STRUCTURAL STUDIES IN THE RIOUX QUARRY, COWANSVILLE, QUEBEC.

by

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INTRODUCTION

The Rioux Quarry is located in the Sutton map-area within the western part of the Appalachian fold belt in Southern Quebec (Eakins, 1963). It lies about half way between the western margin of this belt as defined by Logan's Line and the major tectonic axis of the Sutton-Green Mountain anticlinorium.

This region is underlain by Paleozoic rocks of the Oak Hill Group of Cambrian Age and the Ordovician St. Germain Complex, which have been folded and thrust westward onto an Ordovician foreland sequence. The quarry itself lies just west of the Oak Hill Group in the St. Germain Complex, a zone in which outcrop is scarce, low, and rubbly. Bedrock generally is obscured by vegetation and deeply weathered. The presence of the Rioux Quarry, with freshly exposed faces up to 40 feet high, offers a unique opportunity for examination of the mesoscopic structures of the St. Germain section of the fold belt.

Hills (1963, p. 88), discussing the relationship of stress and deformation, states: "Detailed study of

local geology is required to interpret the origin and causes of structures, and from the synthesis of such local studies, inferences as to the applied forces and their mode of application may ultimately be made on a regional basis. This is perhaps the ultimate aim of structural geology in the sphere of natural philosophy, and one that preserves the essential role of the field-geologist in geological science".

The present investigation is one such local study. It includes a detailed account of

1) the development of crenulation cleavage,
2) structures ascribed to submarine sliding,
3) the deformational history.

Previous Work:

The modern regional stratigraphic divisions were made by Clark (1934), and more recent studies have done little to alter this excellent work. The formations have been correlated across the international boundary into Vermont by Booth (1950), Dennis (1964), and Stone and Dennis (1964). Rickard (1959) outlined the structural problems in the immediate area of the quarry. A map and description of the Sutton map-area was compiled by Eakins (1963).

A synthesis of the regional structure was made by Cady (1960). Detailed structural studies have since been made by de Romer (1961), Osberg (1965), and Roth (1965) all in the vicinity of the Sutton anticline to the east.

An important recently published contribution is the regional structural analysis made by Rickard (1965) on the evidence of isotopic age dates of micas developed in the cleavages of the area.

Regional Setting:

The position of the quarry with respect to the regional geology is shown in Figure 1. It lies within the Stanbridge Formation of Clark (1934), an ill-defined unit better referred to as the St. Germain Complex (P. R. Eakins, personal communication). It is composed of interbedded limestones and shales.

The nature of the contact between the St. Germain Complex and the older Oak Hill Group is not certain. Clark proposed a thrust fault separating the two units, but there is no convincing evidence for this (Eakins, 1963).

In the quarry the regional trend is exhibited by the upright open folding of the strata, which plunge gently to the northeast.

Age:

Graptolites collected in the quarry were examined and identified by Dr. John Riva. The fauna is equivalent to the Llanvirn of the standard section and is considered to be lower Middle Ordovician in age. The identifiable species are listed in the table.

These are the oldest known Ordovician rocks in the region. The importance of the fauna is that it proves the continuity of the Lower Ordovician shale belt between Troy, New York, and Levis, Quebec (Riva, personal communication).

TABLE OF GRAPTOLITES

Glyptograptus dentatus (Brongniart)	c
Isograptus caduceus var. *nanus* Ruedemann	r
Didymograptus sp., extensiformid type	r
Cryptograptus antennarius (Hall)	r
Glyptograptus austrodentatus var. *americanus* Bulman	r
Tetragraptus pendens, new variety	r
Tetragraptus sp	r
Tetragraptus similis Hall	c
Glossograptus cf. *G. hincksii* (Hopkinson)	c
Hallograptus etheridgei (Harris)	r

c = common, r = rare.

Field Techniques:

The field work in the quarry involved:

1) mapping the outline of the quarry and immediate vicinity,
2) measurement of the attitudes of structural elements,
3) collection of rock specimens for further study and sectioning,
4) tracing out of bedding planes so as to delineate the structure,
5) photographing the quarry faces.

The last two points deserve further comment. At the instigation of Professor Eakins, spray cans of paint were used to trace out bedding planes which are visible only on close inspection of the quarry walls. Since many of the faces are good transverse profiles, the painted beds reveal the complexities of the structure in spectacular fashion.

There are some disadvantages:

i) The beds cannot always be traced very far.

ii) Higher parts of the faces are sometimes inaccessible.

iii) It is a time-consuming technique.

iv) Colour photography is essential for recording the patterns, as black and white prints do not distinguish painted beds from veins.

Photographing the quarry faces in part supplements the painting technique as beds can be drawn directly on the prints. While faster, this method may be less accurate.

Geographic Location and Access:

Cowansville, Quebec, is located on Highway 40, about 55 miles southeast of Montreal. The Rioux Quarry is easily accessible by automobile. It is located a few hundred feet from the road leading to West Brome about one mile east of Cowansville.

THE RIOUX QUARRY

Quarrying is carried out by blasting. Advantage is taken of the well-developed joints, and faces formed are usually either parallel to the major joint set, and thus almost planar, or at right angles to it. The broken rock is removed by truck and crushed. Stockpiles of crushed rock are built up in abandoned areas of the quarry and sometimes obscure the walls. The crushed rock is used for road metal.

The present (1965) outline of the quarry is shown in Figure 2. Also indicated are the positions of former faces, since destroyed, which furnished valuable structural information. Those faces approximately normal to the regional trend exhibit the structure most favourably because they are approximately profile sections whose development is controlled by cross joints.

The faces parallel to the regional strike are rough, irregular in nature, and do not present a uniform profile of the strata. However they do provide useful information because they focus attention on minor structures oblique to the regional trend.

GENERAL GEOLOGY

Introduction:

To acquaint the reader with the geological features of the quarry a documentary account of the important quarry faces is first presented. The discussion outlines the main stratigraphic character of the section and draws attention to the important structural elements. It also provides a record of geological structures that have been or will be destroyed shortly by further quarrying. The quarry faces have been numbered as shown in Figure 3. The traces of the two major faults transecting the quarry and representative strikes and dips of the strata are also shown. The late regional folds plunge N 28° E at 8°.

Documentation:

Face # 1:

This face is shown in Figure 4. It is not well exposed -- broken rock and mud obscure much of it -- but it is one of the few faces which shows finely laminated bedding at a distance. Thin beds of limestone and shale compose the section; they outline open folding. Many small folds, not related to the open folding, are visible upon close inspection (Figs. 48 and 50). These are discussed later.

At the extreme right, just outside the photograph, a ledge of limestone of unknown thickness containing an intraformational breccia occurs.

Face # 2:

Directly opposite Face # 1 is a low ridge of outcrop, mostly rounded and obscured by vegetation, mud, and loose gravel. It is important since it is dominantly composed of limestone beds: they are interbedded with a few thin shale layers and in part show the characteristics of an intraformational breccia.

Face # 3:

This is an irregular face, up to 12 ft. high, which trends obliquely to the regional structure. At the eastern end the face is largely obscured by mud and gravel, but the laminated shale and limestone present outline a small anticline, in the core of which a gray, brecciated limestone layer at least 3 ft. thick is visible.

The western portion of the face exhibits a sequence of gray laminated shales containing two prominent limestone layers up to 14 in. thick which defines a broad open upright syncline (Fig. 5). The upper limestone layer is actually a double layer and can be correlated stratigraphically across the base of the syncline. Below this double layer the laminated beds are noticeably thinner in the eastern limb of the fold.

The outstanding feature of this face, however, is the presence of a zone containing tight isoclinal folds. The folds occur within an argillaceous sequence containing several thin (1 in. to 2 in.) limestone beds. The complexity of the fold style is shown by the painted layers in Figure 6. This zone occurs within the core of the syncline outlined by the open folding, but the trend of the isoclinal folds is oblique to the trend of the syncline. The kinematic significance of this zone is considered later. The rough, jagged face of the outcrop allows a good three dimensional view of the structure and permits accurate measurement of the fold axes.

Face # 4:

This face is essentially a continuation of Face # 3 except for a slight offset along strike in the quarry wall (Fig. 7). The double layer of limestone of Face # 3 thins along strike to the single layer seen at the left of the section. Above the limestone a homogeneous succession of finely laminated limestone and shale can be broadly traced across the face, although it is often difficult to follow individual beds for any great distance. Two thin layers of intraformational breccia occur within four feet of the limestone layer.

Face # 5:

Except for an offset along strike of about 30 feet, this face shows the continuation of the succession visible at the right end of Face # 4 (Fig. 8). An important feature of this face is the fault zone trending N 23° E and dipping 53° SE. Although the rocks are lithologically similar on both sides of the fault, individual beds cannot be correlated. The beds are essentially flat lying with gentle open folds.

Face # 6:

The laminated or thin-bedded shales and limestone layers continue across this face more or less horizontally, but become involved in contorted folds towards the right side of the face at the southwest corner of the quarry. A zone of prominent quartz veins is visible here, but the finer structural details are mostly obscured by the dirty surfaces of the quarry. (Fig. 9)

Face # 7:

This face forms the west wall of the quarry. Large portions of it are practically parallel to the strike of the beds, thus providing a longitudinal section through the regional structure. However, the surface is very irregular and no useful view is presented by this face as a whole. A more regular surface of this type is shown by Face # 11. Figure 10 provides a typical view.

Short offsets of the quarry wall parallel to the dominant joint set provide glimpses of the structure and stratigraphy in approximately transverse profile at intervals along the face. One such view is shown in Figure 11. Fault A is seen on the left with the beds sharply flexed up towards it. Towards the north end of the face the dip of the beds increases steeply to the southeast, and a strong cleavage nearly parallel to the bedding is developed along which the rock breaks readily. This happy coincidence of cleavage and bedding provides an opportunity for examining the bedding surfaces closely, and the writer was quickly rewarded by the discovery of several graptolite-bearing horizons. This fossil locality is indicated in Figure 3.

It is perhaps appropriate to sound a warning to others who may be examining this or similar faces in the future. Figure 12 shows an oblique view of the dip slope near the fossil locality. The several tons of broken rock at the base of the quarry wall are the result of a sudden collapse which occurred without warning. Fortunately the writer was examining another face at the time.

Several minor folds, mostly oblique to the regional trend may be seen in this face, but their exact attitudes are difficult to measure.

Face # 8: (Destroyed summer 1964)

This was an excellent exposure of the structure and stratigraphy along a transverse profile. The most interesting feature is a large isoclinal fold near the left end of the face (Fig. 13). The fault zone at the right is only about a foot wide -- it is shown obliquely in the profile section. The sense of drag shown by the beds adjacent to the fault zone is consistent in all three exposures of this fault (fault A).

Face # 9: (Destroyed summer 1965)

This face was located along strike from # 8, but because of the regional plunge most of the section seen here represents a higher stratigraphic level (Fig. 14).

The beds outline a broadly synclinal structure, but it must be noted that the attitudes of the beds in the right limb are not strictly controlled by folding about the regional axis. Several small folds and associated low angle reverse faults are oblique to the regional trend here.

A few very tight isoclinal folds occur near the left end of the face. The dominant vertical cleavage is manifest in the photographs. It is clearly later than these minor folds which it transects obliquely. The fault zone is a continuation of that seen in Face # 8. The dashed lines schematically represent concentrations of quartz-filled fractures.

Face # 10: (Destroyed summer 1965)

The quartz-impregnated fault zone visible at the right of Faces # 8 and # 9 forms the surface of the quarry wall here. A portion of this face is shown in Figure 15. The wall is fairly planar but shows some warped zones.

Face # 11: (Destroyed summer 1964)

Figure 16 shows the longitudinal profile which this face represents. The dominant joint set is seen edge-On. The warped bedding at the base of the face again indicates that not all the deformational features can be related to the regional fold axis.

Face # 12: (Destroyed summer 1964)

A number of thick limestone beds characterized this face (Figures 17 and 18). The thickness of the beds is extremely variable along the profile of a bed, and many of the changes are exceedingly abrupt. A thin fault zone interrupts the bedding at left center -- the beds cannot be absolutely correlated across it, but this may be a reflection of the abrupt changes in the thickness of the beds.

The major fault zone seen in Face # 5 (fault B) occurs at the right end of the face. A tight fold in a thick limestone bed is visible to the right of the fault. It is not clear whether the beds above this fold are all overturned about its axis as this part of the wall was not accessible for detailed examination.

Face # 13: (Destroyed summer 1965)

Broken rock had not been removed from this face when it was examined and much of the face is hidden from view (Fig. 19). Beds appear to be more or less flat-lying across the top of the face although gently folded. The continuation of fault B is seen in the center of the photograph, Figure 20.

Face # 14: (mostly destroyed during 1964 and 1965)

A rough, longitudinal profile of the regional structure which was not notably informative except for an additional view of fault B, thus confirming its continuity.

Face # 15:

This face is low, and only partly visible, but some spectacular views of different styles of deformation are presented.

The northwest end illustrates some of the most complex structures in the quarry (Fig. 21). A few limestone beds up to one foot thick in a finely laminated shale section are intensely contorted, disrupted, and possibly folded back on themselves. Quartz veins or tension gashes up to 6 in. thick are irregularly distributed. Vertical crenulation cleavage is well developed and a second oblique cleavage is developed in the vicinity of the most contorted layers.

Near the southeastern end of the face a recumbent fold outlined by an 8 in. thick limestone bed and laminated shale provides another magnificent example of the style of deformation (Fig. 22). Boudinage structure and slide surfaces are visible.

Face # 16:

This is a short face, about ten feet high, which illustrates the complexity of the structures. Individual limestone beds have all been sprayed with yellow paint and the discontinuous, disrupted nature of the bedding is apparent. Several planes of rupture truncating the bedding planes at low angles can be followed for several feet until they become parallel to the bedding. These planes are visible only where they truncate the bedding and are almost certainly synsedimentary structures. Several "rootless" limestone fold hinges are also visible. A very irregular quartz-filled fault zone with associated quartz-filled tension fractures truncates the section containing the thick limestone beds just left of center. (Fig. 23)

Other Features:

It is worth noting that very large blocks left after blasting are spread out on the quarry floor, there to break up by a natural freeze-thaw process. While no longer properly oriented, of course, they are usually very clean and often show detailed structural relationships better than the faces (Fig. 24).

Blasting operations for a new lower level have now begun (September 1965) which may provide valuable new structural evidence.

STRATIGRAPHY AND LITHOLOGY

A stratigraphic section has not been attempted. The presence of two major faults with unknown displacement prevents correlation across the quarry, and changes in thickness of some layers, recumbent folding, and the presence of slide-planes parallel to the bedding, would make such a section unreliable.

The lithology is important because of the control on the deformation exerted by the relatively more competent units.

Megascopic Description: Layers of gray, impure limestone up to about two feet thick are interbedded with fine grained, dark gray, graphitic shales. The former constitute relatively more competent layers in a dominantly incompetent shale sequence. Limestone layers over one inch thick are not numerous, but thin, 1/8 inch to 1/2 inch beds often form thick laminated sequences with thin shale interlayers.

A few thin layers (4 in. to 6 in. thick) of intraformational limestone breccia occur interbedded with the shales. They are composed of elongate subangular to subrounded fragments in a limestone or shale matrix. A greater unknown thickness of limestone breccia occurs on the west margin of the quarry. An example of the breccia seen in a loose block is shown in Figure 25.

Local concentrations of pyrite cubes and irregular masses from 2 mm to 4 mm across are present. One large round nodule 1 1/4 in. in diameter shows a "pressure shadow" of crystalline quartz up to 1/4 in. wide above and below it and indicates the extension of the rock parallel to the cleavage direction (Fig 26).

Microscopic Description: The limestone beds are generally composed of subhedral calcite rhombs and interlocking grains, averaging about 0.05 mm in diameter, with an interstitial matrix of interlocking quartz grains. The quartz content averages about 25 %, but may be as high as 60%. A few feldspar grains were observed.

The shale layers, where cleavage is not developed, show fine parallel orientation of opaque and cloudy argillaceous lamellae. Low relief and birefringence characterize this material. Much of the opaque material is graphite derived from carbonaceous matter. Interstitial quartz is also a major constituent.

Rarely, incipient development of white mica is observed, most often in the highly siliceous carbonate layers. Some pyrite is usually observed in each thin section. It occurs as fine granular material or euhedra. The euhedral grains are sometimes corroded and replaced by quartz. Pressure shadows are common around pyrite grains in the argillaceous layers and indicate extension parallel to the cleavage direction.

STRUCTURAL GEOLOGY

A detailed account of the individual structural features is now presented. Analysis of the form, origin, orientation, and interrelationship of the structures illustrates the chronological sequence of deformational history. Structures considered are bedding, joints, boudinage, lineation, faults, cleavages, and folds.

It is convenient in any structural study to treat the penetrative elements statistically. For convenience both in the field and for reference and display it is useful to designate them in abbreviated form.

Planar structures: Structurally significant planar features are termed s-surfaces and are numbered consecutively. Those treated in this study are:

S1 : bedding.

S2 : crenulation cleavage.

S3 : cross joints.

S4 : quartz-filled tension fractures.

Other joints, cleavages, and faults were not statistically important enough to warrant numbering.

Linear structures: Lineations are also numbered for reference:

L1 : the intersection of S1 and S2, usually developed as fine crinkles on bedding surfaces.

L2 : boudinage necklines.

L3 : early fold axes.

BEDDING (S1)

The bedding in the quarry is clearly delineated by the lithologic layering. It is the marker to which all deformation is related.

Individual beds or layers are homogeneous with the exception of some thick argillaceous layers which have darker more graphitic streaks indicating some sort of turbulence. There is no evidence of graded bedding in any of the layers examined. However, the bedding is distorted in response to stretching or piling-up of beds accompanying soft sediment slumping or sliding, which has an effect on the later deformational style.

Within the argillaceous layers a fine lamellar structure probably reflects the initial shape of sedimentary particles, accentuated by compaction, and hence represents S1 also. It may also represent orientation due to outflow of interstitial fluid during compaction (Maxwell, 1962). This might account for some of the turbulent structure visible in streaky shale layers(Fig.27). This idea implies that the limestone layers were relatively impermeable at the time and that the fluid flowed along the bedding planes until it reached some form of escape channel. However, no such channels were observed within the quarry. The intraformational limestone layers may represent lateral "expressways" for the release of fluid.

JOINTS

Turner and Weiss (1963, p. 100) state: "Joints are regularly spaced subparallel planar fractures which may be open or cemented with fillings of minerals such as quartz, calcite, or albite".

They further recognize two common types which are thought to reflect response to residual stresses in the rocks:

(1) cross joints, approximately normal to fold axes.

(2) conjugate or oblique joints occurring in pairs

symmetrically inclined to a linear feature.
They also recognize a third type unrelated to flow, such as tension joints.

Joints visible in the quarry correspond to this classification. Several sets are recognized:

(i) Cross joints: (S3)

This set is the most prominent in the quarry. The joints are essentially vertical and form planar surfaces along which the rock breaks readily(Fig. 28). Calcite is sometimes present in them. The greatest concentration strikes about 15° clockwise from the normal to the regional trend of the late folds, but the trend of the joints swings around in the quarry with no apparent structural control (Fig. 29).

(ii) Quartz-filled tension fractures: (S4)

Sets of closely to widely spaced quartz-filled fractures occur locally concentrated throughout the quarry. Examples are shown in Figures 30 and 31. The puckered and folded form clearly shows that they are earlier than the folding. They are related to the quartz-filled fault zones described later.

Rickard (1959) has correlated these fractures with a slaty cleavage developed in rocks of the Oak Hill Group, but the writer disagrees with this view. No differential offset of bedding planes across these fractures is observed. When examined under the microscope, nowhere is there any evidence of deformation in the fine lamellar argillaceous structure adjacent to these fractures which can be attributed to their formation. Clearly the textural evidence is against formation under conditions of shear or compression normal to the fractures. For these reasons they are believed to represent quartz-filled tension fractures.

(iii) Conjugate joints:

Calcite- and quartz-filled joints form conjugate sets within the limestone layers. Nearly all are perpendicular to the bedding planes (Fig. 32). Attitudes are difficult to measure. On the rare occasions where a dip slope exhibiting the surface of a limestone bed exists, the conjugate nature of the joints may be seen by the lineations formed from the intersection of the joints with the bedding plane. One such bed showed trends of N 40° E and N 40° W on a fairly horizontal layer: here the trends were obviously not symmetrically related to the regional folds.

The relationship of the conjugate joints to the tension fractures (S4) further complicates the picture. The tension fractures are seen both cutting and being cut by conjugate joints, suggesting that they formed in response to more than one period of deformation. In part they may be contemporaneous with (S4).

BOUDINAGE

The term, introduced by Lohest (1908), refers to the structure produced when a competent layer is stretched to the point where necking or even complete rupture occurs, so that in cross section the layer has a sausage-like appearance. Cloos (1947) provides a good discussion of this phenomenon.

A useful classification of terms is provided by Jones (1959). His diagrams illustrating the main features are reproduced here for reference (Fig. 33).

Two varieties of boudinage can be recognized in the quarry. The first exhibits necks only slightly thinner than the layers: the partitions are narrow, generally wider in the center of the layer, closing to the top and bottom; they are filled with coarse grained quartz and calcite in an irregular mixture. These partitions are distinguished with difficulty from the more numerous calcite-filled conjugate joints which often resemble gashes in the thicker limestone layers. In fact the only distinguishing feature may be the presence of a neck.

It is significant that these partitions are mainly developed where the bedding has been flexed in the vicinity of fault A.

The second type of boudinage is more complex. Limestone beds have been torn apart without any scar filling other than an infold of the surrounding shales. This is believed to represent rupture in partially unconsolidated sediment. Details of this structure observed on Face # 15 (Fig. 22) are seen in Figure 34. The rootless limestone layers visible in Face # 16 may be related to this same period of deformation.

LINEATION

The following linear structures are visible in the quarry:

L1: The intersection between the bedding planes or concentric cleavage planes and the regional crenulation cleavage. On the surfaces parallel to the former the lineation often appears as a fine crenulation or rippling. Measured lineations are parallel to the regional axis and strongly suggest a genetic relationship between the cleavage and the folding.

L2: The trend of boudinage necklines. This is visible where thick limestone beds showing boudinage structure jut out from the quarry walls leaving their upper or lower surfaces exposed for a short distance.

Crenulations of type L1 are not exactly parallel to L2 and show that the boudinage structure is not related to the late deformation.

L3: This represents the axes of the early folds. This is a statistical property of the folds concerned and may be accurately measured where the folds are cylindrical and fold hinges are well exposed. Measured L3 are widely dispersed in the quarry (Fig. 36).

FAULTS

Two major faults, essentially planar with respect to the area of the quarry, are recognized (faults A and B, Fig. 3). Smaller fault zones are present, but cannot be traced from face to face.

Fault A: This fault forms a narrow zone of crushed rock impregnated with quartz extending across the quarry at N 37° E, dipping 88° northwest on the average. The beds within a few feet of the fault are consistently dragged into near parallelism with the fault zone, and this is taken to indicate the sense of movement on the fault plane. Slickensides observed on the fault surface on Face # 10 pitch 65° to the south. The fault is properly designated a translational, high angle, oblique-slip, normal fault (Gill, 1941).

More conclusive evidence of the fault movement is provided by a consideration of the relationship of the quartz-filled fractures (S4) to this fault. The orientation of the fault and the fractures adjacent to the fault are shown in the cyclogram (Fig. 37). If a genetic relationship between the fault and fractures with respect to a stress system is postulated (Anderson, 1951; Badgely, 1959), the observed relationship is quite compatible with the theory of rupture. The fractures represent tension joints or gashes and contain the major and intermediate stress axes: the direction of slip on the fault plane is normal to the intersection of the fractures with the fault and corresponds to a slip direction plunging and pitching steeply to the southwest. The fault zone occurs at an angle of about 35° to the principal stress. The net slip cannot be determined.

A few smaller irregular quartz-impregnated faults are observed in the quarry, but their trends are uncertain and they cannot be traced. They are also associated with quartz-filled fractures suggesting contemporaneity of origin.

Fault B: The second major fault, fault B (Fig. 3), strikes N 23° E and dips 53° to the southeast. It is marked by a zone of finely crushed, uncemented rock flour up to 3 feet across (Fig. 8). Slickensides are observed pitching 65° southerly and 50° northeasterly. The net slip is unknown. The exposure of the fault on successive quarry walls testifies to its continuity and regularity. The absence of vein filling, the abrupt truncation of all other structures, and the unconsolidated nature of the fault gouge strongly suggest that it is the youngest structure in the quarry. It is a translational, high angle, oblique-slip fault. The sense of slip is not known, but the attitude of the fault plane and the variability of direction of slip is compatible with normal faulting in response to stress systems associated with relaxation of orogenic forces.

<u>Slide planes</u>: The only other faults observed are planes of rupture associated with penecontemporaneous deformation. They are considered to be planes of thrusting or sliding associated with loss of cohesion in water-saturated sediments.

These faults are usually recognized together with the early folds where stretching in the middle limb of the folds has extended to the point of rupture, or where folding is a result of drag along the slide plane. They may be more frequent than is at first apparent since they occur parallel or nearly parallel to the bedding planes for long distances. (Fig. 35).

They are characterized by complete rehealing with little or no argillaceous material introduced into the fault plane: in fact the fault plane itself usually cannot be seen except as a plane of discontinuity.

CLEAVAGE

Three varieties of cleavage are observed in the quarry: crenulation cleavage, concentric cleavage, and oblique cleavage. The most prominently developed is the crenulation cleavage: it is an axial plane cleavage and its development is considered in detail.

Crenulation cleavage:

"Crenulation" cleavage (Rickard, 1961) is equivalent to the "strain-slip" cleavage of other writers. It is preferred because it lacks the genetic connotations of the latter (Rickard; Talbot, 1965).

This cleavage is a prominent structure developed in the shale layers in the quarry. The statistical plot of the poles to cleavage and bedding in the quarry is shown in Figure 38. It suggests that the cleavage is axial plane with respect to the regional open folding.

Development of the cleavage is associated with the following features observed in outcrop and thin section:

(1) The cleavage is virtually restricted to argillaceous layers in which bedding plane lamellae are present.

(2) Cleavage surfaces are highly graphitic.

(3) The cleavage fans gently towards the cores of small folds.

(4) The deformation resulting in the cleavage is entirely

mechanical -- there is no recrystallization of micaceous material involved. However, the solution, migration, and/or precipitation of interstitial quartz apparently exert an important control.

(5) The microscopic appearance of the cleavage is variable, ranging from zones a millimeter in width down to virtually discrete fractures.

Thin sections of rock taken from Face # 3, where small folds in a thin bedded limestone-shale sequence have a symmetrical form, clearly show the textural features of the cleavage. The cleavage planes are seen to be zones of intense shear and allow a consideration of their development in kinematic terms.

Movement picture: Because the cleavage is constrained between thin limestone layers which have deformwd symmetrically by a different (flexural) mechanism, the development of the cleavage in the argillaceous layers may be considered in relation to the movement picture and bulk strain (Turner and Weiss, 1963). This implies a symmetrical orientation of the stress field and the symmetry elements of the fold. This picture is modified slightly by the requirement that incompetent material must migrate towards the hinge areas when confined between flexurally folded competent layers, but where the incompetent layers are thick this effect does not noticeably affect the movement picture.

(1) Cleavage development in the hinge area of a symmetrical fold:

Here the bulk strain is essentially nonrotational (Fig. 39). The cleavage is basically defined by the strongly deformed limbs of microfolds in the argillaceous material (Fig. 40a), which are essentially kink zones on a microscopic scale. A consequence of this microfolding, apparently by flexural-slip on the argillaceous lamellae, is that the interstitial quartz has migrated from the limbs to the hinge areas of the microfolds. This satisfies the requirements of bulk deformation involving lateral compression and vertical extension within the rock and permits the development of a similar microfold form up and down the axial planes.

Whether this migration of quartz is accomplished by solution and reprecipitation or physical squeezing is not apparent, but the end result is the development of narrow vertical domains (the "microlithons" of de Sitter, 1956) in which the argillaceous material is strongly cemented by quartz, separated by thin kink zones representing the microfold limbs and composed dominantly of argillaceous material largely in the form of graphite. The latter zones, by the very nature of their composition, are planes of weakness, readily susceptible to further deformation.

Since the rotational component of bulk strain is zero the sense of rotation in opposing microfold limbs cancels out.

(2) Cleavage development on the limb of the fold:
Here the bulk strain has a rotational component (Fig. 39), and the rotational components of the local shear domains (the kink zones and microlithons) must add up to this value.

After the microfolds have developed (asymmetrically here on the fold limb, Figure 40b), further external rotation is absorbed by rotational shear in the kink zones, while the microlithons resist deformation. This process may lead to such intense deformation that the kink zone becomes essentially a plane of discrete slip. (Fig. 40c).

<u>Correlation with observed features</u>: Several consequences of the process outlined accord with observed features:

(1) It is obvious from Figure 40 that the mechanism must be modified at the competent-incompetent interface. This is accomplished in different ways, all of which have been observed:

a) where a bounding limestone layer is thin it is parasitically folded, conforming to the microfolding in the argillaceous layer.

b) slip on the cleavage plane is propagated through the limestone layer as a shear plane. In this case it must be stressed that the differential slip is in response to the external rotation of a thicker layer: that is, the driving force is the flexural folding of a competent layer above or below.

c) the argillaceous lamellae are constrained into parallelism with the confining layer. Differential slip is now hindered within the argillaceous layer, and the cleavage or kink zones must actually increase in width at the expense of the microlithons in response to further external rotation.

(2) An isolated, thick, folded layer will initiate slip along cleavage planes that is propagated for a considerable distance. When such slip planes pass through a laminated sequence of thin limestone layers, the smaller fold wavelength of the latter sets up an interfering slip pattern. Movement is concentrated along certain cleavage planes and cancels out on others. A puckered appearance results (Figs. 41 and 42). Quartz-filled tension fractures involved in this folding show a similar effect (Fig. 43), proving that they are earlier structures.

Correlation with experimental work: A significant correlation between observation and experimental work is provided by a consideration of the stress conditions in an incompetent layer shown in a study using photoelastic methods (Bell and Currie, 1964). The stress pattern they obtained is reproduced for reference (Fig. 44).

The important feature of the diagram is that the minimum stress trajectories fan away from the hinge area. This suggests that if axial plane cleavage is developed normal to the principal stress it should show a similar symmetrical inclination around the hinge area in a comparable environment.

This is in fact what is observed in thin argillaceous layers bounded by competent limestone layers in folds with a wavelength measured in inches (Fig. 45).

<u>Conclusions</u>: The mechanism outlined here for the development of crenulation (strain-slip) cleavage differs from that envisaged by Hoeppner (1956) and Turner and Weiss (1963). They consider that such cleavage is initially a shear phenomenon and that with continued deformation the shear planes gradually become rotated to a position normal to the principal stress axis. Thus the shear planes cause the microfolding in the rock.

The mechanism favoured by the writer and here outlined is based on the principle emphasised by White (1949), Rickard (1961), and Talbot (1965), that the cleavage planes are the result of and not the cause of microfolding. The evidence of the rocks studied supports this hypothesis.

A corollary of the above discussion is that at all stages of deformation the crenulation cleavage is an axial plane cleavage. This does not rule out slip on the cleavage surfaces in response to a flexural mechanism in associated competent layers, but it must be emphasised that cleavage is not initiated along maximum shear trajectories.

Concentric cleavage:

This form of cleavage is described by de Sitter (1963, p. 292). It is more or less parallel to the bedding planes, and occurs mainly along surfaces separating the more competent limestone beds and the argillaceous layers. It is best developed on the steep limbs of the regional folds; here it is also a penetrative structure within highly argillaceous layers, and forms smooth planes of weakness along which the rock breaks in large slabs. Where this cleavage controls the breaking of large blocks involving minor folds, the appearance of the surface is often quite spectacular (Fig. 46).

That this cleavage is not a true bedding fissility is illustrated where graptolites are abundant. The highly graphitic graptolite remains are parallel to the bedding planes and tend to split open along these surfaces. When the rock is split the slight angle between the bedding and the cleavage is demonstrated by the en echelon exposure of individual graptolites and by the fine flakey texture of the resulting surface.

Smeared films of graphite derived from graptolites indicate slip on these cleavage planes perpendicular to the fold axis. This smearing defines an "a" lineation within the slip plane. This fact together with the observation that cleavage is best developed on the limbs of the major folds is good evedence that it originated by a mechanism of flexural-slip within the folded sequence.

Oblique cleavage:

A few localities in the quarry show the development of a cleavage obliquely cutting the crenulation cleavage. It seems to be developed only in zones of marked heterogeneity and strong deformation, for example in Face # 15 (Fig. 21). It is never very extensive. It probably represents a true shear cleavage formed at a late stage after the development of the crenulation cleavage.

FOLDS

Introduction:

Two periods of folding are recognized in the quarry. The period of deformation to which a particular fold belongs can be distinguished on the basis of form, orientation, relationship to other structural features, and mechanism of formation. Fold forms of both periods are strongly controlled by the relative competency of the beds and thus by the nature of the stratigraphic section.

Late Folds:

The late folds have the following characteristics:

(1) The folds are open, upright, gently plunging to the northeast. The axes define the regional trend.

(2) They vary greatly in size.

(3) Flexural-slip surfaces or concentric cleavage are developed on the fold limbs.

(4) The vertical cleavage is statistically parallel to the axial planes. In one of the largest synclines it fans gently towards the core (Fig. 14).

(5) The competent limestone layers tend to retain their thickness perpendicular to the bedding planes.

(6) Minor folds in thin layers are parasitically developed in the hinge zones of the large folds.

Theoretical considerations: The origin of folding has been considered from many points of view. Idealized geometric models have been constructed by many structural geologists: for example, a classification of folds as either concentric (parallel) or similar serves as a basis for many theories. However, when attention is shifted from theory to practice the geologist is frequently forced to say that both varieties occur together.

A practical approach to this problem is emphasised by Donath and Parker (1964) who point out that the mechanism of folding is dependent on the mechanical anisotropy of the rock. The mechanical anisotropy is a function of the relative competence or ductility of the layers in the sequence, and is reflected in the geometry and internal fabric of the rock. Therefore the folding mechanism can be confidently inferred from the latter features.

Origin of the late folds: The study of the cleavage indicated the mechanisms operative in the late folds. Within the incompetent argillaceous layers, movement along cleavage planes suggests that slip or shear folding was the dominant mechanism. However, it was shown that this movement is controlled by the flexing of competent layers of limestone which retain their thickness perpendicular to the bedding. The evidence of flexural-slip on the exposed parts of the fold limbs also indicates that a flexural mechanism was operative. This combination of mechanisms reflecting the anisotropic character of the layers corresponds to flexural-flow folding, and implies lateral compression in the crust.

The variability in size and wavelength is related to the thickness of the limestone layers which act as relatively competent units or in association with adjacent layers as "structural lithic units" outlined by Currie et al (1962). Another controlling factor which is undoubtedly important is the discontinuous nature of the stratigraphic section which is due to earlier recumbent folding and faulting.

Because of the small area exposed in the quarry, the true form of the largest regional folds is not known. The presence of limestone of unknown thickness at the west end of the quarry invites speculation as to the control it might exert on the fold forms. There is, however, no way of determining whether the overall style is similar or concentric without the necessary exposure. The usefulness of Donath and Parker's (1964) terminology is appreciated in these circumstances since it allows a classification of the folding which obviates this difficulty, and yet is just as informative as to the fold mechanism.

Early Folds:

The style of folding of the early folds also depends on the lithologic succession, and can be considered in this light. However, other features common to most of these folds are as important, and are considered first:

(1) They are locally developed in otherwise unfolded layers.

(2) The axial planes are commonly parallel or make a low angle to the surrounding bedding planes.

(3) The fold hinges are tight or isoclinal.

(4) Cleavage developed in argillaceous layers is not genetically related. It transects the folds obliquely and is clearly later.

(5) Planes of slip or rupture associated with the folding process are completely rehealed and show no vein fillings.

(6) The fold axes are oblique to the regional trend of the late folding, and show wide dispersion of orientation.

Style of folding: A consideration of the fold style emphasises some of these characteristics. As noted before, the lithology is a controlling factor, and the style is considered with respect to two types of section:

(A) Folds developed in finely laminated shales:

A characteristic of this style is the presence of a plane of rupture developed through the middle limb of the fold, which resembles a drag fold. Such planes show no more tendency to fracture than regular bedding planes. Hills (1963, p. 65) terms such a rupture a "slide" plane. Examples are shown in Figures 47, 48, and 49. The amplitude of these folds is a few feet at most.

An unusual style involving this type of lithology is shown in Figure 50. Here the folds represent a sort of piling-up of isoclinal folds within a layer three or four feet thick. The axial planes are at a high angle to the beds above and below.

(B) Folds developed in a shale sequence containing one or more competent limestone beds:

These folds are commonly isoclinal, with axial planes essentially parallel to beds above and below the layers involved in the folding.

The most complex example of this type is the fold zone located in Face # 3 and shown earlier in Figures 5 and 6. The limestone layers are between one and two inches thick. Some of the layers have been sheared through the hinge zones and displaced sufficiently far so as to prevent their being traced throughout the outcrop. Slight differences in lithological character indicate the involvement of at least three different layers. A close examination of a fold hinge showed the following features: rupture of a slightly laminated limestone layer along an irregular surface, disorganization of argillaceous material in part penetrating the rupture surface, and a swirled texture within the limestone layer (Fig. 51).

Figure 52 shows a style of folding intermediate between this style and style (A). On the right the limestone layers are competent enough to maintain continuity of bedding, but on the left, within the thick shale layer the middle limb of the fold has developed into a slide plane.

Several large isoclinal folds with axial planes parallel to the beds above and below are or were visible in the quarry. That on former Face # 8 was the best exposed (Figs. 13 and 53). The beds are thinner on the lower limb, and the trend of the enclosing bedding planes suggests that a slide surface may have been present at the base of the fold. The vertical crenulation cleavage cuts through the fold with no deviation from the regional trend.

The large recumbent fold visible in Face # 15 (Fig. 22) differs from the other early folds in that the less competent layers have exerted a controlling influence on the deformational process and the more competent thick limestone layer has been ruptured, and exhibits boudinage structure. Slide planes, shown in red in the photograph, have been traced where they are somewhat oblique to the bedding: the upper one no doubt continues down through the disrupted limestone bed at the left, but as it approaches parallelism with the bedding it can no longer be traced with certainty.

The bulbous nature of the limestone in the lower limb and the sharp cross fold near the hinge of the recumbent fold at the right are interpreted as effects of compression accompanying the late folding. The late crenulation cleavage is penetrative within the argillaceous beds here as elsewhere.

<u>Orientation</u>: Any discussion of the causes and origin of the early folds must consider their orientation as well as their form. The problem here is that the late deformation has obviously reoriented the early folds: an example of superposed folding is apparent. If the effects of the late deformation could be removed, the original orientation of the fold elements would be determined.

Geometric procedures for establishing former orientations have been thoroughly investigated by Sander (1948), Ramsay (1960, 1961, and 1962), Flinn (1962), and Turner and Weiss (1963). This constitutes the aim of one type of kinematic analysis.

"Unrolling" of early linear structures about a fold axis is subject to several limitations:

(1) The paths traced out by the rotated structural elements depend on the geometry of folding, which is dependent on the mechanism of folding. For flexural-slip folding there is no distortion of the folded surface and linear structures retain a constant angle with the fold axis, and thus describe a cone in space during rotation. On a stereographic or equal-area projection, the linear element traces out a small circle. However, for slip or shear folding, caused by differential movement parallel to the axial plane, the path of the linear element in projection follows a great circle containing the direction of differential movement.

Thus the mechanism of folding must be known in order to carry out the unfolding technique. If both these mechanisms have been operative, as has been shown for the late folding in the quarry, the movement path will be intermediate between a small circle and great circle of the projection.

(2) If, in addition to the folding process, there is a finite component of homogeneous strain present, the movement path will be complicated further.

(3) If the fold axis plunges, arbitrary assumptions about the initial positions of the folded surface and the linear elements must be made, since the fold axis

can be brought into the horizontal by rotation about any axis normal to it (Turner and Weiss, 1963, p. 518).

The orientations of early fold axes measured in the quarry are shown on an equal-area projection (Fig. 36). The wide dispersion is evident even without the effects of the late folding about the regional axis having been removed. In the light of the limitations discussed above, there is no unique way of unrolling the early fold axes about the regional axis. However, it can be seen by inspection that even an approximation to such a process of unrolling about the regional axis would leave the early fold axes, although roughly horizontal, trending in all directions.

Origin: These early folds are interpreted as the result of penecontemporaneous deformation involving sliding or slumping. This concept first became widely popular after a study by Jones (1937) of the rocks in Wales, although earlier workers such as Heim (1908) had invoked similar processes. Conditions for penecontemporaneous deformation were examined by many other geologists with a view to establishing criteria by which such deformation might be recognized (Leith, 1923; Nevin, 1942; Shrock, 1948).

Many recent papers involving this subject are by specialists in sedimentation who are concerned by its effect on primary sedimentary structures, and who wish to derive further information on paleoslopes, etc., from an analysis of the orientation of slump-fold axes and slide-planes. A recent publication by Scott (1966) outlines many of the problems.

Criteria for recognition of nondiastrophic deformation:

Penecontemporaneously deformed bodies vary greatly in size, shape, and structure. Most typically, they occur in the midst of, or alternate with undisturbed sediments. The internal and external structures must show that they could have formed only by:

a) dislocation of loose, incoherent sediment;

b) flowage and folding of hydroplastic beds;

c) fragmentation of partly consolidated sediments.

The following characteristics are frequently present:

(1) Interpenetration of bedding, and fuzzy edges.

(2) Intraformational breccias or fragmentation without cementation by introduced material.

(3) Complex and intricate folding without associated cleavage.

(4) Small scale and local nature of features.

(5) Lack of any regular relation to regional features.

(6) Restriction of the features to individual beds, alternating with undisturbed sediments.

(7) Presence of normal and reverse structures within short distances.

Causes: It is difficult to be certain about the cause of these structures, although the inherently unstable environment of a slope is probably a basic requirement. In such an environment slumping or sliding could be triggered by:

a) earthquakes or associated tsunamis;

b) an increase in hydrostatic pressure caused by trapped interstitial fluid under conditions of continuing sedimentation. This would lead to a reduction of shear stress and consequent loss of cohesion, leading to sliding.

c) faulting or other tectonic movements in the basement, especially those leading to an increase in slope.

<u>Interpretation</u>: The form and orientation of the early folds in the quarry are the best evidence that penecontemporaneous deformation was active. However, the overall character of the section must be taken into account when considering the origin. Clearly most of the strata have retained their coherence. There is little evidence of slurrying of the sediment.

The distribution of the minor folds suggests that large blocks of partly consolidated material have slid over one another, and that where the slide-planes transgressed across the bedding planes the more competent layers resisted loss of cohesion and initiated a folding mechanism. In Donath and Parker's terminology this would be quasi-flexural folding: certain layers are flexed in response to mainly passive deformation of the interbedded material. The style is disharmonic. This occurs only when there is a great contrast between the relative ductilities of the layers. Water saturated argillaceous material interbedded with more competent limestone would satisfy this condition.

This argument suggests that the early folds and slide-planes were formed after a considerable cover was deposited. Noteworthy is the absence of

a) bedding planes truncating the tops of the fold zones;

b) remnants of folded layers swimming in a slurried mass of sediment;

c) graded bedding.

Such features are usually associated with slumping and flow along the sediment-water interface.

The dispersed distribution of early fold axes now remains to be explained. An important question is: what inferences as to the direction of movement or slope can be made on the evidence of fold orientation?

Experimental work suggests that the direction of the axes of slump folds will tend to be perpendicular to the direction of slope (Rettger, 1935). However the mechanism proposed here involves sliding of large units of strata on what must be surfaces of very low friction if loss of cohesion by increased hydrostatic pressure is involved. Under these circumstances inhomogeneities in the layered sequence would almost certainly create unpredictable local stress conditions, and the attitudes of the fold axes would vary accordingly.

On the basis of the fold axis orientations plotted on the diagram in Figure 36 there is little that can be said to justify any particular slope direction. However, there is one feature of some of the early folds that is perhaps significant: the direction of overturning. In most of the early folds examined those with axes in the northeast quadrant show overturning or sliding of the upper beds towards the north and west, suggesting that this was the direction of the slope when sliding occurred. The direction of overturning of the folds trending southeasterly and southerly is indeterminate.

DEFORMATIONAL HISTORY

The sequence of deformational events may be deduced from the relationships of the structural elements studied. The distinction of an early and late deformation is convenient for a classification of the folds, but it may be misleading in that it implies just two periods of deformation. A consideration of the deformational history as a whole emphasises that a gradual structural evolution provides a more realistic picture. However, it is easier to discuss the relationships in steps, and for this reason the deformational history is considered as a sequence of consecutive structural events.

The sequence of events based on the relationships discussed is as follows:

(1) Sliding and slumping of thick units of water-saturated sediment shortly after deposition. The intraformational limestone breccias were probably also formed at this time.

(2) Development of the first calcite-filled conjugate joints in the limestone beds. This would be the first evidence of desiccation in the sediments, and might also be a reliable indicator of the stress field at the time if sufficient joint attitudes could be measured.

(3) Formation of quartz-filled tension fractures and gashes associated with the movement on fault A. Flexing of the beds adjacent to the fault zone, boudinage of the limestone beds, but no development of cleavage suggest that the sediment was still in a plastic state at this time. This event is important because it gives reliable evidence of the orientation of the stress field in the crust at the time.

(4) Compression normal to the regional fold axis, with the development of crenulation cleavage and a flexural-flow mechanism of folding. This constitutes the main deformational phase of the region.

(5) Additional conjugate joints developed in the limestone beds. They cut across the boudinage partitions and quartz fractures.

(6) Four additional minor structural events whose chronology is uncertain:

a) Development of a few ill-defined kink zones affecting the cleavage orientation.

b) Intrusion of a two foot basic dyke associated with the Monteregian intrusives of Cretaceous age.

c) Cross joints developed.

d) Fault B .

REGIONAL CORRELATION

Rickard (1965) provides the most recent interpretation of the regional structure. He envisages three events, based on a study of the cleavages and folding in the Sutton schists and the Oak Hill Group, and on structural events to the south along the Appalachian fold belt.

These are as follows, with a discussion of the Rioux Quarry events where appropriate:

(A) Large scale soft sediment slumping, especially in the Taconic Mountains to the south.

This seems to be a characteristic of deposition in a tectonically active region, and while similar features are recognized in the quarry on a small scale, they are not necessarily contemporaneous.

(B) Thrusting and strong regional fanning of the folds, with an associated slaty cleavage which progressively dips less steeply to the east westward from the Sutton anticline; a regional style that suggests gravitational gliding off a rising tectonic axis.

Fault A and the quartz-filled tension fractures in the quarry could well be correlated with this event. The stress field orientation is compatible with that often associated with low angle thrust faults where high angle reverse faults are developed. (Hills, 1963, p. 195). The presence of tension fractures and gashes and the absence of slaty cleavage would testify to the very shallow depth of burial at the time.

(C) Compressive tightening with the development of crenulation cleavage and open folding.

There is little doubt that the late cleavage and folding in the quarry are local expressions of this event.

CONCLUSIONS

The recognition of the various structural features developed in the St. Germain Complex is due to the excellent exposures in the Rioux Quarry. It is unlikely that the available natural surface outcrops elsewhere in the district would allow nearly as complete an explication of the deformational history. Those examined in the vicinity of the quarry were quite uninformative: only one small fold was observed and its axis could not be measured with certainty because of the flat surface.

These studies of the structures in the quarry have accomplished three main tasks:

(1) an elucidation of the development of crenulation cleavage,

(2) a demonstration of the reality of the early fold structures, and

(3) establishment of the details of the deformational history.

The writer hopes that this investigation will serve as a useful guide to structural investigations in other parts of the St. Germain Complex.

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FIGURES

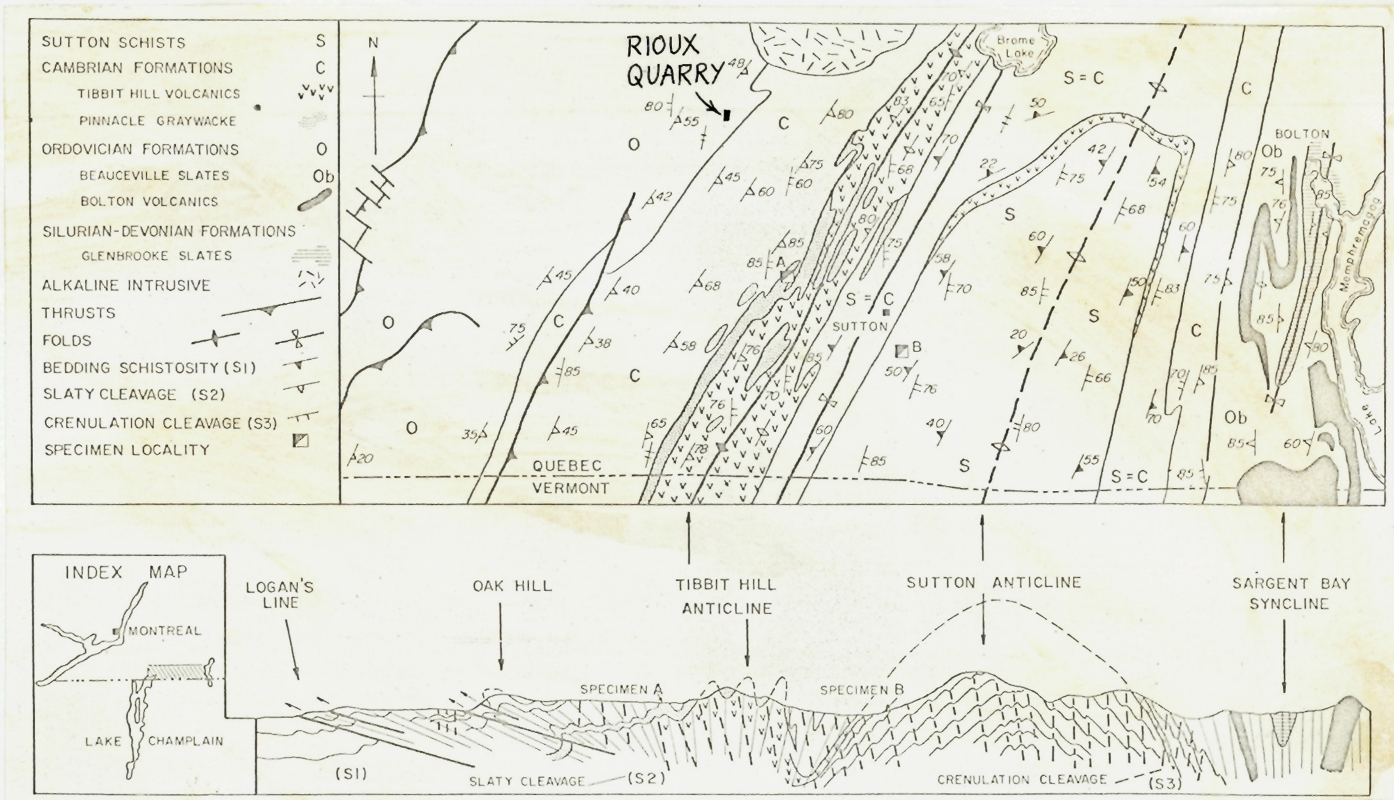


Fig.1. Regional setting of the Rioux Quarry. Reproduced from Rickard (1965)

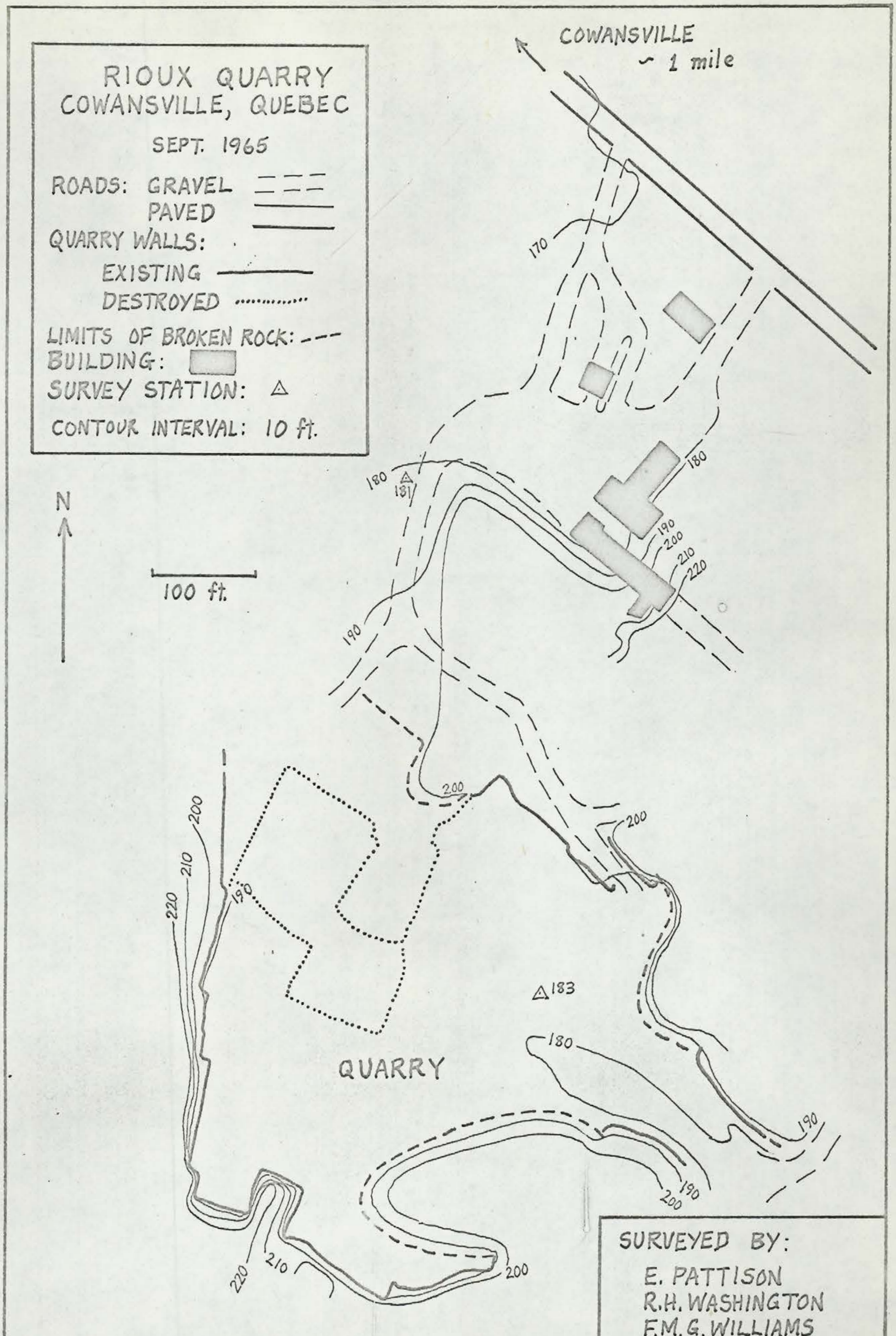


Figure 2. Map of the Rioux Quarry

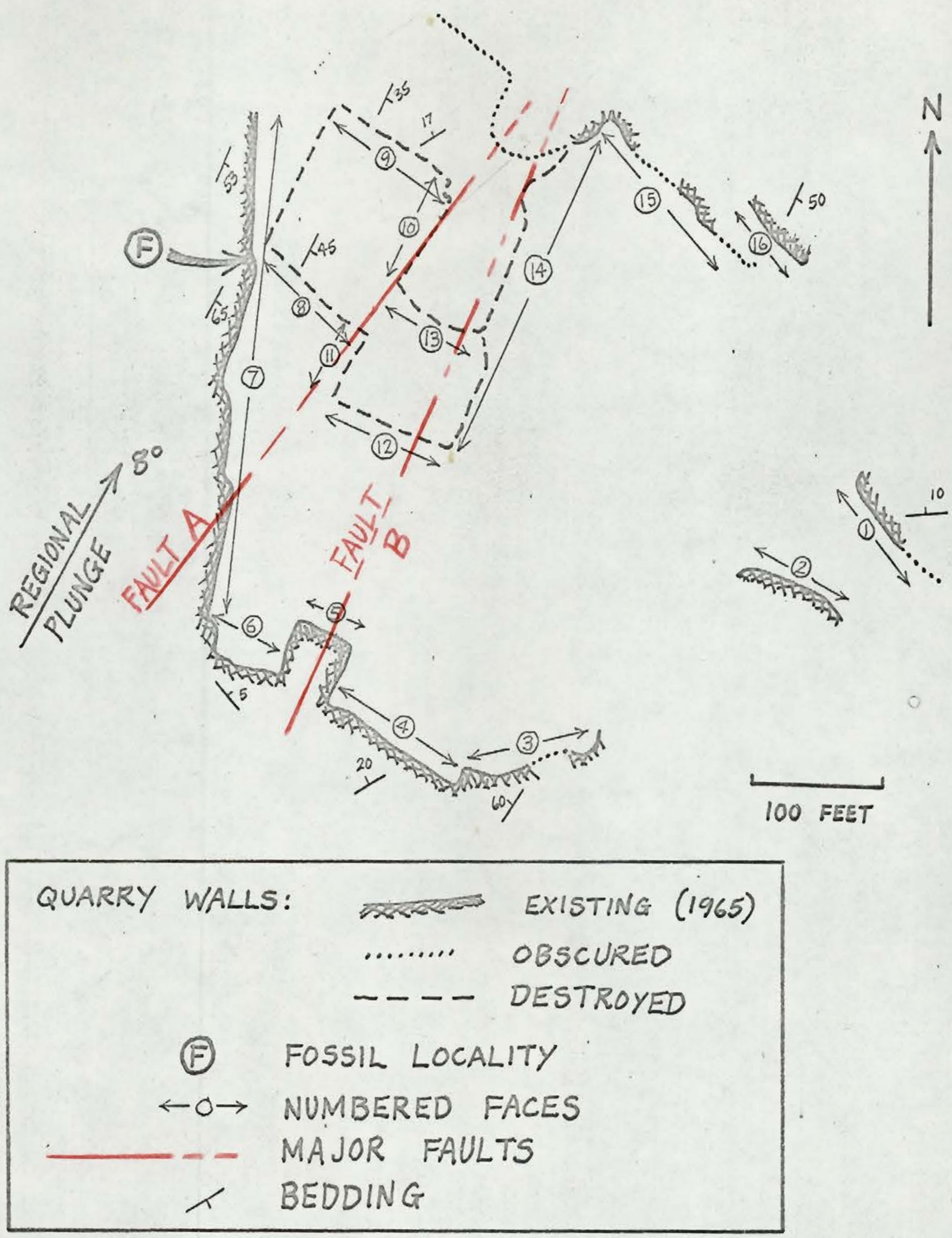


Figure 3. Guide to Face numbers and major structural elements in the Rioux Quarry

Figure 4. Panoramic view of Face # 1. The scale is two feet long.

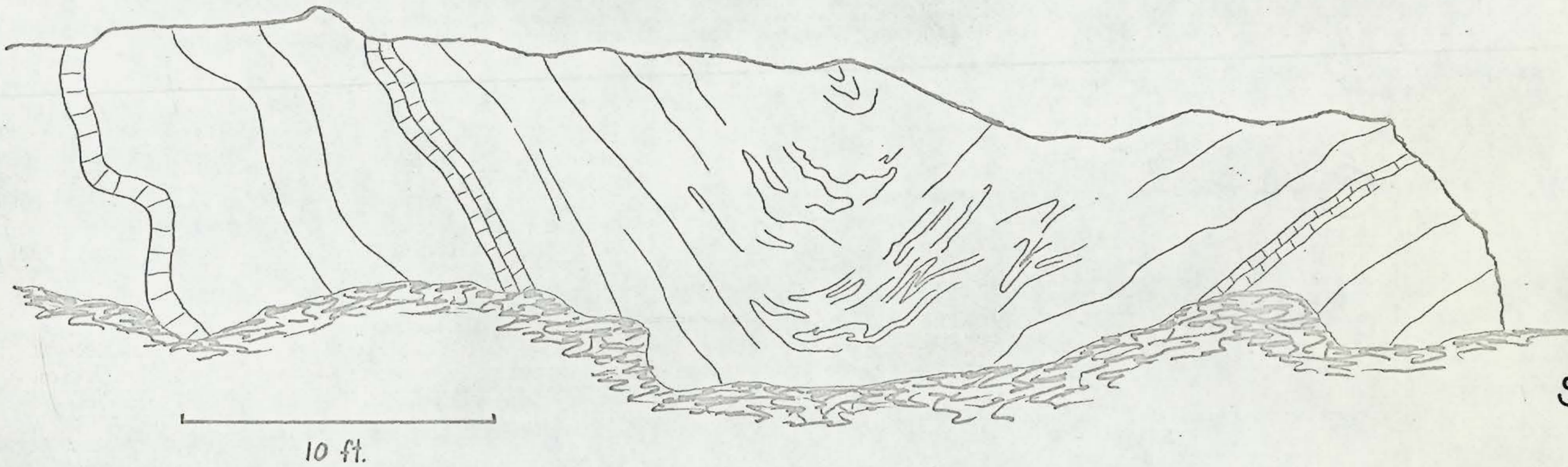


Figure 5. Sketch of bedding planes in Face # 3.

Figure 6. Painted limestone layers show slump folds on Face # 3. Same scale as Fig. 5.

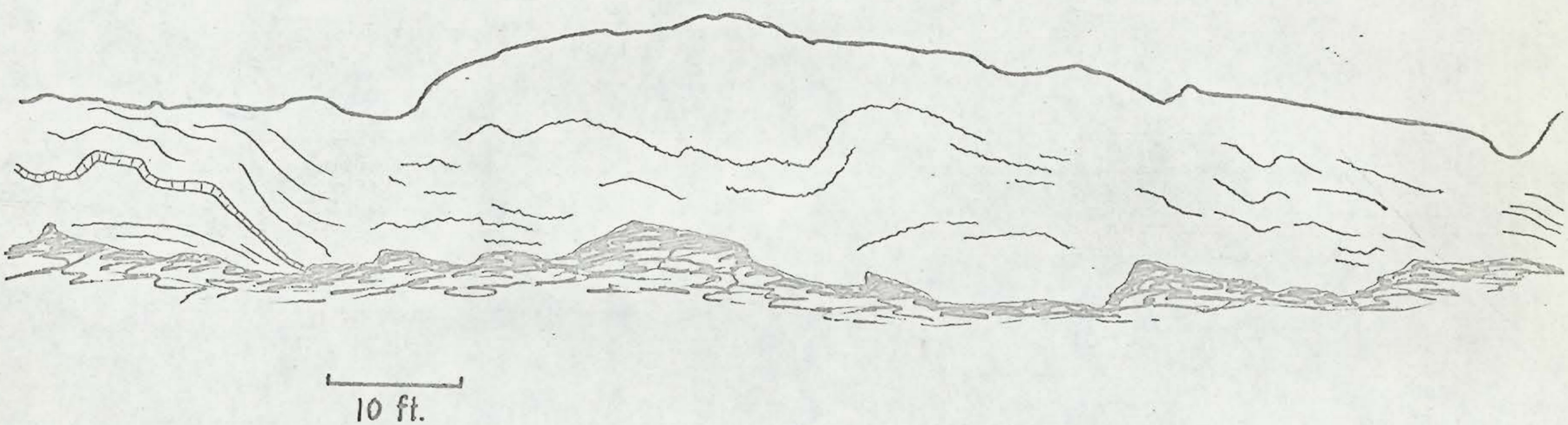


Figure 7. Sketch of bedding planes in Face # 4.

Figure 8. Face # 5 showing 3 ft. wide fault zone. Vertical rod is 2 ft. long.

Figure 9. Face # 6. Beds are nearly horizontal. The vertical rod is two feet long.

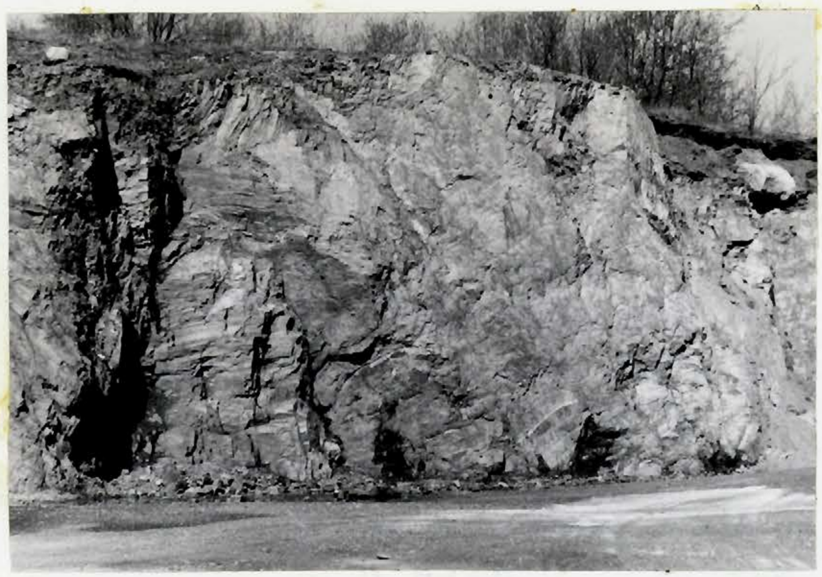


Figure 10. Typical view of Face # 7
Wall is 20 ft. high.

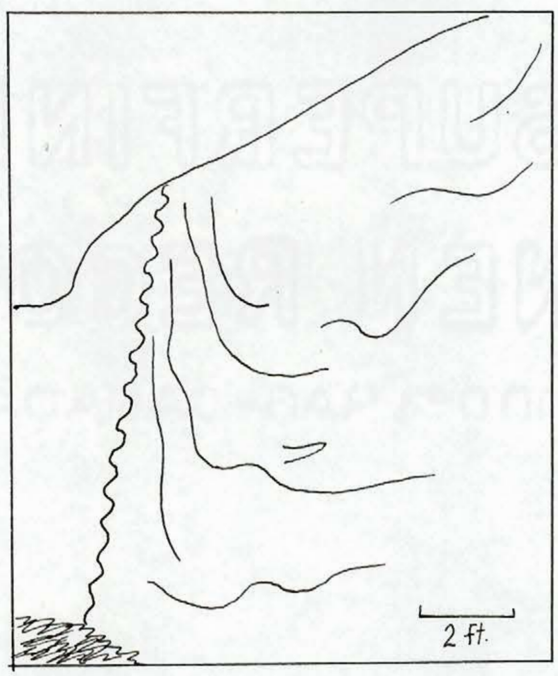


Figure 11. Fault A, and dragged beds on
Face # 7,

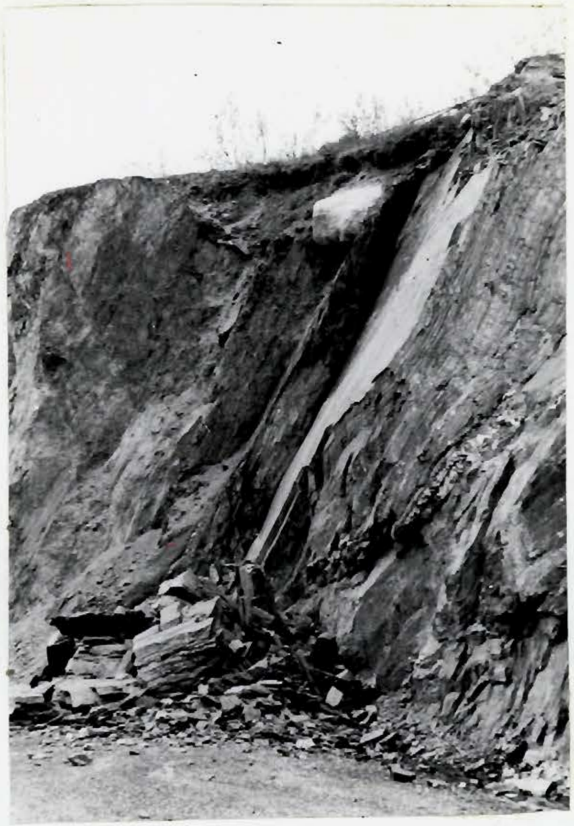


Figure 12. Collapse of quarry wall along dip slope.

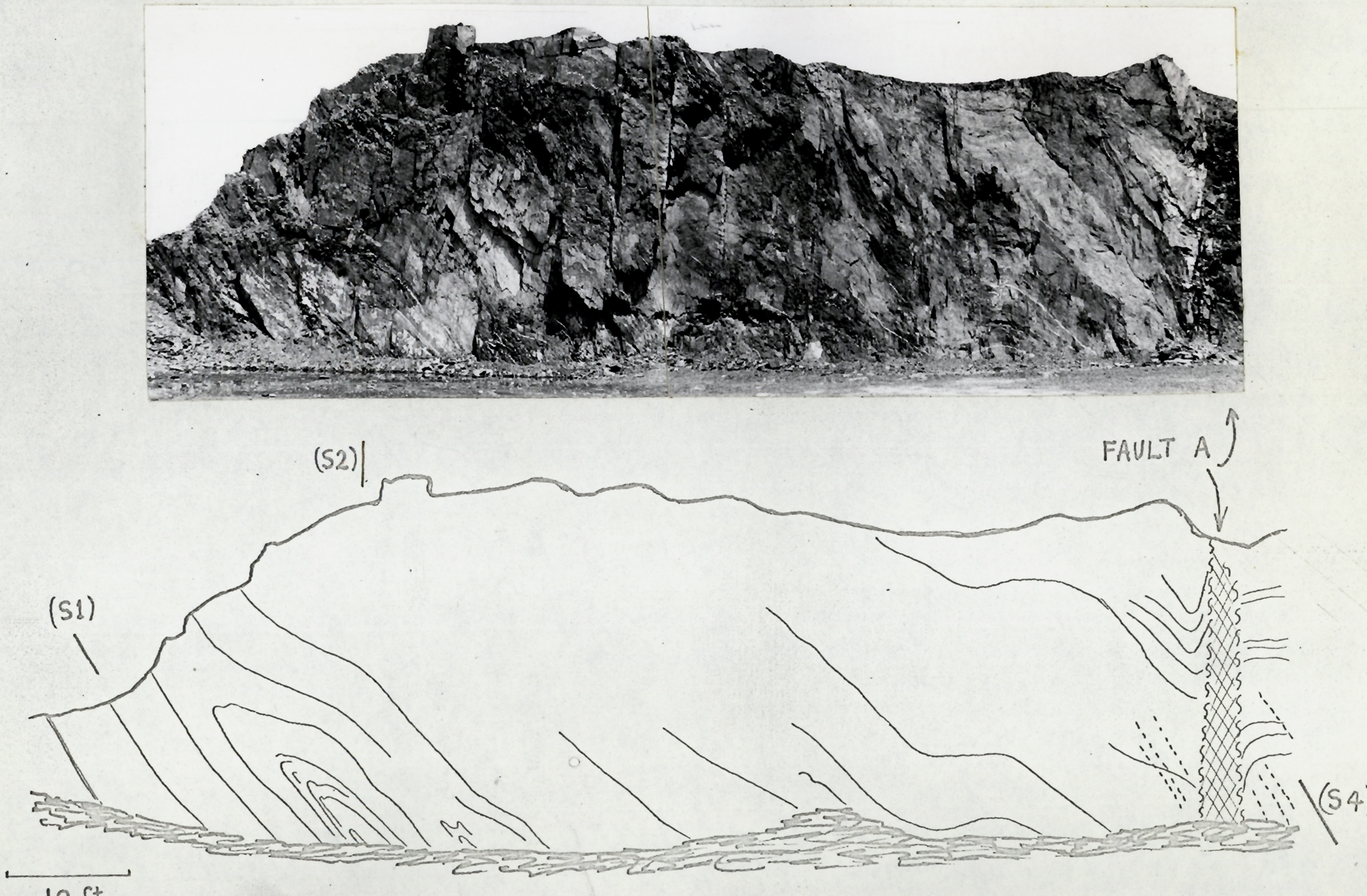


Figure 13. Sketch and photographic panorama of Face # 8. Dashed lines represent quartz-filled fractures.

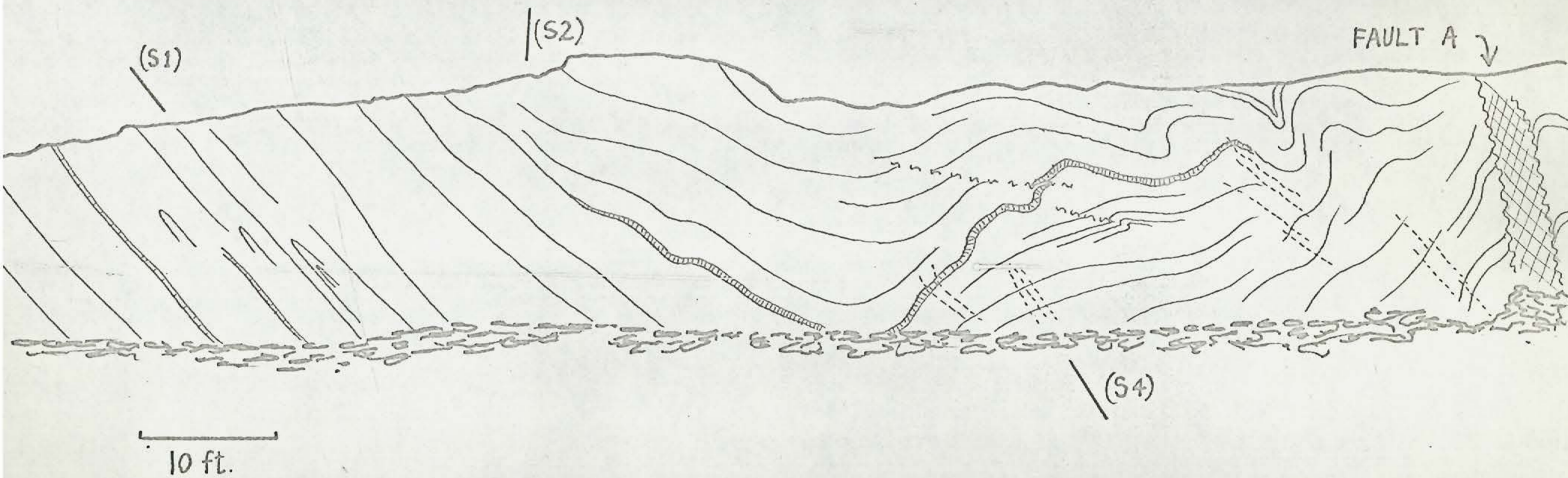


Figure 14. Sketch and panorama of Face # 9.

Figure 15. Face # 10. The wall is covered by a slightly warped layer of quartz-impregnated fault zone material. Hammer shows scale.

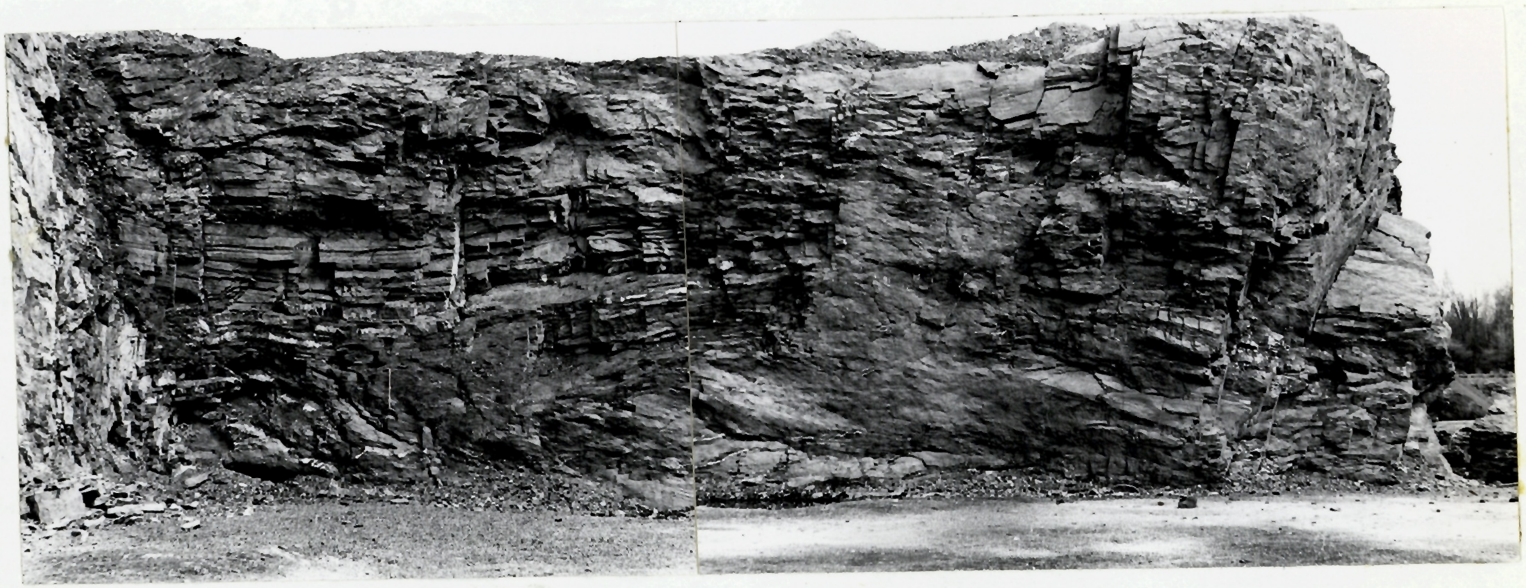


Figure 16. View of Face # 11. The vertical rod is two feet long.

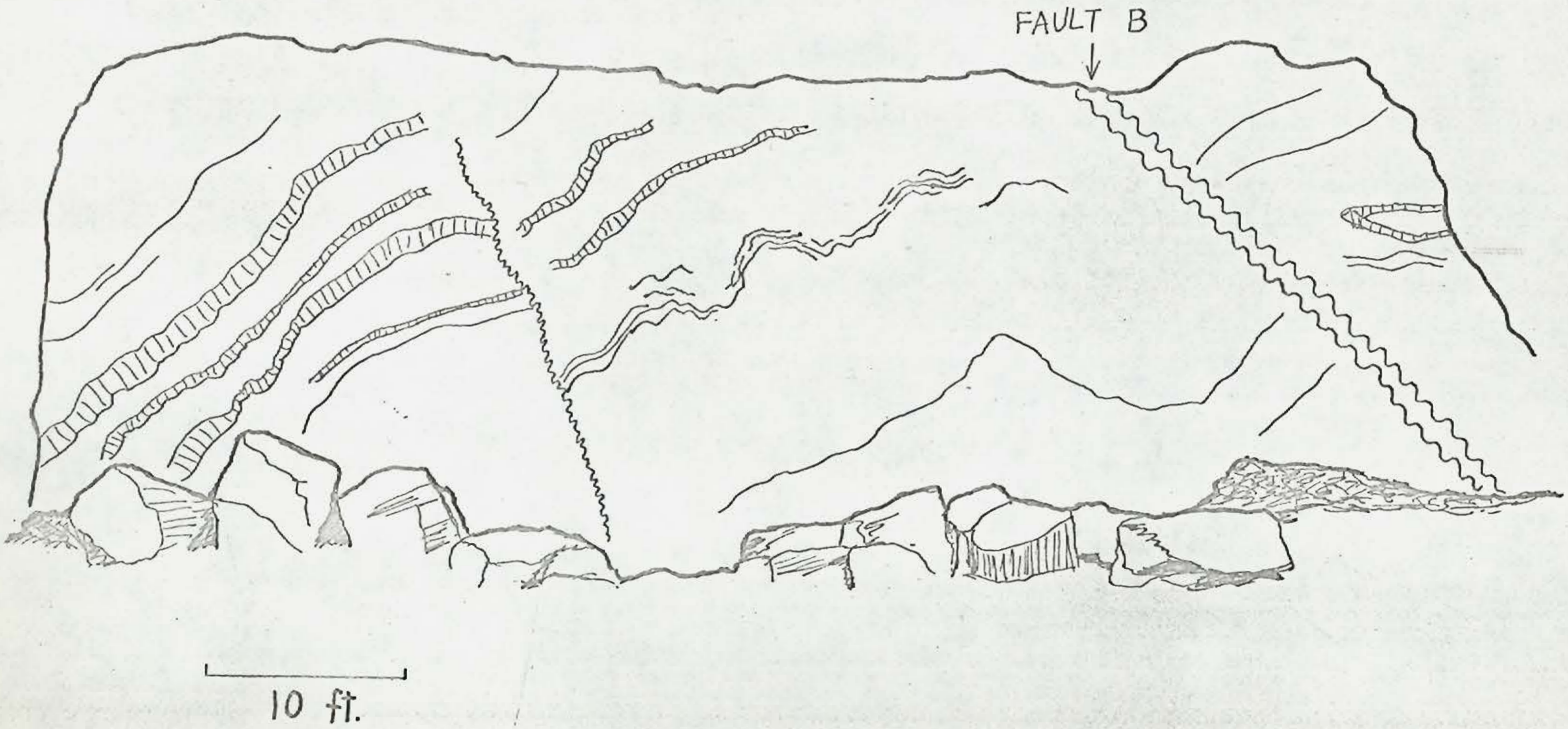


Figure 17. Bedding in Face # 12.

Figure 18. Panoramic view of Face # 12.

Figure 19. Face # 13, partly buried. The wall is about 20 ft. high.

Figure 20. Close-up view of fault B in Face # 13. Hammer shows scale.

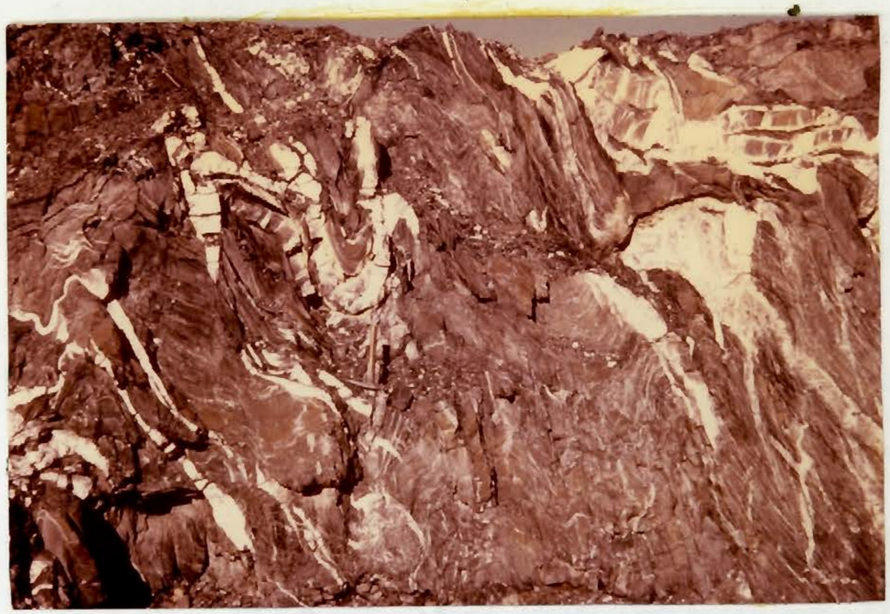


Figure 21. Northwest end of Face # 15 shows complex deformation. Quartz-filled tension gashes up to 6 in. thick. Limestone beds are partly calcite covered. Hammer shows scale.

Figure 22. A spectacular recumbent fold is outlined by yellow painted, boudinaged, limestone layer. The red lines indicate slide-planes.

Figure 23. Face # 16. The walls are about ten feet high. All the limestone beds are painted yellow.

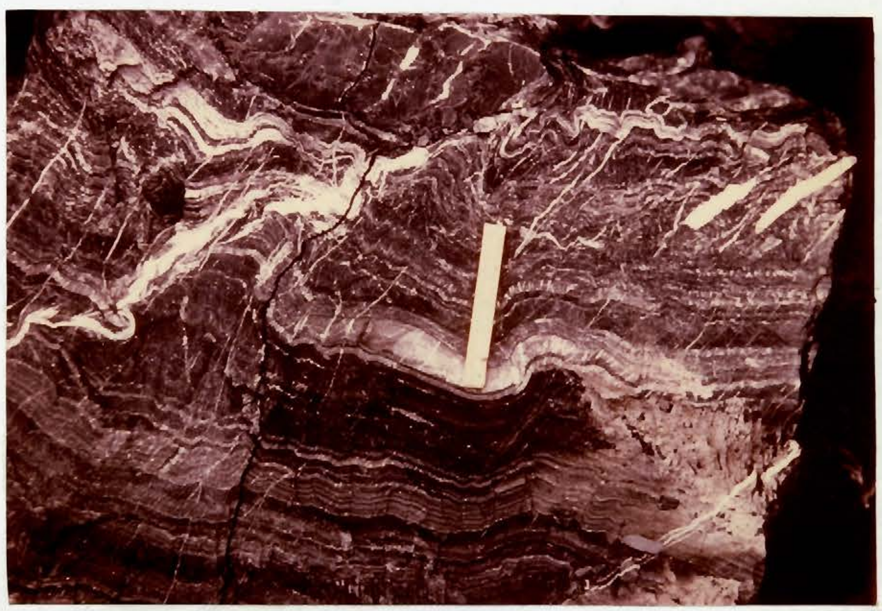


Figure 24. A clean, large block shows structural details clearly -- a small fault and tension fractures are quartz-filled. Scale is 6 in.

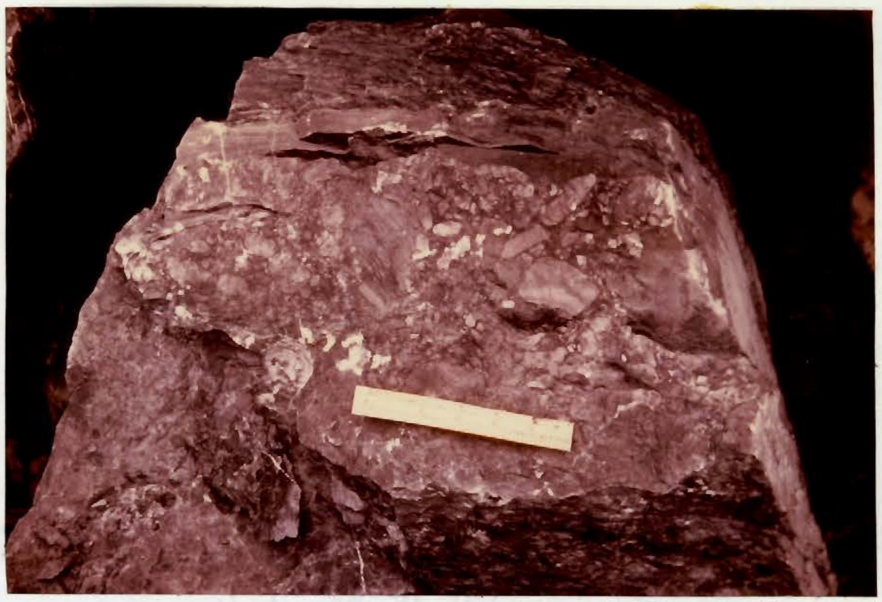


Figure 25. An intraformational breccia seen in a broken block. Scale is 6 in.

Figure 26 A pyrite nodule 1¼ in. across with pressure shadows. The 6 in. scale is parallel to the crenulation cleavage.

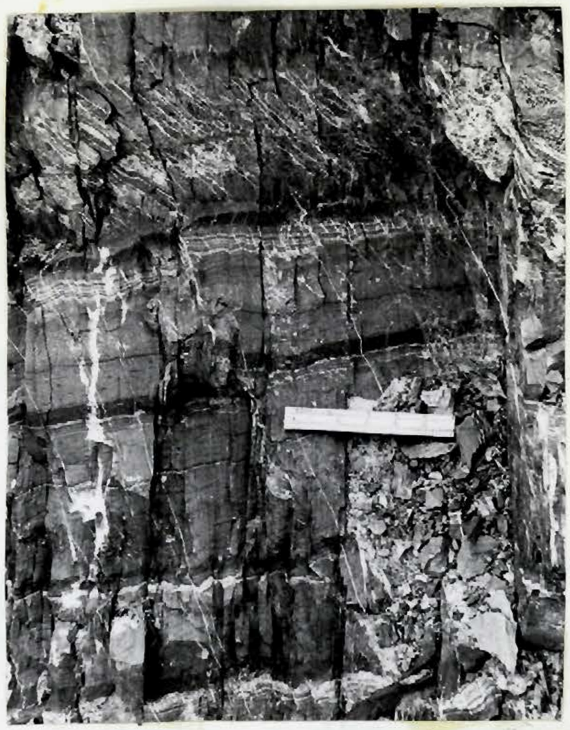


Figure 27. Unusually well exposed bedding shows thin dark streaks in the thick gray shales. Quartz-filled fractures dip steeply to the right. Additional fractures are developed in a late kink zone near the top. Scale is 6 in.

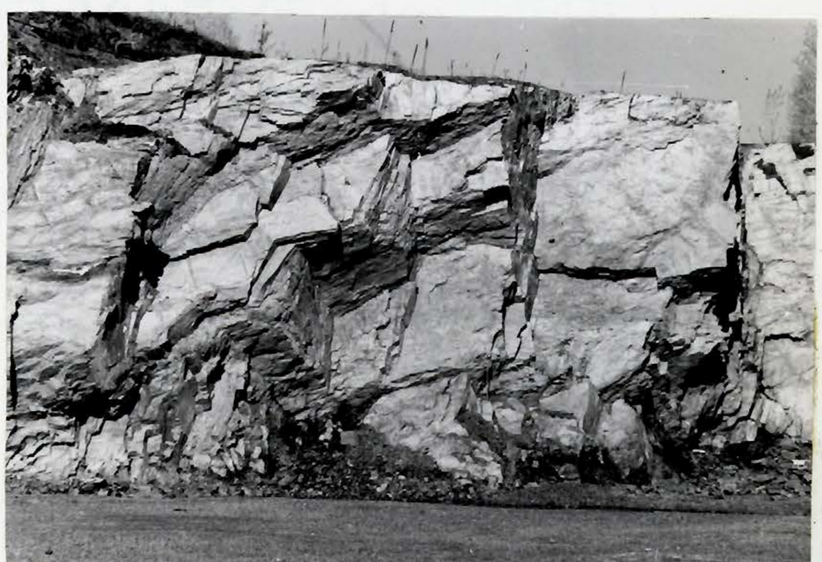
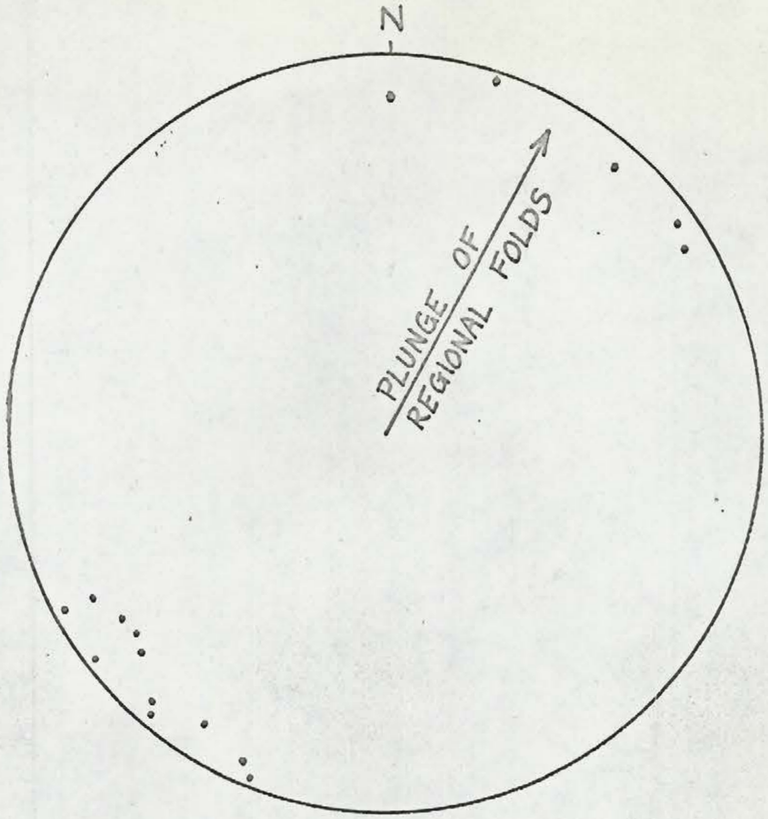


Figure 28. Oblique view of the cross joints in Face # 7. Dip slopes are also well exposed. Wall is about 20 ft. high.



• POLES TO CROSS JOINTS (S3)

Figure 29. Equal-area projection of poles to cross joints. Each point represents a well-developed set of joints.

Figure 30. Quartz-filled fractures on Face # 3. Scale is 6 in.

Figure 31. Quartz-filled tension fractures on Face # 1 deformed by the late regional folding.

Figure 32. Calcite-filled conjugate joints restricted to an 8 in. thick limestone layer. A few quartz-filled fractures cut across them. The scale is 6 in. long.

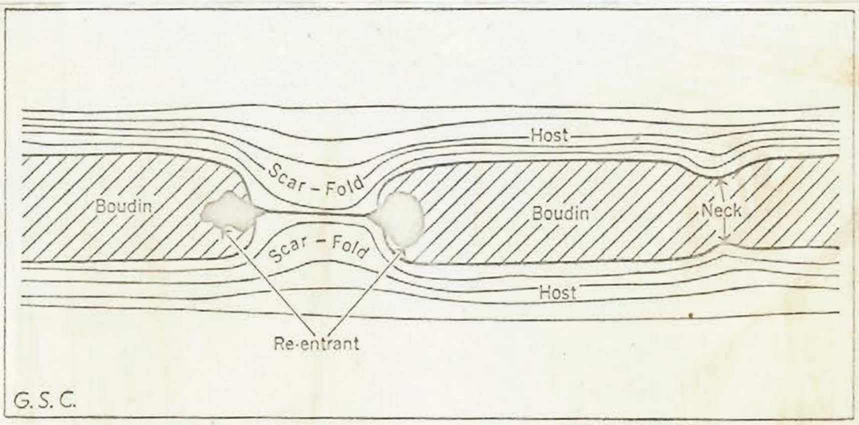


Figure 23. Nomenclature of structures related to boudinage.

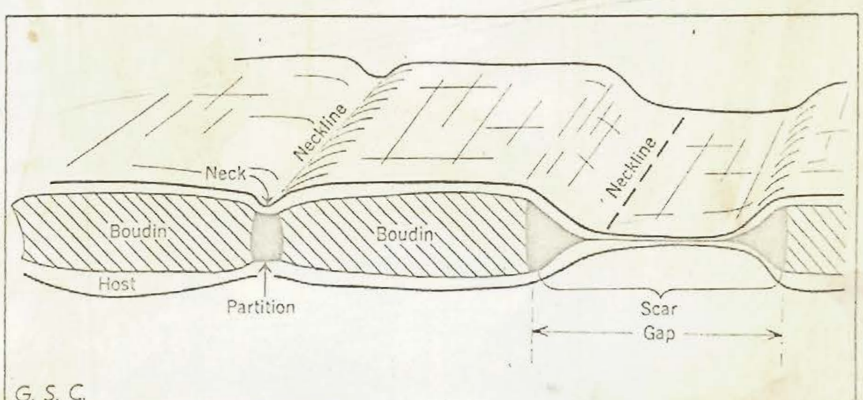


Figure 33. Boudinage terminology reproduced from Jones, A.G., 1959.

Figure 34. Early boudinage in an 8 in. painted limestone layer from Face # 15.

Figure 35. The red line shows a slide-plane offsetting the painted bed for about 18 inches. It becomes parallel to the beds at either end.

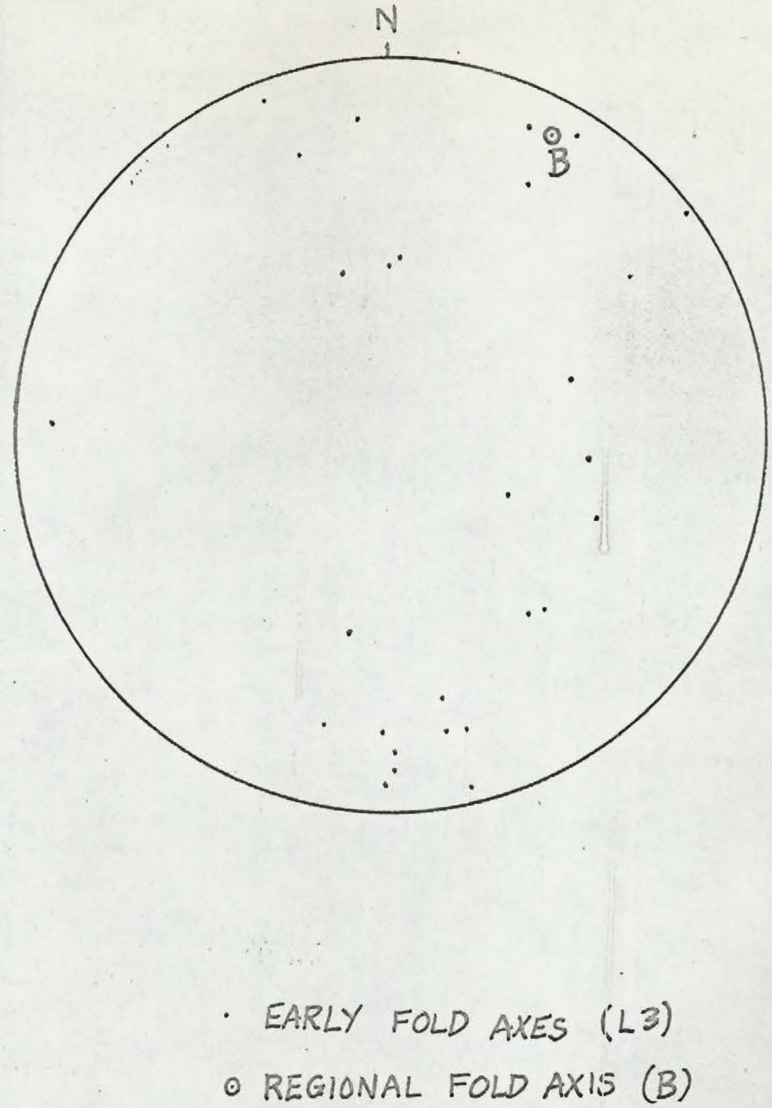


Figure 36. Equal-area projection of early fold axes.

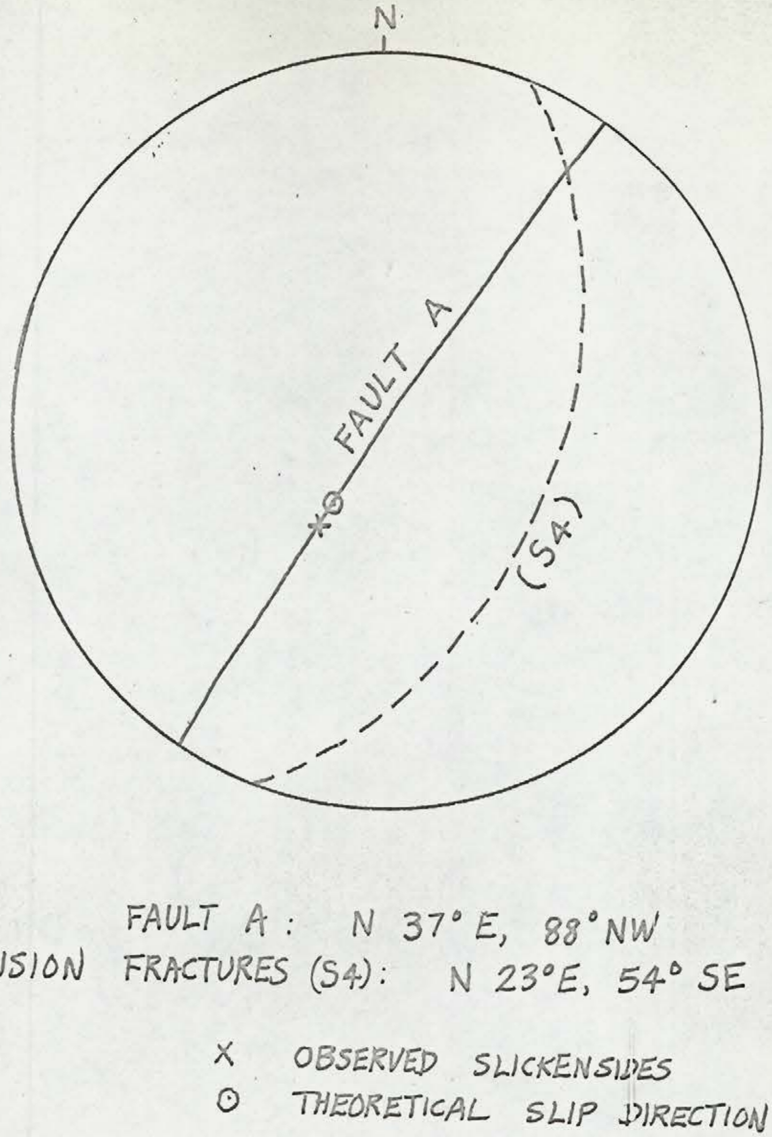
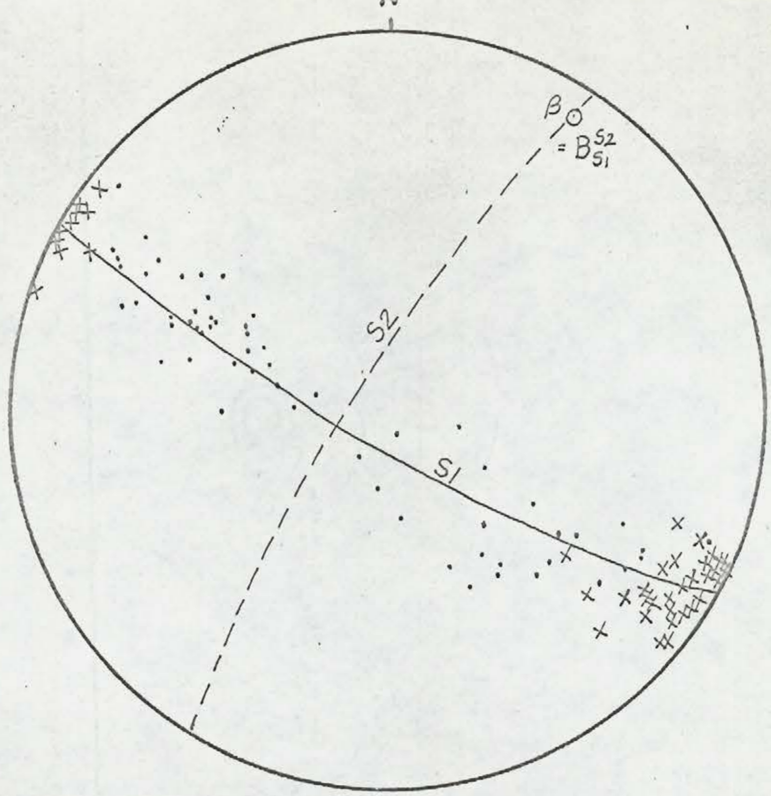


Figure 37. Cyclogram of traces of fault A and adjacent quartz-filled tension fractures.



· POLES TO BEDDING (S1)
× POLES TO CRENULATION CLEAVAGE
$\beta = B_{S1}^{S2}$ N 28°E/8°

Figure 38. Equal-area projection of poles to crenulation cleavage and bedding.

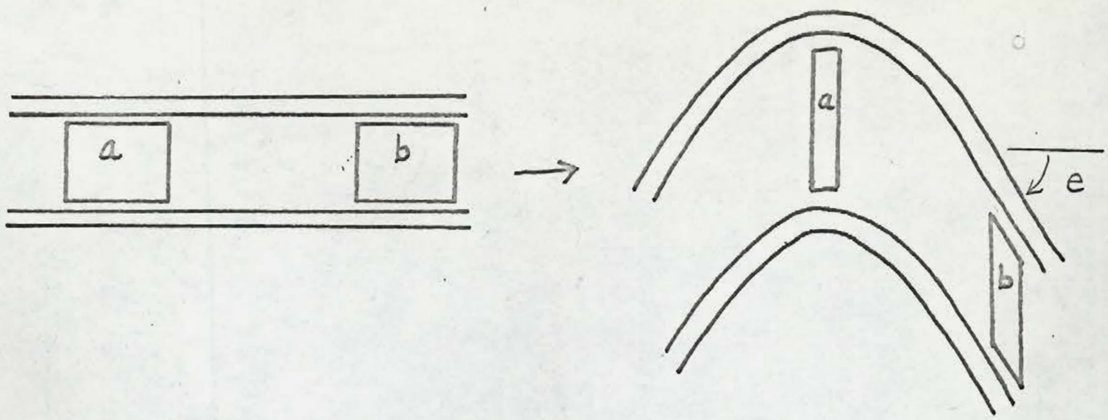


Figure 39. Schematic view of the bulk strain in incompetent layers between two competent flexed layers

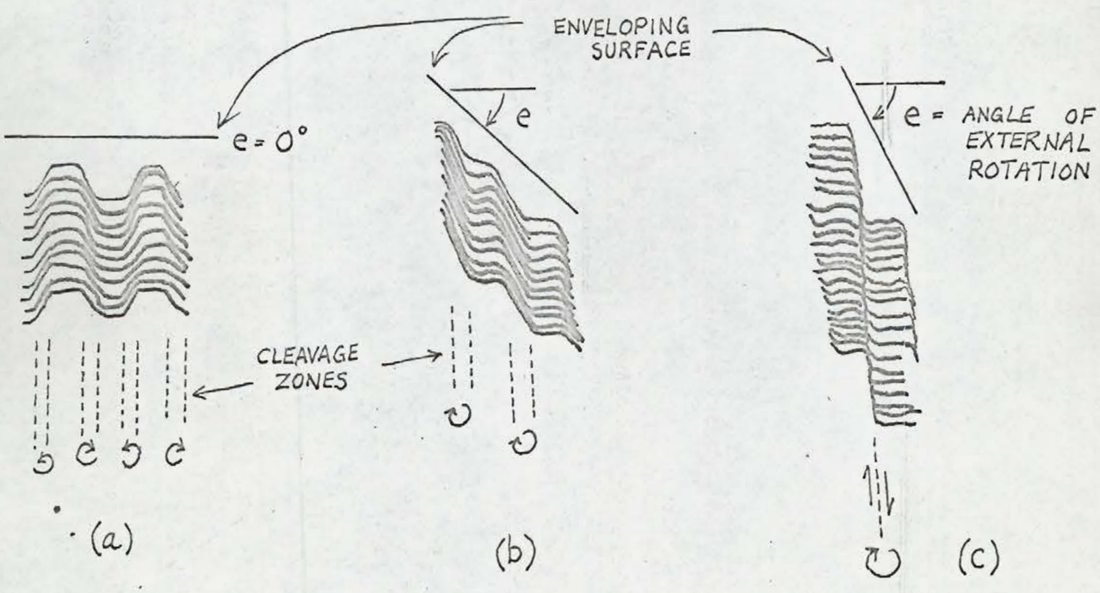


Figure 40. Schematic view of the development of crenulation cleavage:
(a) in the hinge area (no external rotation)
(b), (c) on the limbs of the fold with varying amount of external rotation.

Figure 41. Puckered bedding planes. Also a small early fold. Scale in inches. Located on Face # 4.

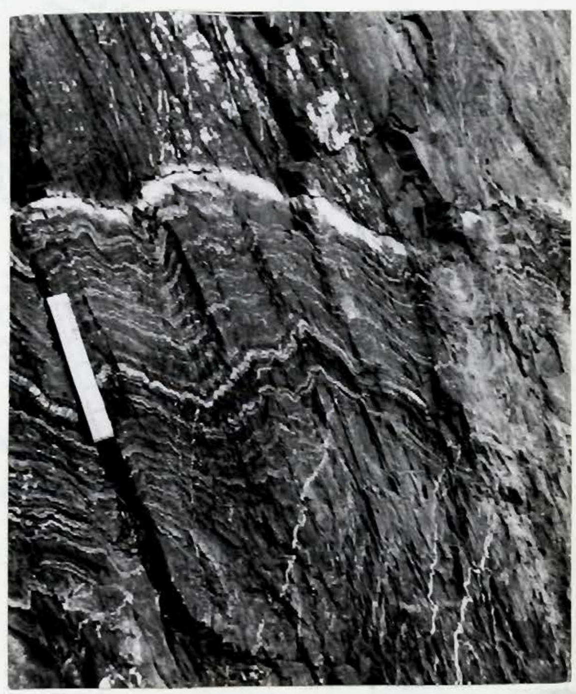


Figure 42. Puckered bedding and a few quartz-filled tension fractures. Face # 4. Scale is 6 in.

Figure 43. Puckered form of quartz-filled tension fractures deformed by the late folding.

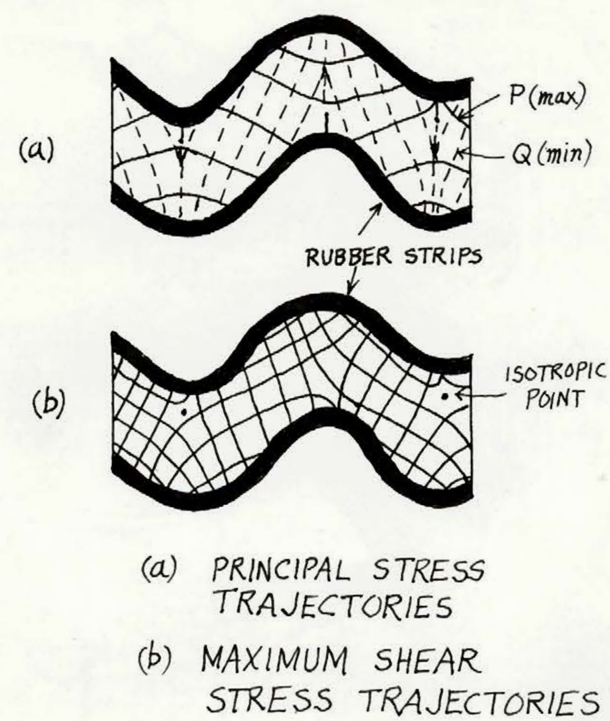


Figure 44. Experimental stress trajectories in an incompetent layer of gelatin folded between competent layers of rubber. Reproduced from Bell and Currie, (1964).

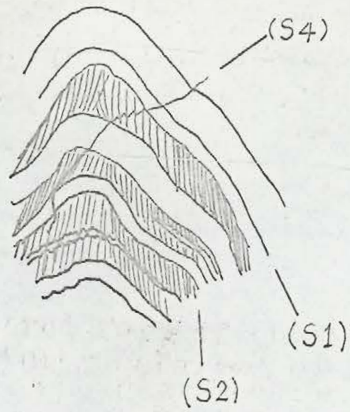


Figure 45. Transverse section through a late minor fold showing cleavage in the incompetent argillaceous layers. The cleavage fans about the axial plane.

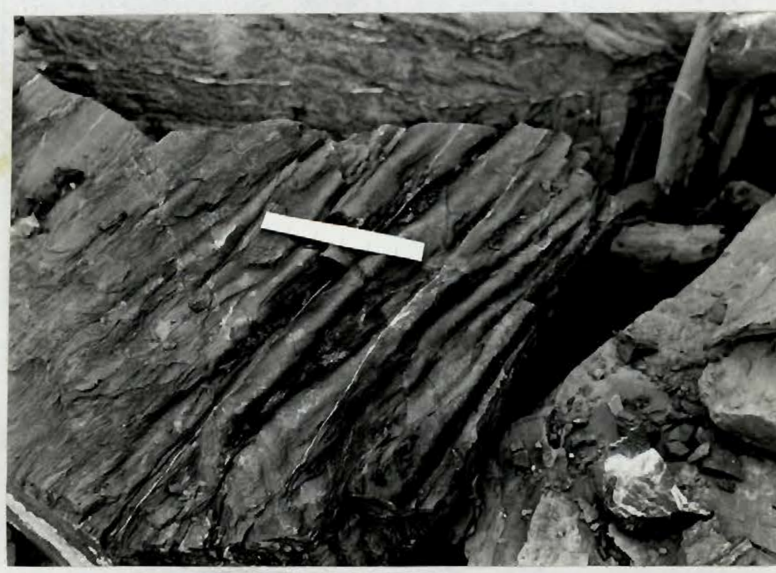


Figure 46. Large block demonstrates the ribbed surface produced when concentric cleavage is developed on the late minor folds. Scale is 6 in.

Figure 47. An early fold on Face # 7 with a slide-plane just above the hammer head.

Figure 48. An early fold cut by later crenulation cleavage. Face # 4. Scale is 6 in.

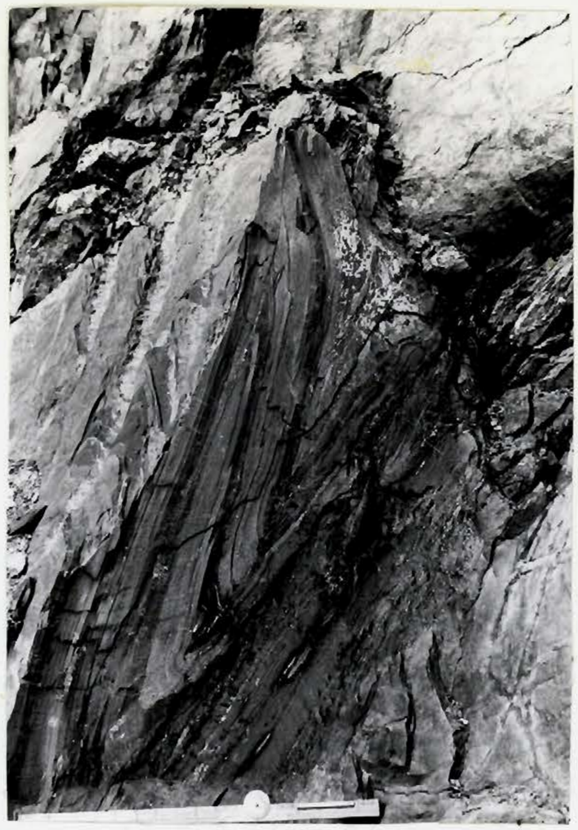


Figure 49. A sharply flexed and ruptured early fold. The scale is 18 in. long.

Figure 50. Isoclinal early folds with axes at high angle to the surrounding beds. Two painted beds are visible. Hammer shows scale.

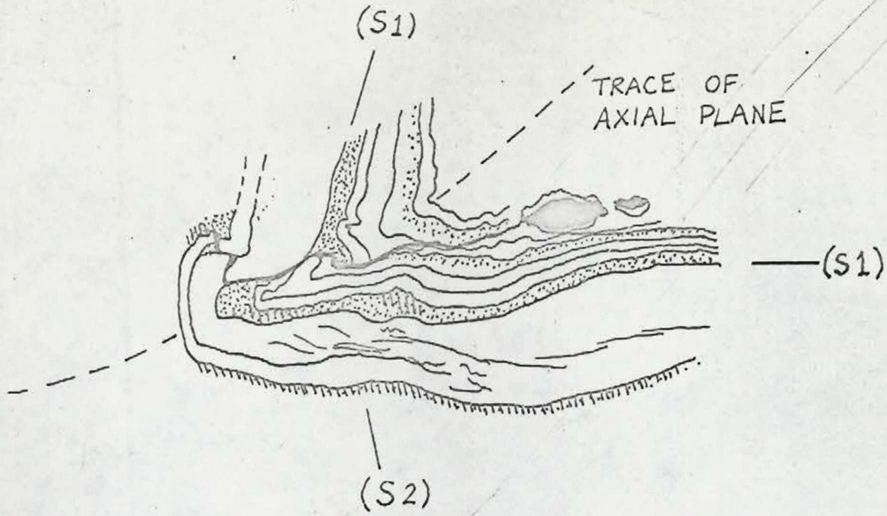


Figure 51. Transverse section of an early fold axis. The plane of rupture cuts irregularly through the hinge area. Natural size.

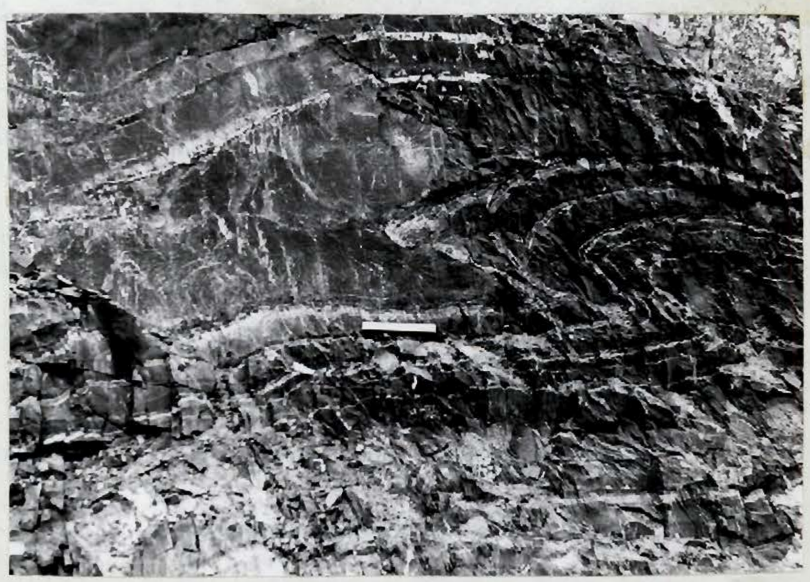


Figure 52. An early fold with a slide extending into the thick shale layer from the folded middle limb. Scale is 6 in. long.

Figure 53. A large isoclinal fold visible on Face # 8. The limestone layers have been spray-painted. Hammer shows scale.