CHARACTERISTICS OF FAULTS AND SHEAR ZONES AS SEEN IN MINES AT DEPTHS AS MUCH AS 2.5KM BELOW THE SURFACE

by

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Summary

The characteristics of fault and shear zones to depths of 2.5km are well documented in deep mines in North America. The characteristics can be summarized as follows:

* Fault zones generally are irregular, commonly branching and anastomosing rather than simple and planar.

* Faults are generally constitued of one or more clay-like gouge zones in a matrix of sheared and foliated rock bordered by highly fractured rock.

* The width of fault zones tend to be greater on faults having greater displacement. Fault zone on which kilometers of displacement have occurred tend to be one hundred or more meters wide; whereas those on which only a few hundreds of meters displacement has occurred are only a few meters or less wide.

* Some zones represent shear distributed across hundreds of meters rather than concentrated in a narrow zone.

* No striking difference is documented for the characteristics of faults over the vertical range of 2.5km.

* Fault zones are invariably wet below the water table, and water moves along them at various rates, but fault zones may also serve as dams, ponding ground water several hundred meters higher on one side then on the other.

Introduction

Deep mines provide perhaps the most advantageous access to faults at depths comparable to the hypocentral depths of some earthquakes. Mine workings, tunnels, and shafts permit the investigator to see, feel, sample, and test fault zone materials and their geometric relations in situ. In contrast, when reaching remote, and deep sites by drilling, all too commonly the fault zone material is either not recoverd, is only partially recovered, or the integrity and thus the geometric relations of the materials are destroyed.

Following are descriptions of faults in selected mines representing depths of as much as 2.5km below the present ground surface and probably as deep as 5km below the ground surface at the time of faulting. The examples are predominately from the Coeur d'Alene mining district in northern Idaho, but additional data are given about the Tintic mining district in central Utah, the Kirkland Lake District of northeastern Ontario, and the O'Brien mine in Quebec.

Faults and shear zones in the Coeur d'Alene mining district in Idaho.

The Coeur d'Alene mining district in northern Idaho, lies in an intensely faulted and sheared structural knot (fig. 1), an important structural element of which is the Osburn fault. The Osburn fault has 26km or right-lateral strike slip (Wallace and others, 1960, Hobbs and others, 1965), large enough to be similar to displacement on the San Andreas fault in California. In the process of recovering billions of dollars worth of ore from the district, the region has been cut by mine galleries, adits and shafts totalling several tens of km in length. Furthermore, ore has been mined over a vertical range of more than 2.2km so that faults and shear zones have also been exposed over that vertical extent. At few places in the world is there a set of faults as well exposed both in lateral and vertical extent as in the Coeur d'Alene and the similarity of the Osburn fault to the San Andreas fault warrants special attention. All types of faults are grouped and discussed together in this paper. No noteworthy characteristics that are different on normal, reverse or strike-slip faults or on faults of different ages seem obvious from the present analysis.

At present, faults are exposed at the surface at elevations above 2000 meters to depths more than 300 meters below sea level. How deep the faults were buried at their time of formation is unknown. but Fryklund (1964), from a study of the environment of ore formation, ,suggests that 5km may be a likely depth for the deepest ore bodies. Inasmuch as some of the faults are exposed more than 2 km vertically below a regional upland erosion surface, it seems reasonable to assume that some faults represent faulting at least that deep.

Country rocks involved in the faulting of the Coeur d'Alene district described here are of Precambrian age and range from fine grained argillites and siltites (quartzites having silt-size grains) to fairly coarse grained quartzites. Low grade metamorphism is common. Beds are from a few cm to meters thick, formations are hundreds to thousands of meters thick, and the total sedimentary pile exposed is more than 15km thick. The beds have been warped into folds having amplitudes of several km, so that from the highest unit on the crest of the largest anticline to the lowest unit in the trough of the largest syncline could represent several times 15km. Whether or not any of the fault characteristics described typify characteristics of faults at depths of 30 or more km is questionable, but it seems possible.

Continuity of faults in depth and laterally

Faults in the Coeur d'Alene district characteristically are complex both in their continuity laterally and in depth. A pattern of branching and anastomosing shears describes fault patterns both in vertical section and in map plan, and at scales ranging from faults kilometers long to faultlets and shears a few meters or tens of meters long. Faults are seldom planar.

Larger faults, such as the Osburn, Placer Creek faults and branching faults such as the Alhambra and Polaris form a complex zone of shearing from 4 to 6km wide (figure 1). Figure 2 shows a complex pattern of faults and shears in cross section in the Coeur d'Alene mine, over a depth range of more than a kilometer. Where mine workings intersect the fault zone at 200 foot intervals vertically, the pattern is demonstrated to be complex. To the north and south lie the Polaris and Saint Elmo faults, known near this cross section only at the surface and in one or two crosscuts at depth. In such situations where good exposures are absent, the complexities can not be demonstrated and faults are interpreted diagrammatically as relatively uncomplicated planes. Because of such large vertical and horizontal dimensions and complexities in both fault and vein zones, exploration in the Coeur d'Alene district has depended in large measure on extensive shaft sinking, crosscutting, and drifting. Drilling and coreing are helpful in exploration to distances of a relatively few hundred meters, but incomplete recovery of core and complexities of the fault and vein zones where cut have lead to the practice of obtaining the larger sample and more complete record afforded by mine drifts and crosscuts.

The complexities of fault zones in detail are illustrated on mine maps at original scales of 1 inch to 50 feet and larger. A detail from the Coeur d'Alene mines is shown in figure 3. Note especially the differences in the fault at points A, B, C, and D. The fault changes in strike and width over short distances in number of strands, and in the dip of individual strands of the fault in the same exposure of the fault zone. Projection of such a fault to more than a few hundred meters, thus is difficult.

In summary, at all scales individual faults are complex and undulating, not planar, and at all scales a network of fractures is characteristic rather than a single rupture surface.

Many strike-slip faults are in reality tear faults in the upper plates of low dipping thrusts. It is commonly assumed that such faults terminate at the thrust plane at a steep angle; in many areas this is not the case. In the Burgin mine of the East Tintic mining district, Utah, the ore-bearing Eureka standard tear fault strikes N. 45" E. and dips about 55° NW. from the surface to the 1,400-foot level of the Eureka Standard mine, where it has about 762 m (2,500 ft) of right lateral, horizontal displacement. As this fault is followed eastward toward the concealed trace of the north-striking, west-dipping East Tintic thrust the dip gradually decreases and the strike gradually turns northward until it merges imperceptibly with the thrust (fig. 4). Other tear faults in the Burgin mine also merge into the thrust in the same manner, indicating different amounts of tectonic transport on different parts of the thrust plate.

Geometry of fault and shear zones

Few faults are truly planar features. One of the best documented deep-breaking, undulating, strike-slip faults is the Lakeshore fault of the Kirkland Lake gold-mining district in Ontario, Canada (fig. 5). This district contains the deepest mines in North America--the Lake Shore and Wright-Hargreaves mines--having reached depths of 2,461 m (8,075 ft) and 2,491 m (8,172) feet respectively (Charlewood, 1964). In these mines the N°12°-25° E.-trending Lakeshore fault has been followed to a depth of 2,332 m (7,650 ft) and according to Hopkins (1948), shows no evidence of termination, or even of diminished throw. From the surface to the 2,300-foot level of the Wright-Hargreaves and adjacent mines the fault dips east-southeast at about 80°; at this level the dip steepens and is more or less vertical to the 3,600-foot level, where the fault becomes somewhat sinuous, but rolls over and assumes a dip of about 80° west-northwest; in the lowest levels of the mine the fault is actually northwest of its surface position. Horizontal displacement on the Lakeshore fault is about 198 m (650 ft) and vertical displacement is about 99 m (325 ft). The east side has moved generally north, and north plunging striae occur on the fault plane. The fault zone is sharply defined but contains only 1-5 cm of clayey gouge.

Even greater vertical irregularities are shown by the Beck and Centennial faults of the main Tintic mining district, Utah (figs. 6 and 7). Both of these faults are exposed in mine workings to depths of 825 and 550 m where they cut the vertical west limb and nearly flat trough of the Tintic syncline. These faults both strike northeasterly; the dip of the Beck fault ranges from 60° NW. to 70" SE.. and of the Centennial from 37" SE. to 70° NW. The displacement on both faults is left lateral, and is about 550 m on the Beck and 335 m on the Centennial. Horizontal mullions about 1-3 m deep on the Beck fault indicate virtually no vertical component of displacement.

Figure 8 shows irregularities on the vein of the O'Brien gold mine, Quebec depicted by structural contours. The vein, formed along a fracture, is offset by later faults. Ore has tended to form in linear zones along elongate relief on the original fracture, probably in zones of tension. The irregularities on this fracture surface might represent the types of irregularities or asperities that on active faults account for micro-earthquakes.

Fault and shear zones comnonly have many forms other than simple planar or curved surfaces. Displacement is not uncommonly distributed through a volume of rock that is wide compared to its lateral dimensions or its displacement. The term "shear zone" commonly is applied to distinguish these relatively broad brecciated or sheeted zones from those on which displacement is concentrated in a narrower zone.

Shear zones that display strong schistosity may develop in any of a variety of rock types ranging from fine-grained quartzites, and siltites to argillites, but generally are not as pronounced in coarse-grained, well-indurated quartzites or massive carbonate rocks. The plately, micaceous minerals of argillites favor the development of foliated shear zones, and where smaller bodies of quartzite are surrounded by argillite, very thin tablets and lenses of quartzite bounded by shear planes (fig. 9) may develop in response to the pervasive shearing through the argillite, which becomes phyllitic under shearing.

Many ore bodies display a foliated structure indicating shearing, even in massive galena. This shearing has developed across bodies of ore many meters wide even though offset of rock units across the zone demonstrate relatively little total offset. The model, thus, may be one of primarily a tensional zone, which served as a host for mineralization, but which presented a zone of weakness to later stresses of slightly different orientation, thus inviting a moderate component of shear.

Width of gouge, shear and brecciated zones

In the Coeur d'Alene mining district of more than 60 faults described by Hobbs and others (1965) essentially all are comprised of three elements, a discrete clay-like gouge zone, a zone of sheared rock, and a zone of fractured rock. The gouge zone generally is a fraction of the total width of the fault zone. The following table (table 1) gives representative values. In general, the larger the fault displacement, the wider is the zone of disruption. To summarize, given kilometers of displacement, the width of the zone of faulting ranges between 100-300 m, of which a tenth is gouge. Given several tenths of a km displacement the width of the zone of faulting is several m and the gouge zone ranges between 0.1 and 1 m. The ratio of the width of the total fault zone to the width of the gouge zone thus is on the order of 10-1 through a range of fault displacements and types of faulting.

TABLE 1

Relation of displacement and width of fault zones in the Coeur d'Alene mining district, Idaho

		Width of (m.)		
Fault	Displacement, KM	Gouge	Shear	Fractured rock
Osburn	26	20-30	180	?
Dobson Pass	5.6	25	240	
O'Neill Gulch	1±	(1±)		
Commander	0.6±	(4-6)		
Carlilse	0.6±	0.1	1	
White Ledge	0.31	1	6	
French Gulch	0.3±	0.1	0.3	12-16
Polaris	0.15-1.8±	(0.6-1.5)		
Mineral Point	0.15±	(1-3)		
Sonora	?	0.3		0.2-3
Sonora	?	0.6		3-7
National	?	0.3		1-10
Blue Star	?	0.6		0.6-6
Standard	?	0.3	(2.5)	
Frisco	?	0.15-.45	1±	

Relative position of gouge within fault zone

The gouge zone may lie near the center of the zone of shearing and brecciation, at one margin of the zone of shearing and brecciation, or be in several discrete bands woven throughout the zone (fig. 10).

Garth Crosby (personal communication, February 1979) reports that in the Coeur d'Alene mining district many gouge zones have developed at the margins of fault zones. and appear to be invading the unbroken wall rock. According to Crosby a gradation can be seen from unbroken wall rock to wall rock containing thin, incipient shear planes. to highly sheared and broken rock. Individual blocks, broken off the wall rock block, retain their integrity even though surrounded by comminuted gouge-like material. Eventually the blocks become completely comminuted according to Crosby.

Within the Osburn Fault zone, as shown in figure 11, the principal gouge zone, several tens of meters wide, tends to be more or less centered within the fault zone, which is a few hundred meters wide, although small shear and gouge zones splay off into the wall rock on either side.

Very commonly gouge zones form an anastomosing pattern throughout the fault zone as described in the following (Hobbs. and others 1965). On the Blue Jay fault zone "the fault trace... is along the north side of a broad zone so severely sheared and altered that it is difficult to delineate individual faults. Innumerable shear planes and gouge-filled seams suggest movement, but there is no way of identifying those in which significantly more movement occurred".

Permeability of fault and shear zones

Faults and shear zones comnly are conduits for vadose and moving ground waters, and range from structures that are tight and dry to wide premeable zones that may contain large volumes of water. In the Coeur d'Alene district the faults and shear zones are almost invariably wet where exposed In the mine workings. The gouge material commonly is saturated with water and plastic, resembling modelling clay. Mine workings require timbering to support the moist, highly fractured and sheared rock. Most such zones "make" water, that is, water percolates along the fault, in some places slowly, so that only a few gallons an hour drain out of the rock. whereas other zones produce many gallons a minute. Some zones are tight and relatively impermeable, ponding ground water to a greater extent on one side than on the other. Not uncommonly some mine galleries intersect water channels that are in what seems to be only moderately fractured rock, and yet the fractures are obviously highly permeable. The nearest large shear zones, perhaps hundreds of meters away, produce water at only a small fraction of the rate produced by the moderately fractured rock. The coarser grained quartzites of the Coeur d'Alene district appear to be able to support open fractures that make channels of high permeability.

Similar conditions prevail in the Tintic district, where mining was terminated because of the high pumping costs required to dewater the ore-bearing areas. In the Gemini and Chief No. 1 mines it was discovered that caverns developed in carbonate rocks along fault and shear zones near the original water tables at the 1.500-foot level could be used for the disposal of large volumes of water pumped from the 3,100-foot level and workings above it. Obviously the caverns and fault zones provided sealed conduits which extended to water-free areas hydrologically lower than the apparently perched water table in the mining district. In the Tintic district, as in the Coeur d'Alene district, some fault zones are effective dams for ground water. An example is the Eureka Lilly in the North Lily mine, northwest of which the ground water stands almost 50 m higher than it is on the southwest side, although the fault cuts normally permeable quartzite in this area.

In both the Tintic and Coeur d'Alene districts many faults appear to have provided access for hydrothermal solutions. An example is shown in fig. 12. In some places the hydrothermal alteration is confined to only one side of a fault. indicating ponding and diversion of the solutlons.

In summary, faults commonly are conduits for water and in the past have served as channelways for hydrothermal solutions. However, in many mining districts, they may not be the only permeable zones and even may be far less permeable than less conspicuous fractures and pervasive joint systems having little displacement.

Faulting vs. Foliation

Foliated rocks such as phyllites and schists are common in the Coeur d'Alene district and, certainly, some have an origin related to shearing and faulting. Sheared argillites in and near fault zones almost everywhere have a schistose structure. Figure 13 illustrates a shear zone, the Deadman Shear zone, in which a zone of foliated rocks is several hundred meters wide. The body of foliated rocks itself is believed to represent large-scale, strike-slip shear distributed relatively uniformity across a broad zone. But later disruption of the foliated body by shear, represented by concentrated zones of gouge a few cm across. has taken place. In addition kink banding has developed in the highly foliated body. The planes of kink banding dip at various low angles, and the intersections of kink-band planes are subhorizontal suggesting predominately vertical displacement as the last displacement within the zone produced originally by strike slip.

Distributed shear is also indicated in the steep flanks of large anticlines, that is, those having amplitudes and wavelengths of a kilometer or more. Figure 9 illustrates how beds of quartzite are in places separated by closely spaced shear zones into thin tablets at most a few cm across, although the entire bed may not be offset appreciably. A common error in geologic mapping has been to consider the vertical shear planes as bedding because in detail they are lithologic boundaries. The true bedding planes (see dark unit) cross the foliation or shear planes at an angle.

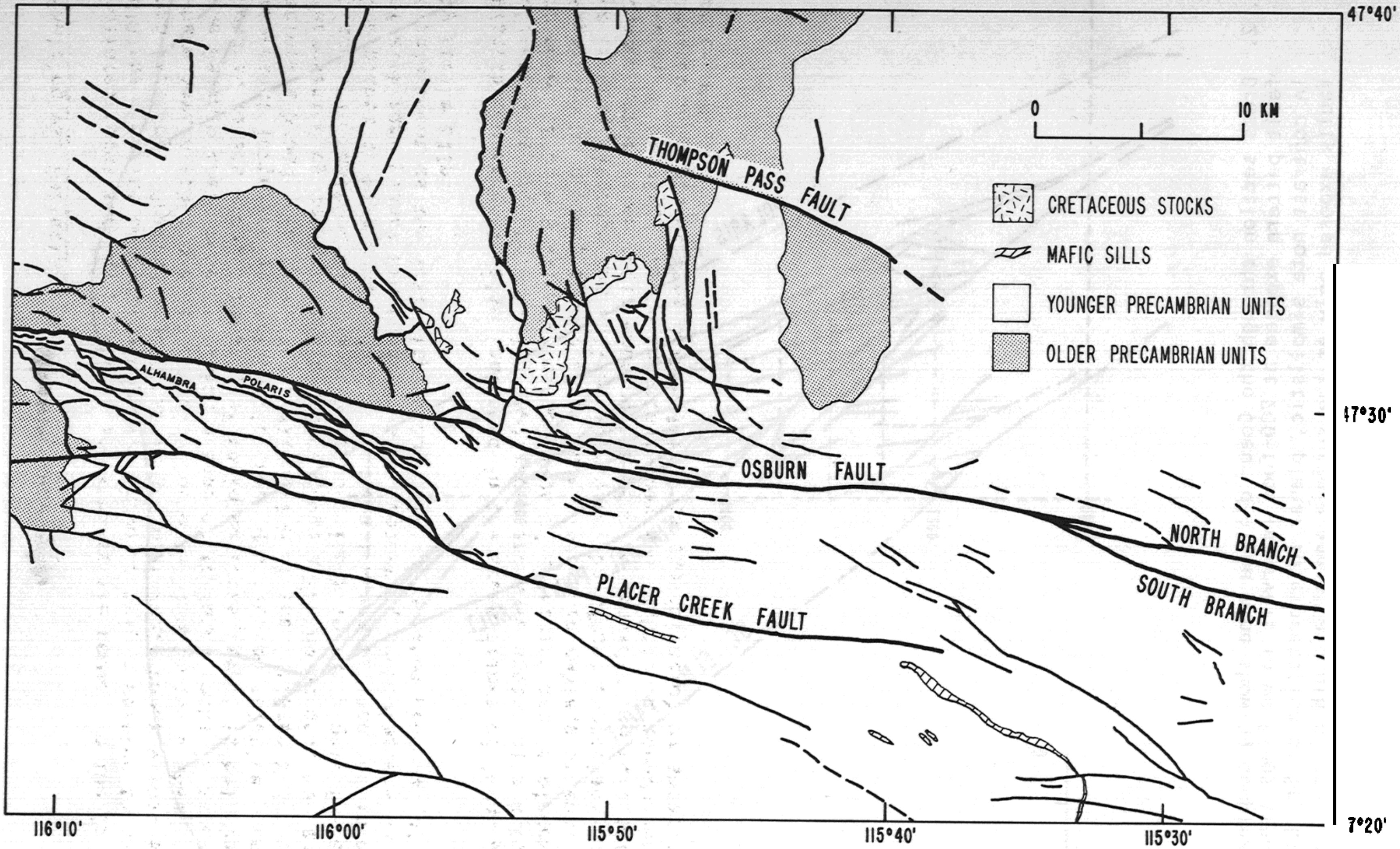


Fig. 1. The Osburn fault in northern Idaho displays 26km right-lateral strike slip and the Thompson Pass fault displays approximately 5km right-lateral strike slip. At both large and small scales the fault pattern is complex.

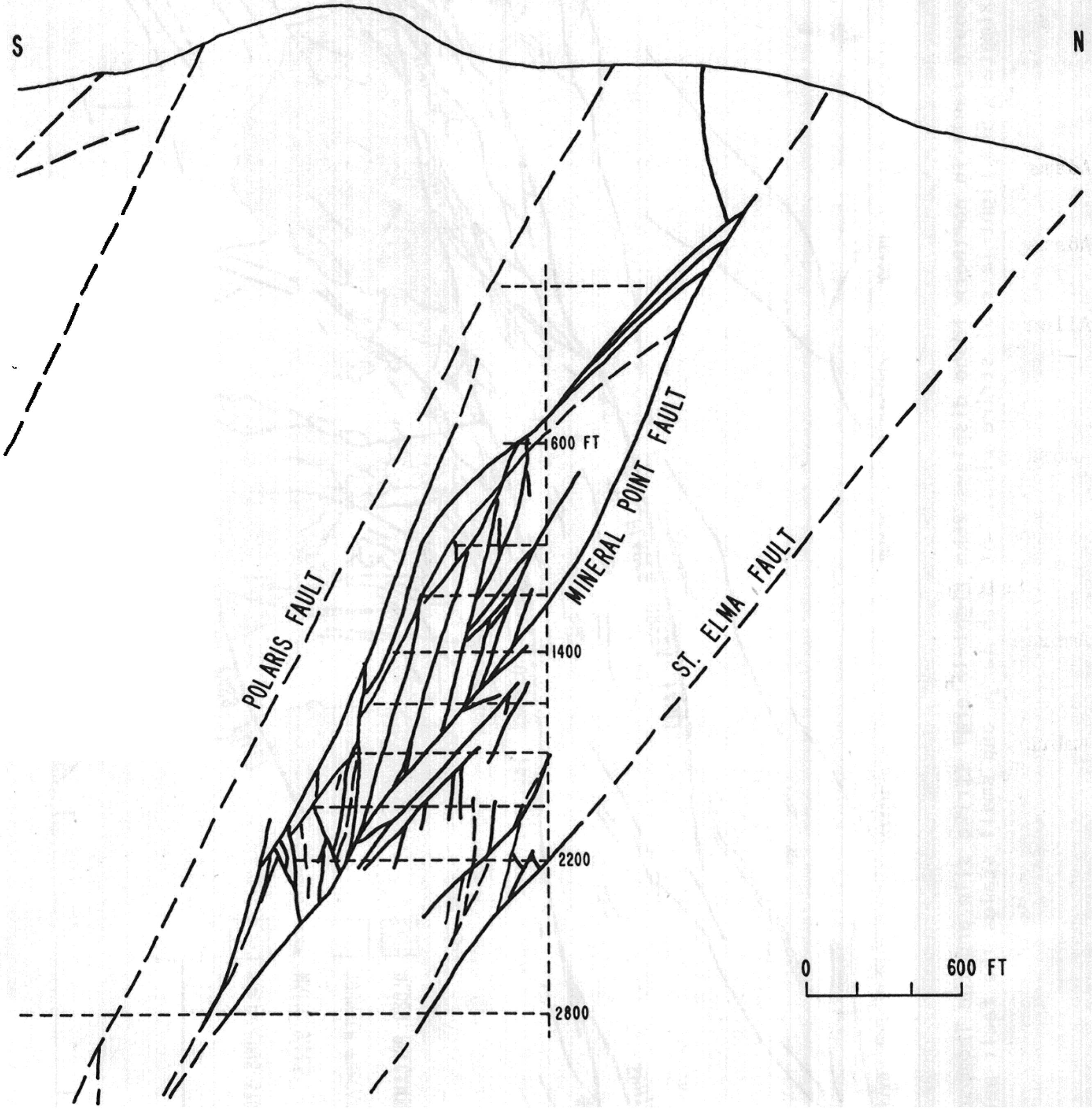


Fig. 2. Cross section through the Coeur d'Alene mine showing complex anastomosing fault pattern exposed at ZOO-foot intervals in workings (short dashes). In contrast note simplistic, planar interpretation of St. Elmo and Polaris faults exposed only at the surface and at a depth of 2800 feet.

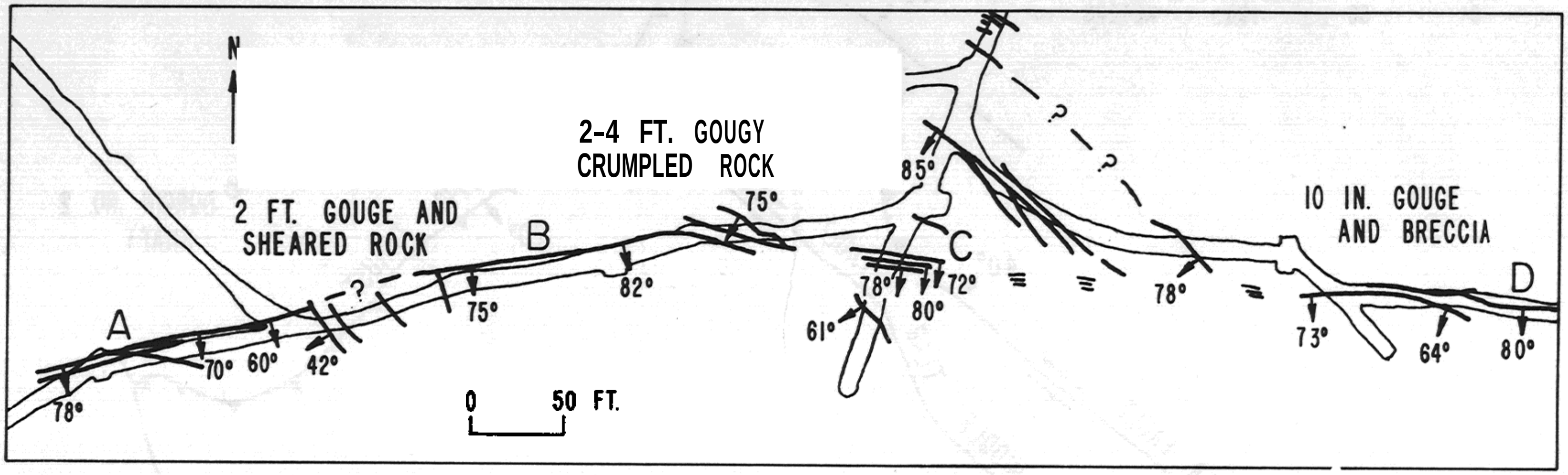


Fig. 3. Characteristic irregular pattern of faults exposed in mine workings of the Coeur d'Alene mine. Note change in strike and dip over short distances and branching habit, near A dips range from 60° to 78° over a strike length of 100 feet; near C strands within the fault zone range in dip from 72° to 80°; between B and D the width of gouge ranges from 10 inches to 4 feet.

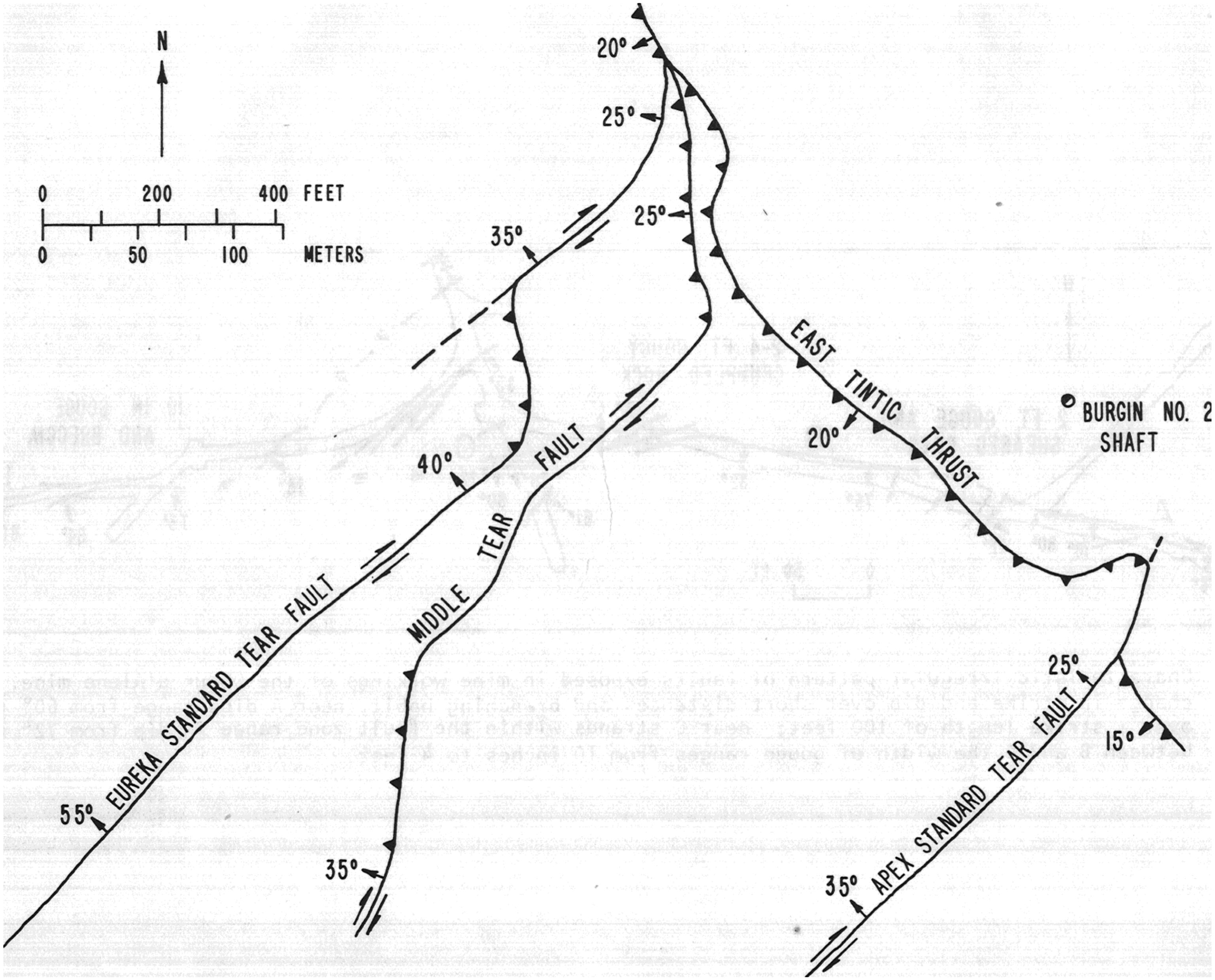


Fig. 4. Structural diagram of part of 1050-level of the Burgin mine, East Tintic district, Utah, showing relationship of the Eureka Standard and other tear faults to the East Tintic Thrust.

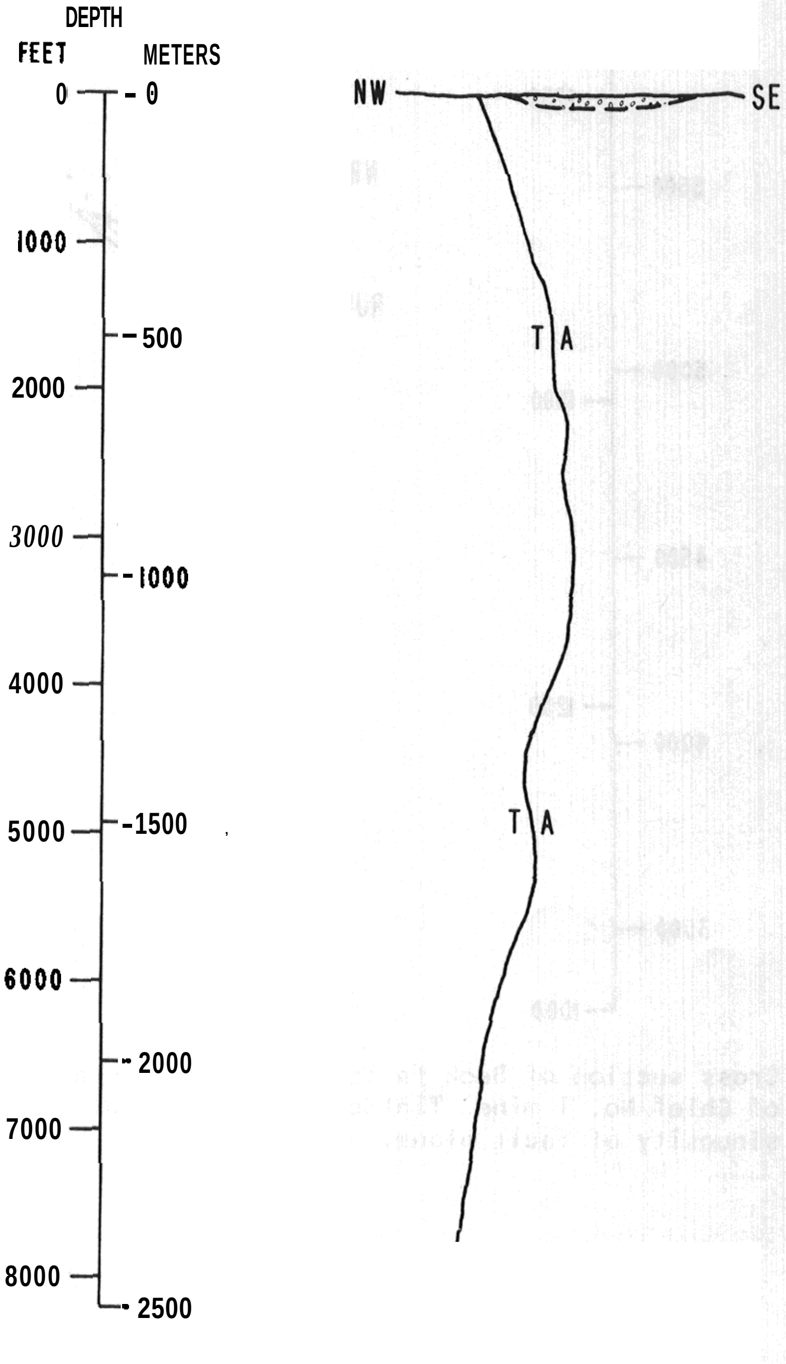


Fig. 5. Cross section of Lakeshore fault, Wright-Hargreaves mine, Kirkland Lake district, Ontario, showing curving nature of fault plane. "T" indicates block that moved relatively toward viewer; "A" indicates movement relatively away from viewer.

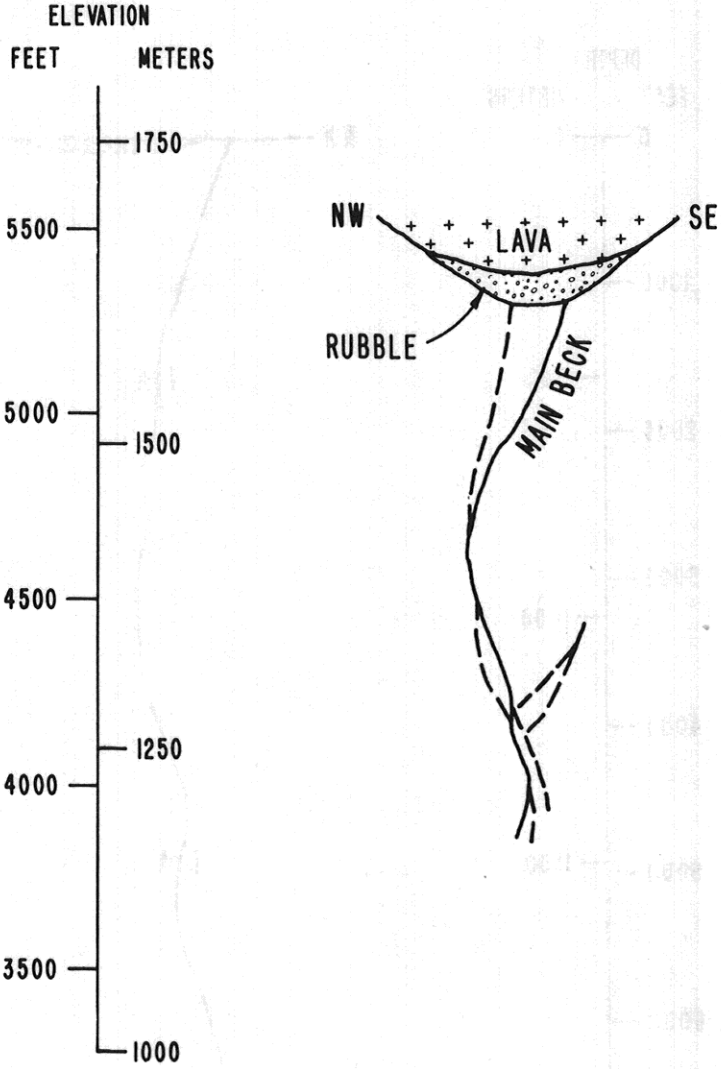


Fig. 6. Cross section of Beck fault between 1,200- and 2,700-foot levels of Chief No. 1 mine, Tintic mining district, Utah showing sinuosity of fault plane.

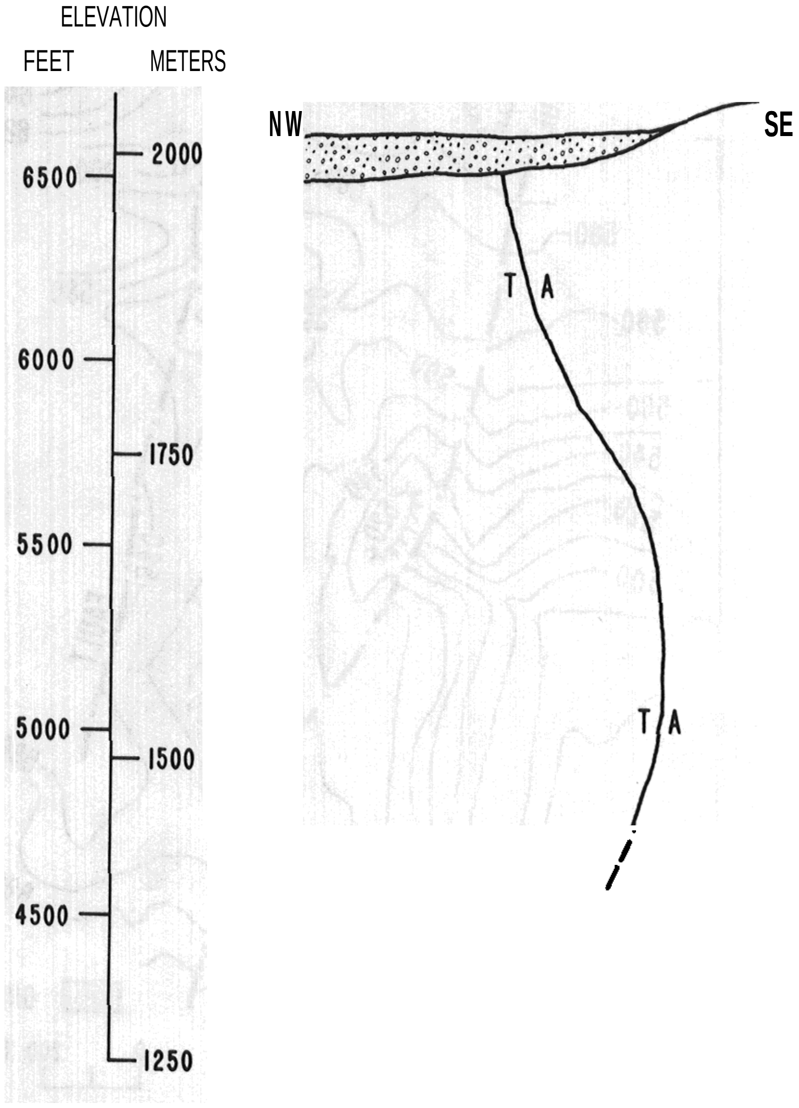


Fig. 7. Cross section of Centennial fault in southern part of Chief No. 1 mine, Tintic mining district, Utah showing curving nature of the fault plane. "T" indicates block that moved relatively toward viewer, "A" relatively away.

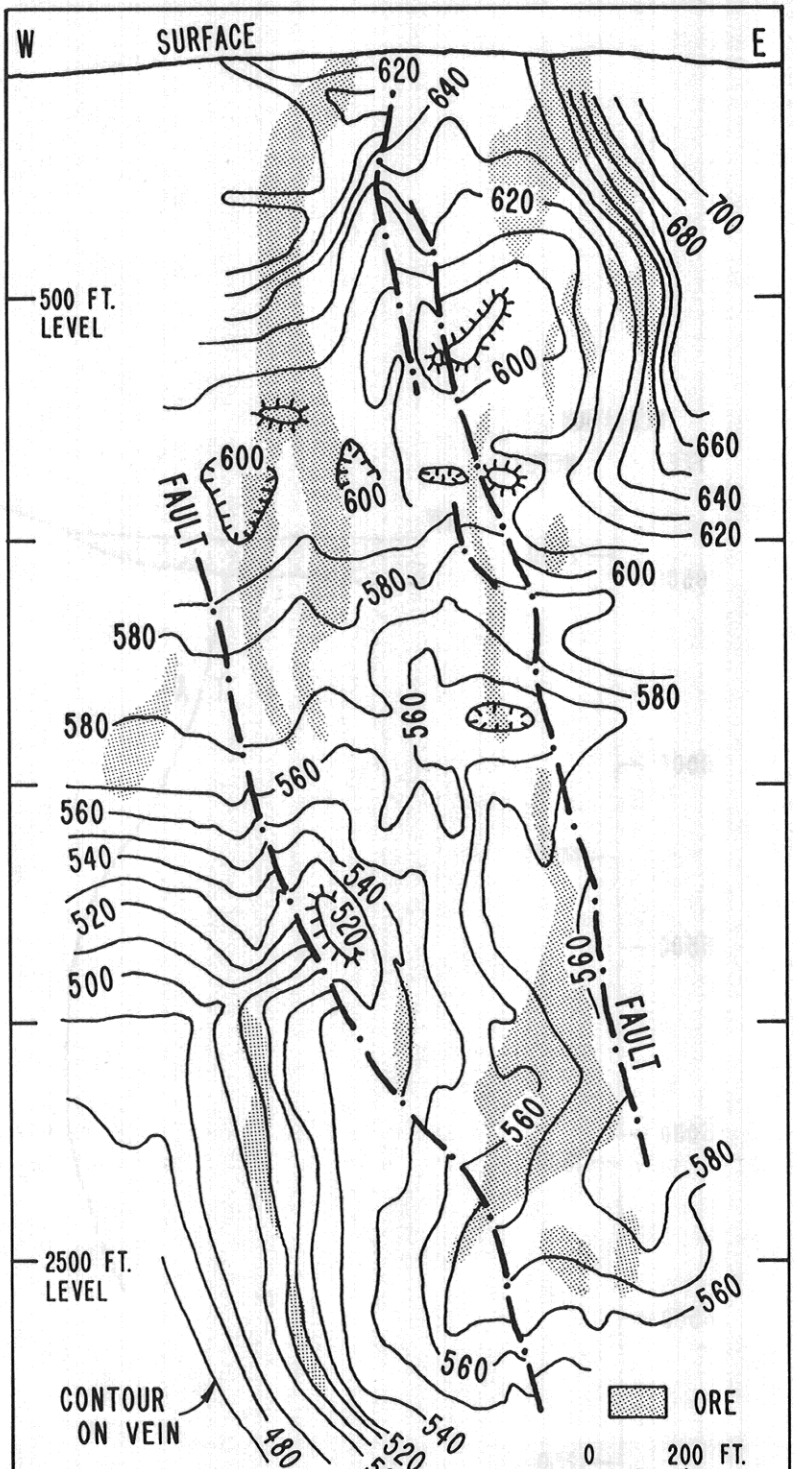


Fig. 8. Structural contours on vein at the O'Brien gold mine, Quebec, showing relation of ore to irregularities of vein. (After J.W. Mills, 1950)

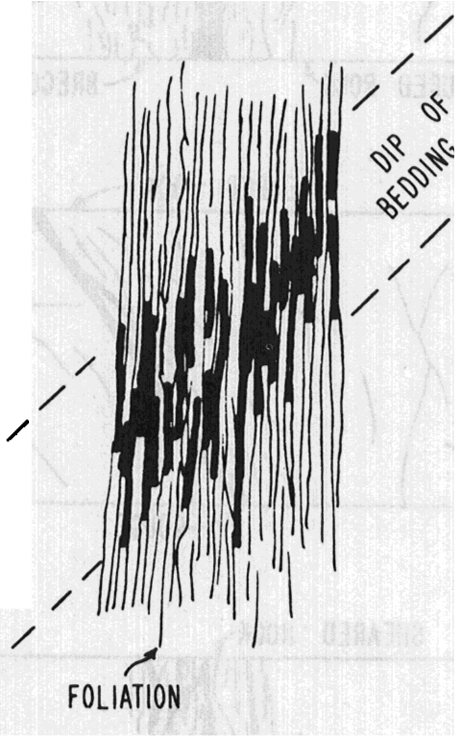


Fig. 9. Foliated rock displaying shear. Beds are disassembled by amounts of a few cm to a few m along closely spaced shear planes.

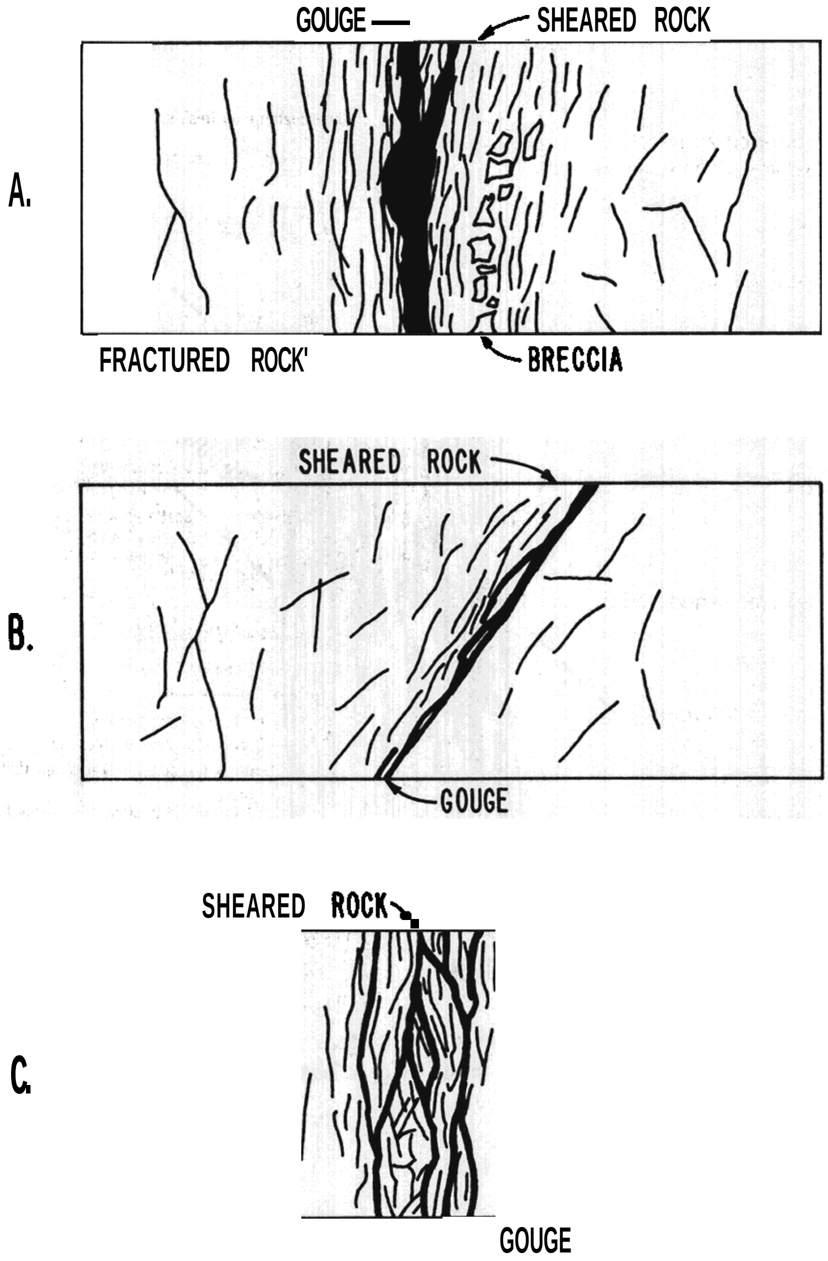
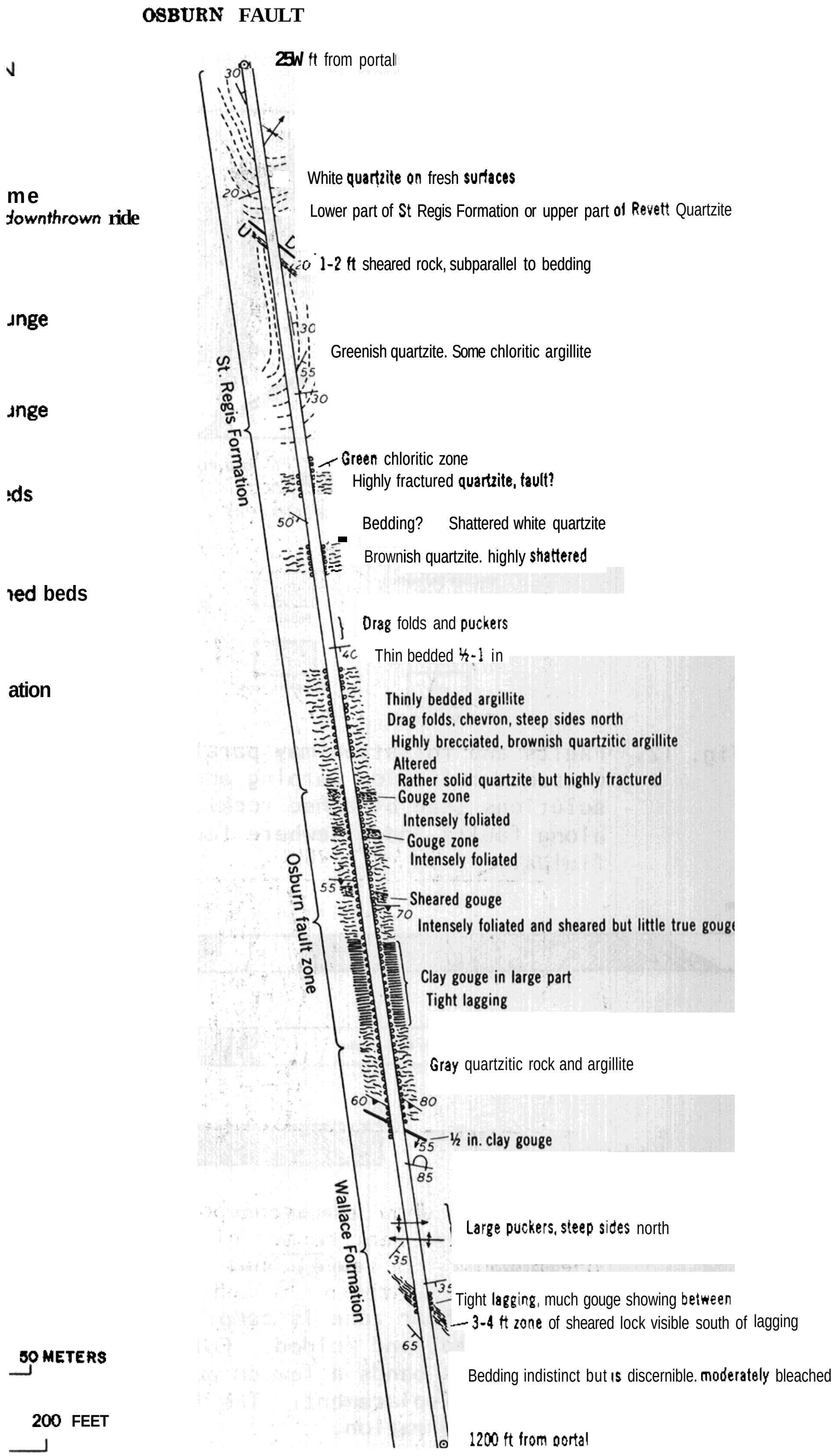


Fig. 10. **Diagrams to show different positions of gouge within fault zone. A. Gouge zone near center of fault zone. B. Gouge localized at one boundary of fault zone. C. Thin gouge seams forming anastomosing pattern through fault zone.**



sburn fault as exposed in the main cross cut of the Morning is between 70 and 125 m wide, 24 m of which is predominately -like gouge. The fault has 26 km right-lateral strike slip.

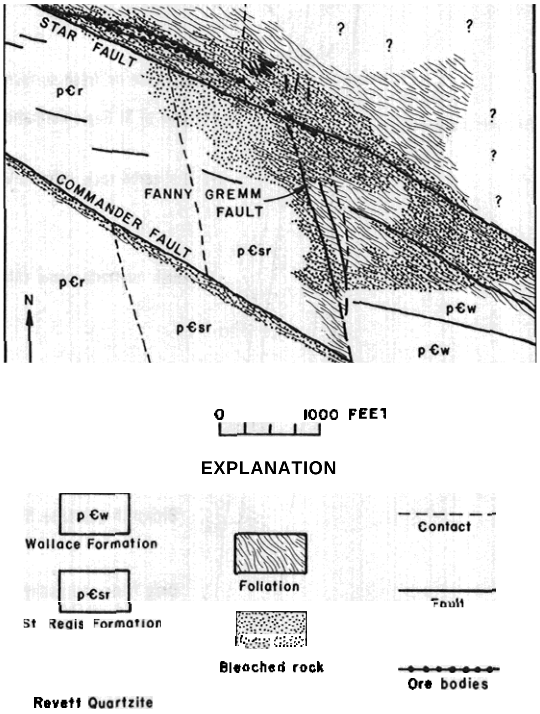


Fig. 12. Faults and foliation may parallel one another or faults may crosscut foliation warping and crenulating it. Hydrothermal solutions (see bleached rock) in some places are channelled along faults and elsewhere faults present a barrier to the fluids.

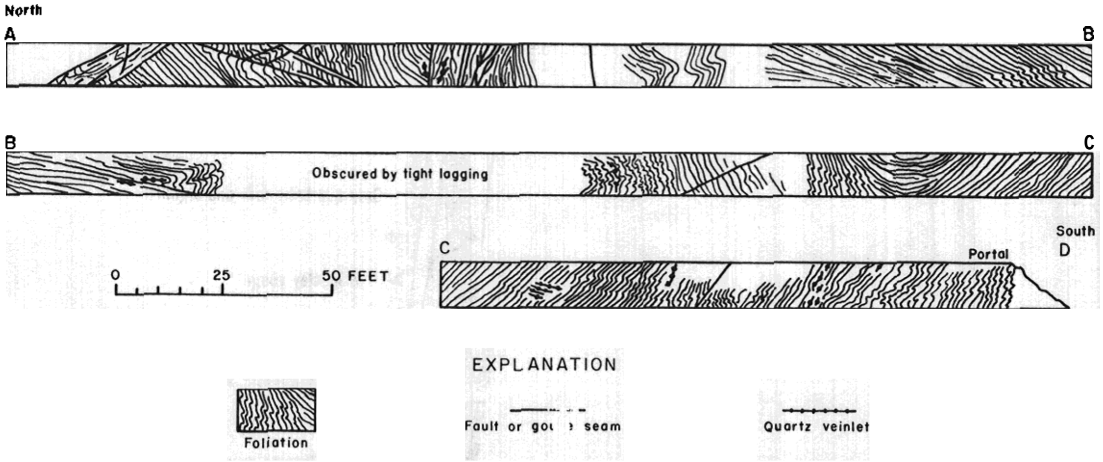


Fig. 13. The Deadman shear zone is comprised of well foliated rocks, highly sheared, and folded. Folds range from tens of meters across to kink bands a few cm across representing planar shears of a few cm displacement. The folds and kink bands represent secondary deformation.