

METAL-RATIO ZONATION IN THE KENO HILL DISTRICT, CENTRAL YUKON

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ABSTRACT

Silver has been won from narrow vein faults in the Keno Hill district for nearly 70 years. During this period, 3.9 million tonnes (4.3 million tons) of ore have yielded 5754 million grams (185 million ounces) of silver. All of this production has come from sub-cropping ore shoots; supergene enrichment is not an important factor in most deposits. Parallelism of the ore zone with the present surface has been seen in other Cordilleran vein camps, but despite considerable effort, operators in these camps have met with little success in their search for blind ore shoots.

The potential for blind ore in the Keno Hill district is examined from the perspective of metal-ratio zonation. An approximate reconstruction of the original fracture pattern in the district and the metal-ratio definition of a hydrothermal system acting within these fractures suggest that some ore shoots have been eroded, some are exposed at the present surface, and others remain preserved at depth.

INTRODUCTION

The Keno Hill district, 354 km north of Whitehorse, Y.T. and 274 km east of the Alaska-Yukon border (Fig. 1), has been a prolific silver producer for nearly 70 years. During this period, 14 significant deposits, each containing more than 7.8 million g (250,000 oz) of silver have yielded a total of 5754 million tonnes (4.3 million tons) of ore mined. The historical silver ore production grade has averaged 1475 g/t Ag (43.0 oz/ton), 7.2% Pb and 4.7% Zn. By way of comparison, the Slocan district produced 1711 million g (55 million oz) of silver, the Cobalt district 11,353 million g (365 million oz) of silver and the Coeur d'Alene district is approaching 31,103 million g (1 billion oz) of silver production.

All of the known significant Keno Hill district deposits subcrop. In 11 of these mines, the ore shoot(s) dies out 91 m (300 ft) to 152 m (500 ft) vertically below subcrop, even though the enclosing vein fault structure remains strong at depth. The Hector-Calumet mine, the deepest in the district, has been mined to 366 vertical metres beneath the outcrop, yielding just over one half the total district silver production. If this mine is excluded, the 0 to 122 m vertical depth zone of the remaining 13 significant mines account for 90 percent of the combined silver production. Supergene enrichment is not an important factor in most deposits. The elevation difference between the top of the highest deposit and bottom of the lowest deposit is 1036 metres. Most deposits show an increase in sphalerite and decrease in argentiferous galena with depth. In exploration for new deposits, the apparent parallelism of the ore to the present surface is an important consideration. If it is real, there is little likelihood of finding deep or blind ore in the district.

United Keno Hill Mines Limited has been operating in the Keno Hill district since 1947. Successful exploration programs, both underground in the operating mines and on surface using rotary percussion drilling on a grid pattern (Van Tassell, 1969; Franzen and Van Tassell, 1981), have enabled the company to maintain mining operations. Completion of 15,000 grid rotary percussion holes, at an average depth of 37 metres per hole, has tested many of the known shallow targets in the district. The long term future of the district may depend on the discovery of deep and blind ore shoots.

This paper describes metal-ratio zonation in the Keno Hill district. The potential for deep ore is considered in terms of a large, metal-ratio defined hydrothermal system.

Previous Work

Detailed descriptions of geology, mineral deposits and mining operations in the Keno Hill district have been given in various publications. McTaggart (1960) and Green (1971) established the fundamental stratigraphy and structural geology, whereas Aho (1963) and Boyle (1965) considered the geology of the silver deposits. Tempelman-Kluit (1970) described the regional geology of the Keno Hill Quartzite. More recently, Sinclair *et al.* (1980), and Sinclair and Tessari (1981) have reported on vein geochemistry

of individual deposits and K-Ar age dates of vein mineralization. Mining operations are described by The Staff (1961). The reader is referred to the above mentioned papers for detailed background information.

KENO HILL DISTRICT GEOLOGY

The Keno Hill district is 29 km long in an east-west direction and 6.5 km wide (Fig. 2). Within it, some 70 vein deposits are known along sub-parallel vein fault structures, with a total strike length of 56 km. The steeply south-dipping vein faults are for the most part confined to the structurally favorable Central Quartzite Unit of probable Lower Cretaceous age. This unit has an apparent structural thickness of 914 to 1829 m (3000 to 6000 ft) and consists of variably-bedded orthoquartzite with interbeds of graphitic phyllite and less common greenstone sills. Compositional layering dips moderately to the south and the rocks are strongly foliated parallel to it. The geology of the district is complex and not fully understood. Small isoclinal folds with axial planes parallel to the foliation are common and the apparent thickness of rock units and the stratigraphic succession may be the result of large-scale isoclinal folding or thrusting.

The Central Quartzite Unit is underlain by the Lower Schist Unit of probable Jurassic age and overlain by the Upper Schist Unit of uncertain age. Both consist of thin-bedded quartzite, phyllitic quartzite and sericitic to graphitic phyllite. In addition, the Lower Unit contains numerous greenstone sills and on Keno Hill, the No. 9 Quartzite Member near the top of the unit. Greenstone and quartzite of the Lower Schist Unit contain mineralized vein structures. Cretaceous granitic stocks intrude the structural succession, although there are no known occurrences of granite in the vicinity of the mine workings.

In the Keno Hill district, open folding outlined by rocks of the Central Quartzite Unit has been superimposed on earlier, complex structures. Most important is the McQuesten anticline, an open, upright structure that plunges gently to the west (Fig. 3). Near the summit of Keno Hill, the strike of the rocks swings to the southeast on the flank of another open structure, the Mayo Lake anticline. The vein faults strike more or less parallel to the axial plane of the anticline, their orientation and spatial distribution suggesting that the structure has controlled their development. On the south limb, much of the Central Quartzite Unit has been eroded, while other portions remain buried beneath the rocks of the Upper Schist Unit. It seems logical to assume that some portions of the accompanying vein faults have been eroded, while others remain buried, the present erosional surface cutting obliquely through the original Keno Hill district fracture pattern.

At the west end of the structure, the Central Quartzite Unit outcrops close to the anticlinal crest (Fig. 4 - Point A). Traversing easterly along the quartzite outcrop one moves obliquely down the limb of the anticline (Fig. 4 - Point B). In effect, at the present erosion level one sees an en echelon view of isolated portions of individual vein faults rather than a true section across the original

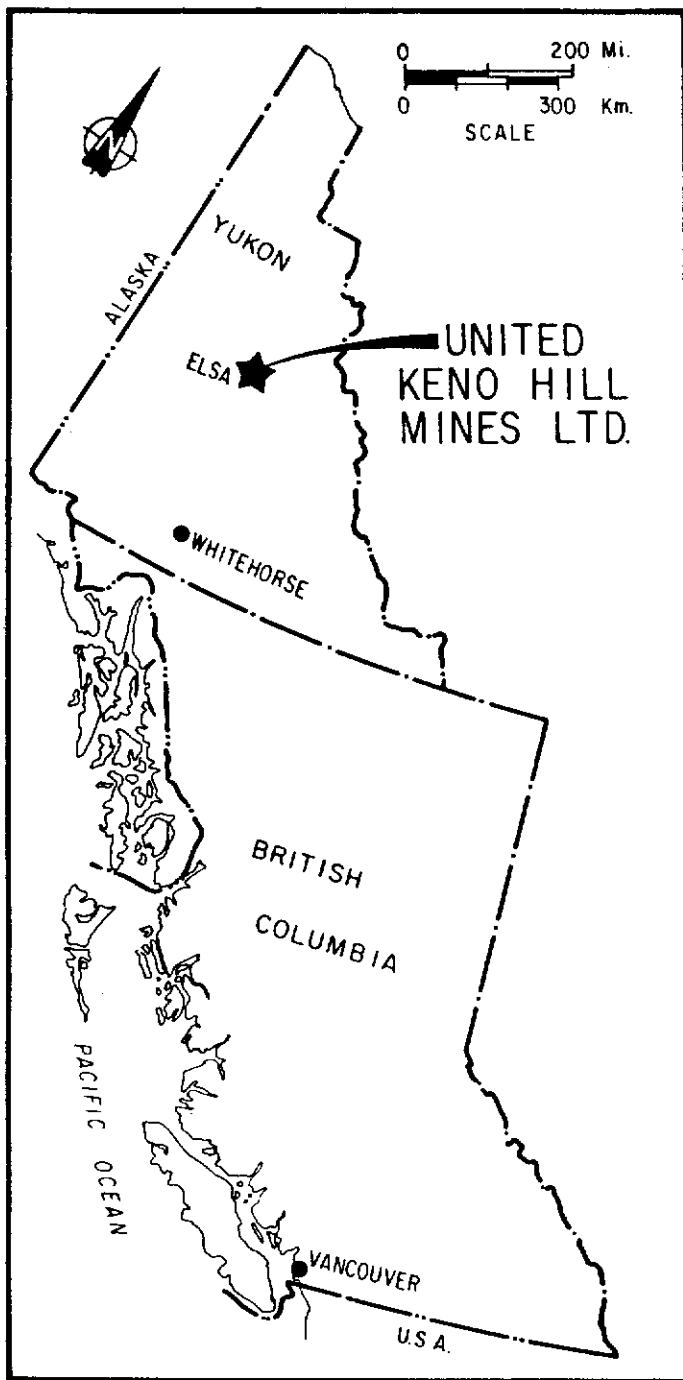


Figure 1. Location map of Keno Hill district.

fracture pattern. Before examining metal-ratio zonation between and within these vein faults, it is important to know what this original fracture pattern looked like. Figure 5 is a generalized cross-sectional reconstruction, normal to the anticline hinge line, of the original fracture pattern on the south limb of the McQuesten anticline. This cross section was constructed by compressing the en echelon known portions of individual vein faults (Fig. 4) onto a common or composite cross section. Construction of such a section requires a horizontal and vertical coordinate for each vein fault in the district. The horizontal position of individual vein faults was determined by measuring, in plan, the normal distance between a reference line parallel to the surface trace of the axial plane and the location of the vein fault. The vertical position of individual vein faults is simply the stratigraphic position of the vein fault in the structural succession. Constructing a district composite or generalized cross section in this manner avoids strike variation problems inherent in actually projecting individual veins to a common section line. Figure 5 shows that vein faults occur in an 8 kilometre wide zone on the south limb of the anticline. The rare

vein faults on the unproductive north limb of the anticline dip in the opposite direction.

VEIN FAULT STRUCTURE AND MINERALIZATION

Deposits in the Keno Hill district share a common structural style, but differ markedly in the character of their mineralization. The vein faults are breccia zones or sheeted zones or transitions between these two types. Drag along vein fault wallrocks indicates that the last sense of movement along these zones was of the normal type. Vein fault widths vary between 0.6 and 30 m, but are most commonly in the 1.5 to 4.6 m range. Individual ore shoots vary in size from tens of metres to a few hundreds of metres vertically and laterally. These ore shoots commonly occur in or near structurally complicated zones within the vein fault where cymoid loops, junction zones, and cross faults make for difficult mining conditions.

Many of the Keno Hill deposits are mineralogically distinctive. Visual inspection of a hand size sample will often allow the geologist to identify the mine and stope source of the material. Gangue mineralization typically consists of variable amounts of quartz, calcite and manganiferous siderite. The latter generally predominates in the ore zones. The main ore minerals are argentiferous galena, freibergite and sphalerite. Primary pyrrargyrite, stephanite and polybasite sulphosalt mineralization accompany the normal argentiferous galena-freibergite association at the rich Husky Mine. In some of the mines the oxidation zone extends to a depth of approximately 152 m. In this zone, cerussite and anglesite are common; native silver and argentiferous jarosites may also occur. For a detailed account of the structural geology and mineralization in individual deposits, the reader is referred to Boyle (1965).

DISTRICT METAL-RATIO ZONATION

Like many other high-grade, narrow vein deposits mined elsewhere in the world, those of the Keno Hill district have required careful geology and grade control. It is a 70 year accumulation of documented geological and grade information that forms the basis of this metal-ratio zonation study.

There is a wide range in the size of significant deposits in the Keno Hill district. Table 1 summarizes production data to September 1979 for the 14 significant deposits considered in this study. Hector-Calumet Mine is in a class by itself. This deposit has produced 2955 million g (95 million oz) of silver from 2.4 million tonnes (2.6 million tons) of ore. Structural arguments and mineralogical considerations (Franzen, 1978) suggest that the Elsa and Husky Mines were originally a single deposit, now separated by cross-faulting. This combined deposit has produced 1120 million g (36 million oz) of silver from 523, 666 tonnes (577,297 tons) of ore and continues to operate. Consequently, the Hector-Calumet and Husky-Elsa deposits account for 70 percent of the silver production in the district. Most of the remaining significant deposits fall into the range of 31 to 467 million g (1 to 15 million oz) of silver and 27,213 to 272,130 tonnes (30,000 to 300,000 tons) of ore. In general, a deposit containing in excess of 311 million g (10 million oz) of silver is considered to be a major deposit in the district. On a reconstructed cross section (Fig. 6), major deposits, with the exception of Keno 9, are confined to a 1.8 km wide zone that is close to, but dipping away from, the axial plane of the McQuesten anticline (Fig. 6). The apparent vertical or up-dip continuity of these major deposits is noteworthy. Minor producers and deposits with important mineralization are scattered across the reconstructed section. This distribution of known deposits indicates that mineralizing solutions were either more readily available adjacent to the anticline axial plane or that proximity to the axial plane is a prerequisite for effective tapping and localization of mineralizing solutions. In either case, the general distribution of silver suggests a decreasing production potential, with increasing distance from the zone of major producers.

The ore mineralogy of vein faults does not vary systematically with the position in the structural succession. However, total ore production metal ratios from the significant deposits show a definite zonation in reconstructed cross section. These structural and metal-ratio reconstructions assume that production metal ratios from known deposits are representative of eroded and

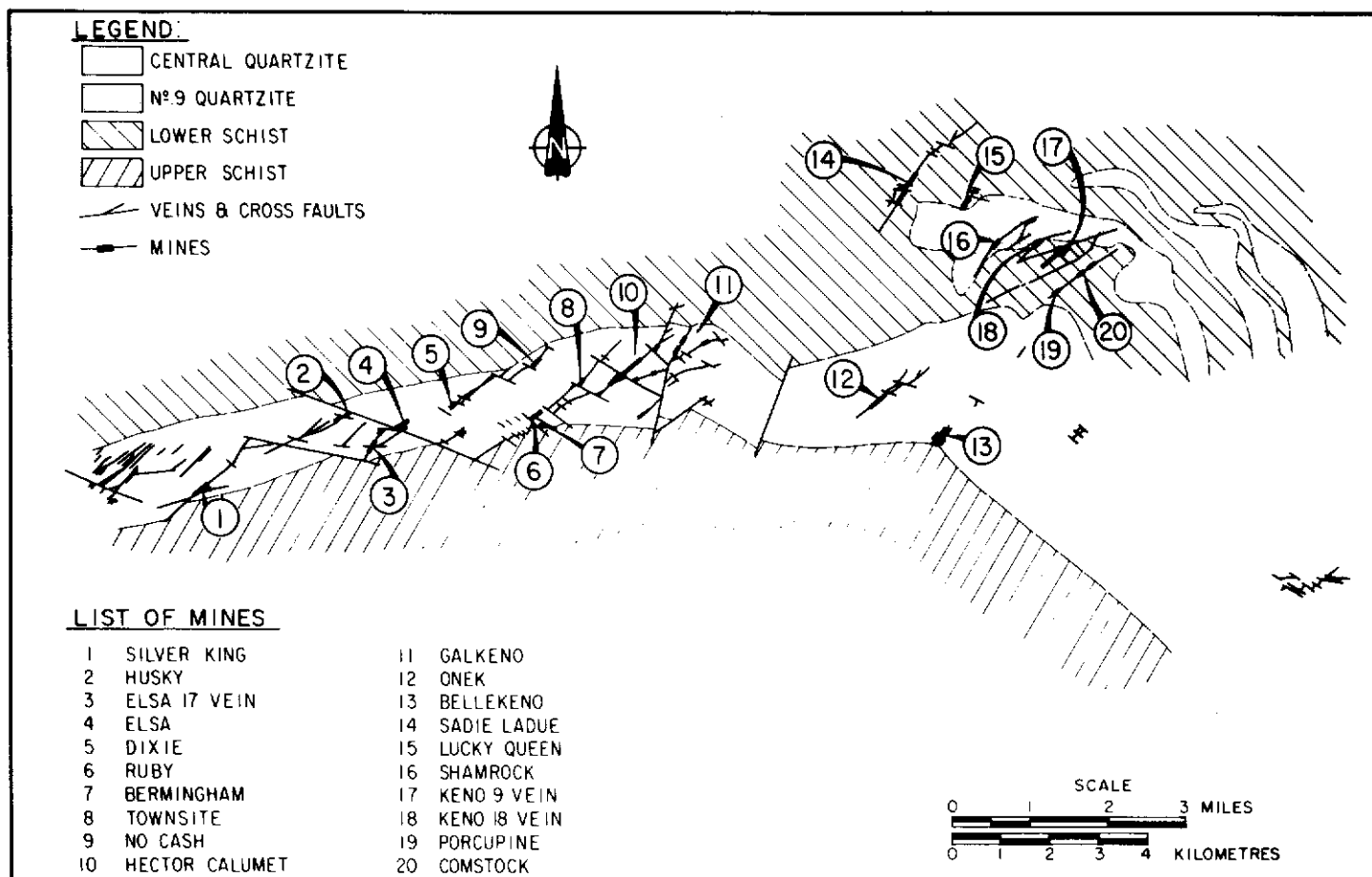


Figure 2. Mines and fault structures on Galena and Keno Hills.

buried along-strike portions of the vein faults. Metal-ratio contours for Ag/Pb, Pb/Zn and Ag/Zn (Figs. 7, 8 and 9 respectively) show a dominant and regular, concave-up pattern deep in the structural succession. The axis of this concave-up pattern is coincident for Ag/Pb and Ag/Zn values; the Pb/Zn axis shows a shift to the south. For all three ratios, the axis of the concave-up pattern is approximately parallel to the dip of vein faults in the camp. Higher in the structural succession, Ag/Pb and Pb/Zn values define a variant, subordinate metal-ratio trend whose axis parallels compositional layering. The large and high-grade Husky-Elsa deposit is at the centre of this. Studies within individual veins in other mining districts (Goodell and Petersen, 1974) have shown that the shape of metal-ratio contours can outline zones of maximum permeability and, as a result, indicate the direction of flow of mineralizing solutions. The dominant and deep-seated metal-ratio dome indicated for Keno Hill district suggests that mineralizing solutions moved up through the structural succession along the centre of a pervasively fractured zone on the south limb of the McQuesten anticline. The Lucky Queen and Hector-Calumet vein systems have been the site of major flows of mineralizing solutions. Deposits in the Lower Schist and No. 9 Quartzite are tight and generally lack textures indicative of open space filling. The relatively gentle metal-ratio gradients of these deposits suggest that they were relatively deep-seated at their time of formation; Pb/Zn values are typically low. Deposits in the Central Quartzite commonly show open space vein filling textures. The steep metal-ratio gradients of these deposits suggest that they were relatively shallow at their time of formation. In them, deposition of metals from ore solutions appears to have been rapid, perhaps in response to marked temperature-pressure fluctuations in a high level environment; Pb/Zn values are generally high. This district variation in Pb/Zn values has also been noted on an individual deposit scale, with many of the mines showing an increase in zinc relative to lead with depth. In the author's opinion, the deposits mined to date in the Lower Schist and Central Quartzite Units carry the distinctive signature or fingerprint of an eroded, metal-ratio defined hydrothermal system. This metal-ratio signature varies with vein fault

position in the hydrothermal system and in the structural succession.

Testing of District Metal-Ratio Zonation

The concept of a district metal-ratio pattern that defines the "fossil" hydrothermal system presents some problems. The base of the metal-ratio dome in Figures 7, 8 and 9 is well established with five metal-ratio control points. Unfortunately, erosion has removed structurally favorable rocks higher in the dome and, as a result, there are no control points directly below the Central Quartzite Unit; metal-ratio contours are, at best, speculative in this area. It could be argued that positioning alone of certain Central Quartzite-hosted deposits has generated a dome shape that would not otherwise exist. The representativeness of district metal-ratio contours was examined in an independent test.

Detailed Deposit Metal-Ratios

To assign metal-ratio values to a particular deposit, production from that entire deposit was considered (Table 1). The resulting metal-ratio value, in conjunction with other deposit metal-ratios, was used to establish contour lines of the reconstructed cross section (Figs. 7, 8 and 9). If these district contours are meaningful, one must expect some correspondence with depth variations in metal-ratios in individual deposits. Figures 10 and 11 show detailed level by level metal-ratio profiles in six deposits, for which there are sufficient data. A comparison of these detailed down-dip mine profiles with the down-dip trends, as observed and interpolated in district contours, shows the two trends to be in general agreement. Ag/Pb values show the best correlation between detailed and district trends. This probably reflects the fact that the bulk of mining activity has concentrated on silver- and lead-rich, and zinc-poor zones in the deposits. These observations support the suggestion of a metal-ratio zonation in the district.

Regional Considerations

In the author's opinion, the metal-ratio zonation in the Keno Hill district suggests that we are looking at an eroded root zone of a

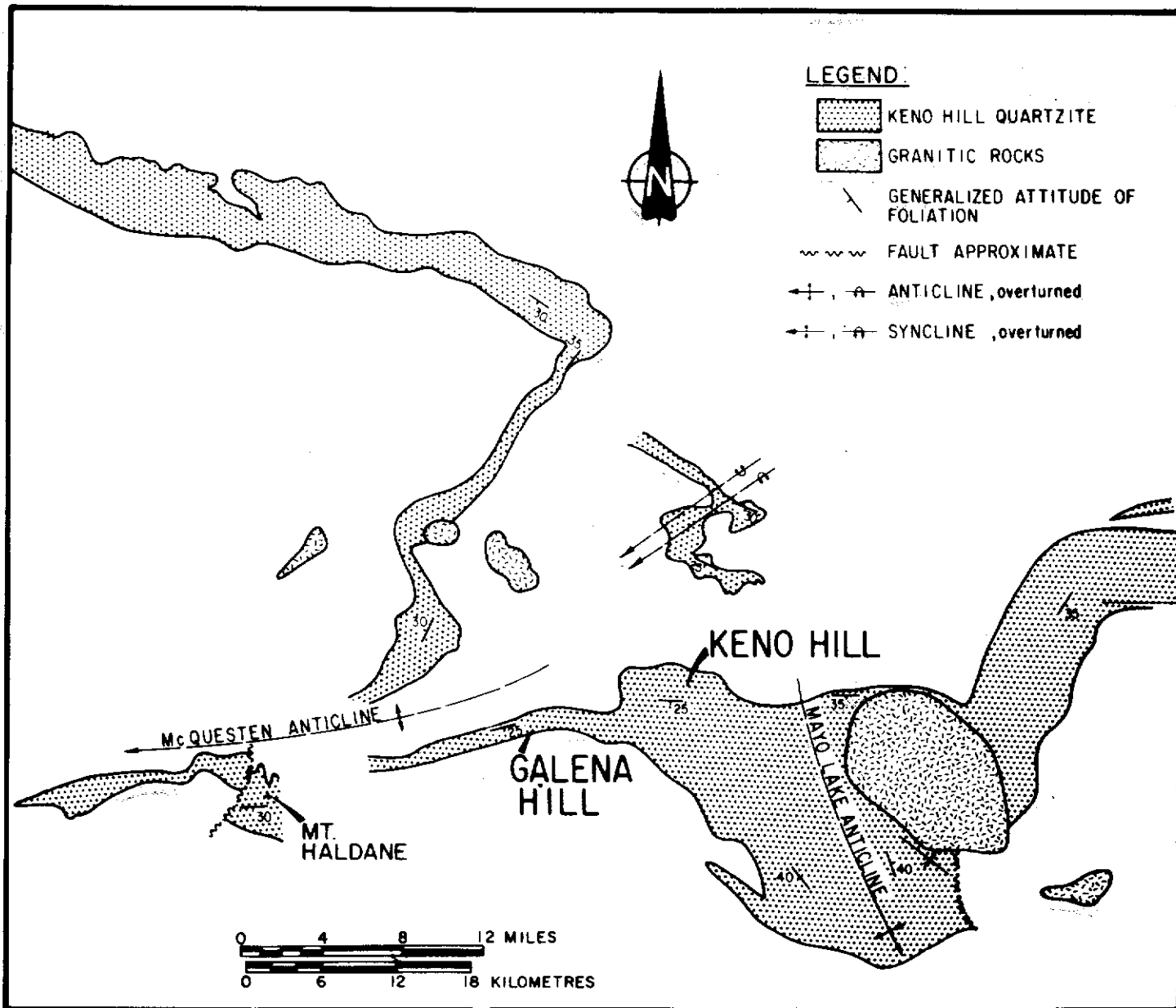


Figure 3. Structural elements in the Keno Hill district (after Green, 1971).

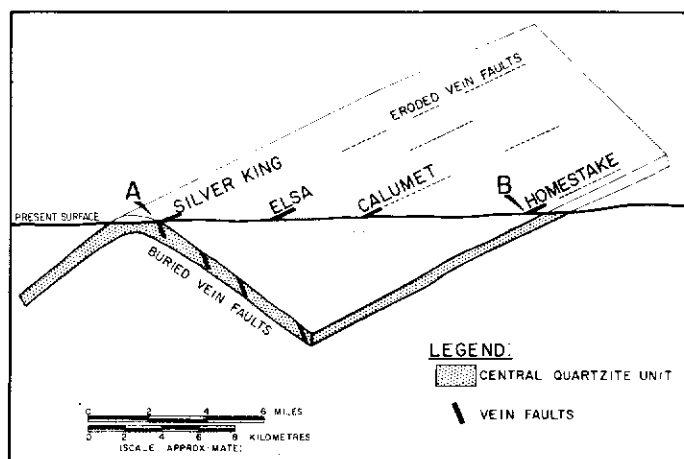


Figure 4. Schematic diagram of the south limb of the McQuesten Anticline showing the positioning of the anticline and vein faults relative to the present surface.

hydrothermal system at the eastern end and the top of a system at the western end, with much of the latter buried beneath cover rocks of the Upper Schist Unit (Figs. 12a and b respectively). The overall shape and orientation of the system appear to be similar to that of the vein fault-controlling McQuesten anticline. Additional mining and the discovery of new deposits may change this shape.

Considering the vein faults in terms of stratigraphic position or original depth, rather than viewing them solely as near surface features, can be supported by an examination of stratigraphic Ag/Pb zonation in the region. The average Ag/Pb value for deposits in Keno Hill district proper is 6/1; the average Ag/Pb value for three small deposits (Rambler, Foley and Paul) in the Lower Schist Unit in the core of the McQuesten anticline is 1/1 (Fig. 12b). This difference is significant and indicates that deposits in low stratigraphic positions have been deposited from relatively silver-deficient mineralizing solutions. If one considers the Lower Schist Unit as the source of the ore fluid (Boyle, 1965), then at least two explanations can account for this systematic Ag/Pb variability:

- 1). Low level deposits with low Ag/Pb ratios have been generated by hydrothermal solutions that have experienced limited upward migration through Lower Schist source rocks prior to reaching structurally favorable host rocks. Mineralizing solu-

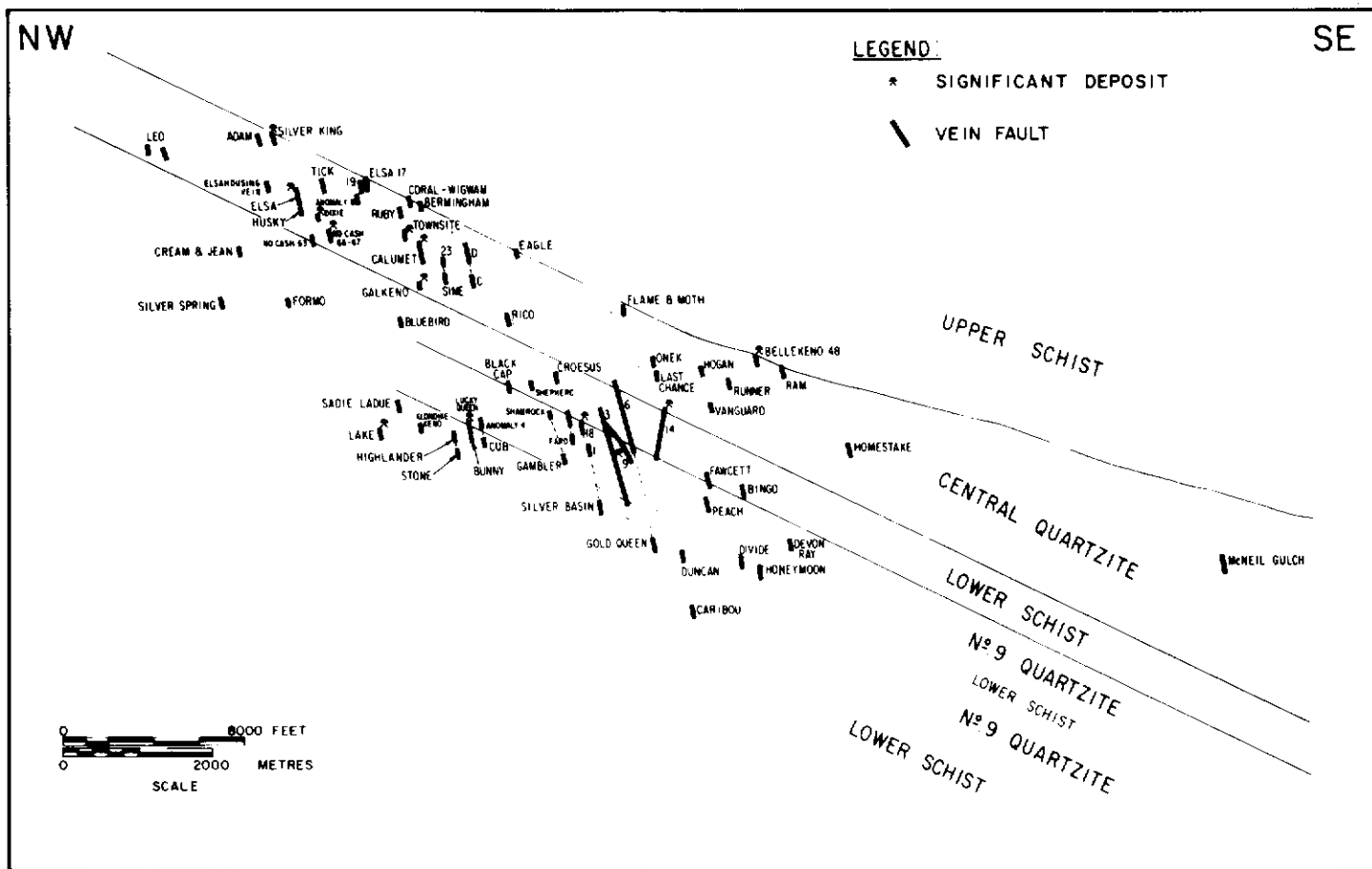


Figure 5. Approximate composite cross section reconstruction of the original fracture pattern on the south limb of the McQuesten Anticline.

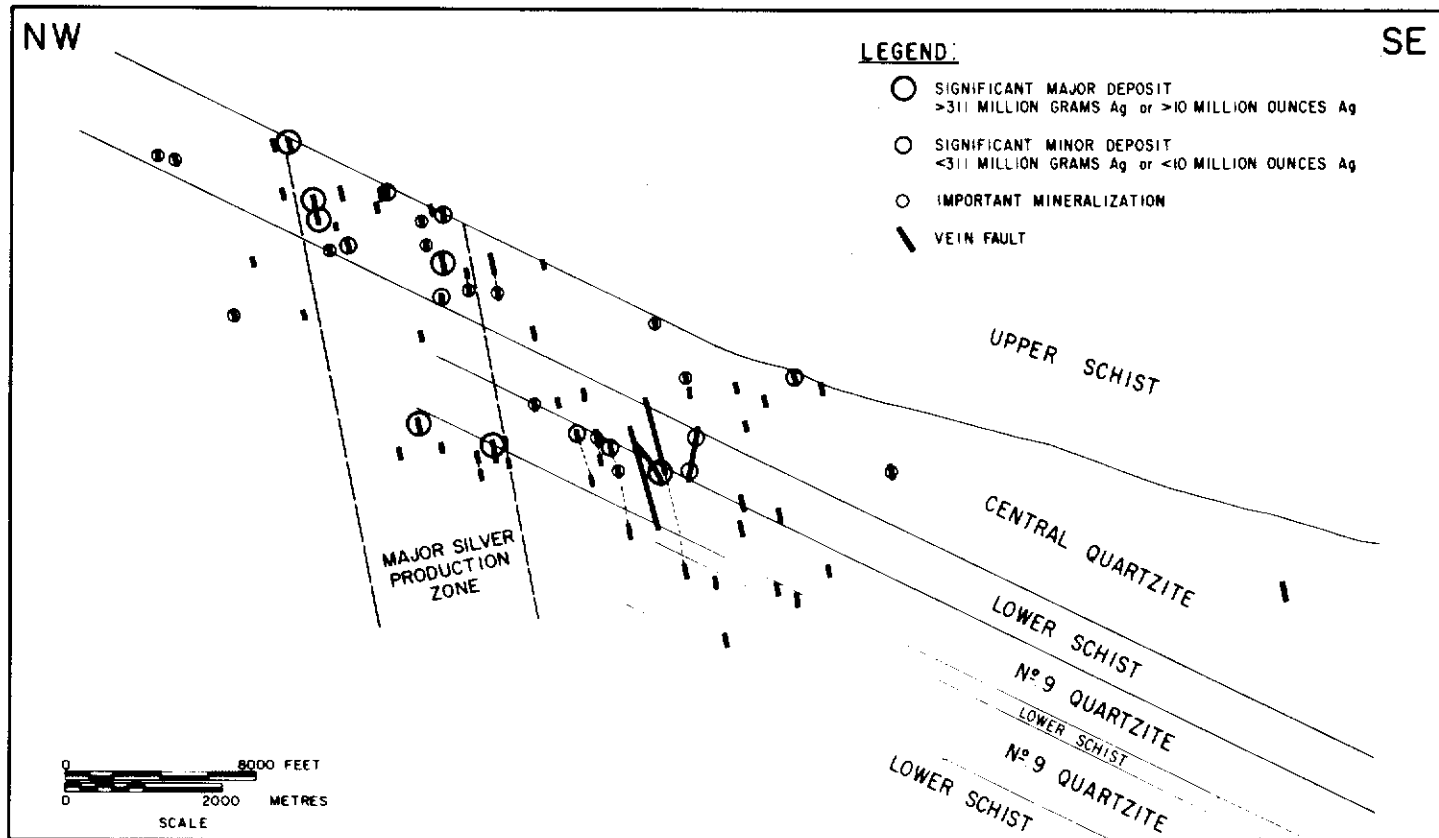


Figure 6. Approximate composite cross section reconstruction of the original fracture pattern showing silver production from significant deposits in the Keno Hill district.

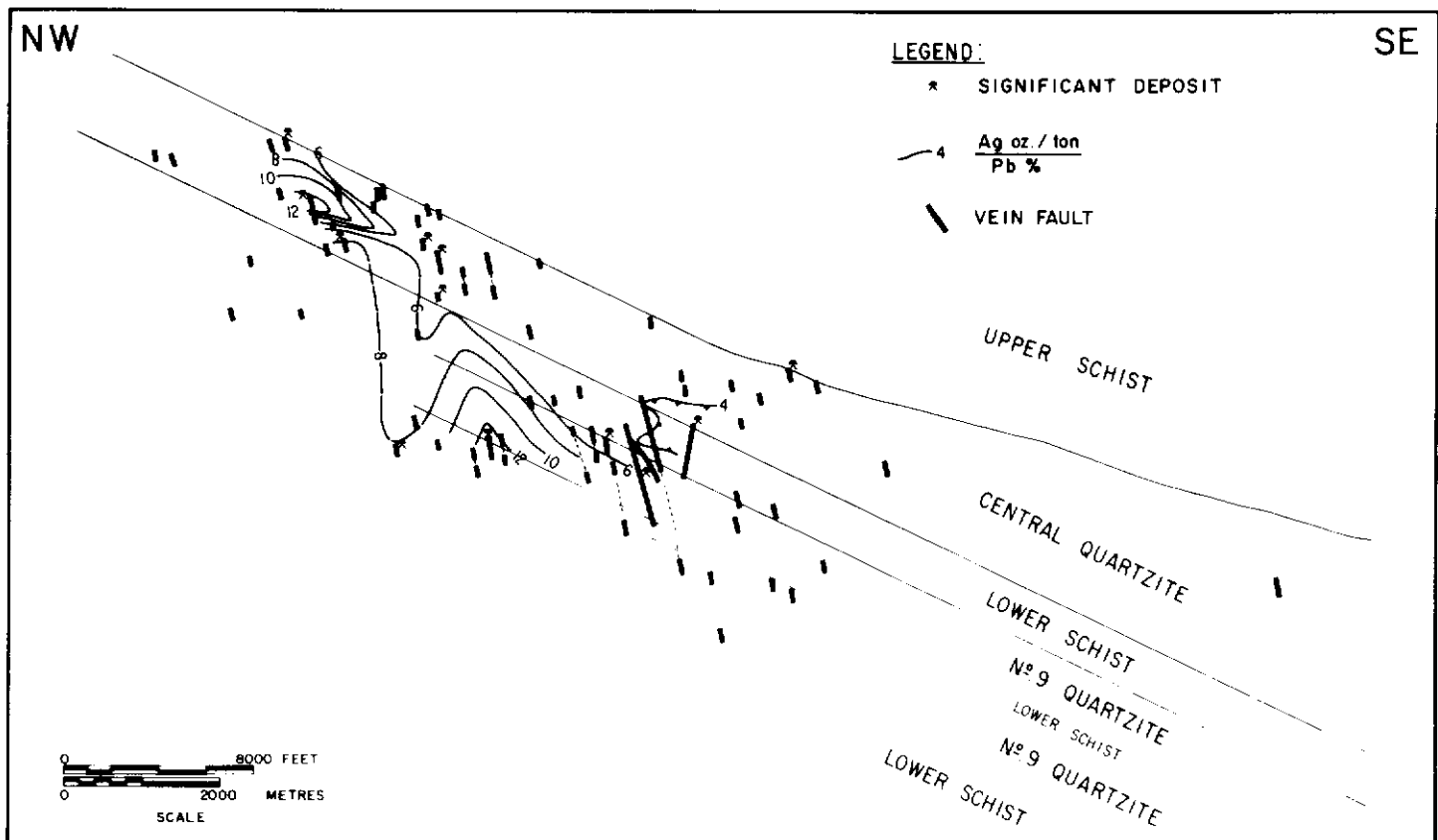


Figure 7. Approximate composite cross section reconstruction of the original fracture pattern showing the zonation of Ag (oz/ton)/Pb (%) values between significant deposits in the Keno Hill district.

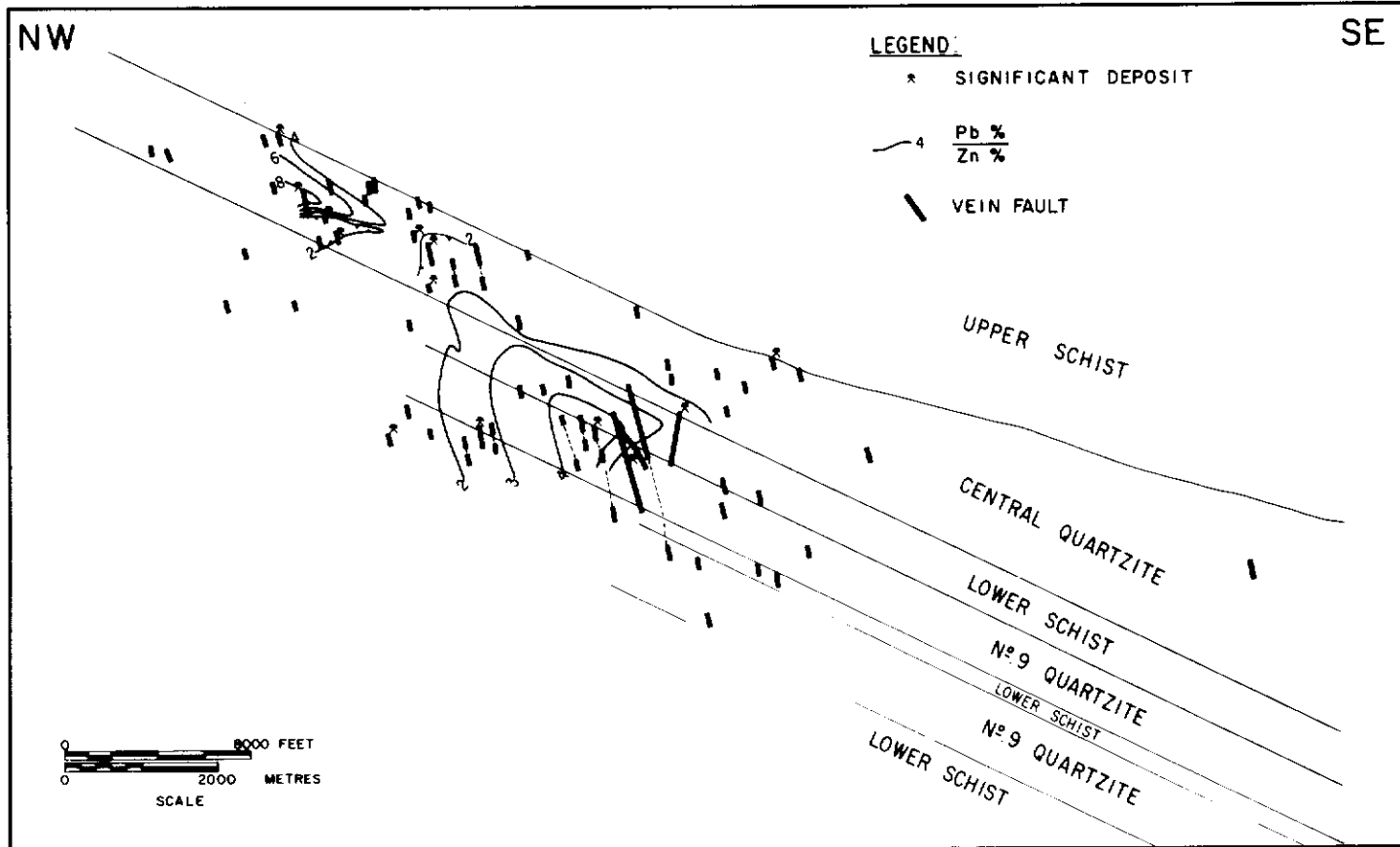


Figure 8. Approximate composite cross section reconstruction of the original fracture pattern showing the zonation of Pb(%) / Zn(%) values between significant deposits in the Keno Hill district.

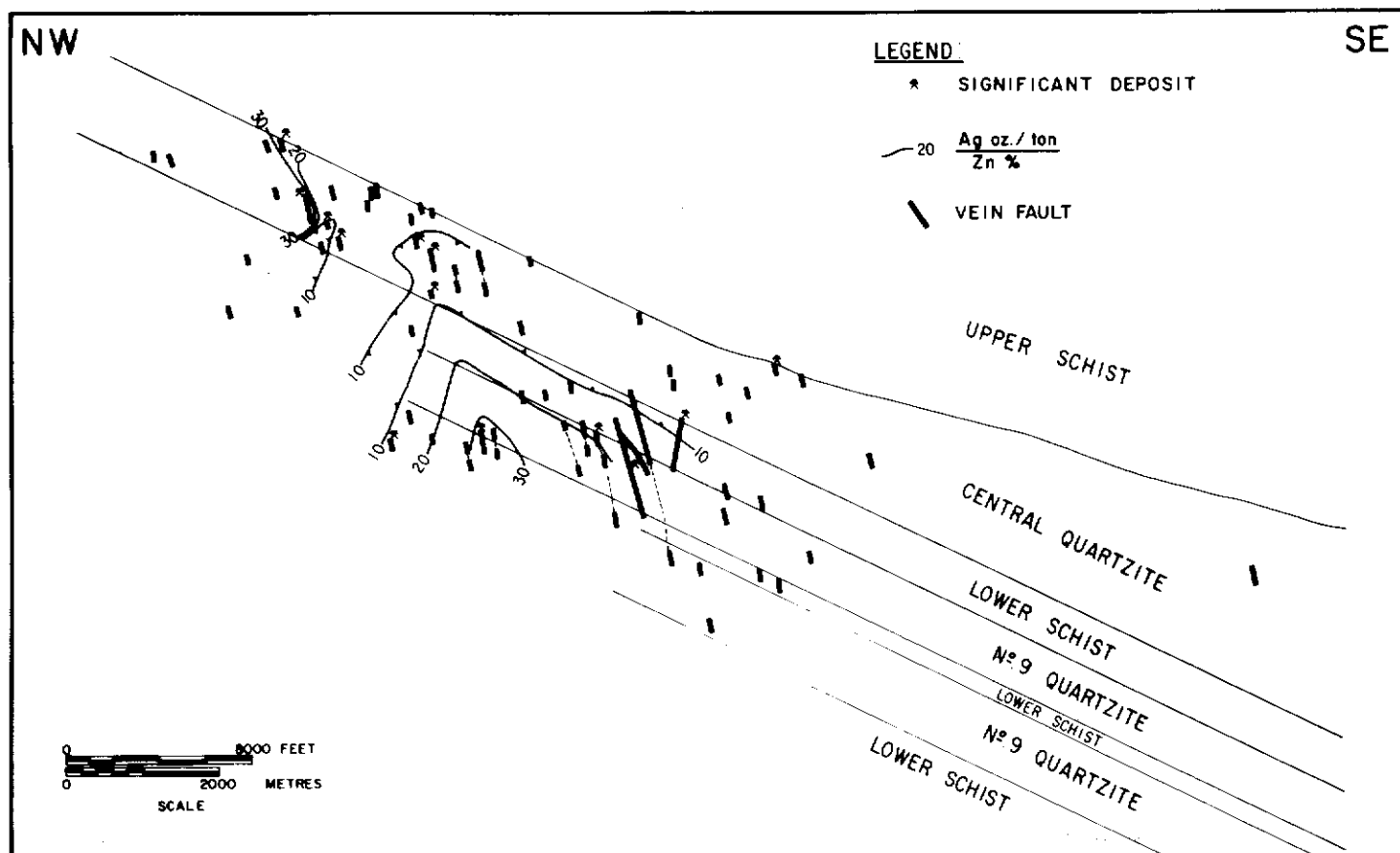


Figure 9. Approximate composite cross section reconstruction of the original fracture pattern showing Ag (oz/ton) / Zn (%) values between significant deposits in the Keno Hill district.

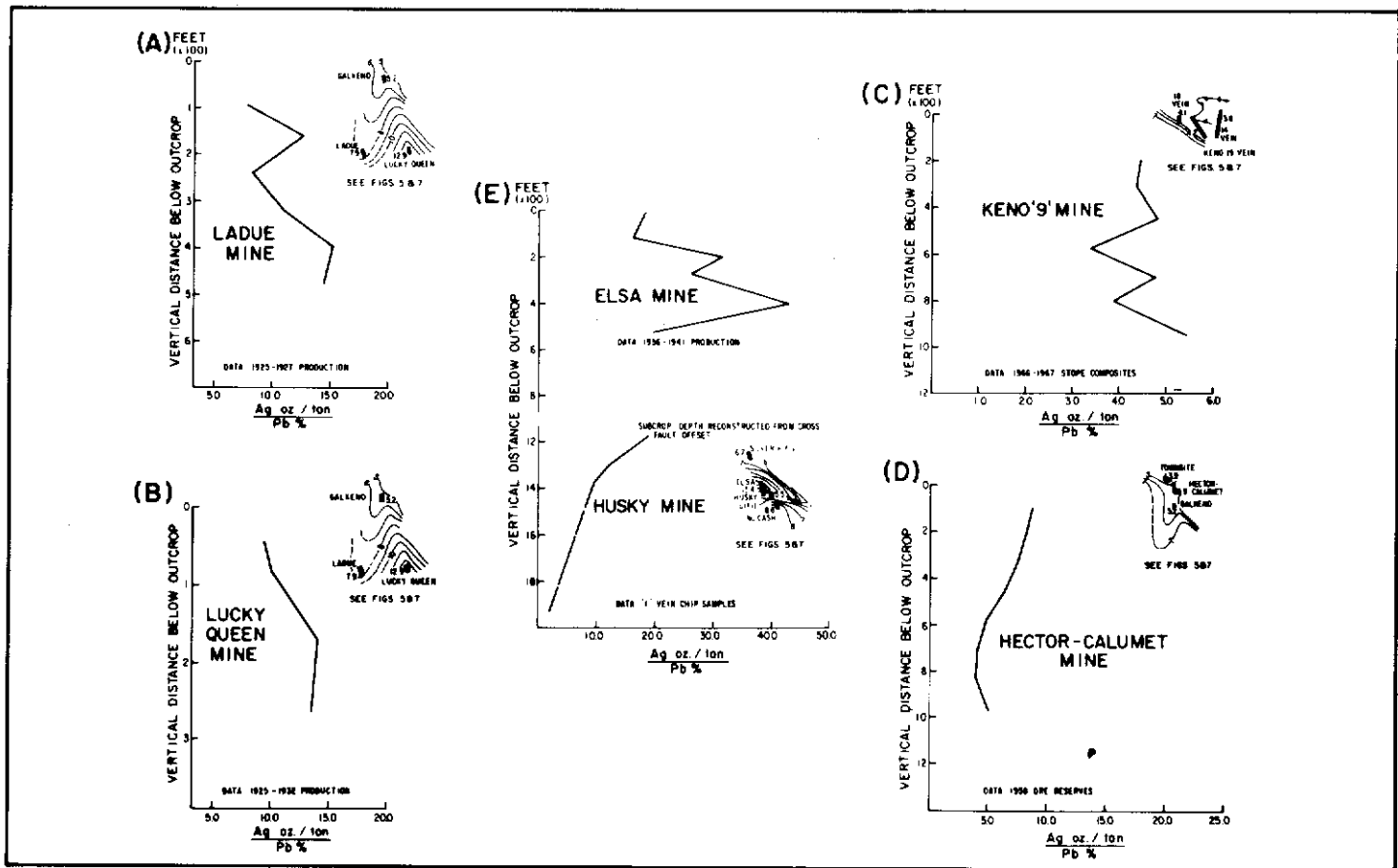


Figure 10. Level by level Ag/Pb metal-ratio profiles for (a) Ladue Mine (b) Lucky Queen Mine (c) Keno '9' Mine (d) Hector-Calumet Mine (e) Elsa-Husky Mines.

tions have been unable to scavenge sufficient metals. In contrast, high level deposits are the result of mineralizing solutions that have extracted metals from the entire Lower Schist section before deposition in structurally favorable host rocks. These latter fluids were silver-rich. Success in metal extraction may be related to the relative solubilities of silver and lead in the mineralizing solution. In early or "immature" low level deposits, "equal" amounts of silver and lead were extracted. As mineralizing solutions moved up-section to high level or "mature" positions, silver was being extracted from source rocks at a rate much greater than lead. Hence resulting high level mineralizing solutions were enriched in silver, relative to the low level deposits.

- 2). Alternatively, a horizon geochemically rich in silver may occur in a high stratigraphic position in the Lower Schist Unit. Low level mineralizing solutions have been unable to accumulate metals from this horizon and are, in effect, stranded. In contrast, mineralizing solutions that have reached high level stratigraphic positions have extracted and up-graded ore shoots accordingly. Blusson (1978) has postulated such a metal-rich source bed for the Keno Hill deposits, but, if present, it has yet to be found.

Sinclair *et al.* (1980) have demonstrated that the mineralizing solutions flowed through some of the vein faults in the district about 90 million years ago. Indicated Pb isotope model ages for carbonate-hosted lead-zinc mineralization in the Kathleen Lakes area (80 km northeast of Keno Hill) and the Keno Hill district are consistent with a common age of mineralization in the two districts (Godwin, Sinclair and Ryan, 1982). Because granitic stocks in the district have similar ages, Sinclair *et al.* (1981) suggest that vein mineralization is related to a hydrothermal system driven by thermal energy from these granitic intrusions. During the subsequent 90 million years, it would be possible to remove some 3000 m of the structural succession at normal rates of erosion. These observations suggest that parallelism of ore with the present surface in the district is fortuitous and is primarily a function of shallow explora-

tion and mining programs.

SUMMARY AND CONCLUSIONS

Parallelism of ore zones with the present surface topography is a recurring problem encountered in many Cordilleran vein deposits. In the Keno Hill district, records covering seventy years of mining provide an opportunity to examine this relationship. Productive vein faults in the Keno Hill district are associated with and are sub-parallel to the McQuesten anticline. An approximate cross sectional reconstruction of this pattern indicates that the south limb of the McQuesten anticline has been pervasively fractured and that the present erosional surface cuts obliquely through this fracture pattern. Production metal-ratios from deposits within these fractures show a definite zonation. Detailed metal-ratio studies within individual deposits support the suggestion that production metal-ratio zonation outlines the movement path of mineralizing solutions in the district. The deposits mined to date carry the signature of this hydrothermal system. The present surface, with about 1000 metres of relief, cuts across it, exposing deposits at different levels within it and at different positions in the stratigraphic succession. In the author's opinion, the data suggest that parallelism of the ore with the surface topography is fortuitous. Rather, some deposits have been eroded, others are exposed at the present surface and still others remain preserved, as yet undiscovered at depth.

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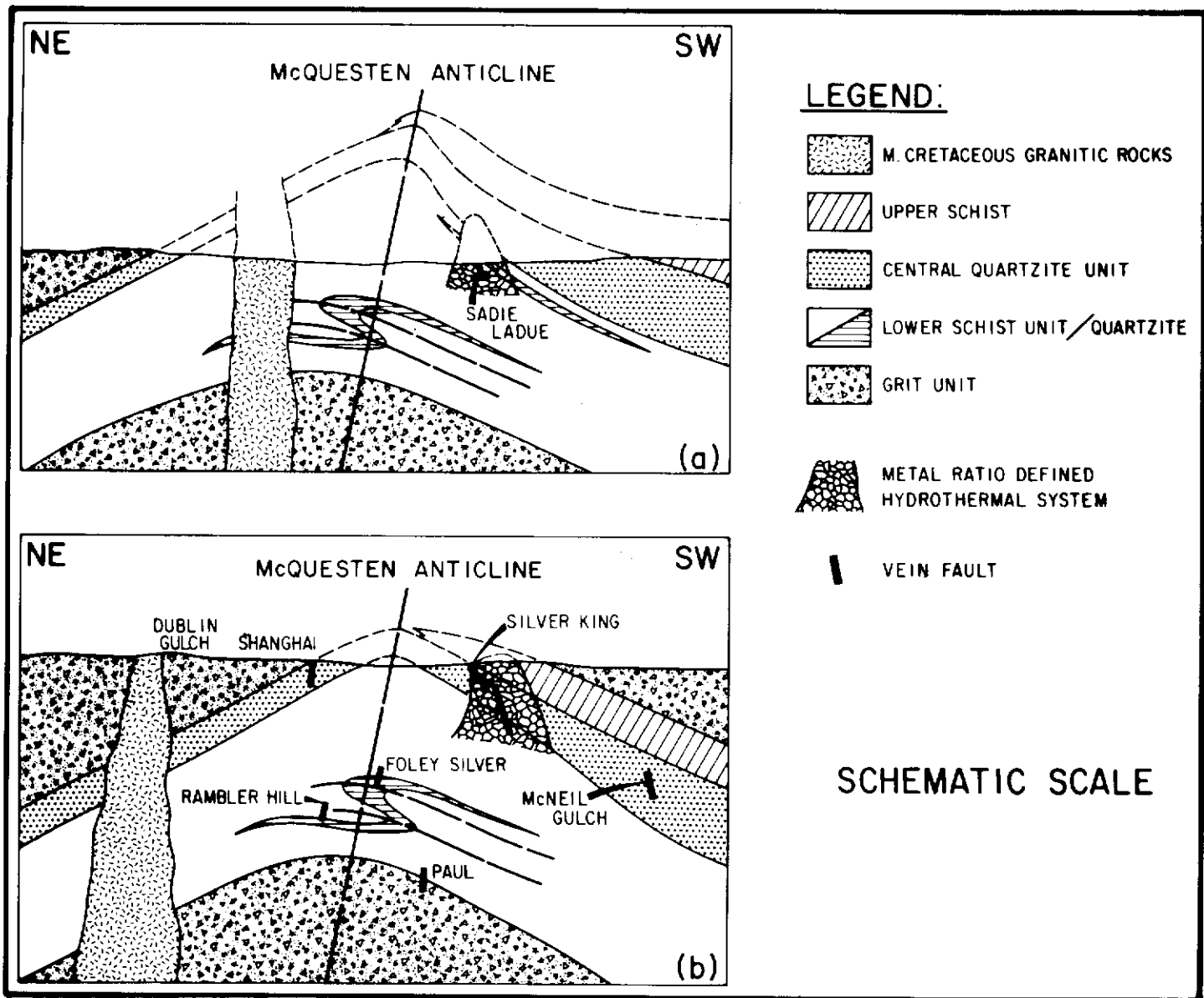


Figure 12. Regional cross sections normal to the McQuesten Anticline. Section (a) is at the eastern end of the district and contains the Ladue Mine. Section (b) is at the western end of the district and contains the Silver King Mine. See Figure 2 for the approximate location of section lines.

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