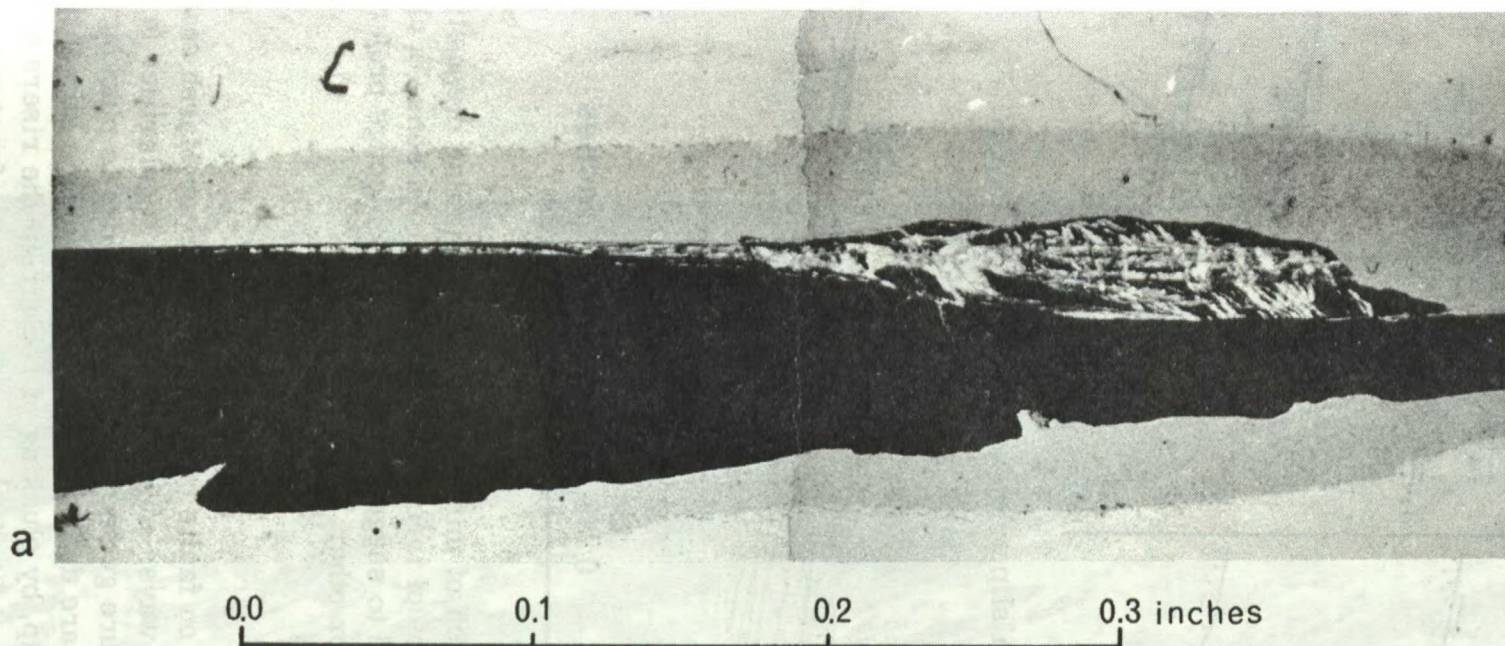


Plate 7. Thin sections of steps on bedding in roof of Upper Marsh seam. Note sigmoidal tension gashes in step in Plate 7a and family of mineralized tension cracks in roof rock in 7b.

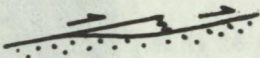
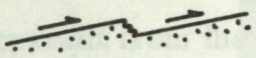
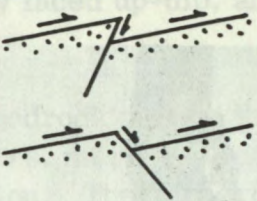
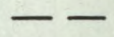
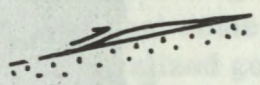
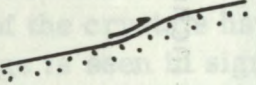

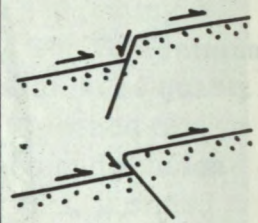
Steps	ACCRETION	FRACTURE		
		Pluck	Synthetic	Antithetic
Congruous				
Incongruous				

Figure 7. Kinds of steps on slip surfaces (schematic).

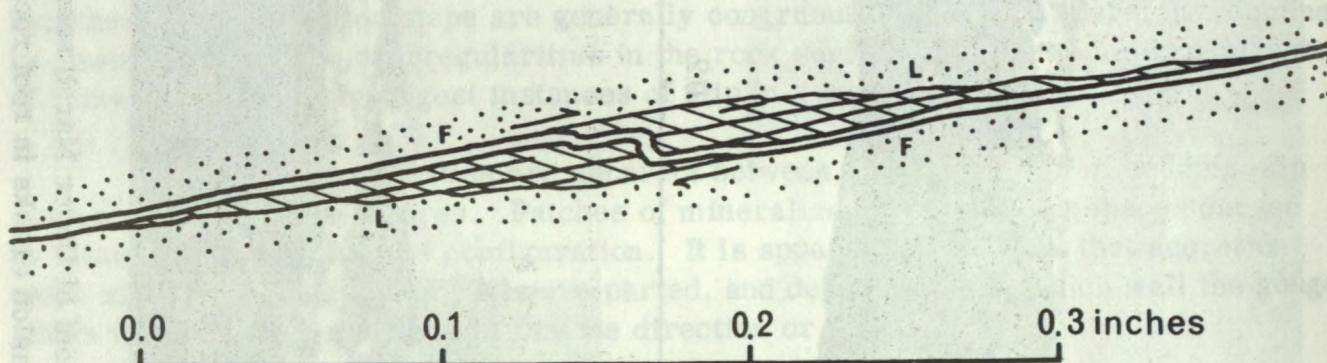


Figure 8. Schematic cross-section of patch of mineralized gouge showing disposition of lee (L) and forward (F) flanks of irregularities for a given sense of slip. Surfaces are slightly separated to suggest manner in which gouge preferably sticks to the one surface or other.

### Fracture Steps

Fracture steps on bedding and on faults cutting across Upper Marsh seam appear to have originated in at least three ways: some are simply irregularities in surface configuration due to original fracture geometry; others are due to plucking of plates from the slip surface. Still others are due to faults intersecting the slip surface. All may be modified by abrasion during slip, by plucking of rock from the risers and by plastering with gouge. On bedding the height of fracture steps due to fracture configuration or plucking is commonly from one- to two-tenths of an inch although on faults at an angle to bedding, it may be up to several inches (Plate 3). Those (fault) steps with synthetic displacement (Hoeppener, 1955, Fig. 7) are necessarily congruous and those with antithetic displacement, incongruous (Fig. 7). All types of fracture

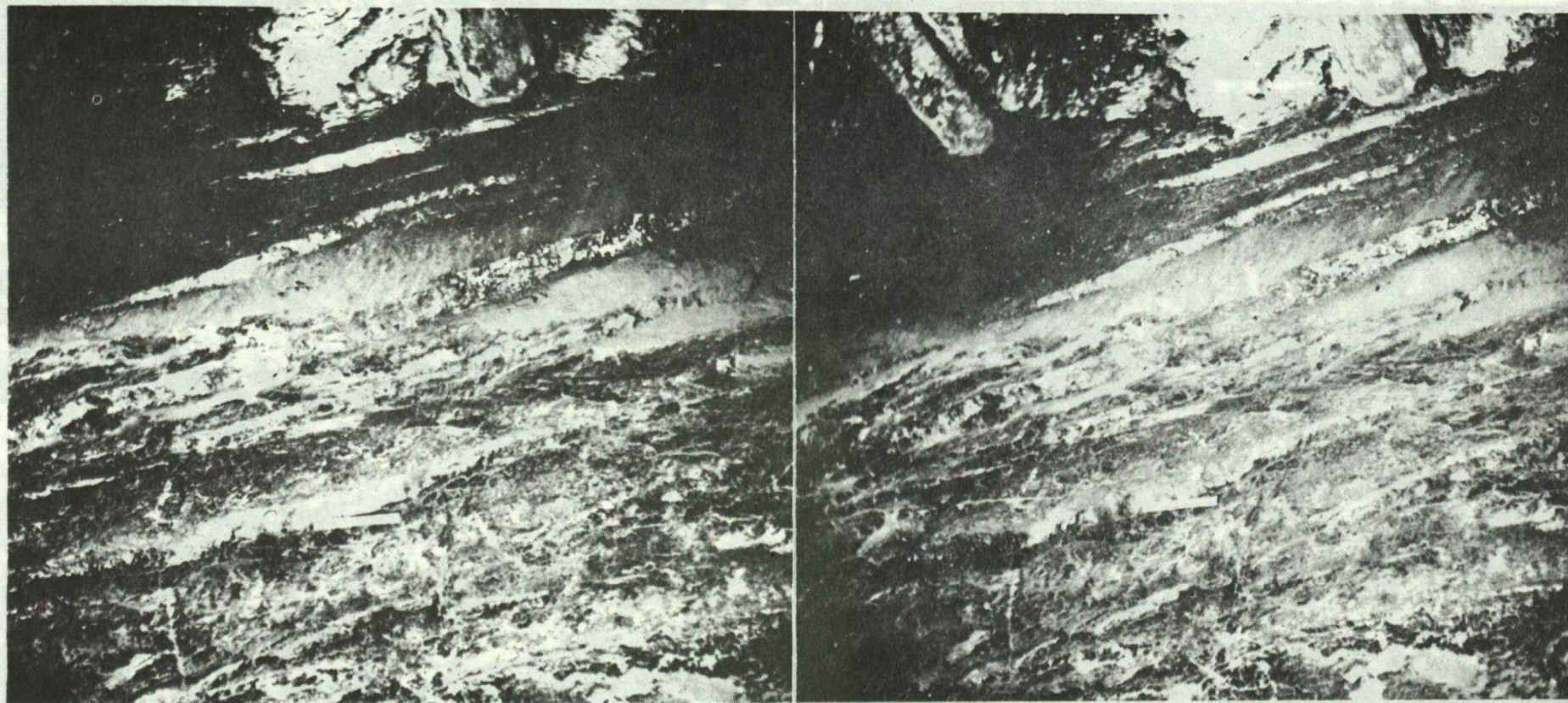


Plate 8. Family of extension faults in floor of Stewart seam, Canmore, Alberta. Note variation in separation along individual faults. Maximum displacement is about three inches. Stereoscopic pair. Scale is 6 inches long.

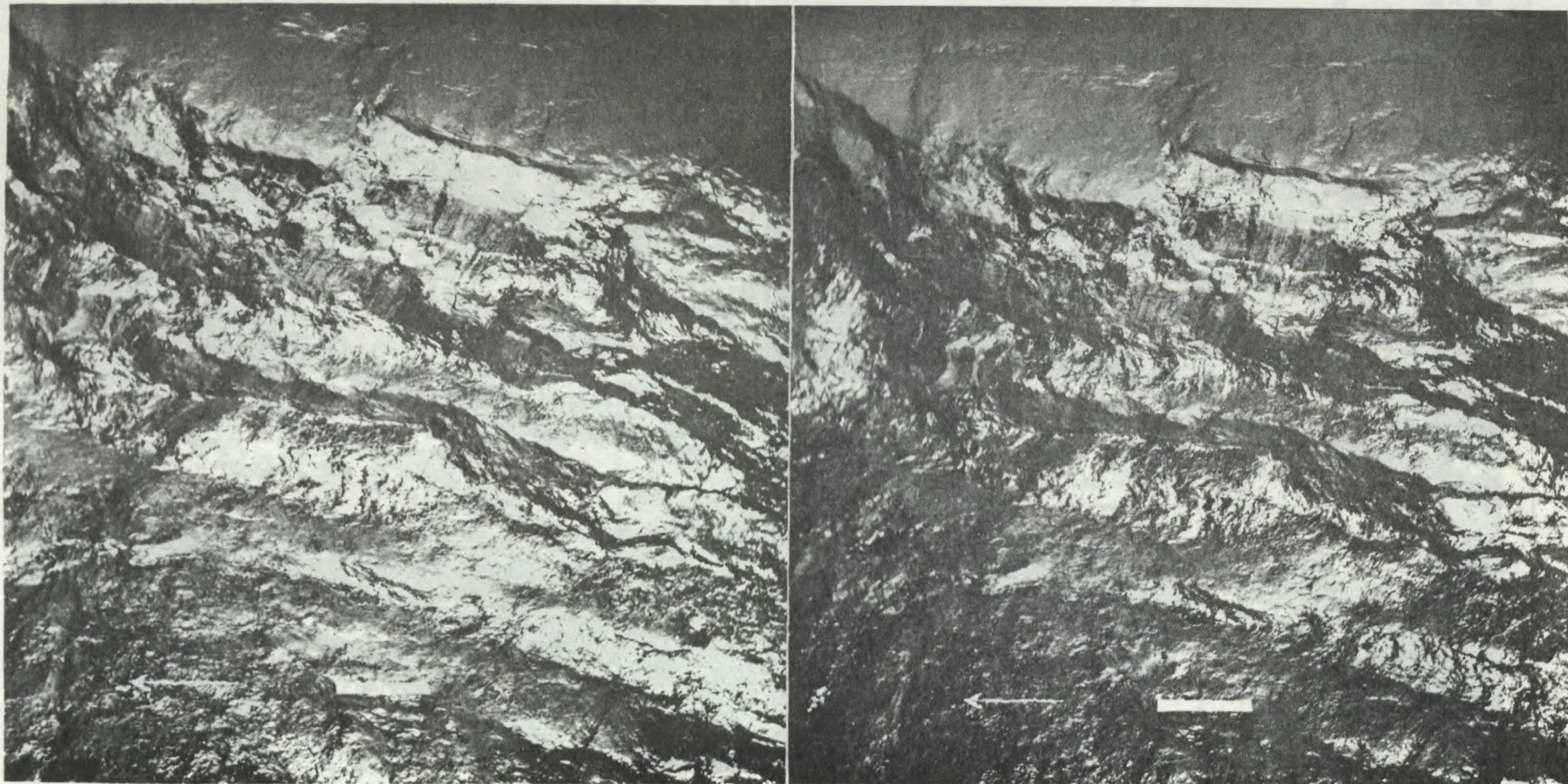


Plate 9. Family of extension faults in floor of Stewart seam, Canmore, Alberta. Maximum stratigraphic separation on faults ranges from 1 to 12 inches. The unfaulted floor of the seam is the flat area at top of photos and beneath the ruler at the bottom. Stereoscopic pair. Scale is 6 inches long.

steps of appreciable size in the immediate roof or floor of the coal seams have caused total destruction of the depositional and structural fabric of the coal as they plowed their way.

Synthetic and antithetic fracture steps commonly occur in swarms, generally trending parallel or at an acute angle to the strike of the coal measures. They range in net slip from the microscopic scale to several feet. If widely spaced, they appear as in Plate 8, and if closely spaced, as in Plate 9. The aggregate or net slip in the latter changes only gradually over the length of the swarm, although displacement on individual elements may change moderately rapidly along their length. This variation in displacement for the aggregate and for individual faults works in a general way the thrust and normal fault habit of the east-central Cordillera.

### POLISHED BEDDING

Throughout the coal mines of the eastern Cordillera polish is abundant on bedding and on surfaces parallel to bedding. It is the product of shear brought about by differential motion in the layered succession by thrusting and by flexural slip.

In Upper Marsh mine there was opportunity to examine these polished surfaces and to gain some insight into the mechanical response of the measures when they were faulted and folded. Slickensided surfaces were observed at many stratigraphic levels in the first few feet of roof and floor; they were spaced at intervals ranging from one-quarter inch to one foot within mudstone or siltstone beds and paralleled textural lamination.

While attempting to withdraw a specimen from the roof of Upper Marsh seam, which ostensibly contained the lateral extension of the slip surface shown in Plate 2, the authors discovered that the surface ended virtually at the limit of the exposed area. The significance of this lies in the conclusion that within beds slip surfaces may be of limited area. They overlap one another in space and perhaps also in time of origin. Highly stepped and slickensided though they may be, the amount of movement on them can be microscopic. Movement on contacts between beds, however, could undoubtedly be many orders of magnitude larger because of the greater areal extent of beds. This is seen for example in coal seams which are detached at their contacts over areas measured in square miles. There, parts of faults may be displaced from one another by several tens of feet. Accommodation of the measures to shear parallel to the layering took place within as well as at contacts between beds.

### STEPS AND STRIAE ON ARTIFICIAL FAULTS

Steps and striae were produced in the laboratory on prepared and induced slip surfaces in cylindrical specimens of soapstone, mudstone and siltstone loaded axially under confining pressures up to 9,000 psi. For the prepared specimens, diagonal cuts were made at angles of approximately 25 and 30 degrees to their longitudinal axis. The surfaces of these cuts were then lapped to ensure even contact. The specimens were placed in a triaxial bomb and confining pressure was raised to 1,500 psi. The axial load was then increased while maintaining the confining pressure

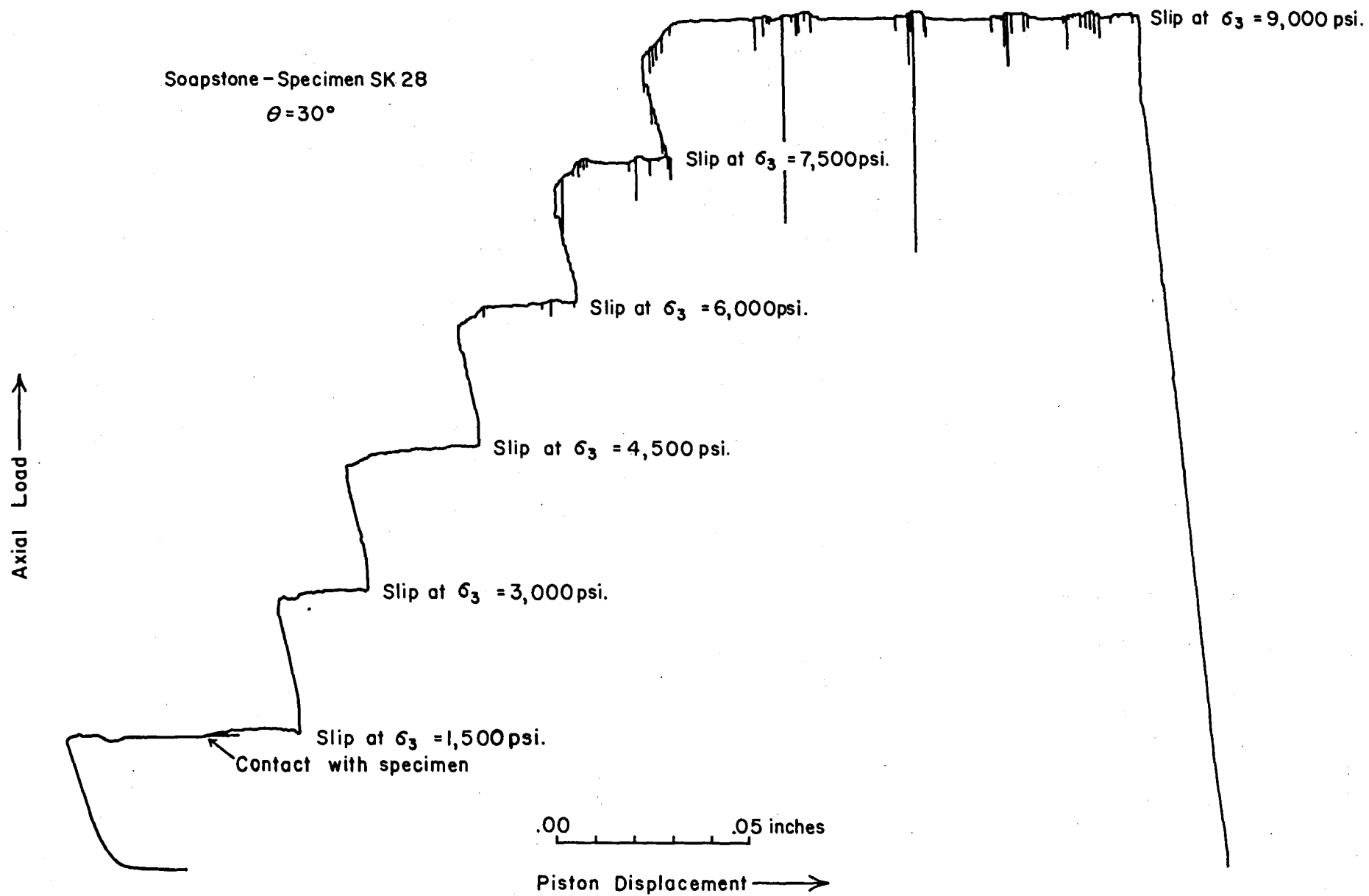


Figure 9. Typical XY recording of a slip test on a cut specimen.

at 1,500 psi by bleeding oil from the bomb, until slip occurred. The axial load was recorded on the one axis of an XY recorder and the displacement of the loading piston on the other. Slip was clearly indicated when there was steady piston displacement without increase of axial load. The confining pressure was then increased to 3,000, 4,500, 6,000, 7,500 and 9,000 psi in steps and the axial load increased at each step until slip occurred. On occasion abrupt deflections in axial load occur at higher confining pressures and are accompanied by an audible snapping sound which results from the alternating stick-slip of the juxtaposed surfaces, the typical behavior of moving unlubricated surfaces under load (Bowden and Tabor, 1964, p. 78). The specimens were then unloaded by carefully releasing both the axial and confining pressures so that little or no further displacement of the slip surfaces occurred. Figure 9 shows a typical XY recording obtained in such an experiment.

In order to conduct similar tests on uncut specimens it was first necessary to produce slip surfaces. This was done by loading solid, cylindrical specimens in the triaxial bomb until failure occurred. All these failures were produced at the confining pressure of 9,000 psi. After specimen failure, the axial and confining pressures were dropped to zero and slip tests, identical to those described for the prepared specimens, were carried out over the same range of steps and confining pressures from 1,500 to 9,000 psi. On removal from the triaxial bomb, the halves of these and prepared specimens were separated and visually inspected.

In most cases the specimens failed on only one plane. However, in some instances specimens had wedge type failures, because of slip on conjugate shear sets. In other cases, two non-intersecting failure surfaces occurred, the surfaces making approximately the same angle to the specimen axis, although not necessarily parallel or subparallel to one another.

Striae and steps were most easily produced on lapped and fracture slip surfaces on soapstone, to some extent on mudstone and with least success on siltstone. The striae were characteristically in the plane containing the long axis of the specimen. The steps were similar to the two basic types observed in the field and both types were oriented approximately perpendicular to the direction of the striae. Risers on accretion steps were observed to face in opposing directions (as did those of steps comprised of ground up coal on the roof or floor of Upper Marsh seam) depending largely on whether the fragments of compressed gouge stuck to one side or other of the specimen when the slip surfaces were separated for viewing. Among the 36 specimens studied, however, one had the appearance of that displayed by Paterson (1958, Plate 2) from the Wombeyan marble. The steps produced in these laboratory tests, therefore, were not consistently congruous. Prominent fracture steps were observed to be due to deformation of the principal slip surface by displacement on the conjugate shear set. They were antithetic and therefore incongruous.

The lapped surfaces on one specimen of soapstone were found to have triangular patches of gouge on them which suggested a mechanism of generation of rock flour and of formation of accretion steps (Plate 10). The patches of gouge were observed to be plastered in indentations, to be in the shape of isosceles triangles up to one-half inch high in the plane of slip, and to have small-scale steps at their base.



Plate 10. Triangular patches of gouge on lapped slip surface on soapstone.

It would appear that gouging begins at numerous points on the lapped surface, and is self-reinforcing so that the more rock flour present, the wider and deeper the indentation. This concept is supported by the fact that the height of the triangular patches of gouge is commonly greater than the magnitude of slip. Under the confining pressures of the triaxial bomb, the accumulated gouge is presumed to press against the forward end of the indentations, causing them to shear off as a series of imbricate scales, which are ground up to produce more gouge. The result is a family of triangular indentations on each slip surface, filled or overflowing with ground rock, with their apices pointing in the direction of motion of the block of which they are a part.

Depending on whether the compressed gouge stuck to the one or other surface, indentations and steps were formed and the risers faced in either direction. The orientations of the risers, therefore, could not be used to determine sense of slip but the direction in which the apices of the triangles were pointed, could. The apices on adjoining surfaces face in opposite directions and point in the direction of slip of the surface on which they lie.

## COMPARATIVE STUDIES

In order to evaluate further the nature of the relationship of the distribution of azimuths of a kinematic axes and of the orientation of steps to tectonic environment, comparative studies were carried out in the fold belt of the northern Appalachians and on the craton of the St. Lawrence Lowlands. Samples of striae and steps from tectonic environments dominated by thrust faulting and by folding were compared with those from a simple fold in an area of essentially flat-lying rocks.

### Southern Anthracite Field

A detailed study of the floor of the Mammoth seam in the Southern Anthracite Field of Pennsylvania revealed an abundance of striae which was due to displacement of the coal relative to the rock. The plot of the cumulative per cent of kinematic axes against azimuth (Fig. 10) is approximately circular normal and very similar in appearance to that for the Upper Marsh seam. It seems reasonable to assume that the distribution of orientations of a kinematic axes must represent a significant part of the movement picture; overprinting here as elsewhere was not effective in totally erasing the kinematic past.

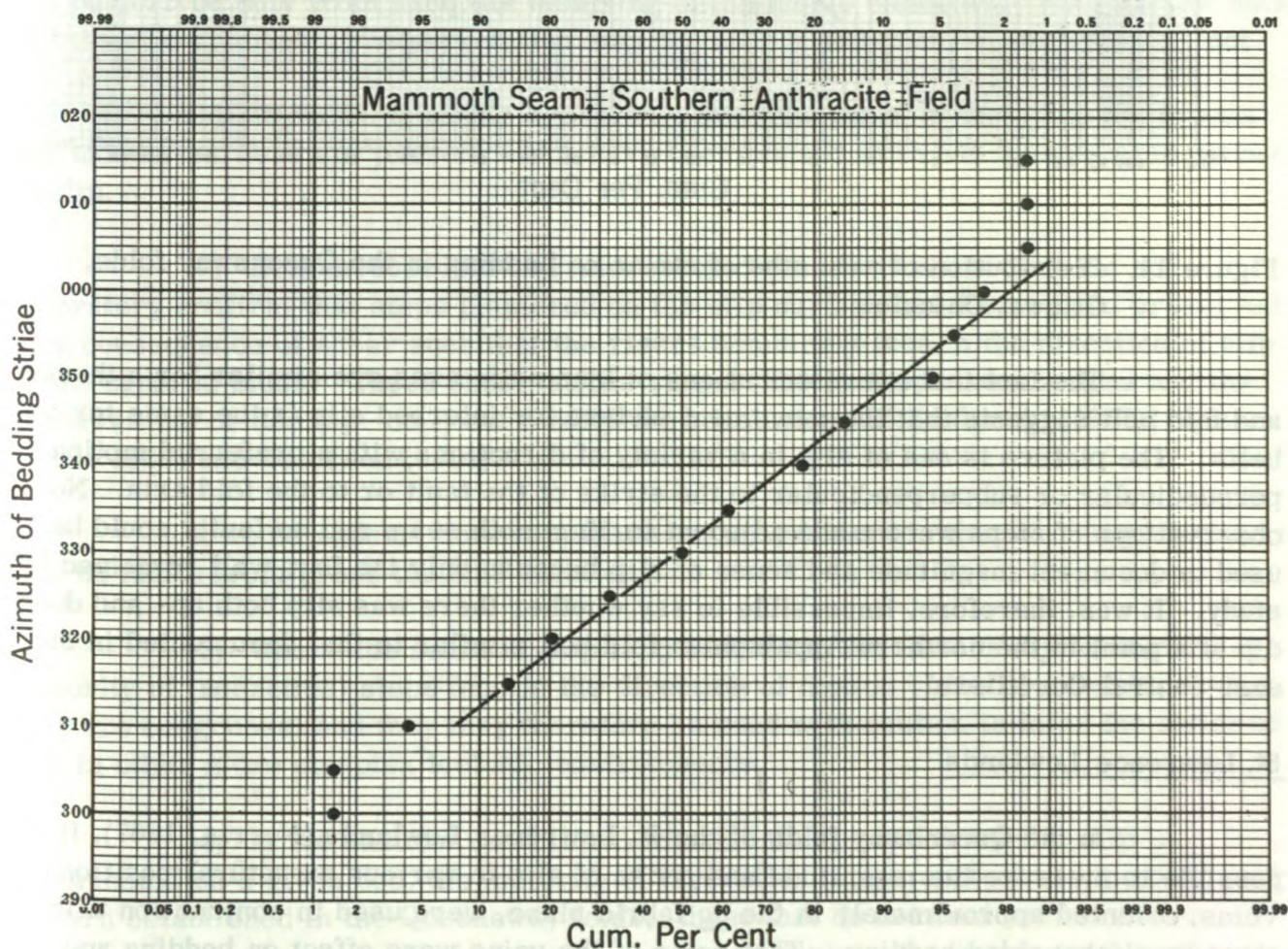


Figure 10. Distribution of azimuths of striae on bedding in the Mammoth seam, Tamaqua, Pennsylvania.

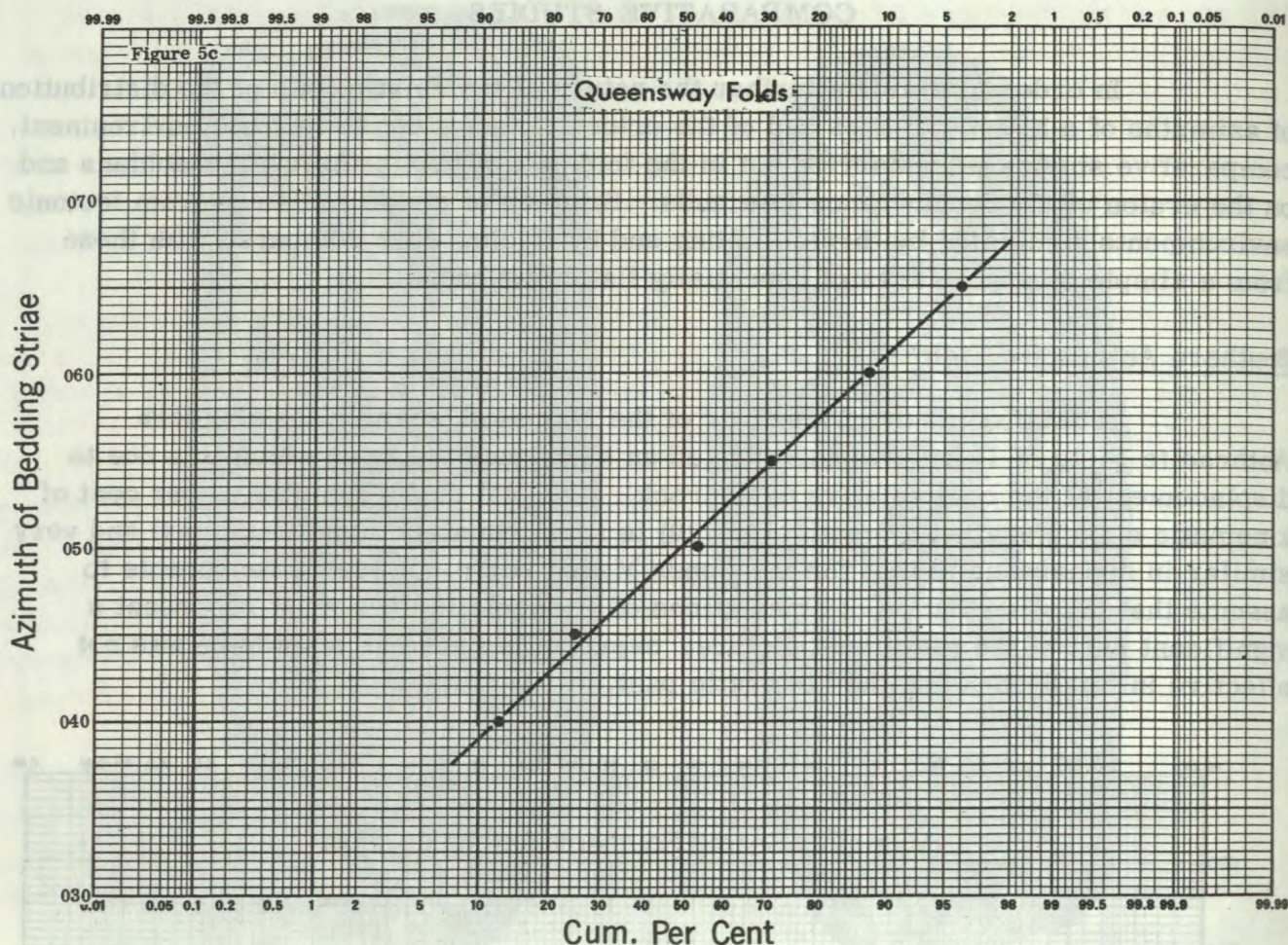


Figure 11. Distribution of azimuths of striae on bedding in the Queensway folds, Ottawa, Ontario.

The fact that the distributions of kinematic axes are similar for a thrust and fold belt suggests that the movement picture for interbed slip is the same for both belts. The picture is one of slip in a variety of directions with a preferred motion perpendicular or subperpendicular to the strike of the fault or to the fold axis. No observations of steps were made adjacent to Mammoth seam and no faults could be used to document magnitude and sense of slip because only the foot-wall remained for study. It was, therefore, impossible to say whether there was slip both up- and down-dip at a point in the northern Appalachian fold belt similar to that documented in the east-central Cordillera.

#### St. Lawrence Lowlands

In the Queensway folds of the St. Lawrence Lowlands (Norris, 1967), it was possible to measure the magnitude and sense of slip in various structural positions. Veins, oriented approximately in the bc fabric plane, were used in conjunction with steps on slickensided bedding. That some of the veins were offset on bedding and others were not would suggest that some veins may have developed after folding. Others in the syncline and on one flank of the anticline indicated sliding of higher strata over lower ones away from the axial surfaces, in conformity with the classical model

of flexural-slip folding. Of the twelve accretion steps observed, nine were congruous with the sense of slip established by means of the mineralized fractures (Norris, *idem*, Fig. 12). The preponderance of data therefore support the textbook descriptions (e. g. Billings, 1954, p. 149) that the risers face in the direction of relative slip of the opposed block. The presence of accretion steps which do not conform to the textbook descriptions would suggest that some may be plastered on the slip surface in the manner simulated by Riecker (1965, p. 746) during shear experiments on powdered olivine pellets, or that some may be due to minor slip in a reversed sense.

The distribution of a kinematic axes in the Queensway folds is approximately circular normal (Fig. 11) as in the Mammoth seam and on the flank of Mount Allan syncline. It would appear, therefore, that such a distribution is not characteristic of the thrust belt of the east-central Cordillera, the fold belt of the northern Appalachians or of the craton of the St. Lawrence Lowlands, but rather is fundamental to interbed slip in a variety of tectonic environments.

### CONCLUSIONS

Meaningful interpretations of movement pictures of thrust plates and folds can be derived only from adequate sampling of the fabric elements. With too few data a kinematic or dynamic interpretation may be more a statement of faith than of fact.

(1) Slickenside striae define only the orientation of the a kinematic axis and unless markers are present which have been faulted little can be said of the sense of slip.

(2) Both mesoscopic and microscopic observations in the field and laboratory confirm that steps plastered on the slip surface are formed and preserved as a consequence of shear such that the risers commonly face in the direction of slip of the opposed block. These observations support the textbook descriptions and the observations of Rod (*op. cit.*) but modify the conclusions of Dzulynski (1953), Tjia (1964, 1967) and Paterson (1958).

It would appear, however, that a major problem is the inferring of sense of slip on faults from gross tectonic relations.

(3) Where the sense of slip is known, as in the Queensway folds, the majority of (accretion) steps face in the direction of motion of the opposed block (i. e. they are congruous) and they may therefore be used with caution to infer the sense of slip in other more complex tectonic environments.

(4) In the eastern Cordillera, where both up- and down-dip slip is documented on a given bed, the majority of (accretion) steps conform to the dominant pattern established in the Queensway folds; those that do not conform may have developed as a consequence of reversed motion or because the gouge stuck to the opposing surface and the need to appeal to the arguments of Dzulynski and others is avoided. It is difficult to conceive how steps of either of the two basic types can be preserved in their sharp and undeformed state if they are oriented to oppose slip.

(5) Risers which are known to face in opposing directions or which do not conform to textbook descriptions suggest complexities in the movement picture. Steps need not necessarily be congruent with sense of slip inferred from the regional structure although those that are congruent should predominate. When their nature and origin are recognized, steps may be used with meaningful samples of measurements of pitch of striae to establish at least part of the kinematic history of faulting and folding in orogenesis.

#### ACKNOWLEDGMENTS

The writers wish to thank F. P. Agterberg and N. C. Ollerenshaw of the Geological Survey of Canada for helpful discussions and for critically reviewing the manuscript. They are also indebted to S. Carbone for preparing the thin sections of steps on slip surfaces and to S. Cook and J. Sullivan for preparing the test specimens for laboratory studies of structural features on slip surfaces.

#### APPENDIX

##### Statistical Analysis of Pitch Measurements

The mutual independence of adjacent measurements of the a kinematic direction on a given bed was first tested. Unless stochastic independence is fulfilled it is impossible to conduct meaningful significance tests on measurements (Agterberg and Briggs, 1963, p. 397).

Observations on roof of Upper Marsh seam were used. The arithmetic mean of the a kinematic directions and the deviations from the mean  $\Delta j (= x_j - \bar{x})$  were determined. The deviations are, of course, both positive and negative and their algebraic sum must equal zero. According to Agterberg and Briggs (idem) in cases of dependence, a certain value will be preceded and followed by values of the same size. If  $\Delta j$  is taken as the abscissa and adjacent value  $\Delta j + 1$  is taken as the corresponding ordinate, all values would scatter around the line  $\Delta j = \Delta j + 1$ , having a slope of 45 degrees. It is evident from Figure 4, a scatter diagram for these roof data, that there is no such concentration about this line. Because the scatter is shotgun it may be safely assumed that successive measurements are stochastically independent and that a basic condition for further statistical testing is met.

Insofar as statistical theory is based on the so-called normal distribution, the tests applied to the data necessarily imply certain assumptions about the distribution of the a kinematic directions. Theoretically the orientation of directional features is circular normal because it is a modification of the case in which the data have a cyclical distribution (Agterberg and Briggs, op. cit., p. 398). There appears, moreover, to be no significant difference between the circular normal and normal distributions when the standard deviation is 30 degrees or less because the distribution functions give similar values of the dependent variable for small values of the exponent (Agterberg and Briggs, idem).

The arithmetic means and standard deviations of the a kinematic directions for roof and floor of Upper Marsh seam were calculated on the assumption that the samples may be approximated by normal distributions. The results are tabulated in Figure 3. Although the means are the same, the problem remains whether the standard deviations are sufficiently similar to justify the belief that the samples from the roof and floor are from the same population of striae. The ratio of variances, denoted by F, equals  $100/78 = 1.28$ . If this value is not significantly greater than one, it may be assumed with some degree of assurance that the variances are for the same population of striae. For the roof, there were 73 observations, and therefore 72 degrees of freedom; and for the floor, 67 observations, and 66 degrees of freedom. From tables (Hoel, 1966, p. 339) it is found that at the 95 per cent level of confidence, the corresponding F value is 1.76. Since  $F = 1.28$  for this problem is appreciably less than the critical value from the tables, the data are in agreement with the hypothesis that the samples of orientation of a kinematic axes from roof and floor are from the same population of striae.

Because of the possibility that two or more populations could be mixed whose means and standard deviations were close to one another the combined data were plotted on arithmetic probability paper (Fig. 5). A normally distributed sample will plot as a straight line whose slope is determined by the standard deviation of the sample. If the sample were in fact a mixture of two or more distributions which are themselves normally distributed, the plot will give rise to a curve which is the resultant of two or more straight lines (Harding, 1949, p. 142). If one ignores the extremities of the plot where the data are few, it is apparent that the curve is sublinear and that the sample approximates a circular normal distribution.

Although intersecting striae on bedding are common adjacent to Upper Marsh seam, the determination of the relative ages of two or more sets is often difficult. A most careful search of roof and floor revealed 39 sets whose relative ages could be established with reasonable confidence (see Fig. 6). It is apparent from the distribution of (b) axes of slip that the relatively older or younger axes are not confined to one or other part of the fabric diagram but are intermingled along the trace of mean bedding in the projection.

To test the possibility that these sets could have arisen from more than one movement picture they were divided into two groups, that containing the relatively younger striae and that containing the relatively older. Their mean orientations and standard deviations were calculated and F and t tests performed. Designating the mean orientation of the kinematic a axis for the relatively older striae as  $\bar{a}_o$ , for the younger as  $\bar{a}_y$  and their respective variances by  $\sigma_o^2$  and  $\sigma_y^2$ , the following values were obtained:

$$\begin{array}{ll} \bar{a}_o = 61^\circ & \sigma_o^2 = 653 \text{ sq. deg.} \\ \bar{a}_y = 62^\circ & \sigma_y^2 = 558 \text{ sq. deg.} \end{array}$$

$$\text{Now } F_{\text{obs.}} = 653/558 = 1.17 \text{ and according to Hoel (ibid)}$$

$F_{\text{tab.}} = 1.72$  at the 95 per cent level of confidence for 38 degrees of freedom in the numerator and denominator of the ratio of the variances. Thus  $F_{\text{obs.}}$  is appreciably less than  $F_{\text{tab.}}$  and we may, with reasonable assurance accept the hypothesis that the variances of the samples of older and younger striae are sufficiently alike to warrant the assumption that they are independent estimates of the same population variance.

To test the hypothesis that the arithmetic means  $\bar{a}_o$  and  $\bar{a}_y$  are independent estimates of the same population mean, we calculate Student  $t$  (see Moroney, 1951, p. 228, for example), where  $t_{\text{obs.}} = \frac{|\bar{a}_o - \bar{a}_y|}{\sigma_o} \sqrt{n-1}$  and  $n = \text{no. of observations of } a_o$ .

$$\text{Thus } t_{\text{obs.}} = \frac{1 \times 6.16}{25.6} = 0.241$$

Now  $t_{\text{tab.}} = 2.02$  at the 95 per cent level of confidence, for 38 degrees of freedom (Hoel, op cit., p. 330). Thus  $t_{\text{obs.}}$  is appreciably less than the tabulated value and the difference in means is probably not significant.

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#### DISCUSSION

W. F. Brace asked D.K. Norris if he had attempted to section some accretion steps generated in the laboratory and what the section might show.

D.K. Norris said he had not, because of technical difficulties with the impregnation of the ground-up material.

R. A. Price asked D.K. Norris if the apparent 'cross-bedding' laminae of some accretion steps might represent small accretion increments built up in the horizon of the step.

The author said that he considered the gouge of accretion steps to be built up as well as eroded through successive instances of slip, dilation and mineralization. Some cross-laminae are, therefore, actually truncated by the slip surface. What he was looking for and found in accretion steps was some record of the slip history of the surface.

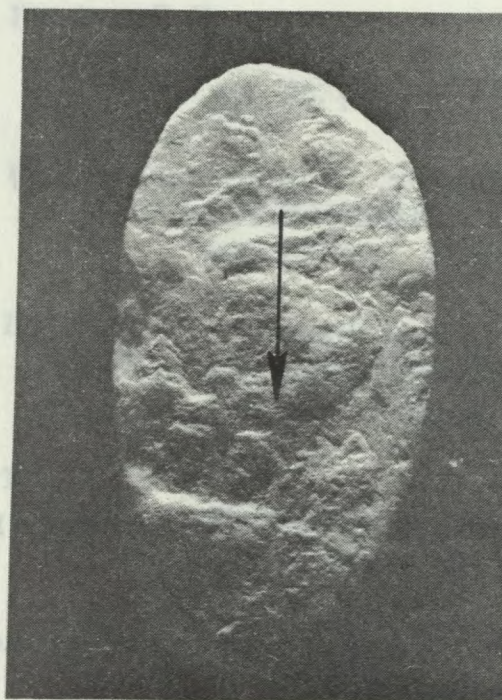
J.B. Currie (written comments)

Legend for Figures

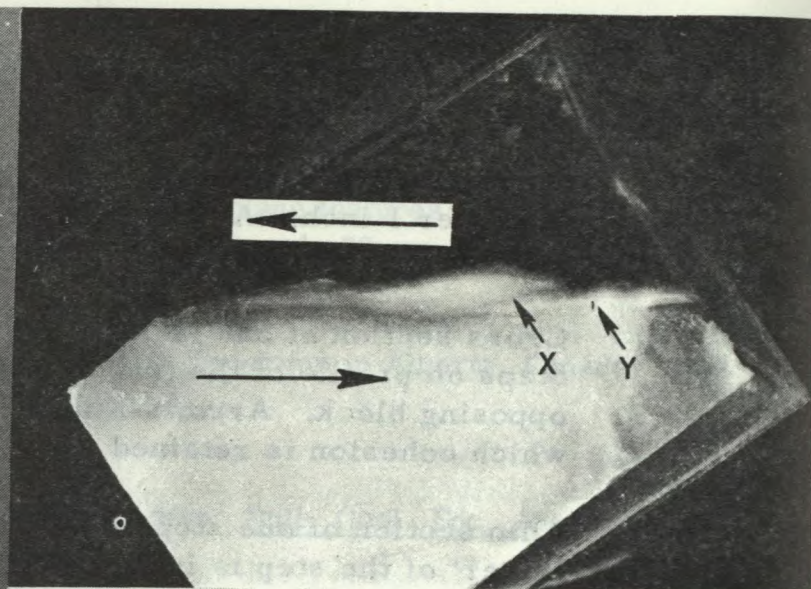
- Figure (1a) Steps on a fracture surface in alabaster. Cylindrical sample; diameter 1 inch. Arrow indicates motion of the upper block. Confining pressure 69 bars.
- (1b) Cross section of one fault block; sample diameter 1 inch. Steps on profile of the fracture surface face the motion of the opposing block. Arrows X and Y point to fractures along which cohesion is retained.
- (1c) Thin section of one step on a fracture profile (X25). The gentle 'riser' of the step is indicated by the arrow at Z.
- (1d) Thin section showing cross fractures that comprise part of the deformation within steps on a fracture surface in alabaster (X25).

Figure 2 on page 171

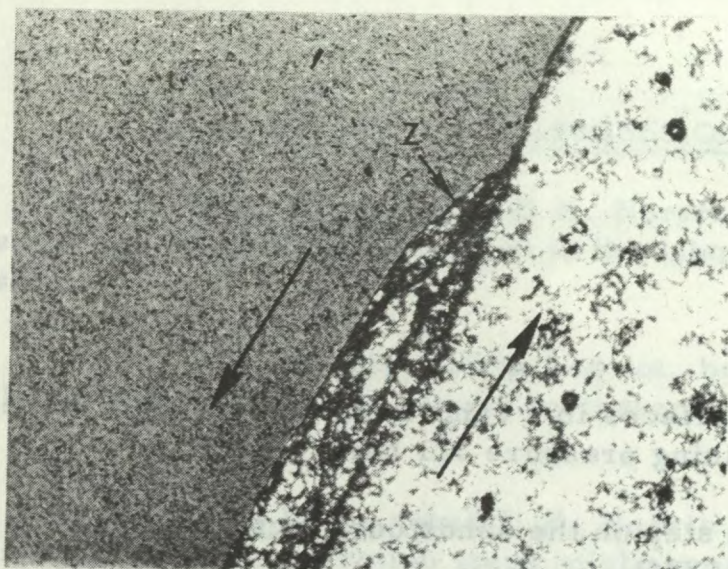
- (2a) Steps on fracture surfaces in a sandstone cylinder, 0.6 inches in diameter. Confining pressure 321 bars.
- (2b) Thin section of one step on the sandstone fracture surface illustrated in (2a), (X25).
- (2c) Steps on fracture surfaces in a limestone cylinder, 0.6 inches in diameter. Confining pressure 1,046 bars.
- (2d) Thin section of one step on the limestone fracture surface illustrated in (2c), (X100). A major fracture can be traced from K downward to its terminus. A minor stepped fracture zone is evident at L.



a



b



c



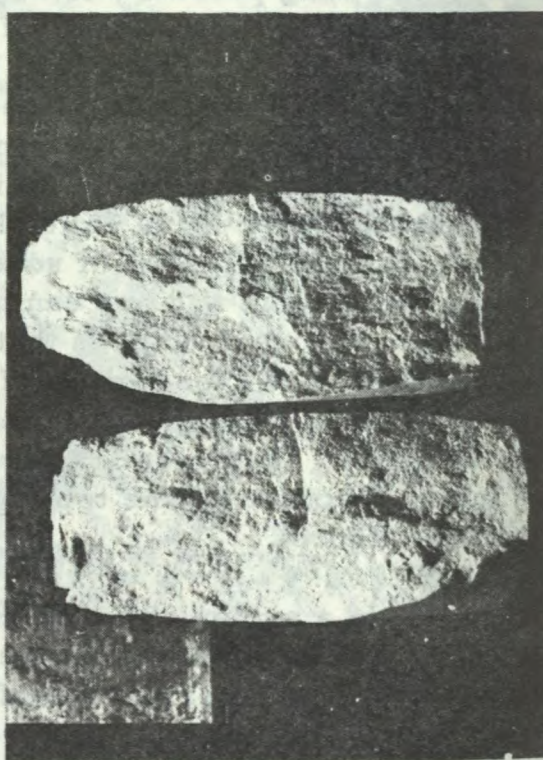
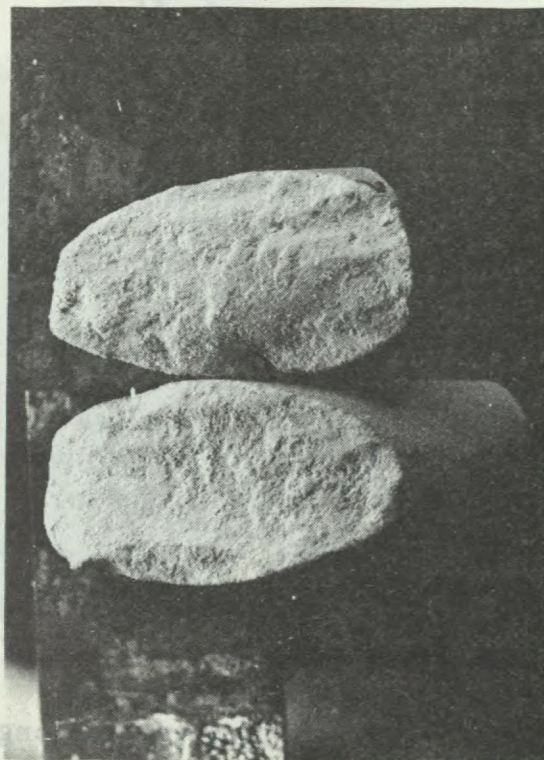
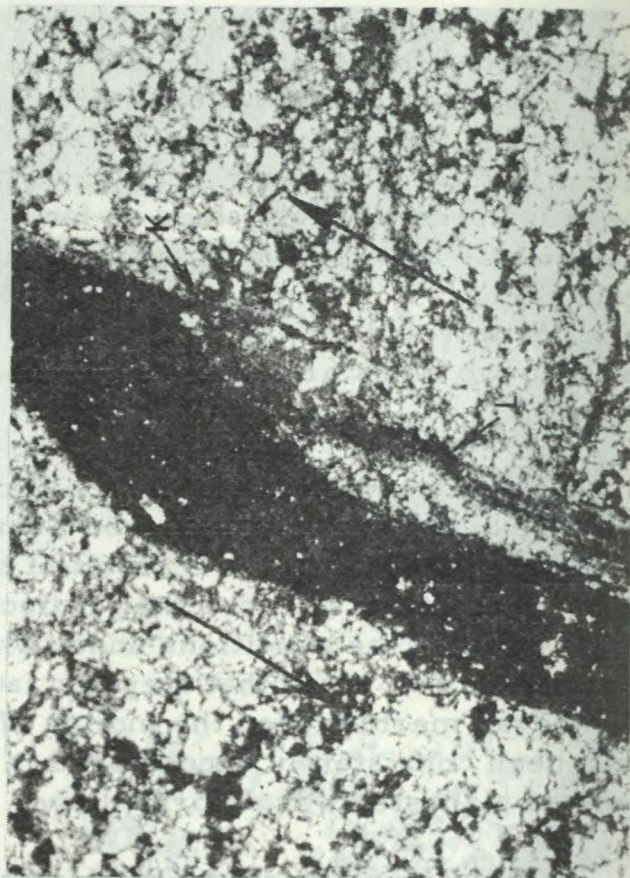
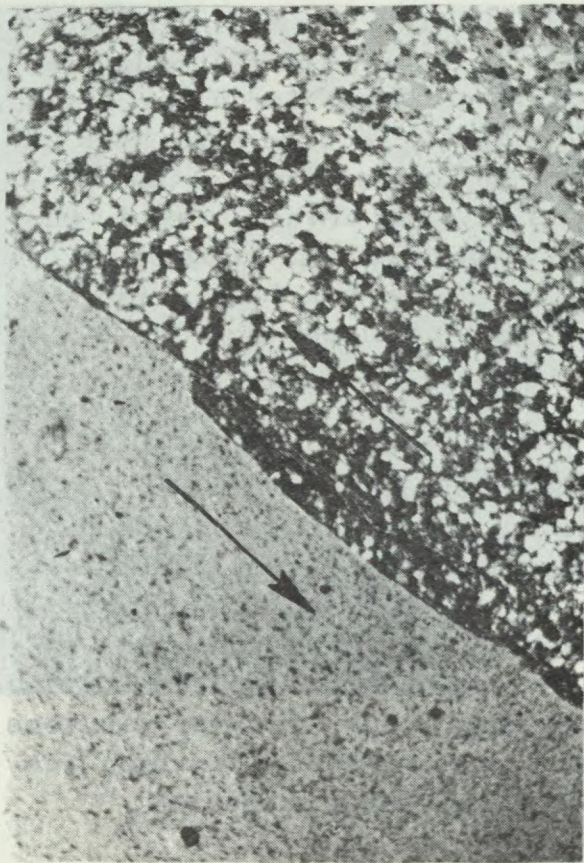
d

The field and experimental evidence cited by Norris and Barron draws attention forcefully to the value of studying features on fault surfaces. They have shown how these features, in the case of Upper March coal seam, serve to document the kinematic pattern. Tjia (1967) records more than six distinct types of geometric features that occur on fault surfaces. One of these features, namely steps on fault surfaces, has not always served satisfactorily as an unequivocal indicator of displacement sense. In partial explanation, Rod (1966) suggests that 'steplike breaks' can develop in more than one way and, in fact, Norris and Barron conclude from their study that at least two types are recognizable, i.e. 'accretion' steps and 'fracture' steps.

One might explore, therefore, the possibility that the character and type of features developed on a fault surface may depend on the conditions of deformation. As a result of this dependency the facing and nature of steps on fracture surfaces may reflect not only the sense of displacement on faults but also the conditions under which rupture and movement took place. Paterson (1958) noted that steps on fault surfaces produced in cylinders of Wombeyan marble faced the motion of the opposing block. Similar relations have been consistently encountered in a series of experiments in which fine-grained alabaster was deformed over a range of confining pressures.

Figure 1a shows the fracture surface that accompanied rupture under a confining pressure of 69 bars. Steps on the surface trend approximately normal to the direction of fault movement and their 'risers' face against the movement undergone by the opposite fault block (indicated by arrow). Figure 1b provides a sectional view of the fault surface. The steps face against the motion of the opposing block. Two arrows (X and Y) point to fractures that are part of the main rupture zone but along which cohesion has been retained. In Figure 1c is shown the thin-section view of a step on the fracture surface. Traces of several fractures almost parallel to the main rupture are evident and one can note also a general parallelism among the less obvious cross-fractures that trend subparallel to the 'riser' segment of the step (at Z). A closer view of these minor cross-fractures is afforded by Figure 1d taken from an experiment in which cohesion along the main fracture was retained. The cross fractures evidently permit continuity of slip between one major fracture (at the top right of the figure) and another (at the lower left of the figure).

In a series of experiments covering a range of confining pressures, one notes that development of steps on fracture surfaces in alabaster is most obvious within an interval of confining pressures between about 20 and 200 bars. Below this interval rupture causes an irregular fracture surface along which some granulation of material is evident. Above confining pressures of some 200 bars, failure takes place within a deformation zone, of variable width, along which cohesion is retained even in advanced stages of strain.



a

b

Deformation of a fine-grained sandstone having a micaceous matrix has also shown the development of steps on fracture surfaces. Figure 2a highlights steps on both pieces of a fractured cylinder. The direction of fault displacement, parallel to the sample axis, is made visible by vague slicken-sides. A thin-section of one step on the fracture profile (Fig. 2b) illustrates its shape and the degree to which material in the step is deformed. Deformation of fine-grained limestone, at relatively low confining pressure (Fig. 2c), further illustrates the development of steps on fracture surfaces. Besides the several obvious steps visible on the fault surface, close inspection shows a very large number of small steps across the entire area of the fracture. For microscopic examination the two pieces of the specimen were cemented together and thin-sectioned. Figure 2d depicts a close sectional view of one step on the fracture. From the point K one can trace a major fracture downward toward its terminus. At L, a minor 'stepped' fracture zone is evident. Prominent development of steps on fractures in the sandstone and limestone samples employed in these experiments appears to occur over a definite interval of confining pressures. For the sandstone, this occurred between 300 and 500 bars, a somewhat higher range than that encountered in the alabaster experiments.

The foregoing evidence suggests that development of stepped fracture surfaces in experiments is governed by the conditions under which samples are deformed. For this series of tests their occurrence was controlled by the confining pressure at which experiments were conducted. This does not imply that temperature, pore pressure and strain rate are not also significant variables. The results do suggest however that at least one type of structural feature commonly found on fault surfaces may reflect something of the conditions of deformation, in addition to revealing the sense of fault displacement. The occurrence of other fault-surface features, such as pluck marks or drags, may also be conditioned by deformational parameters. If this is so, they may acquire greater value in structural interpretation.

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Authors' reply to J. B. Currie (written comments) The authors would like to thank Dr. Currie for his contribution; he has raised some interesting points. The steps shown by Dr. Currie would appear to be 'fracture steps' as defined by us in the paper, i. e. they are irregularities of the

fracture surface. As such, when the surface is first formed, we believe that these steps could face in either direction. However, if movement occurs on this surface it would seem likely that those facing against the motion of the opposite surface would gradually get destroyed. It would seem likely therefore that the specimens shown in Dr. Currie's photographs have been subject to little or no relative movement between the surfaces. Had there been significant displacement between these surfaces there should be evidence of gouge (and possibly accretion steps), which is not apparent on the photographs. Unmodified fracture steps, therefore, rather than indicating the sense of motion between surfaces, might perhaps be considered to indicate a lack of relative motion between the surfaces.

The evidence presented by Dr. Currie that the occurrence of stepped fracture surfaces is dependent in some way on the confining pressure is significant. However, rather than attributing this to be the 'degree of deformation' of the specimen, we think that this is related to the fracture mechanism occurring in the specimen. A plausible qualitative explanation might be as follows:

At low confining pressures the rock behaves in a brittle manner and fracture initiates in the rock from single 'Griffith's cracks'. Now if the confining pressure is sufficiently low, conditions can be defined in which this fracture initiation propagates immediately to 'ultimate failure' of the specimen, the crack propagating at, presumably, terminal velocity. This would result in crack forking, granulation etc. on the surface. Above this level of confining pressure the material would still behave in a brittle manner, fracture initiating at critically oriented Griffith's cracks. However, the confinement is now sufficiently high to prevent this initiation propagating immediately to failure. Instead fracture will initiate at successively less critically oriented cracks and critically oriented cracks will grow in a stable manner, until at some stage this array of microcracks coalesces to form the fracture surface. In this region the fracture surface has been formed in a more or less controlled manner, consequently granulation of the surface because of unstable fracture propagation will be minimal; it might be expected that pronounced fracture steps would be apparent (which could face in either direction).

At very high confining pressures the material would behave in a completely ductile manner and a shear failure of the specimen would be anticipated on which there would be no fracture steps. There will, of course, be some transition zone between completely brittle and completely ductile behaviour of the rock, in this region a gradual fading out of fracture steps would be anticipated as confining pressure increases.

If the above tentative explanation is true then it would be of interest to examine the development of potential fracture surfaces in the brittle region prior to ultimate failure, and to see if in fact potential fracture steps are indicated and if there is a preferred direction of the steps. This could be

done by stopping a test before ultimate failure but after the onset of fracture initiation, and then examining thin sections of the specimen. Now fracture initiation in the specimen can be recorded in an experiment by observing the onset of microseismic activity. In consequence it would be possible to test a series of specimens at gradually increasing stress levels above onset of fracture initiation and before failure.

Hoek (1965) did stop one experiment before failure and examined the microcracks in it. His photograph (Fig. 24, p. ) shows that steps in the crack path can face in opposite directions.

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W.C. Brisbin asked J.B. Currie about the effect of confining pressure on fractures developing during the long translation of one side past the other in his experiments.

J.B. Currie answered that much of the slope is due to curving of the fracture steps, as a result of the movement of one side past the other.

# In Situ Stresses

H.U. Bielenstein\* and K. Barron\*\*  
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## INTRODUCTION

This paper presents a summary of the presentations made during the session on in situ stresses. The objective of this session was to discuss, with examples, some of the problems and approaches to the interpretation and significance of in situ stress determinations from both the engineering and geologic viewpoints. The session coordinators (BIELENSTEIN and BARRON) posed a series of questions aimed at identifying problem areas; individual contributors (HERGET, BENSON, VARNES, BROWN and GOODMAN) reported on specific studies aimed at trying to answer some of these questions and, in turn, raised a number of more detailed problems. This summary is not comprehensive but merely attempts to report some of the highlights of the session in a cohesive framework. Many of the questions posed remain unanswered, some ideas presented may be controversial, but nonetheless it is thought that this session achieved a frank discussion between engineers and geologists and some mutual appreciation of how each discipline might aid the other in the search for answers.

## TERMINOLOGY

The terminology currently used to describe in situ stresses shows great diversity; to avoid lengthy argument on terminology the contributors were asked to follow a specific terminology, provided that it did not offend their sensibilities, or alternatively to indicate clearly where they deviated from it. This suggested terminology is illustrated in Figure 1 and defined below:

Induced stresses are man-made stress components due to removal or addition of material. They are superimposed on natural stresses which exist prior to excavation. The natural stress field can be composed of gravitational stresses (due to mass of overburden); tectonic stresses and residual stresses (a much used and abused term, taken to mean "stress components that remain in the structure if external forces and moments are removed"(1)). Tectonic stresses may be active tectonic stresses (due to active present day straining of the earth's crust) and/or remanent tectonic stresses (due to past tectonic events which have only been partially relieved by natural processes).

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## OBJECTIVES OF IN SITU STRESS DETERMINATIONS

Natural stresses in rock are the cumulative product of events in its geologic history; as, for example, the strength or the mineralogy of a rock are also determined by geologic processes. The geologist is concerned with the understanding of tectonic events and processes that took place in geologic time. These must be deciphered from the evidence currently available. A knowledge of the natural stresses, in conjunction with the geometry of the geologic structures and the kinematics of their formation, play an important part in tectonic analysis and should aid in answering such questions as:

- (i) Is the current state of stress tectonically active or passive?
- (ii) What tectonic events in space and time have affected this rock?
- (iii) Do remanent tectonic stresses affect the style of deformation during subsequent tectonic events?

The engineer is primarily interested in designing and excavating safe structures in rock. He therefore needs to know the natural stresses, active in the rock, together with a knowledge of the mechanical behaviour of the rock when subjected to natural and induced stresses. His design must also take into account the useful working life of the structure, which may extend from milliseconds in the case of blasting to, say, 100 years for dam foundations. (In geologic terms this time spectrum would be regarded as "instantaneous".)

With these objectives in mind the following questions were posed: What is actually measured using current techniques? ; how are these measurements interpreted and what assumptions are involved? ; what is the influence of geometric scale on the measurements and their interpretation?

## INFORMATION OBTAINED FROM CURRENT MEASURING TECHNIQUES

The majority of current "stress measuring" techniques in fact sense or measure strain; these strains must be transformed, using some assumptions of material behaviour, to give "stresses". Most of the techniques measure the strain produced by cutting out or overcoring instrumented rock specimens. These strain relief measurements can be split into the categories of short term (within two hours of overcoring the specimen) or long term strain relief (relief occurring after two hours).

If the strain relief measurements are confined to the domain beyond the influence of induced stresses then both short and long term relief may in turn be divided into two categories: that attributable to the relief of residual stresses and that attributable to relief of the other natural stresses (tectonic and/or gravitational), as illustrated in Figure 2.

### Short Term Strain Relief

Short term strain relief measurements obtained by overcoring techniques are interpreted in terms of stresses assuming that the rock behaves as an elastic material, and that the elastic constants are obtained from tests on the overcored specimens.

(a) Overcoring of Rock In Situ. If in situ rock is overcored and the stresses determined in a number of localities are consistent then these stresses may be interpreted as tectonic and/or gravitational. The tectonic component would have to be determined as the difference between the calculated gravitational component at any one locality and the determined stresses.

The engineer would regard these stresses as the "active stress" on his structure without differentiating the various components. The geologist is more interested in the tectonic component; particularly in its spatial relationship to the principal axes derived from structural analysis. Stress determinations themselves cannot be used to differentiate between active tectonic and remanent tectonic stresses. This type of interpretation must be based on analysis of the kinematics of deformation (2).

It is in this category of stress determination, short term in situ relief assuming elastic behaviour, that most work has been done as was well illustrated by the presentations of both HERGET and BENSON.

HERGET reported on a well documented study aimed at relating stress determinations to geologic structure. A tectonic analysis and stress determinations were carried out to obtain the pre-mining stress field at an iron mine in the Lake Superior region. The siderite orebody is part of the Archean rocks which have been folded about regional ENE trending fold axes. Slaty cleavage, slickensides and extension fractures indicated, for this phase of deformation, a compression in a horizontal NNW direction. This picture was modified due to the development of NW to N trending folds which preceded the development of prominent faults of similar strike. Finally the youngest recognizable deformation phase was indicated by shearing along late Precambrian diabase dykes, development of kink bands and quartz filled fractures suggesting a compression for the mine area in an E to NE direction. On the assumption that no haphazard changes occurred and that tectonic stresses existed in the area, HERGET speculated that the maximum stress should be associated with the youngest deformation phase and thus should be oriented horizontally NE to E.

Short term elastic strain recovery measurements were carried out at six sites at three elevations in the mine. In each case the calculated stress tensor was the value of the best fit data from 30-60 strain-recovery measurements in three or four holes. The results showed clearly that there was no uniform direction for the maximum principal compressive stress. At three sites the measured directions were in agreement with those predicted from the kinematic analysis of the most recent deformation phase (NE to E). However, at another two sites, the measured directions were very close to the maximum principal compressive stress direction of the, earlier, major deformation phase (i.e. NNW). HERGET thus concluded that, in this case, it is not possible to predict the principal stress directions from the tectonic fabric in these basement rocks. The stresses must be determined; although the sites for stress determinations should be selected on the basis of tectonic analysis. Finally he concluded that, since there is no prevailing principal stress direction, the area investigated was truly an area of remanent tectonic stress. For a current build up of tectonic stresses he would have anticipated a more uniform stress field.

This study by HERGET clearly illustrates some of the difficulties of interpretation that can occur despite carefully taken and well documented measurements. His conclusion that the stress directions were probably attributable to remanent rather than active tectonic stresses is interesting, although it might well be the subject of some debate.

BENSON reported what could be regarded as a typical engineering application of in situ stress determinations aimed at assisting the design and layout of the underground chambers for the power house at Churchill Falls. Initially finite-element stress analysis studies were carried out for model chambers of various shapes assuming boundary conditions given by a vertical overburden stress,  $\sigma_v = \gamma_z$ , with a horizontal stress,  $\sigma_h$ , ranging from  $0.3 \sigma_v$  to  $2.0 \sigma_v$ . For each ratio of the boundary conditions,  $K = \sigma_h / \sigma_v$ , the chamber

shape was changed to minimize the tensile zones around the openings. On completing this analysis a knowledge of the in situ stress conditions was required in order to select the optimum design for the actual boundary conditions of the site. (Note: in this case, the determination of the ratio  $K$  is more important than the actual magnitudes of the individual principal stresses.) Stress determinations were carried out at four locations with three to five holes at each location. Each hole was 20-25 ft long and fifteen tests were made in each hole using three axis deformation meters. It was estimated that 80% of the data for any given hole were within 15% of a median value, and this was considered to be confirmation of a general and predictable natural stress field in the rock mass. No preferred direction of lateral stress components was found. The results showed vertical gravity loading and an average  $K = 1.7$  (ranging from 1.1 to 1.9). On the basis of these results the design was checked, and alterations were made as necessary to provide compliance with the results of the finite element model.

BENSON raised two very important points pertaining to this data analysis. Firstly he emphasized that measurements of this nature yield an excess of data over the minimum required for calculating the stress tensor. Consequently it is essential to average this data by means of suitable computer programs yielding best fit solutions to all the gathered data. The second major point concerned the value and determination of the Young's modulus of the rock. Usually the uniaxial modulus from laboratory tests is used in the stress calculations. In this case this yielded suspiciously high values for the stress components. Since this overcoring technique is essentially a biaxial measurement method they devised and carried out a test for Young's modulus determination under biaxial loading. This yielding a significantly lower value of Young's modulus ( $E_{\text{biaxial}}/E_{\text{uniaxial}} \approx 4 \times 10^6 / 8 \times 10^6$ ). This, obviously, significantly changes the stress magnitudes calculated (although not affecting the ratio or direction).

The importance of this latter point raised by BENSON cannot be overemphasized. In attempting to interpret stress magnitudes, rather than directions, total reliance is placed on the value of the modulus used in the calculations. Considerable effort must therefore be made in checking modulus values to ensure that correct values are used.

(b) Overcoring of Relieved Specimens. When an overcored specimen is itself overcored any resulting short term strain relief is attributed to relief, or more probably, partial relief of residual stresses. The degree of partial relief experienced must be dependent on the scale of the specimen compared to the scale on which the stresses are locked in. Whilst it is possible to interpret this strain relief in terms of stresses, assuming elastic properties, it is difficult to know what significance such magnitudes would have.

VARNES and LEE expressed the concept of residual stresses well in their presentation. In summary this concept may be expressed as follows: Most rocks have at some time in their past been under higher pressure than they are today. Any tendency of rock to relax under lessened or removed load is restrained by the interlocking fabric of anisotropic mineral grains, cement between grains, or by shear stresses along fractures. Consequently, equilibrium of rather large internal forces may be attained within completely free rock bodies.

From this concept VARNES and LEE stated the hypothesis that if a new free surface is created within a body that contains a system of balanced forces in static or dynamic equilibrium, the geometry of the body will change and the direction and amounts of the balanced forces will be altered. The effects may be instantaneous (short term) or time dependent (long term), or

both. The free surface may be created by the slow process of natural erosion or by the rapid processes of tunnelling or drilling. The process of readjustment starts at the free surface and works inward. The initial rate of adjustment is more rapid near the free surface and depends upon the composition, fabric, and the structure of the rock and upon exterior loads, if any.

Some of the consequences of this hypothesis have considerable, practical and theoretical importance, amongst them are:

- (1) Forces balanced on a microscopic scale can perhaps be mobilized to act on volumes of significance to engineering structures, and to add their effects to any active exterior tectonic loads. Real unbalanced stresses may be mobilized which are much larger than accounted for by overburden; they may amount to an appreciable fraction of those under which the rock consolidated or was last annealed.
- (2) If the rate of relaxation varies with distance from a newly created face then there will be a size effect. From this it may be inferred that a rock of a certain size or shape having particular physical properties can contain a balanced system of forces of only a certain maximum intensity without application of exterior loads, and that corresponding to a particular level and distribution of internal stresses there is a volume or shape of "locking domain" in the rock that can contain this system of equilibrium. If the hypothesis is true then not only is there an equilibrium volume or "locking domain" for residual stress but this volume can be altered, generally enlarged, by the creation of a new surface.

These ideas proposed by VARNES and LEE have numerous implications. One very important one concerns the interpretation of short term, in situ strain-relief measurements of the type (a) described above. The engineer generally ignores residual stresses since, if they remain locked in the rock on the scale of the excavation, they cannot be regarded as stresses acting on the structure. In this case the effect of residual stresses will be apparent only insofar as they must affect the strength of the rock and its isotropy. Provided that the engineer can obtain a satisfactory measure of strength and its directional variation he may safely ignore residual stresses on the scale of these measurements. However, as VARNES and LEE pointed out, if the stresses are locked in the rock on a scale larger than that of the excavation, then excavation and in situ overcoring will relieve or partially relieve the residual stresses. In which case the result of sampling could be to infer, incorrectly, that the exterior boundaries of the body are under active tectonic load. It would also follow in such a case that stress relief techniques may be dependent on the shape and size of the instrumented body of rock that is freed from its surroundings.

Whilst the engineer may or may not be justified in ignoring residual stresses the geologist certainly cannot afford to do so. Residual stresses must reflect some aspect of the geologic history of the rocks. The magnitudes may be unreliable, but the principal stress axes obtained from measurements should again be compared with those derived from kinematic analyses. Unfortunately to date there is insufficient data to establish the usefulness of this approach; further research work is obviously warranted.

### Long Term Strain Relief

The long term strain relief measurements are measures of time dependent strains experienced by overcored specimens. [Care must, of course, be taken to ensure that strains caused by temperature changes or by drying out of the specimen are eliminated or corrected for in the test procedures.]

Assuming that a true measure of time dependent relief is obtained this can be attributed to two possible sources.

(c) Overcoring of Rock In Situ. Time dependent relief of tectonic and/or gravitational stresses; i.e. this could be regarded as the viscous relaxation of engineering active stresses.

(d) Overcoring of Relieved Specimens. Time dependent relief, or partial relief, of residual stresses through similar viscous mechanisms. It is immediately apparent that; currently, a distinction cannot be made between these two sources of time dependent strain relief.

Relaxation of type (c) has engineering significance since it involves the active deformation of the structure. Thus, although the engineer currently ignores these components, it would be desirable to separate the two components. Perhaps the results of type (c) relaxation might then be interpreted in terms of stresses assuming some rheologic model of material behaviour. Whether or not the engineer could then safely ignore the effects of residual stresses would then depend, as before, on the scale of measurement as compared to the "locking domain". If the overcoring size were greater than the equilibrium volume the effects of residual stresses could be ignored since in this case they would be reflected as time dependent strength variations.

A distinction between the two sources of time dependent relaxation could be important to the geologist. No interpretation in terms of stresses would be attempted but the geologist would seek to compare his kinematic analysis with the axes of principal strain relaxation. Little work, even without distinction between the causes, has been done in this area. For this reason the presentation by BROWN was particularly interesting.

BROWN reported on both short term and long term strain relief measurements obtained, using photoelastic gauges, from in situ overcoring in a number of rock outcrops at several locations from Texas to Wyoming. The results were divided into initial (short term) and final (stable condition reached after several days) measurements. The initial and final principal strain axes were not coincident, but each could be related to distinct geologic features or stress environments.

Measurements in the Llano uplift, Texas, were made on the periphery of a "mini-mesa". The initial major extension paralleled the strike of NE trending normal faults and was perpendicular to the regional fold axes. The final major extension was radial to the "mini-mesa" (SSE, at the point of measurement) and was interpreted as relief of radial strain; the tangential strain having been relieved by a penetrative set of radial fractures.

Near Cody, Wyoming the strain relief measurements were made in the crystalline core of a tilted block uplift and the sedimentary envelope forming a drape fold over this uplift. Initial major extension axes were compatible with current incumbent loads at the measuring sites: vertical within the crystalline core and parallel to bedding dip at the base of the nearly vertical limb in the drape fold. The final major strain axes were related to the formation of the uplift. Within the core, major extension was perpendicular to bedding overlying the uplifted block; but at the base of the nearly vertical limb major contraction paralleled the bedding dip reflecting the extension of this limb during uplift.

Measurements at the Rangely anticline in Colorado showed a consistent rotation of initial to final major extension axes, from N70°E to N85°E. BROWN related this rotation to the changing stress environment of the developing

anticline.

Combination short and long term strain relief measurements of the type described by BROWN open up a potentially valuable research approach for the geologist. Short term strain relief approximates elastic behaviour whereas long term relief may be regarded as creep; the measurements thus represent distinctly different mechanical behaviour in the rock. If the orientation of major strain axes is different between the short and long term strain relief, then the long term strain must reflect an older stress environment, with a younger, purely elastic, component superimposed on it. Long term strain relief, when measureable, could be a significant aid in the structural interpretation of some areas.

#### THE INFLUENCE OF GEOMETRIC SCALE ON MEASUREMENTS AND THEIR INTERPRETATION

Some aspects of geometric scale have already entered the discussions given above; they are sufficiently important to warrant specific consideration. Firstly, let us define three geometric scales; the microscopic, the mesoscopic and the macroscopic. Following Turner and Weiss (3) they may be defined as follows: The microscopic scale is considered to cover bodies up to a size that may be conveniently examined under a microscope (i.e. for most rocks, containing a large but finite number of grains). Consider the mesoscopic scale to cover rock bodies from hand sample size up to exposures that may be directly observed as in normal engineering excavations. The macroscopic scale covers bodies and structures too large or too poorly exposed to be examined directly in their entirety.

Currently all strain relief measurements by overcoring fit into the mesoscopic scale, as do most engineering excavations. Much care must be exercised in extrapolating results from one scale to the next. Consider first some of these problems in relation to standard overcoring techniques which relieve tectonic and/or gravitational stresses.

Whilst measurements on a mesoscopic scale might be expected to average out variations occurring on a microscopic scale they will not do so for variations on the mesoscopic scale. Thus a measurement at any one site should be regarded purely as a "sample" stress determined at that site. To extrapolate these results to cover a much larger rock volume (even though still in the mesoscopic scale), as the engineer often wishes to do, it is necessary to sample at a number of sites and only if individual site variances are comparable with the total variance is the extrapolation justified. This situation is akin to the problems facing the mining engineer when he wishes to assess overall ore grades from drill holes: - how many samples does he need and how reliable are his estimates? Sophisticated statistical techniques for assessing the adequacy of sampling procedures must therefore be adapted for use in these problems.

For the geologist wishing to extrapolate results in the mesoscopic scale to applications in the macroscopic scale sampling problems become even more difficult. Sampling procedure must ensure that measurements from representative lithologic units are obtained. This type of problem is not new to the structural geologists; they have been confronted by it in the analysis of mesoscopic fabric elements.

For residual stresses the following complexities, already partially discussed, are introduced when geometric scale is considered. Do residual stresses exist in the macroscopic scale? If so, then by overcoring on a mesoscopic scale they will be relieved completely, or nearly completely, and would thus be interpreted as tectonic stresses. To the engineer this misinter-

pretation as to cause would not necessarily be important since they would be active stresses on his structure. To the geologist however there is a significant difference in meaning which would affect his interpretation of tectonic events. It might be argued that the existence of residual stresses on a macroscopic scale would seem unlikely since this would imply that extensive volumes of rock would be in tension. The little evidence available to date suggests that such extensive volumes of rock in tension do not exist; thus this argument may be valid.

Likewise there is reason to doubt that residual stresses exist in the mesoscopic scale since this would require that discontinuities on the mesoscopic scale (such as joints, etc.) would be required to transmit tensile stress across them.

It would seem probable therefore that residual stresses only exist on the microscopic scale. The volume of rock containing this balanced system of forces must surely be dependent on the continuity on the rock mass. However, when these forces are mobilized by excavation of a free surface, on what scale are the effects of mobilization observed? VARNES and LEE postulate that these effects might be observed on a scale large enough to be of engineering significance. The authors are inclined to think that forces mobilized from residual stresses at the microscopic scale would affect a volume of rock close to that scale. At present there is little evidence to support either viewpoint; obviously this is an area for future research needs particularly with regard to effects on engineering structures.

#### GENERAL GEOLOGIC CONSIDERATIONS IN RESPECT TO NATURAL STRESSES

As pointed out previously, both the natural stresses and the physical parameters of a rock mass can be regarded as the cumulative product of all geologic processes active in the formation of the rock mass. The influence of some geologic parameters on natural stresses was discussed by GOODMAN. He considered briefly the heterogeneity of natural stresses linked to "hard" and "soft" regions or formations, and suggested that higher stresses might well be expected in the stiffer layers. He also pointed out that faults divide a rock mass into mechanically distinct blocks and disrupt the continuity of the stress field. Finally, GOODMAN presented some interesting ideas on the possible influence of erosion on the stress state:

Assuming that the rock originates from a molten state at depth  $Z_0$ , it inherits an initial natural stress state that is lithostatic. Thus the stress state at depth  $Z_0$  can be represented as follows:

$$\sigma_{\text{horizontal}} = \sigma_{\text{vertical}} = \gamma Z_0$$

where  $\gamma$  is the rock density.

If the earth's surface approaches the granite through erosion  $\Delta Z$ , the vertical and horizontal stresses are reduced by amounts proportional to the depth of erosion. Corresponding to removal of  $\Delta Z$  feet of rock, assuming the rock to be isotropic and linearly elastic, the stress changes are as follows:

$$\Delta \sigma_{\text{vertical}} = - \gamma \Delta Z$$

$$\Delta \sigma_{\text{horizontal}} = \frac{\nu}{(1-\nu)} \Delta \sigma_{\text{vertical}} = - \frac{\nu}{(1-\nu)} \gamma \Delta Z$$

where  $\nu$  is the Poisson's ratio of the rock.

The vertical stress reduction is such that the vertical stress tends to zero as the depth approaches zero. However, the horizontal stress is reduced at a slower rate and is therefore always finite and greater than the vertical stress.

The stresses at depth  $Z - \Delta Z$  are:

$$\sigma_1 = \sigma_{\text{horizontal}} = \gamma Z_0 - \frac{\nu}{(1-\nu)} \gamma \Delta Z$$

and

$$\sigma_2 = \sigma_{\text{vertical}} = \gamma(Z_0 - \Delta Z)$$

As erosion increases, the stress difference becomes increasingly severe and the rock may fail. Any failure criterion expressible in terms of  $\sigma_1$  and  $\sigma_2$  can be transformed through these equations to have the depth ( $Z_0 - \Delta Z$ ) as the independent variable. The resulting stress state ( $\sigma_1 = \sigma_{\text{horizontal}}$ ;  $\sigma_3 = \sigma_{\text{vertical}}$ ) is thus postulated to follow the loci shown in Figure 3). Comparison with published stress measurement results indicates such a theory is not an unreasonable explanation for measured stresses. Further it shows that most measurements of horizontal stress fall along the failure portion of the locus (curve 3, Figure 3), i.e. that the natural stress field is almost never measured as it lies too deep.

The above ideas presented by GOODMAN give a satisfying explanation of the existence of high lateral stresses close to the surface and this may be particularly relevant for intrusive rock. Indeed it is this theory that Cadman (4) invoked to account for sheeting in granitic rocks; to do this Cadman chose to use a maximum extension strain theory of failure rather than the more general theory  $\sigma_{1f} = f(\sigma_3/\sigma_1)$  given by GOODMAN.

#### ACKNOWLEDGEMENTS

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R.A. Price, Dept. of Geological Sciences, Queen's University, Kingston, Ont. chaired the session. The authors, who acted as session coordinators, would like to express their appreciation to all the above for making this a lively conference session. In particular, all credit is due to the contributors who made their notes available for compilation of this summary. Authors of a summary of this kind must always hope that not too many errors, accidental or personal, have been made.

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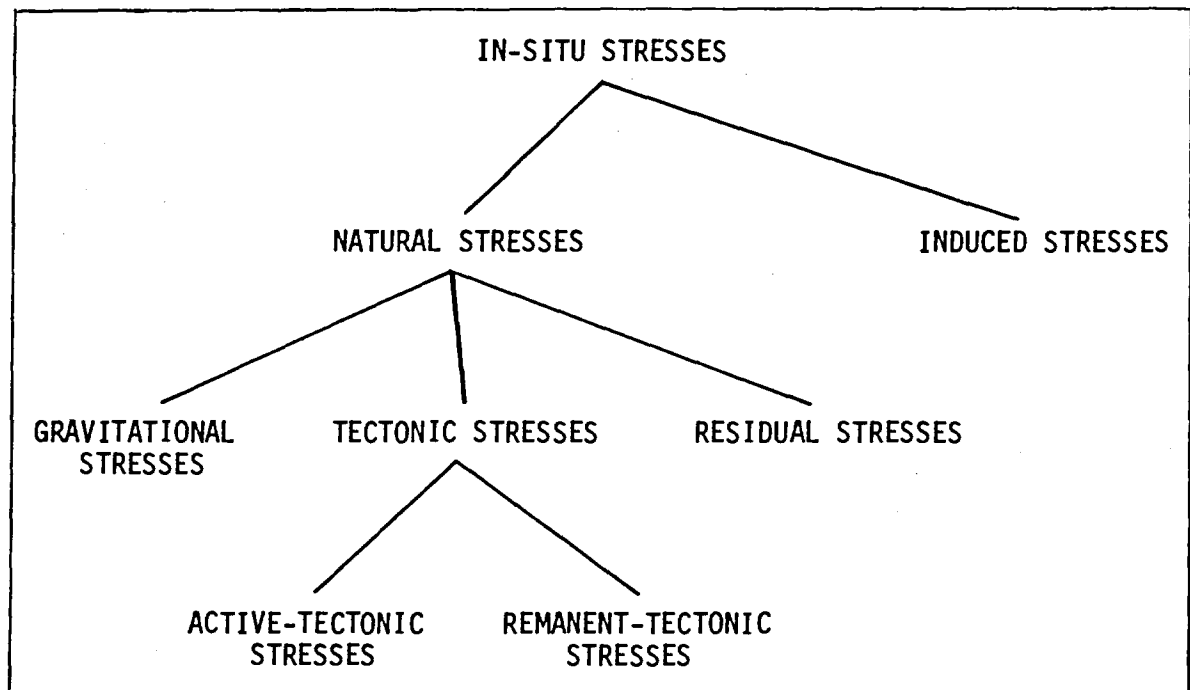


Figure 1

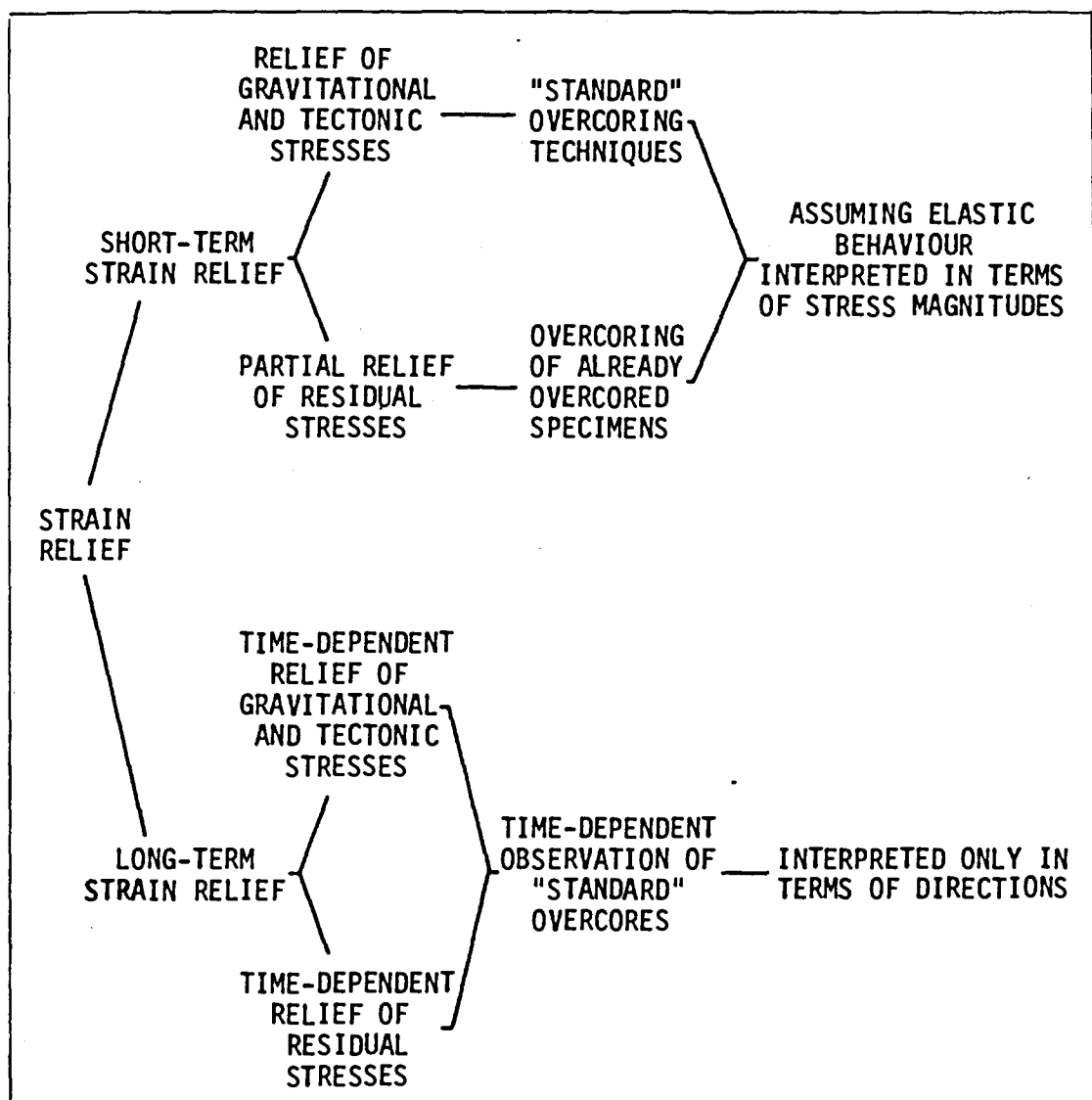


Figure 2

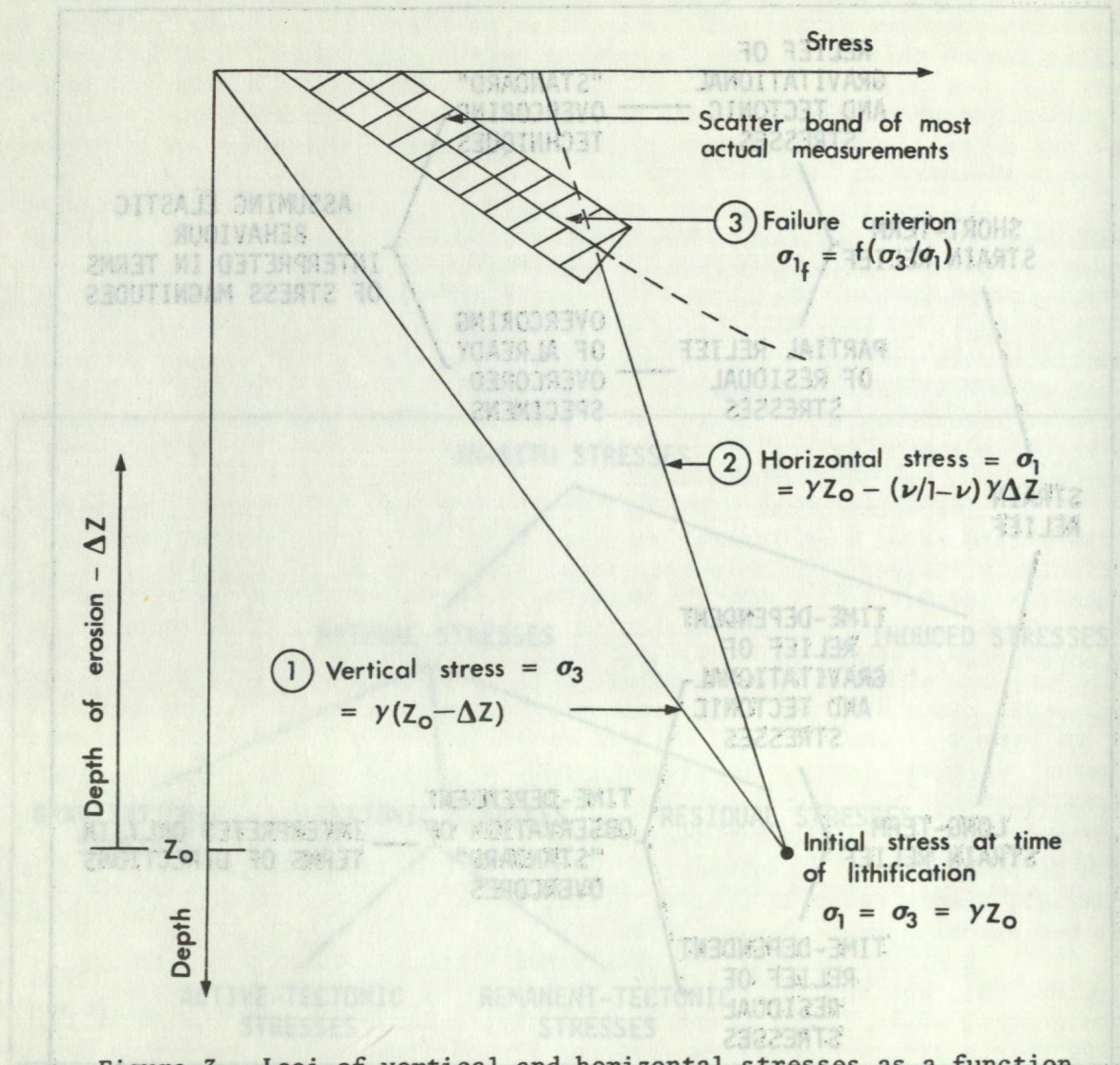


Figure 3. Loci of vertical and horizontal stresses as a function of erosion.