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J.L. JAMBOR
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Energy, Mines and Resources Canada
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SULPHIDE ZONES AND HYDROTHERMAL BIOTITE ALTERATION IN PORPHYRY COPPER-MOLYBDENUM DEPOSITS, HIGHLAND VALLEY, BRITISH COLUMBIA

Abstract

Regional variations in biotite alteration and sulphide mineral ratios have been determined for a 50 km^2 area of the central Highland Valley in which the Valley Copper, Lornex, and Highmont porphyry copper-molybdenum deposits occur. Sulphide zonal patterns in the southern half of the area are elongate near the pre-ore Gnawed Mountain composite dyke. In contrast, the Valley Copper deposit in the northern half of the area mainly has concentric sulphide zones. The sulphide variations support the idea that Valley Copper and Lornex formed as separate deposits which had overlapping alteration zones.

Thin-section studies indicate that hydrothermal biotite alteration in the area has a well-defined spatial association with the known copper-molybdenum deposits, and the intensity of biotite alteration decreases as metal grades decrease. Hydrothermal biotite is confined mainly to the copper-rich areas at Highmont and Lornex, but the biotitic aureole at Valley Copper extends well beyond the known deposit.

The Lornex orebody is truncated by the north-trending Lornex fault. Disruption of the regional sulphide patterns and biotite alteration indicate that post-ore, apparent right-lateral translation along the fault was 2400 to 3100 m. The displaced terminal segment of the Lornex orebody is interpreted to be in a largely untested area approximately 900 m south of Quiltanton (Divide) Lake. Reconstructed regional sulphide zoning and hydrothermal alteration patterns suggest that there was peripheral overlap of the Valley Copper and Lornex deposits.

Résumé

On a déterminé les variations régionales des auréoles d'altération contenant de la biotite et des concentrations en minéraux sulfureux dans une région de 50 km^2 au centre de la vallée Highland, où se situent les gisements porphyriques de cuivre et de molybdène de Valley Copper, Lornex et Highmont. Dans la moitié sud de cette région, on rencontre des zones allongées de minéralisation en sulfures, près du dyke composite de Gnawed Mountain dont la mise en place est antérieure à la phase de minéralisation. Au contraire, le gisement de Valley Copper, dans la moitié nord de la région, est caractérisé par des zones de minéralisation concentriques. L'existence de deux modes de minéralisation suggère que les gisements de Valley Copper et Lornex se sont formés séparément, et que leurs zones d'altération se recoupent.

Les études de lames minces indiquent que dans la région, les zones d'altération hydrothermale contenant de la biotite sont clairement associées aux gisements connus de cuivre et de molybdène, et que l'intensité de cette altération diminue au fur et à mesure de la diminution de la teneur en minéraux métallifères. A Highmont et Lornex, la biotite d'origine hydrothermale se limite surtout aux zones en cuivre, mais à Valley Copper l'auréole de biotite s'étend bien au-delà du gisement connu.

Le corps minéralisé de Lornex est tronqué par la faille de Lornex, orientée vers le nord. Le dérangement de la zonalité régionale des minéralisations en sulfures et des auréoles d'altération contenant de la biotite indique qu'il s'est produit un décrochement dextre de 2400 à 3100 mètres après la phase de minéralisation. L'extrémité du corps minéralisé de Lornex a subi un déplacement, et se trouve sans doute dans une région largement inexplorée, située à environ 900 mètres au sud de Quiltanton (Divide) Lake. La reconstruction à l'échelle régionale de la zonalité des minéralisations en sulfures, et des auréoles d'altération hydrothermale, suggère que des portions périphériques des gisements de Valley Copper et Lornex se sont autrefois recoupées.

INTRODUCTION

Porphyry copper-molybdenum deposits in the Highland Valley of British Columbia currently rank in the forefront of Canadian production of copper concentrate and, with aggregate reserves in excess of two billion tonnes of +0.4% copper ore, the deposits are one of Canada's most important near-future sources of the metal. The largest deposits are tightly clustered within an area of less than 4 km radius in the central part of the Highland Valley, about 370 km northeast of Vancouver (Fig. 1).

In 1976, Lornex Mining Corp. (Fig. 2) milled approximately 43 000 tonnes per day from open-pit reserves estimated at more than 450 million tonnes grading 0.41% copper and 0.015% molybdenum (Waldner et al., 1976). The 1976 *Annual Report* of Bethlehem Copper Corporation indicated that the Iona and Jersey deposits, which are the only other producers in the area, have combined open-pit reserves of approximately 41 million tonnes averaging 0.46% copper. The *Annual Report* also stated that the J.A. deposit, if mined by underground methods, would yield about 120 million tonnes grading 0.51% copper and 0.027% molybdenum. Valley Copper, which is the largest of the unexploited deposits, has reserves of about 800 million tonnes grading 0.48% copper (Osatenko and Jones, 1976). The No. 1 deposit at Highmont (Fig. 2) has open-pit reserves of about 111 million tonnes grading 0.287% copper and 0.042% MoS_2; reserves in the No. 2 deposit are 24 million tonnes grading 0.273% copper and 0.093% MoS_2 (Reed and Jambor, 1976).

As part of a study of the mineralogy and hydrothermal alteration at Canadian porphyry copper deposits, the first author (J.L.J.) examined Valley Copper, Lornex, and Highmont during parts of three field seasons from 1970 to 1975. The majority of time was spent at Highmont, which is the lowest grade and least intensely altered of the three deposits, and all its approximately 30 000 m of drill core were logged in detail. Valley Copper is the most intensely altered of the three deposits, and less time was spent to examine a similar amount of its core. Lornex, which is intermediate in

Figure 1. Location of the Highland Valley deposits, British Columbia.

metal grades and in alteration intensity, was examined in least detail. The Bethlehem and J.A. deposits were not studied. The results of the Highmont study have been published (Reed and Jambor, 1976), and other aspects of the hydrothermal alteration and its implications at Highland Valley have been discussed in Jambor and McMillan (1976), Jambor (1976), Carson and Jambor (1977), Jambor and Beaulne (1977), and Jambor and Delabio (1978). Although excellent papers dealing with Lornex and Valley Copper have been published (Waldner et al., 1976; Osatenko and Jones, 1976), the present report was prepared in order to provide additional data for these two deposits, to provide a more uniform basis for comparisons with Highmont, and to deal with all three as a single entity in terms of regional sulphide zoning and hydrothermal biotite alteration.

Acknowledgments

This study could not have been done without the generous co-operation of the management and staff of Bethlehem Mining Corp., Cominco Ltd., Highmont Mining Corp., Lornex Mining Corp., and Noranda Exploration Co. The writers gratefully acknowledge the assistance of E. Andersen, R. Anderson, and J. Collins of Bethlehem, J.M. Allen, R. Nichols, and M. Osatenko of Cominco, M. Waldner and G.D. Smith of Lornex, A.J. Reed of Highmont, D.J. Carson of Noranda, and P. Tsaparas and M. Skopos, who formerly were with Bethlehem and Lornex, respectively. We owe much to W.J. McMillan of the British Columbia Department of Mines and Petroleum Resources, Victoria, who has mapped the Guichon Creek batholith in detail and has shared his knowledge and provided invaluable data to the writers on numerous occasions.

Field aspects of this study were done as part of a project for the Geological Survey of Canada. Most of the laboratory studies were done at the Canada Centre for Mineral and Energy Technology (CANMET), who also financed a brief visit to the deposits by the first author (J.L.J.) in the spring of 1976. The writers are grateful to CANMET for patiently enduring the preparation of this report. Microprobe analyses by D.R. Owens and preparation of polished sections by Y. Bourgoin were done at CANMET. The photomicrographs for Figures 20 and 21 were taken by D.J.T. Carson.

Critical reading of the initial manuscript was done by R.V. Kirkham of the Geological Survey of Canada, and W.J. McMillan of the British Columbia Department of Mines and Petroleum Resources. Their comments and suggestions are appreciated and gratefully acknowledged.

GENERAL GEOLOGY

The Upper Triassic Guichon Creek batholith and its geological environment are discussed in detail by McMillan (1976). The batholith is approximately 65 km by 20 km at surface and consists of several nearly concentric phases which are progressively younger toward the pluton core which contains the major porphyry deposits. These core rocks consist of Skeena granodiorite and the slightly younger Bethsaida phase of granodiorite to quartz monzonite. A distinctive feature of Skeena rocks in the area is that they contain up to 8 per cent poikilitic, coarse grained hornblende whereas, in contrast, the Bethsaida phase characteristically

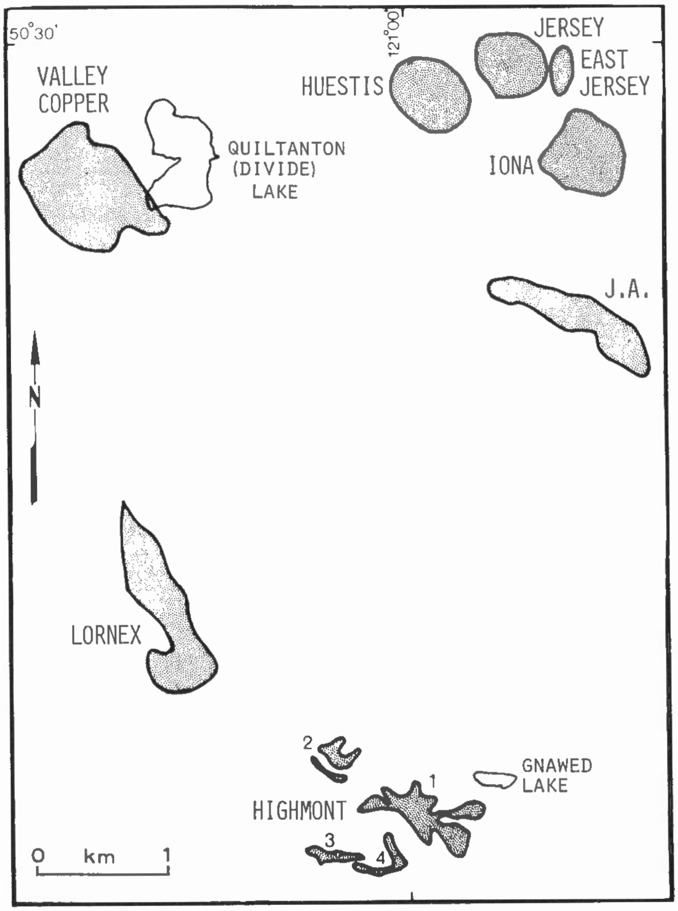


Figure 2. Locations of the principal Highland Valley deposits referred to in this study. The area is about 30 km southeast of Ashcroft and about 50 km southwest of Kamloops.

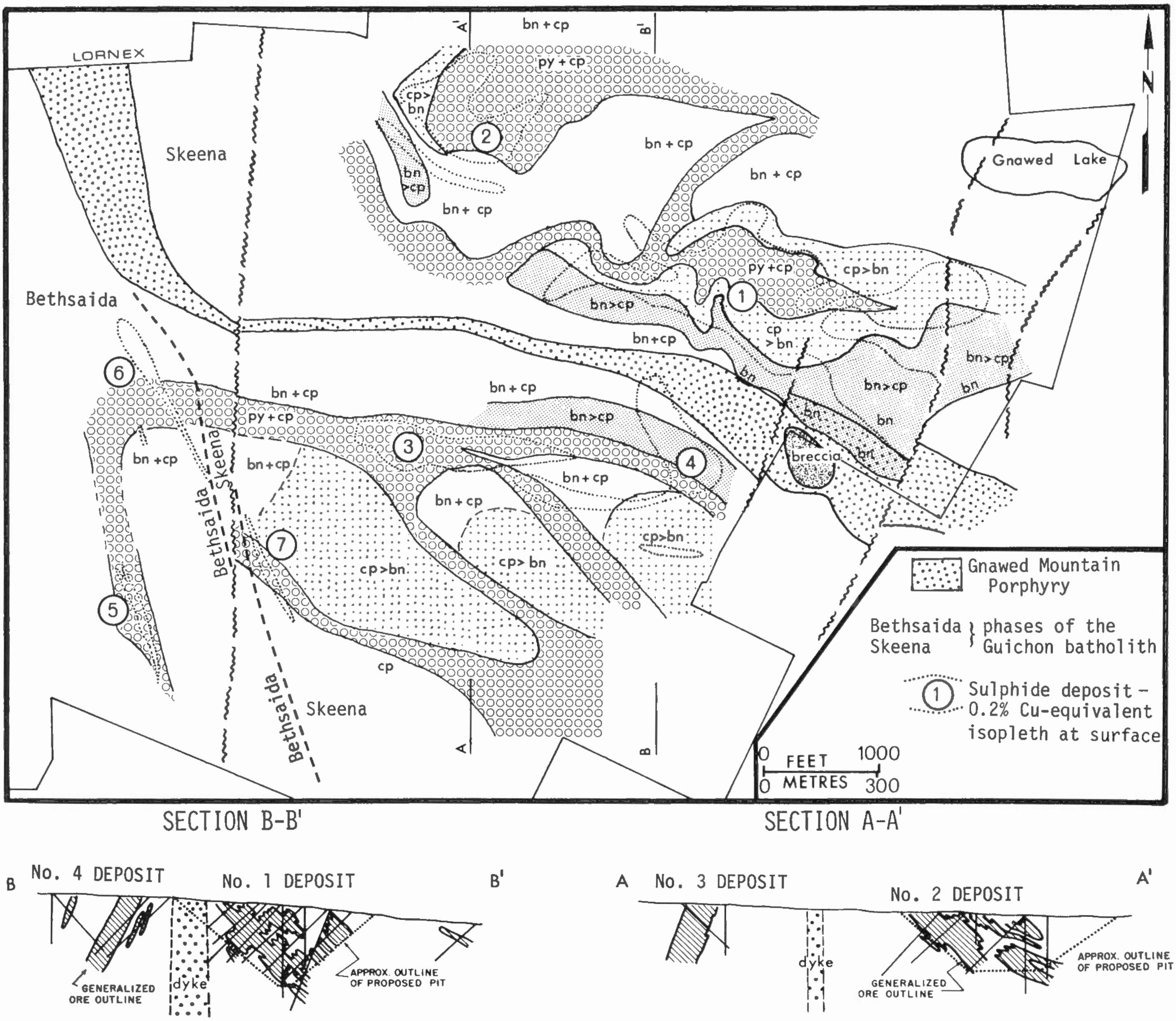


Figure 3. Geology and sulphide zonal patterns at Highmont. The plan shows that the sulphide zones are elongate near the pre-ore Gnawed Mountain Porphyry dyke, and the cross-sections show that deposits near the dyke dip away from it. (Adapted from Reed and Jambor, 1976).

contains about 6 per cent coarse grained euhedral biotite, only about 1 per cent amphibole, and has quartz "eyes" which average about 7 mm in diameter.

The detailed geology at the Highmont, Lornex, and Valley Copper deposits has been discussed by Reed and Jambor (1976), Waldner et al. (1976), and Osatenko and Jones (1976). The Valley Copper deposit is in Bethsaida host rocks; Lornex and Highmont are principally in Skeena granodiorite, but minor amounts of their copper zones extend into a major dyke, the Gnawed Mountain Porphyry. At Highmont, the dyke is a west-northwesterly trending composite intrusion up to 240 m wide that consists of a porphyritic quartz-eye variety of the Bethsaida phase, a leucocratic quartz porphyry, and breccia. The westernmost part of this pre-sulphide dyke at Highmont trends northwards and appears to follow the Skeena-Bethsaida contact into the southern part of the Lornex deposit (Fig. 3). In addition to this major dyke, various minor pre-sulphide dykes occur in the area. The most abundant are quartz plagioclase porphyries with contacts chilled against Skeena and Bethsaida rocks. Although the dykes are generally only a few metres wide, an exceptionally large intrusion of this type is present along the western margin of the Valley Copper deposit (Fig. 6).

SULPHIDE ZONES

Introduction

Delineation of sulphide zonal patterns at the three deposits and adjoining areas is based on megascopic examination of drill cores. Supplementary results for the less-common sulphide minerals were obtained from reflected-light studies of about 700 polished sections.

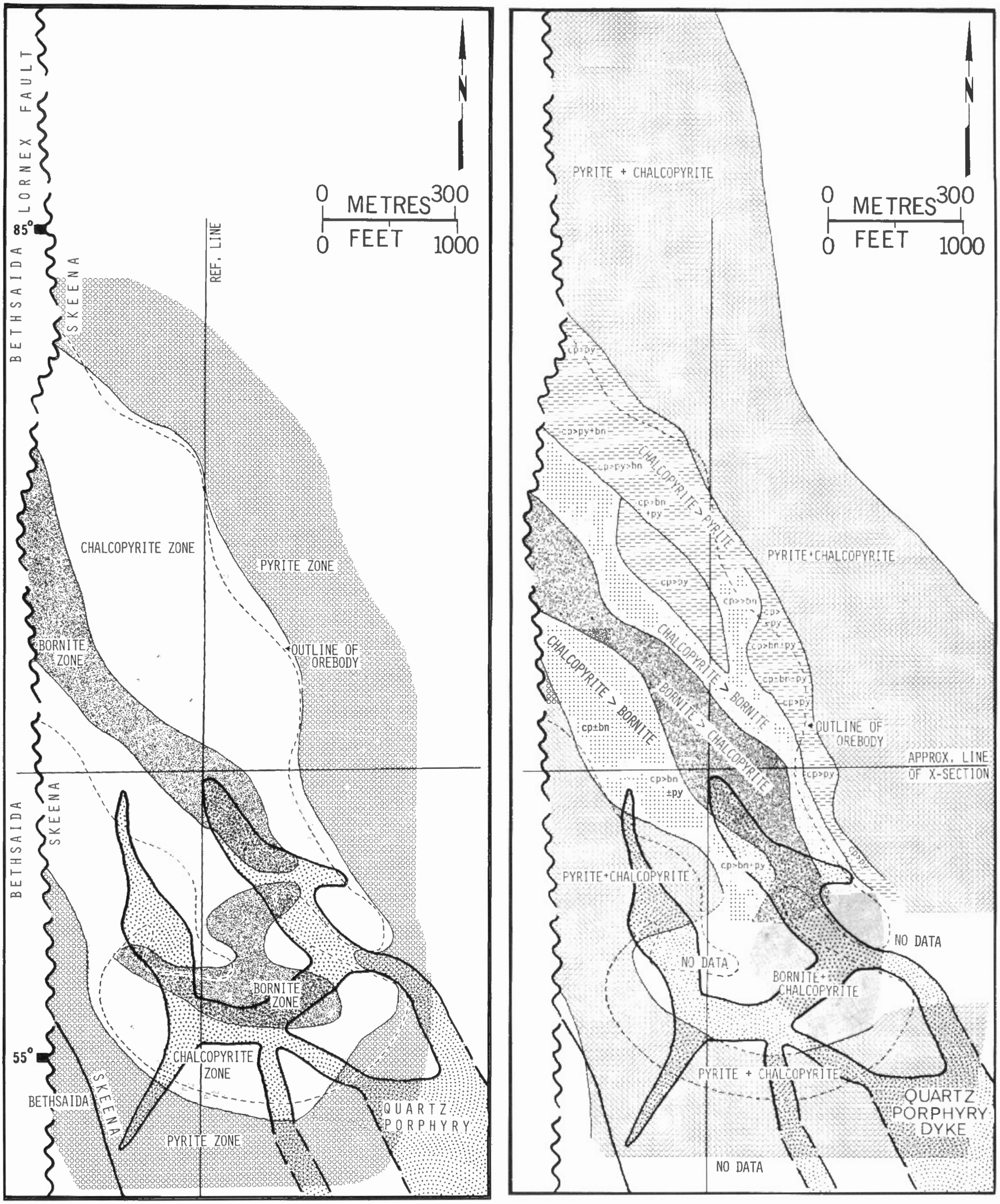


Figure 4. *Sulphide zonal patterns at Lornex. Left diagram shows the geology and sulphide patterns determined by Waldner et al. (1976) for the 1370 m (4500-foot) level; right diagram shows the sulphide patterns of the present study (modified from Jambor and Beaulne, 1977), projected to original bedrock surface (1375-1525 m) and superimposed on the Waldner et al. geology base map. The cross-section is shown as Figure 5.*

Although the deposits have mappable pyritiferous zones, these zones are not marked by the significant increases in pyrite which characterize the haloes around most porphyry deposits. Maximum sulphide abundances occur within the copper zones and decline outwards. Thus, at Valley Copper, the copper-grade contours given by Osatenko and Jones (1976) reflect the total sulphide content fairly accurately. The isopleth for 0.2% Cu-equivalence at Highmont (Reed and Jambor, 1976) is an equally good indicator of sulphide content. At Lornex, however, parts of the deposit contain abundant pyrite, and copper grades at the margins of the orebody commonly reflect only about half the total sulphide content. This is especially the case in the area south of the Lornex orebody, where pyrite exceeds chalcopyrite and a relatively well-developed pyrite halo is present. Total sulphide content of the Lornex ore zone has been estimated by Waldner et al. (1976) to be 1 to 1.5 weight per cent, and this estimate is also appropriate for the southern pyrite halo. In all other areas at Lornex, sulphides are most abundant in the central part of the ore zone and decline outwards. About 200 m outside the ore zone, sulphide content drops generally to less than half a per cent.

The predominant sulphide minerals throughout the area are pyrite and chalcopyrite. Bornite, although less abundant, is predominant in some parts of the deposits. However, bornite is also widespread in areas where sulphides are barely above background levels. Molybdenite, although quantitatively only a minor mineral which is very much less widespread than bornite, is an appreciable economic component of the Lornex ore. Molybdenum contents are much lower at Valley Copper than at Lornex. Among all of the Highland Valley porphyry deposits, Highmont has the highest grade of molybdenum, without which the property would not be potentially economic under present conditions.

Sulphide ratios

Sulphide ratios were estimated megascopically and were categorized as follows:

(1) bornite zone: bornite present, but pyrite and chalcopyrite absent or rarely seen. Zones of this category occur only at Highmont.

(2) Bornite>chalcopyrite and

(3) chalcopyrite>bornite: these categories reflect the predominance of one sulphide over the other, with the implication that both minerals were seen commonly and that pyrite is absent.

(4) Bornite=chalcopyrite: proportions of the two minerals are approximately equal; rather than an obvious equality, this category was most commonly accepted because of uncertainty as to whether bornite or chalcopyrite was the more abundant.

(5) Bornite+chalcopyrite: this category was generally used where sulphides are extremely sparse and a meaningful ratio either was not determinable or, in a few other cases, where the data obtainable were inadequate for a more precise allocation.

(6) Pyrite+chalcopyrite: pyrite abundances throughout the area are generally extremely low; thus, zones referred to as pyritiferous are intended to signify only that pyrite is present. However, chalcopyrite exceeds pyrite in the Valley Copper and Highmont ore zones, and in nearly all of the Lornex orebody.

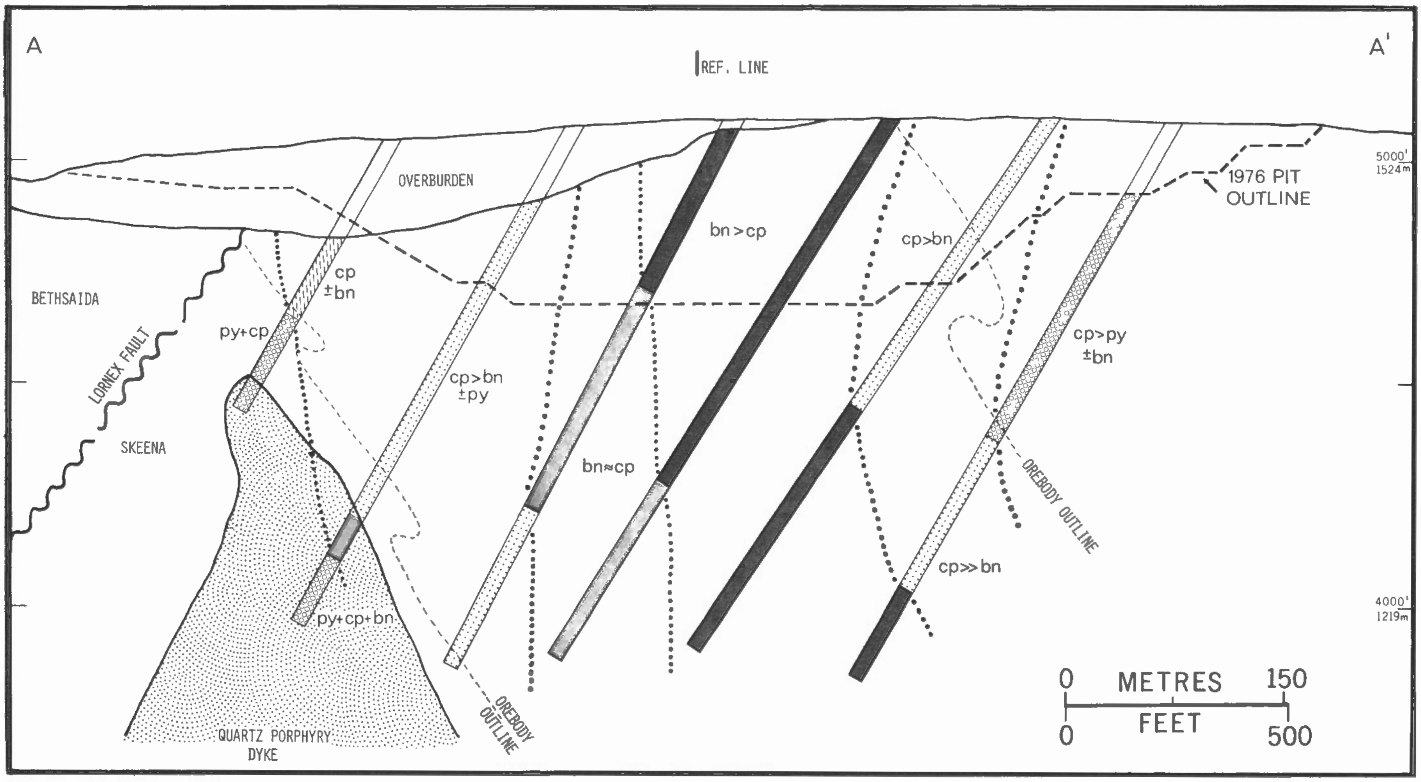


Figure 5. East-west cross-section of the Lornex ore zone, along the approximate line of cross-section on Figure 4, showing the more numerous sulphide subdivisions which have been generalized in the plan. (Base-map data modified from Waldner et al., 1976).

(7) Pyrite+chalcopyrite+bornite: this combination is extremely rare in the Valley Copper orebody, and is uncommon at Lornex. In contrast, several large zones in the category have been mapped at Highmont (Fig. 3), but large parts of these have pyrite contents amounting to a very low percentage of total sulphide. Pyrite and bornite are generally antithetic except where sulphide content is less than 0.1 per cent of the rock.

Inclusion of a sulphide in any of the last three divisions indicates that the mineral was observed persistently, even though the amounts may have been small. In cases where a sulphide mineral lacked continuity in occurrences, its sporadic presence has been indicated by the symbol ±. Discontinuous sulphides typically constitute only a fraction of a percentage of total sulphide.

Excluded from the sulphide zoning were numerous occurrences of pyrite which seem to be related to minor faults. Pyrite in these is characteristically euhedral and about 1 mm on edge width, is disseminated rather than in veinlet form, and the host Skeena and Bethsaida rocks are distinctly green because of intense sericitic alteration. The pyrite generally extends only a few centimetres outward from the fault, but some associated altered zones are metres wide. Nevertheless, these occurrences are local and are not correlative with major sulphide zones in any of the deposits.

Highmont

The general geology and sulphide zones at the Highmont deposits are shown in Figure 3. The principal sulphide minerals are pyrite, chalcopyrite, bornite, chalcocite, and molybdenite. Megascopic chalcocite was grouped with bornite because of its sparseness and difficulty of identification. Pyrite is also generally sparse and exceeds copper sulphides significantly only in the northeastern part of the zone of pyrite plus chalcopyrite at No. 1 deposit (Fig. 3). Overall sulphide abundances at Highmont average considerably less than 1 volume per cent.

Sulphide deposition at all of the deposits in the study area was fracture-controlled, and copper grades therefore do not always correlate well with the patterns of sulphide-mineral zoning. Poor correlation is particularly evident at Highmont; fractures here are not uniformly distributed, but instead are clustered in swarms that form areas of higher grade mineralization unrelated to specific sulphide zones.

Part of the Highmont No. 1 deposit extends into the Gnawed Mountain Porphyry dyke, but the dyke is otherwise largely barren of sulphides. Nevertheless, this intrusion seems to have played a major role in the development of the Highmont deposits in that sulphide zones near the dyke are distinctly elongate parallel to its contacts. Moreover, the cross-sections in Figure 3 show that the two pairs of deposits nearest the dyke dip in opposite directions, away from the dyke. The two principal sets of mineralized fractures, which probably control the overall shapes of the deposits, also parallel the contacts of the composite dyke and dip away from it (Reed and Jambor, 1976).

Despite their intimate spatial and structural association, the Gnawed Mountain dyke and the deposits do not seem to have a simple genetic relationship. Reed and Jambor (1976) have pointed out that, after solidification of the dyke, its eastern part was brecciated and healed predominantly with tourmaline and hematite which also spread into the adjacent country rocks. Approximately contemporaneous injection of quartz plagioclase porphyry dykes is indicated by the lack of chilled contacts against tourmalinized breccia. Sulphide deposition occurred after intrusion of the main part of the Gnawed Mountain composite dyke. Sulphide veinlets with well-formed sericitic selvages occur in angular

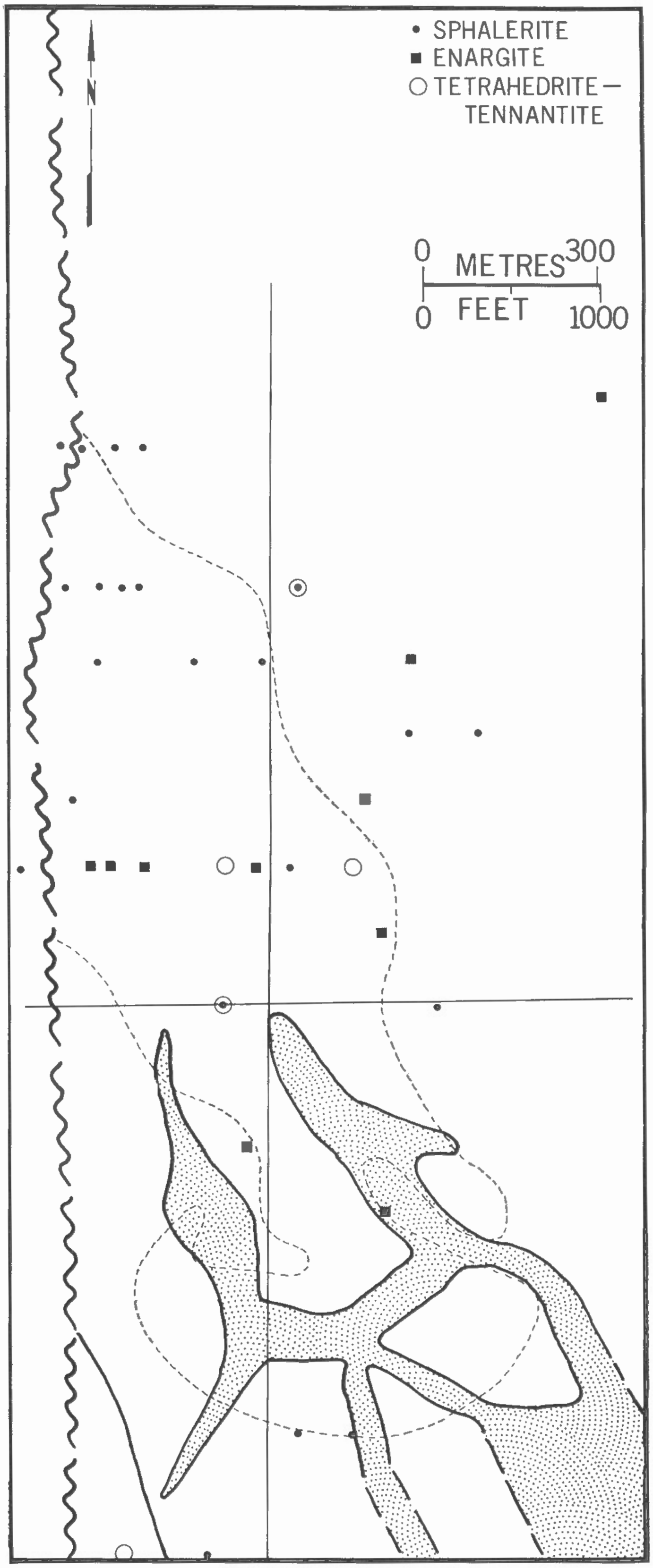


Figure 6. Distribution of sphalerite, enargite, and tetrahedrite-tennantite at Lornex, based on polished section observations.

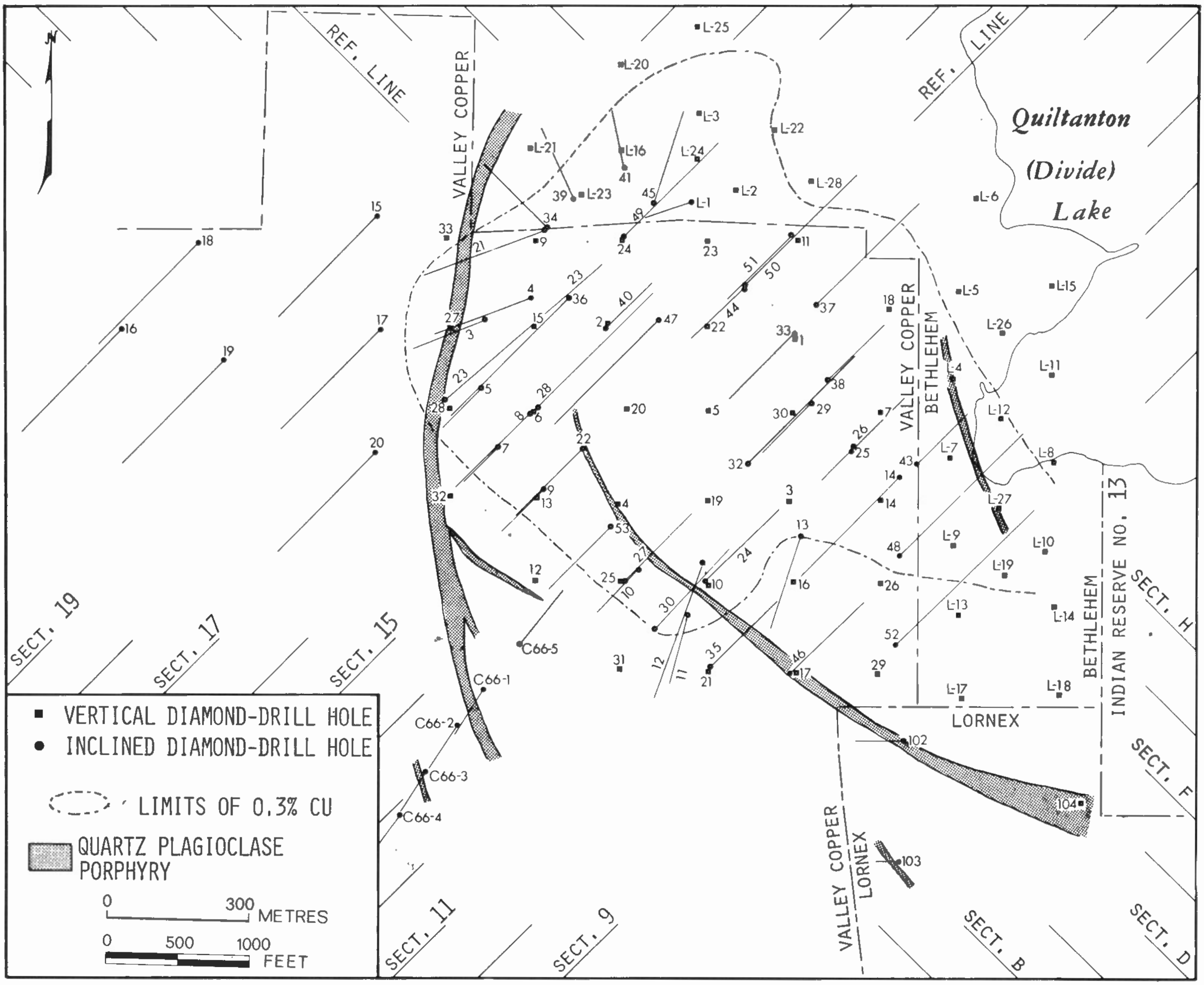


Figure 7. Surface diamond-drill holes at Valley Copper. The host rock is Bethsaida granodiorite to quartz monzonite which locally grades into diffusely-bounded porphyritic varieties. Quartz plagioclase porphyry dykes are pre-ore.

fragments in tourmaline-hematite breccia and indicate that sulphide deposition was well-advanced, or even largely completed, prior to formation of these breccias. That some sulphides continued to be deposited is evident from locally altered and mineralized quartz plagioclase porphyry dykes.

The present writers' interpretation of the above relationships is that the main Highmont deposits were basically coeval, but each had its own local "plumbing system". These plumbing systems were fed by hydrothermal solutions which rose through the batholithic rocks rather than having emanated directly from the Gnawed Mountain dyke. The solutions entered fracture swarms whose attitudes may have been partly determined by the tectonic stresses which did not cease abruptly after forming the dilatent zone along which the composite dyke was intruded. Although fracture attitudes may have been guided by the regional stresses, the main mechanism causing the fracturing may have been high fluid pore pressures. The sudden increase in fluid pore pressure, and consequent fracturing, could have been related to boiling off of volatiles from the Gnawed Mountain dyke, the main part of which has an aplitic groundmass, a textural feature generally accepted as indicating sudden release of volatiles.

Although sulphide mineralization occurred shortly after intrusion of the main part of the composite dyke, the prolongation of dyke-related igneous activity suggests the possibility that thermal and/or hydrothermal effects in the area could have been abnormally large. These effects would have been integrated with the main period of sulphide deposition, and in areas nearest the composite dyke there could have been interference with the aureoles of the copper-molybdenum deposits. Thus, although bornite zones in porphyry deposits generally are centred in the high-temperature potassic assemblage, at Highmont No. 1 deposit a bornite zone is near the composite dyke and is elongate parallel to the dyke contacts rather than being centred in the biotite halo. Sulphide zones distant from the dyke are less linear and presumably reflect less influence from the dyke. (Note that the sulphide zones represent mineral ratios only; higher sulphide abundances and more-intense hydrothermal alteration are deposit-related rather than dyke-related.)

Lornex

A plan and a cross-section of sulphide zoning at Lornex are given in Waldner et al. (1976), who defined their relevant patterns as follows: (1) bornite zone: bn>cp>py; (2) chalcopyrite zone: cp>bn>py; (3) pyrite zone: more than 0.05 per cent pyrite and total copper not more than 0.26 per cent. The ore zone, the bornite zone, and the chalcopyrite zone are elongate northwesterly (Fig. 4), but there is some distortion near the quartz porphyry dyke at the southern end of the deposit. Figure 4 also shows the sulphide zoning based on the scheme used in the present study, and projected to the original bedrock surface (1375 to 1525 m). Gaps in the data for the southern part of the deposit arise mainly because most of the core drilled in 1973-1974 in this area was not preserved.

Figure 5 shows a cross-section of the sulphide zones, from which it is evident that the plan (Fig. 4) is somewhat generalized. This generalization was necessary because of the difficulty in projecting results from section to section; in the northeastern zone of chalcopyrite>pyrite, occurrences both of bornite and of pyrite seem to be erratic. Much less information was obtained for the southwestern area designated as chalcopyrite>bornite; although this is the principal reason for the fewer sulphide subdivisions in this part of the orebody, the results seem to indicate that there is also some asymmetry, that is, areas to the north and to the south of the linear zone of bornite>chalcopyrite are not identical with respect to their sulphide zones.

The Lornex pyrite halo is shown as a zone of pyrite + chalcopyrite (Fig. 4). Although both minerals decrease with distance from the orebody, the gradational decline in chalcopyrite is more rapid so that pyrite exceeds chalcopyrite in at least the outer half of this zone. The much greater width of the pyritiferous zone relative to that given by Waldner et al. (1976) probably reflects the different criteria used to delimit the outer boundary. Despite differences in detail, the present study and that of Waldner et al. (1976) are compatible in that both have a median zone wherein bornite exceeds chalcopyrite and pyrite is antithetic, and both show the major sulphide zones to be more linear than annular. This elongation coincides with the projected strike of the main mass of the quartz porphyry dyke at the southern corner of Figure 4. This dyke is undoubtedly the continuation of the Gnawed Mountain Porphyry which cuts across the Highmont property (Fig. 3) and which has had a distinct influence on Highmont sulphide zoning.

Minor sulphides

Hypogene chalcocite, digenite, and covellite occur in small amounts throughout the Lornex copper zone. Minute quantities of enargite are present in the orebody whereas sphalerite, in marked contrast, seems to have a largely peripheral distribution and is concentrated at the northern and southern ends of the ore zone (Fig. 6). The most abundant sphalerite noted in this study occurs as disseminated grains in an altered felsite dyke near the Lornex fault. Waldner et al. (1976) reported that sphalerite and discontinuous pods of massive pyrite are present in the Lornex fault zone.

A chalcopyrite-rich sample from the central part of the deposit was found to contain disseminated grains of galena, abundant tetrahedrite, and very sparse aikinite and hessite (Ag_2Te). Microprobe analyses indicated that the galena contains 0.3 weight per cent silver, and that the composition of the aikinite is $Cu_{1.0}Pb_{1.1}Bi_{0.9}S_{3.0}$. Waldner et al. (1976) reported that bismuthinite was identified in Lornex copper concentrates.

Minerals in the tetrahedrite-tennantite series occur both in the Lornex ore zone and in the pyrite halo (Table 1). Microprobe analyses indicate that most material is near the tennantite end of the series, as is the case at Valley Copper (Table 1) and Highmont.

Valley Copper

The ore deposit and sulphide zones at Lornex terminate abruptly against the northerly-striking Lornex fault. Geological reasoning that the offset part of the Lornex deposit had moved north was instrumental in leading to the discovery of Valley Copper (Allen and Richardson, 1970).

The Highmont and Lornex deposits are principally in Skeena host rock, but Valley Copper is entirely within the Bethsaida phase of the batholith. Within the Bethsaida phase are pre-ore quartz plagioclase porphyry dykes, up to 35 m wide, which are concentrated along the western side of the deposit (Fig. 7). Similar pre-ore dykes are common at Highmont, where they seem to have been emplaced slightly later than the Gnawed Mountain Porphyry (Reed and Jambor, 1976). At Valley Copper, several dykes of felsite porphyry a few metres wide occur in the deposit. A cluster of these is present in the northern part of the ore zone (in L-3, L-22, and L-24; Fig. 7), but the dykes are erratic in attitude, or discontinuous, and are difficult to project from drillhole to drillhole. Aplite and post-ore lamprophyre are also present, but are volumetrically unimportant. The aplites are pre-ore whereas the felsite porphyry may have been intruded during the waning stages of mineralization (Osatenko and Jones, 1976).

Table 1

Microprobe analyses of some minor minerals

	Valley Copper								Lornex			Skeena	
Wt. %	1	2	3	4	5	6	7	8	9	10	11†	12	13
Cu	42.9	42.2	45.0	41.9	41.5	45.5	47.9	48.4	48.1	38.4	47.4	44.6	42.1
Ag	0.3	0.0	0.0	0.0	0.0	0.5	0.0	-	-	1.0	0.0	0.0	0.0
Fe	2.6	1.8	1.2	1.9	1.9	5.0	1.4	0.9	-	0.6	4.2	7.0	1.8
Zn	5.2	7.4	6.0	6.7	8.2	0.2	0.0	1.7	-	6.8	0.2	0.2	7.6
Sb	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	-	25.4	0.0	0.0	0.7
As	19.6	20.2	19.8	19.8	19.3	19.9	18.7	18.4	18.9	2.3	20.3	20.4	19.7
S	28.2	28.1	28.1	28.6	28.2	27.8	32.3	32.6	32.5	24.6	27.9	28.7	28.4
	98.8	99.7	100.3	98.9	99.1	98.9	100.3	102.0	99.5	99.1	100.0	100.9	100.3

Analyst: D.R. Owens, CANMET. Tetrahedrite-tennantite formulae given below are based on 29 atoms, and enargite based on 6 atoms, both after recalculation to 100 wt. %.

(1) Tennantite, 68-32-78*: $(\mathrm{Cu}_{10.1}\mathrm{Zn}_{1.2}\mathrm{Fe}_{0.7}\mathrm{Ag}_{0.03})_{\Sigma=12.0}\mathrm{As}_{3.9}\mathrm{S}_{13.1}$

(2) Tennantite, 68-19-439: $(\mathrm{Cu}_{9.84}\mathrm{Zn}_{1.69}\mathrm{Fe}_{0.47})_{\Sigma=12.0}\mathrm{As}_{4.0}\mathrm{S}_{13.0}$

(3) Tennantite, 68-30-1234: $(\mathrm{Cu}_{10.46}\mathrm{Zn}_{1.36}\mathrm{Fe}_{0.31})_{\Sigma=12.1}(\mathrm{As}_{3.90}\mathrm{Sb}_{0.03})_{\Sigma=3.9}\mathrm{S}_{12.9}$

(4) Tennantite, L-22-935: $(\mathrm{Cu}_{9.8}\mathrm{Zn}_{1.5}\mathrm{Fe}_{0.5})_{\Sigma=11.8}\mathrm{As}_{3.9}\mathrm{S}_{13.3}$

(5) Tennantite, 69-15-1359: $(\mathrm{Cu}_{9.71}\mathrm{Zn}_{1.87}\mathrm{Fe}_{0.49})_{\Sigma=12.1}\mathrm{As}_{3.8}\mathrm{S}_{13.1}$

(6) Tennantite, 69-17-1100: $(\mathrm{Cu}_{10.68}\mathrm{Fe}_{1.33}\mathrm{Ag}_{0.06}\mathrm{Zn}_{0.04})_{\Sigma=12.1}\mathrm{As}_{4.0}\mathrm{S}_{12.9}$

(7) Enargite, 69-17-1100: $(\mathrm{Cu}_{3.0}\mathrm{Fe}_{0.1})_{\Sigma=3.1}\mathrm{As}_{1.0}\mathrm{S}_{4.0}$

(8) Enargite, 68-30-564: $(\mathrm{Cu}_{3.0}\mathrm{Zn}_{0.1}\mathrm{Fe}_{0.1})_{\Sigma=3.2}\mathrm{As}_{1.0}\mathrm{S}_{3.9}$

(9) Enargite, Lornex 53-648: $\mathrm{Cu}_{3.0}\mathrm{As}_{1.0}\mathrm{S}_{4.0}$

(10) Tetrahedrite, Lornex 25-648: $(\mathrm{Cu}_{10.1}\mathrm{Zn}_{1.7}\mathrm{Fe}_{0.2}\mathrm{Ag}_{0.2})_{\Sigma=12.2}(\mathrm{Sb}_{3.5}\mathrm{As}_{0.5})_{\Sigma=4.0}\mathrm{S}_{12.8}$

(11) Tennantite, Lornex: average comp.†: $(\mathrm{Cu}_{11.01}\mathrm{Fe}_{1.11}\mathrm{Zn}_{0.04})_{\Sigma=12.2}\mathrm{As}_{4.00}\mathrm{S}_{12.8}$

(12) Tennantite, Skeena 69-3-750: $(\mathrm{Cu}_{10.19}\mathrm{Fe}_{1.82}\mathrm{Zn}_{0.03})_{\Sigma=12.0}(\mathrm{As}_{3.9}\mathrm{Sb}_{0.1})_{\Sigma=4.0}\mathrm{S}_{13.1}$

(13) Tennantite, Skeena D.D.H. 69-2, box 31: $(\mathrm{Cu}_{9.8}\mathrm{Zn}_{1.7}\mathrm{Fe}_{0.5})_{\Sigma=12.0}(\mathrm{As}_{3.9}\mathrm{Sb}_{0.1})_{\Sigma=4.0}\mathrm{S}_{13.1}$

*Drillhole year — number — sample footage.

†Composition range: Cu 46.7-49.8, Fe 3.8-4.5, Zn 0.0-0.7, As and S constant wt. %.

Highmont and Lornex have an obvious spatial association with a major porphyritic intrusion which is apparently absent at Valley Copper. Osatenko and Jones (1976) refer to the Valley Copper host rock as medium to coarse grained granodiorite porphyry, but coarse phenocrysts of quartz and biotite are characteristic of the Bethsaida phase as a whole. No data are available to demonstrate that phenocryst or matrix sizes at Valley Copper differ significantly from those in unmineralized Bethsaida. Nevertheless, throughout the deposit there are numerous occurrences in which the matrix of the Bethsaida is fine rather than medium to coarse grained. The volume of this Bethsaida porphyry is difficult to estimate, partly because of obscuration by hydrothermal alteration, and partly because the porphyry seems to be gradational into normal Bethsaida. Other than noting the presence of such porphyry in the deposit, the questions of whether substantial volumes of this rock are present, and whether they form a mappable unit, cannot be answered at this time.

Sulphide zonal patterns at Valley Copper have been investigated by McMillan (1971), Jones (1975), and Osatenko and Jones (1976). McMillan's results were published as two sections across the deposit. Osatenko and Jones published a composite section across the deposit, and several plans, all of which were based on analyses of assay pulp composites from various percussion and vertical diamond-drill holes; copper sulphide ratios and pyrite contents were obtained by point-counting polished sections of sulphide concentrates from the composites. The plans are reproduced here for comparison with the results of the present study (Figs. 10, 12, 14, 16).

Figure 7 shows nearly all of the drillholes examined in this study, and the locations of the northwest- and northeast-trending cross-sections of Figures 8 and 9, respectively. Sections 9 to 13 of Figure 8 are at the southeastern corner of the deposit and show that, in general, the sulphide zonal pattern is from a central bornite-rich area to outer margins which are chalcopyrite-rich and pyritiferous. In detail, however, the zonal patterns are complex. This complexity probably is related in part to a late-stage influx of largely "barren" quartz veins and associated pervasive silicification which are concentrated in the southeastern part of the deposit and decline substantially toward its centre. The area of most-intense barren quartz veining shown in McMillan (1971), Osatenko and Jones (1976), and Jambor and Delabio (in press) coincides fairly well with the complex sulphide patterns in Sections 9-13, and it seems likely that the ratios

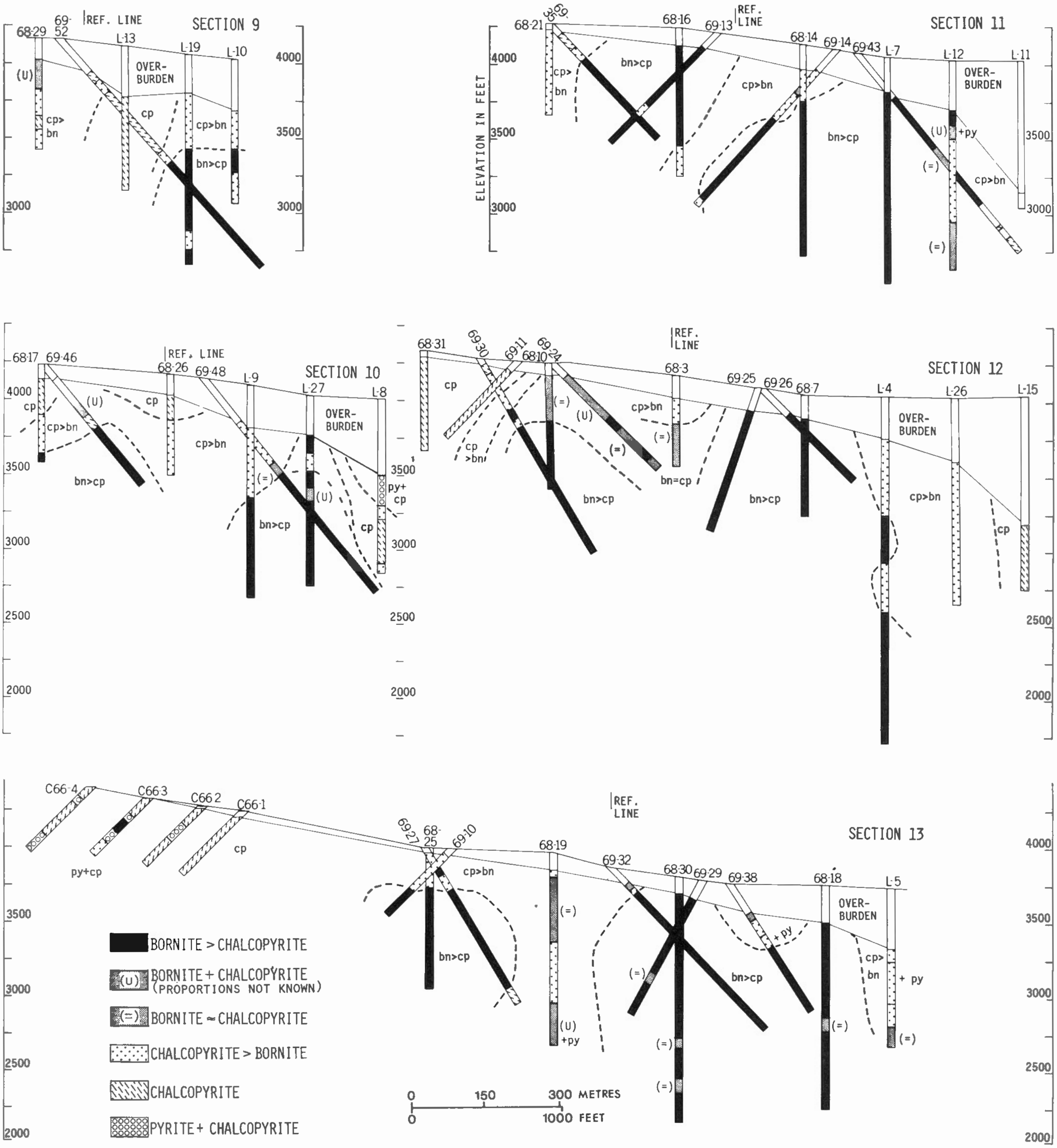


Figure 8. *Northeast-trending cross-sections, located on Figure 7, showing sulphide zones in the Valley Copper deposit. Vertical scale is elevation in feet; horizontal and vertical scales are identical. Sections 9 to 13 are at the southeastern part of the deposit.*

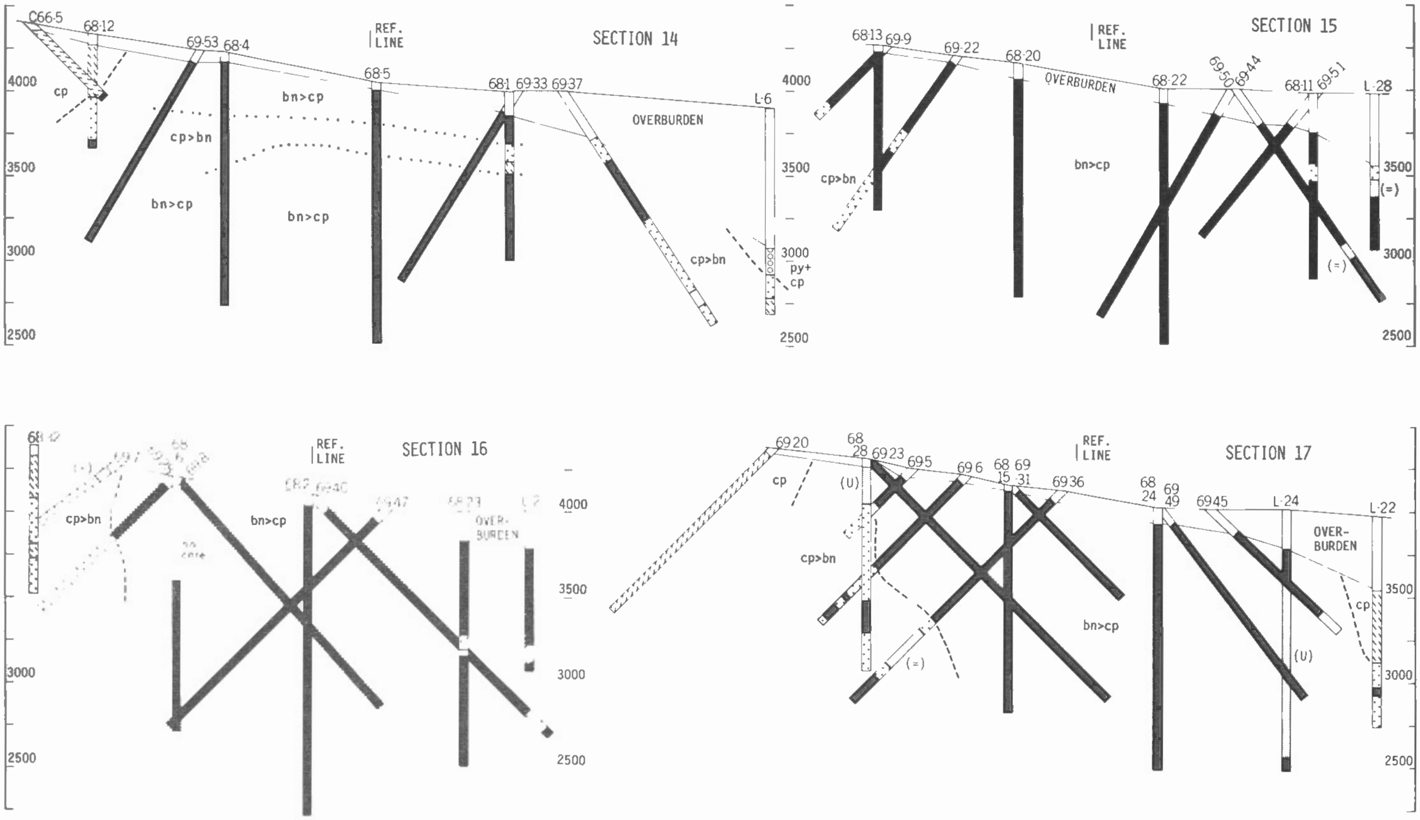


Figure 8 *(continued): Central part of Valley Copper deposit. In Section 14, an underground drillhole indicates that a zone of chalcopyrite > bornite occurs between drillholes 69-53 and 68-4. Although these surface drillholes have bornite > chalcopyrite, the dotted area in Section 14 outlines a zone in which the subordinate chalcopyrite was noted to be exceptionally abundant.*

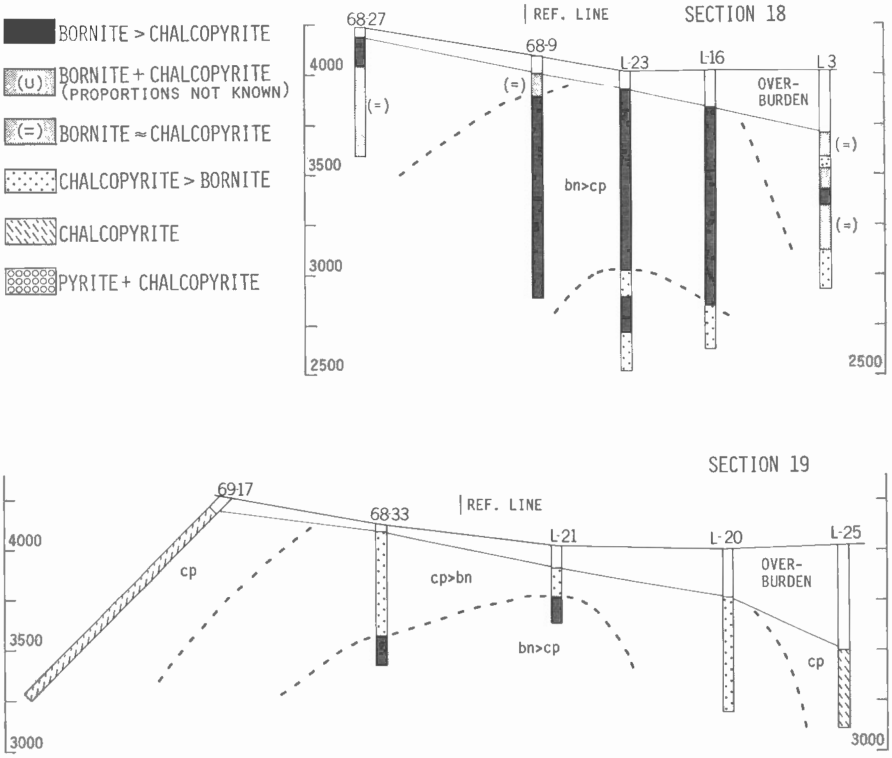
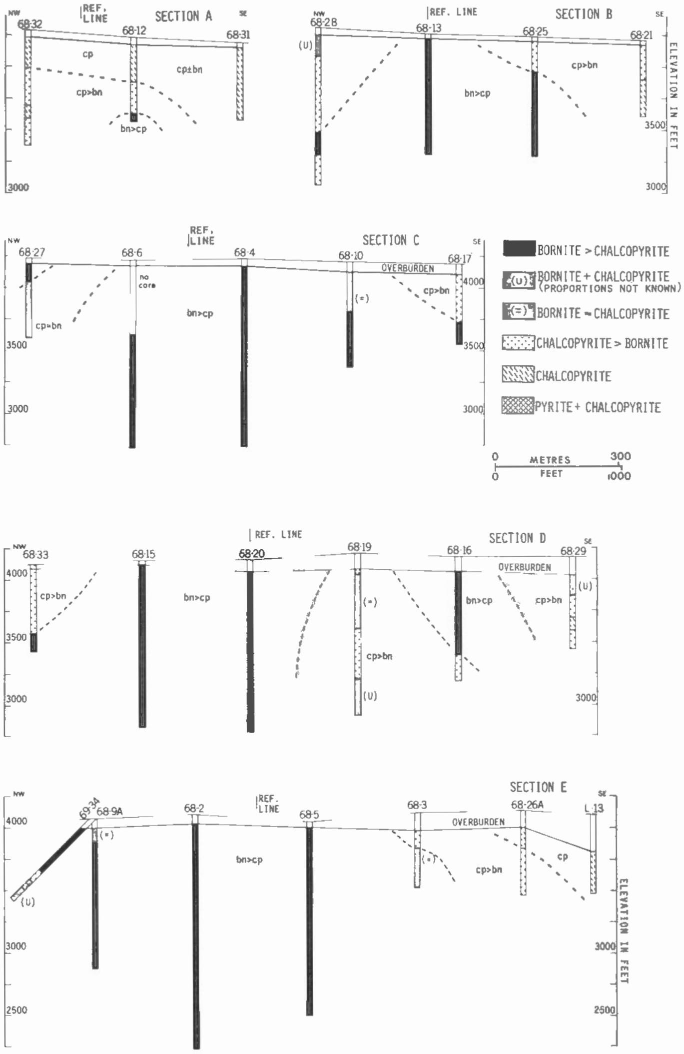


Figure 8 (continued)

Northwestern part of Valley Copper.



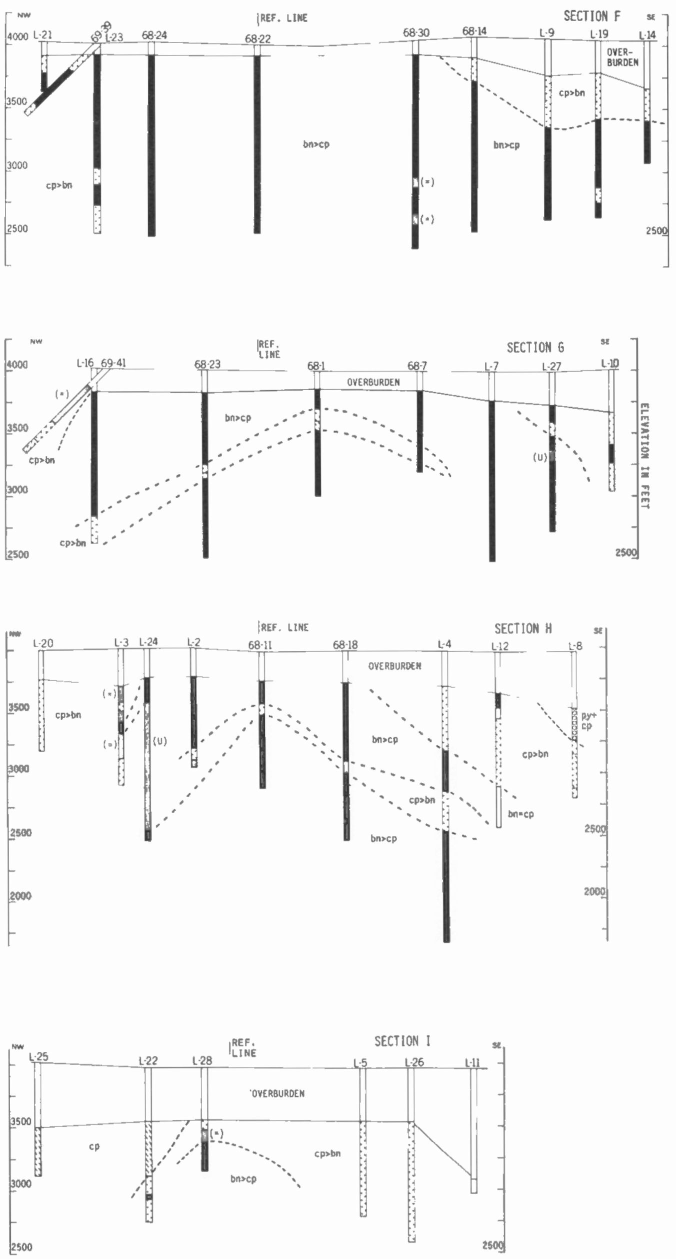


Figure 9 (above and right)

Northwest-trending cross-sections, located on Figure 7, showing sulphide zones at Valley Copper. Vertical scale is elevation in feet; horizontal and vertical scales are identical.

of the original sulphides may have been readjusted during the siliceous influx. Some "barren" quartz veinlets carry minor sulphides, and these are invariably chalcopyrite-rich. Additionally, however, the sulphide zonal patterns seem to have been distorted by the appearance of another bornite-rich zone southeast of the deposit (Fig. 11). This feature is discussed in more detail later in the paper.

Sections 14 to 19 (Fig. 8) are more representative of original sulphide zonal patterns in the deposit. The bornite-rich core passes outward to chalcopyrite-rich margins which in turn have pyritiferous extremeties. Although the bornite zone seems to continue with depth in the central part of the deposit, Osatenko and Jones (1976) have shown that copper grades decline markedly in the lower, central part of Section 14 (between drillholes 68-4 and 68-5). From data in Jones (1975), Osatenko and Jones (1976), and published company reports, the present writers surmise that, in terms of the outer boundary for 0.2 to 0.3% copper, most of the Valley Copper deposit is grossly shaped like an inverted hemisphere. However, sulphide ratios do not necessarily follow this pattern (see also Fig. 10) and in the central part of the deposit it is not evident whether the outer boundary of the bornite zone dips outward or inward, though the latter seems more plausible (Sections 14-17 of Fig. 8). At the northwestern end of the deposit (Sections 18 and 19 of Fig. 8), the bornite zone seems to dip outward.

Northwest-trending cross-sections (Fig. 9) show more clearly that the upper parts of the sulphide zones have a dome or hemispherical shape. Combining the data of Figures 8 and 9, the interpretation is that the upper part of the bornite zone is domed, but the zone as a whole is shaped like an inverted pear. The chalcopyrite-rich zone which surrounds this body is narrow at surface, but widens at depth and dips outward. The outermost sulphide zone is pyritiferous.

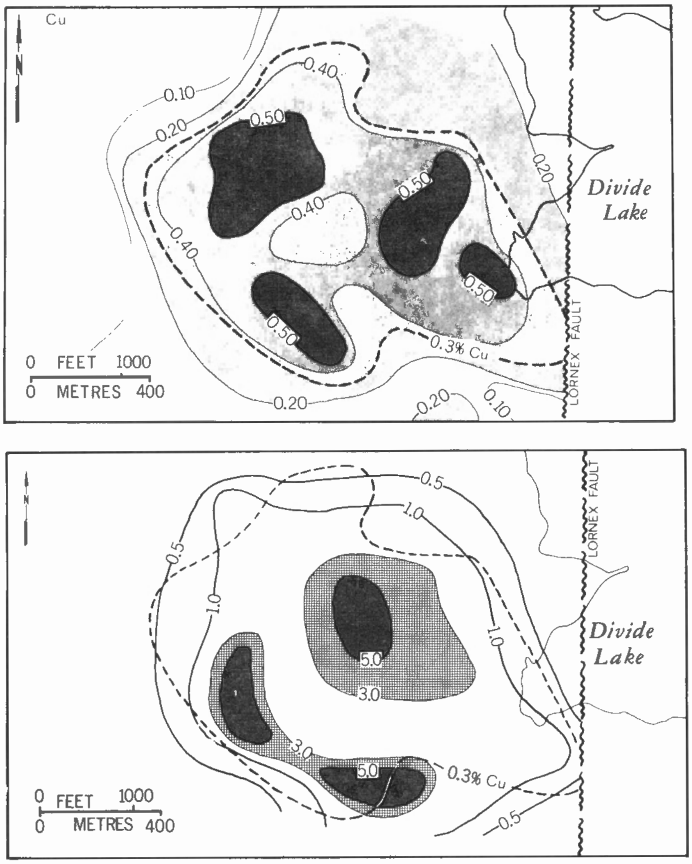


Figure 10. Weight per cent copper (top) and bornite/chalcopyrite ratios (bottom) on the 1158 m (3800-foot) level at Valley Copper. Sulphide ratios are in weight per cent and are based on point-counting polished sections of sulphide concentrates. All data are from Osatenko and Jones (1976).

Pyrite halo

Figure 11 is a plan of the sulphide zones at Valley Copper. A well-defined, chalcopyrite-rich zone surrounds the bornite core and is in turn ringed by a pyritiferous zone in which sulphides are less than one volume per cent of the rock. This relative increase in peripheral pyrite was also noted by Osatenko and Jones (1976) for the 1158 m level (Fig. 12). Pyrite occurs throughout the deposit (Fig. 13), but the amount present in the bornite zone is minute and grains are commonly microscopic in size; nearly all megascopic, persistent occurrences are outside the bornite zone, and peak abundances occur beyond the copper zone.

Minor sulphides

Bornite, chalcopyrite, and pyrite are the most abundant sulphides, and molybdenite is economically significant at Highmont and Lornex. Molybdenum values are much lower at Valley Copper and an average grade is not available. However, the geochemical study of Osatenko and Jones (1976) shows a well-defined halo around the copper zone (Fig. 14). Molybdenite noted in Valley Copper polished sections in the present study has a somewhat similar peripheral concentration (Fig. 15). The occurrences extend well into the copper zone, but are few in the central area which coincides with the bornite zone. A similar antithetic association between bornite and molybdenite is evident on a microscopic scale — molybdenite is invariably associated with chalcopyrite even where the two copper sulphides coexist in a polished section. In the rare cases where a relative age for molybdenite is determinable in polished sections, chalcopyrite is cut by trains of molybdenite flakes which are therefore younger.

Hypogene chalcocite, digenite, and covellite are widespread at Valley Copper, but their amounts are small. Covellite is by far the least abundant of the three, but it extends to the bottoms of the deepest drillholes. Chalcocite and digenite typically occur in complex microscopic intergrowths with bornite, or as partial rims around it. Blebs of digenite in bornite are common. Isolated, homogeneous grains of chalcocite are extremely rare, and chalcocite lamellar intergrowths with bornite are much less common than at Highmont and Lornex.

Zinc at Valley Copper has a well-defined peripheral concentration (Fig. 16), but observed occurrences of sphalerite were uncommon (Fig. 17). Almost all of these are isolated, microscopic grains; megascopic sphalerite veinlets, in which minor galena is also present, are extremely rare. A few microscopically filiform aggregates of marcasite have been noted, but only two polished sections of the 314 examined contain a few pyrrhotite blebs. The rarity of pyrrhotite in all the porphyry deposits in this part of the Highland Valley is notable in that it contrasts markedly with the abundant pyrrhotite noted in British Columbian Tertiary porphyry deposits which have been studied in detail (Carson and Jambor, 1974; Jambor, 1976).

The distributions of tennantite and enargite at Valley Copper are shown in Figures 18 and 19. Microprobe analyses indicate that both minerals contain zinc (Table 1). Occurrences of tennantite in peripheral holes west of the copper zone may be significant in contributing to the zinc halo at this site (Fig. 16 and Table 1).

Other sparse minerals are gudmundite and gold at Valley Copper (Petruk, 1970), and wittichenite and blaubleibender covellite at Highmont (Reed and Jambor, 1976). Johan et al. (1977) reported that electrum, luzonite, and cobaltite also have been found in the Lornex and/or Valley Copper deposits.

POTASSIC ALTERATION

Potassic alteration in the Highland Valley deposits is defined here as comprising hydrothermal biotite and/or K-feldspar. All other minerals are excluded from the definition because they are not considered to be essential components of the potassic assemblage. Omission of sericite may require explanation in that Creasy (1959) originally defined the "potassium silicate facies" as having muscovite (sericite), biotite, and K-feldspar as characteristic minerals. Burnham (1962) suggested that hydrothermally altered rocks be grouped into two principal facies, argillic and phyllic, but he also subdivided the phyllic facies into muscovite and biotite types, with the latter "...mineralogically simple, consisting chiefly of biotite, orthoclase, and quartz, with more or less chlorite, muscovite, and albite" (1962, p. 780). Creasy (1966) subsequently modified his original definition of potassic alteration in that all or any two minerals of the assemblage K-feldspar-biotite-muscovite were considered to be characteristic of the facies. Creasy (1966, p. 61) stated that "The key minerals are new biotite and new K-feldspar. Since muscovite also occurs in the propylitic and argillic alterations, it has no special significance, but so far as I know, it always occurs with the biotite and K-feldspar." It has since been shown (Carson and Jambor, 1974; Gustafson and Hunt, 1975) that muscovite (sericite) does not always occur in the K-feldspar-biotite zone.

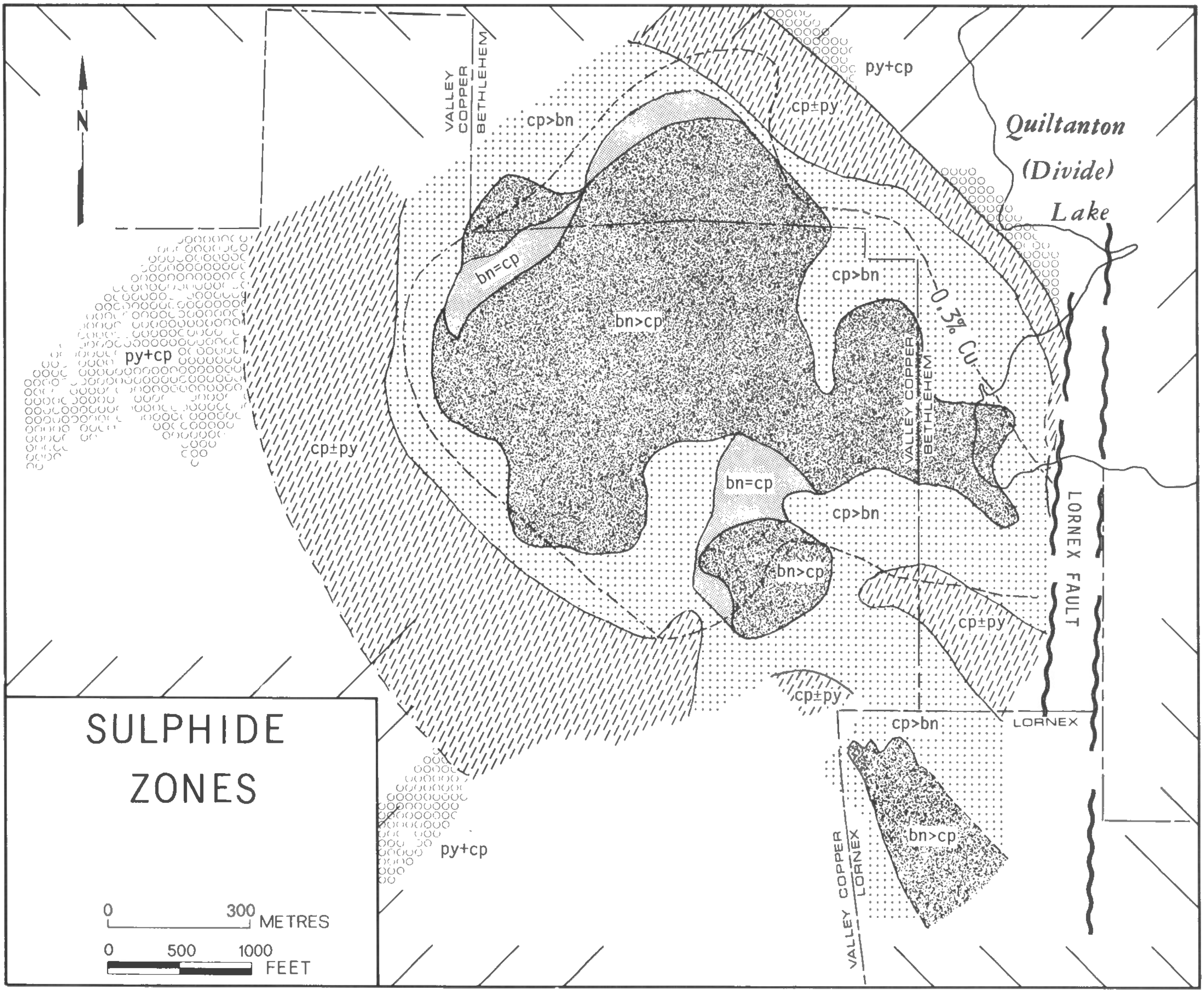


Figure 11. Plan of Valley Copper sulphide zones as determined in the present study. The major faults at the eastern part of the deposit are splays of the Lornex Fault; the main strand is interpreted to be farther east. The faulted area is shown in more detail in Figure 27.

The present writers unequivocally exclude sericite from the original potassic assemblage because detailed studies of porphyry-deposit alteration have demonstrated consistently that sericite is part of later assemblages which are overprinted on early pervasive biotite-K-feldspar alteration (Carson and Jambor, 1977).

Although K-feldspar and sericite may co-crystallize (e.g. Guilbert and Lowell, 1974), this reaction occurs only at the equilibrium boundary between K-feldspar and K-mica. With departure from this finite boundary, either the K-feldspar or the K-mica stability field is entered, and one mineral crystallizes at the expense of the other. Experimentally determined mineral reaction paths (Hemley and Jones, 1964) show that a progression from K-feldspar to K-mica to kaolinite corresponds to a trend of decreasing temperature and/or increasing hydrogen ion activity; this reaction path is consistent with the trends of hydrothermal alteration in porphyry deposits. Thus, the simple experimental model is grossly representative of mineral stability fields documented in porphyry systems. Each characteristic mineral (K-feldspar, K-mica, kaolinite) has a specific stability field and therefore is regarded as an essential component which defines a hydrothermal alteration facies (potassic, phyllic, and argillic, respectively).

In passing from the stability field of one key mineral to the stability field of another, the product will be two key minerals unless circumstances permit the reaction to go to completion. Complete reaction is rarely attained in porphyry systems; the fact that vestiges of the initial alteration facies usually can be documented after careful study has led to the concept that most phyllic and argillic alterations have been overprinted on a potassic zone (Carson and Jambor, 1977). Thus sericite, far from being a component of the original potassic assemblage, is regarded instead as a key indicator that the hydrothermal environment was no longer appropriate for crystallization of the biotite and/or K-feldspar assemblage.

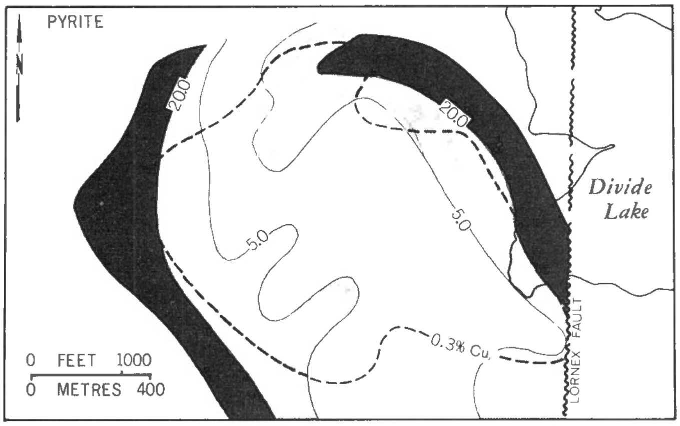


Figure 12. Weight per cent pyrite in sulphide concentrates from the 1158 m (3800-foot) level (Osatenko and Jones, 1976).

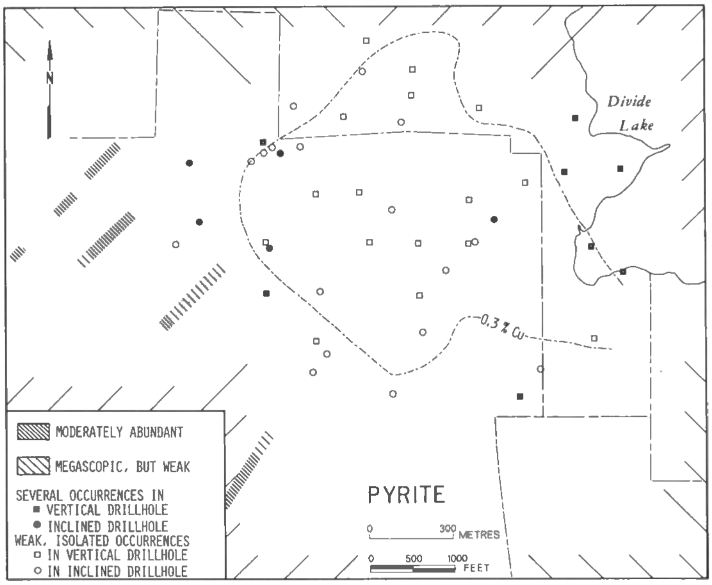


Figure 13. Distribution and relative abundance of pyrite in drill core (this study). Occurrences are projected to surface. Even in the "moderately abundant" category, pyrite is less than one volume per cent of the rock.

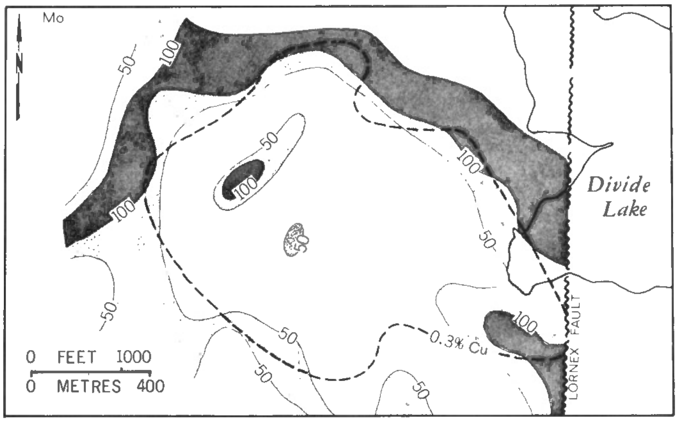


Figure 14. Molybdenum (ppm) on the 1158-m level (after Osatenko and Jones, 1976).

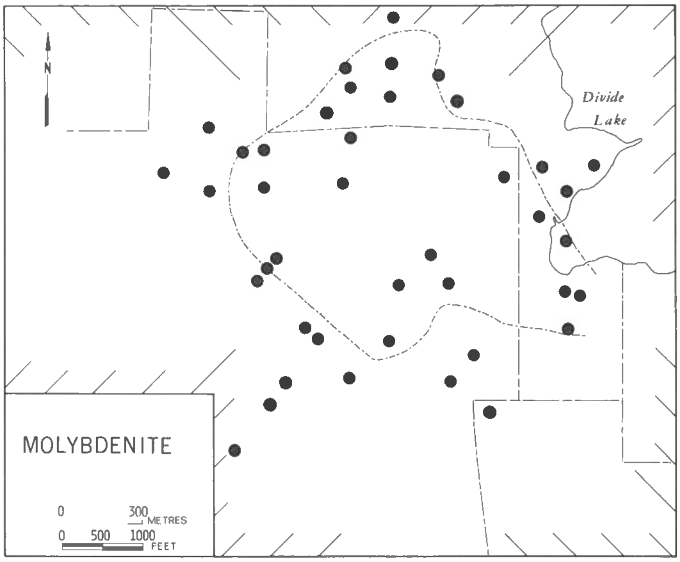


Figure 15. Molybdenite occurrences in drill core projected to surface (this study).

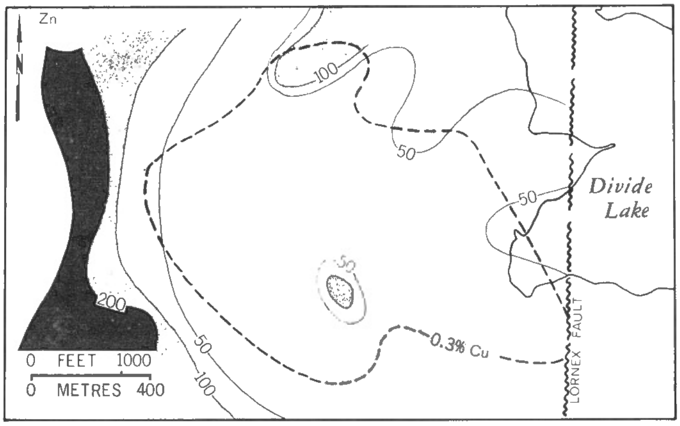


Figure 16. Zinc (ppm) on the 1158-m level (after Osatenko and Jones, 1976).

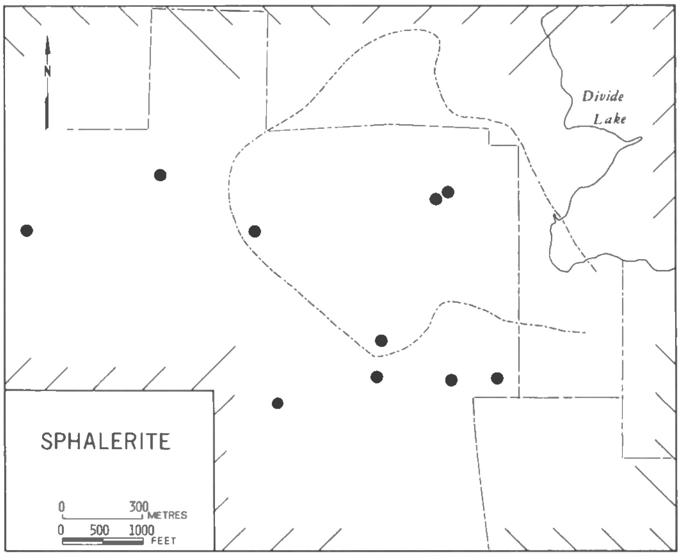


Figure 17. Sphalerite occurrences in drill core projected to the surface (this study).

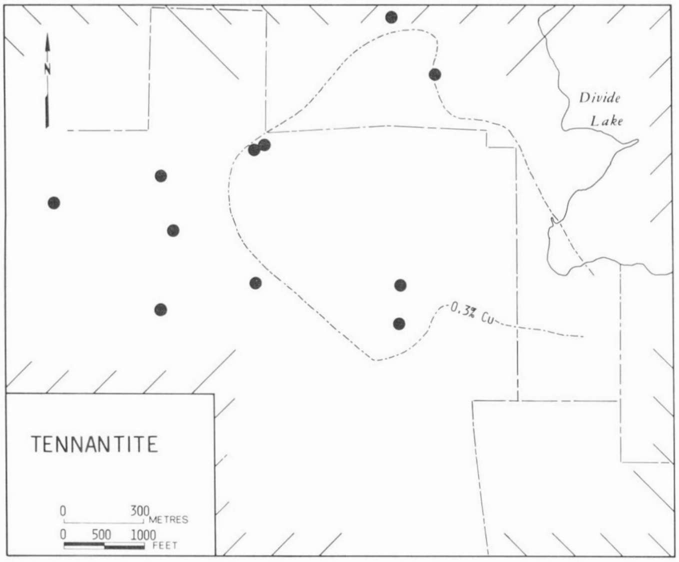


Figure 18. Tennantite occurrences in drill core projected to the surface (this study).

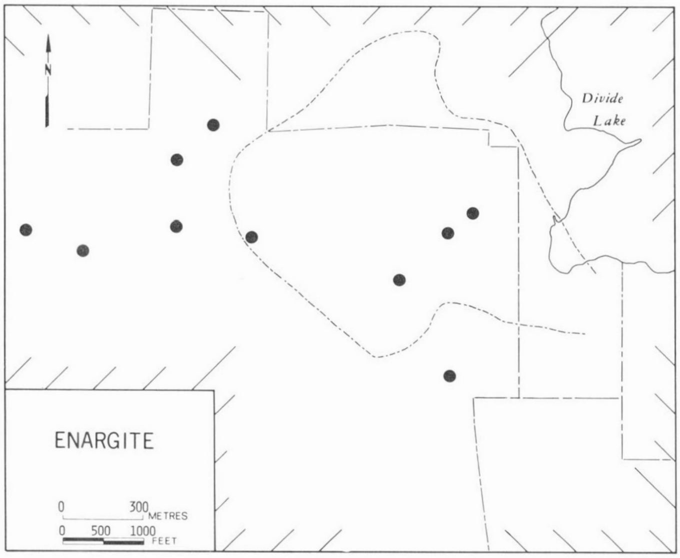


Figure 19. Enargite occurrences in drill core projected to the surface (this study).

The present writers include all hydrothermal biotite as potassic alteration. The widespread presence of such biotite in the Highland Valley deposits has important implications, as outlined above, which bear on the concept of progressively evolving alteration facies in porphyry systems. This concept will be dealt with in detail in another paper. For the Highland Valley deposits, K-mica (sericite) is allocated to phyllic alteration, as was done previously for Highmont (Reed and Jambor, 1976) and Lornex (Waldner et al., 1976).

Reed and Jambor (1976) concluded that K-feldspar alteration is negligible at Highmont; Waldner et al. (1976) noted that K-feldspar veinlets are present at Lornex, but do not form a mappable unit. At Valley Copper, which is the largest and highest grade of the three deposits, a K-feldspar zone occurs in the west-central part of the deposit (Osatenko and Jones, 1976). Mappable zones of pervasive hydrothermal biotite were reported previously only for Highmont.

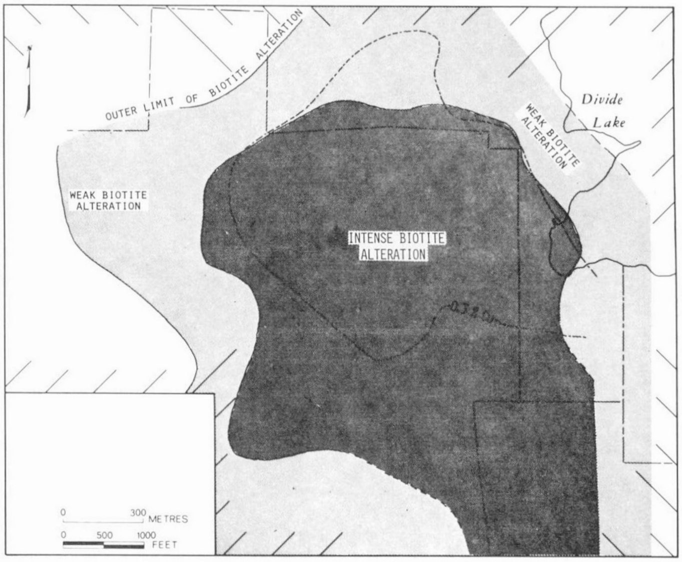


Figure 20. Distribution of hydrothermal biotite at Valley Copper.

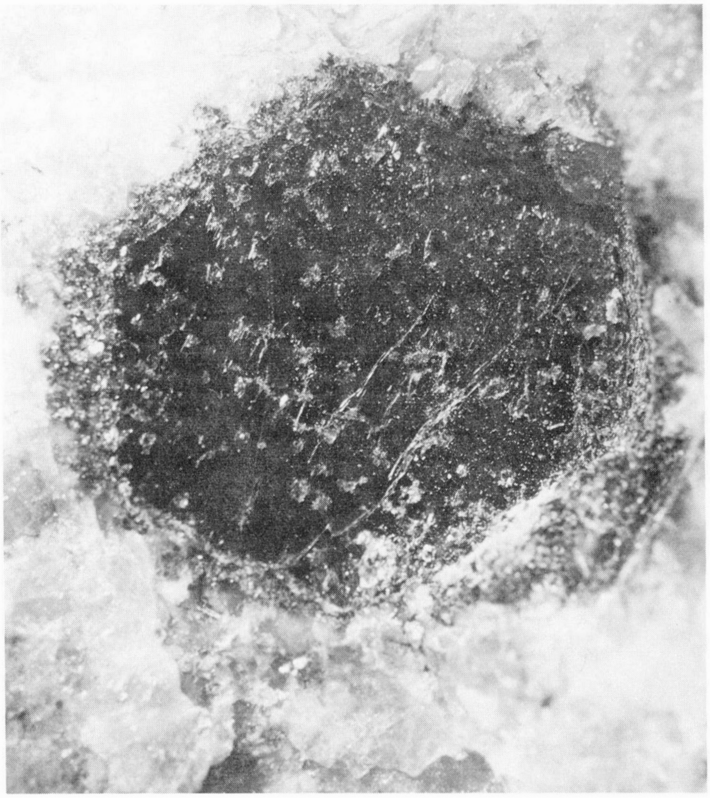


Figure 21. Photograph of Bethsaida host rock from Valley Copper showing primary biotite crystal, 8 mm wide, rimmed with fine grained hydrothermal biotite. (D.D.H. 69-44 at 1472 feet).

The distribution of hydrothermal biotite at Valley Copper, as determined in the present study, is shown in Figure 20. Much of the potassic zone in this deposit has undergone retrograde alteration as a consequence of overprinting by phyllic and argillic alterations. Nevertheless, intense biotite alteration is conspicuous in thin sections of residual "unbleached" rocks which occur throughout the deposit. In these rocks, hydrothermal biotite is present

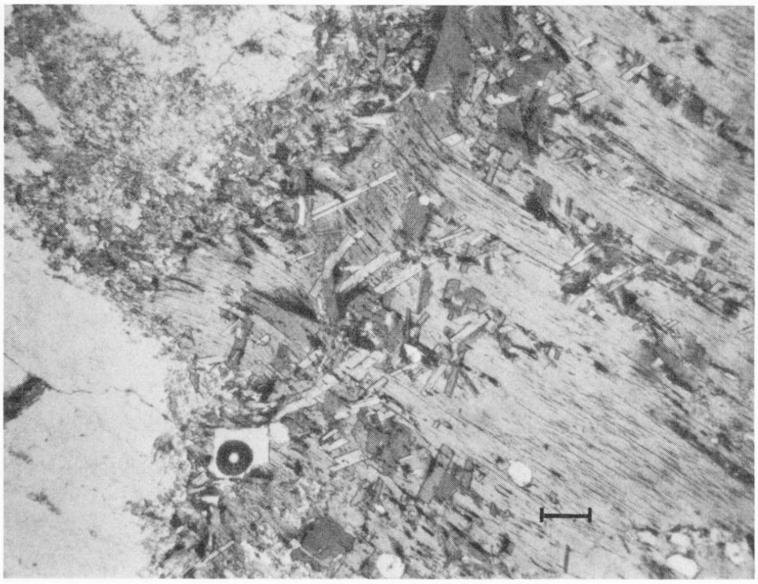


Figure 22

Photomicrograph of thin section showing intense hydrothermal biotite alteration at Valley Copper. Transmitted light, crossed nicols. Bar scale is 0.2 mm.

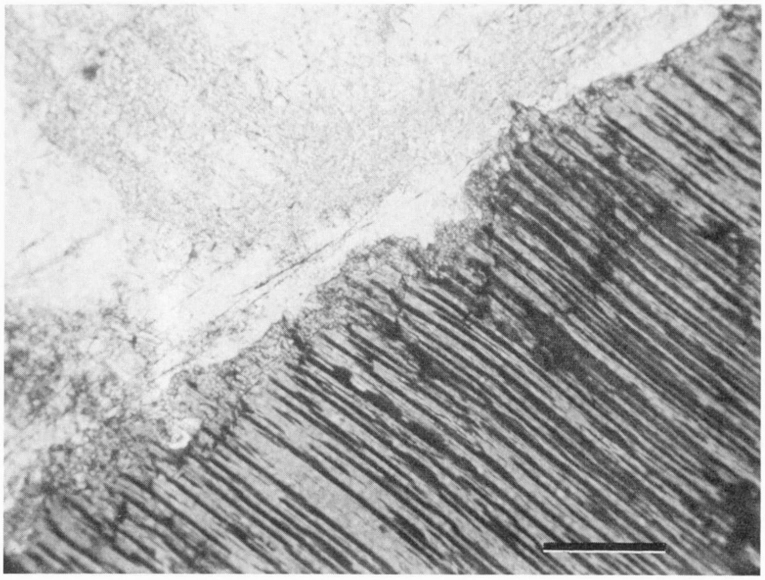


Figure 23

Photomicrograph of thin section showing extremely weak hydrothermal biotite alteration. The sample is from drillhole 69-15 (Fig. 7), near the western limit of biotite alteration. Transmitted light, crossed nicols; bar scale is 0.2 mm.

predominantly as aggregates of brown laths which rim phenocrysts of magmatic biotite (Figs. 21, 22). Microscopic veinlets of hydrothermal biotite also have been noted, as have pseudomorphs after the small amount of primary amphibole which occurs in the Bethsaida host. Occurrences of all these types form a zone which encompasses and encircles the copper deposit (Fig. 20).

The intensity of hydrothermal biotite alteration decreases progressively with increased distance from the copper zone. The decline in intensity is marked by the following features: (1) hydrothermal biotite in areas distant from the copper zone is much finer grained, and the aggregates at phenocryst edges form much narrower and more compact rims (Fig. 23) than those in the copper zone. (2) Dark brown hydrothermal biotites are characteristic in areas with intense biotite alteration, and the colour of the mineral lightens as alteration intensity decreases. Moreover, although the copper zone contains some green and greenish brown hydrothermal biotite interspersed with the brown, distal areas characteristically have only greenish brown biotite — the brown variety is absent. (3) As the intensity of biotite alteration weakens, fewer edges of magmatic biotite phenocrysts are affected. In the outermost part of the biotite halo, phenocryst rims are only partly biotitized, and more phenocrysts have been completely unaffected. (4) The appearance of residual magmatic amphibole at Valley Copper coincides with the outer limits of intense biotite alteration.

The above four criteria have been used to distinguish zones of intense versus weak biotite alteration at Valley Copper. Intense biotite alteration overlaps most of the copper zone (Fig. 20), and a broad aureole of weaker biotite alteration surrounds this core and gradually declines in intensity outward from it.

Throughout Highland Valley, rocks which have been affected only by hydrothermal biotite alteration have megascopically fresh feldspars and dark mafic minerals. With subsequent pervasive overprinting by phyllic, argillic, or propylitic alterations, the feldspars lose their pristine appearance and mafic constituents become greenish or are replaced extensively by chlorite, carbonates, and epidote. The scarcity of rocks with fresh feldspars in the upper part of the Lornex deposit is a megascopic reflection of relatively

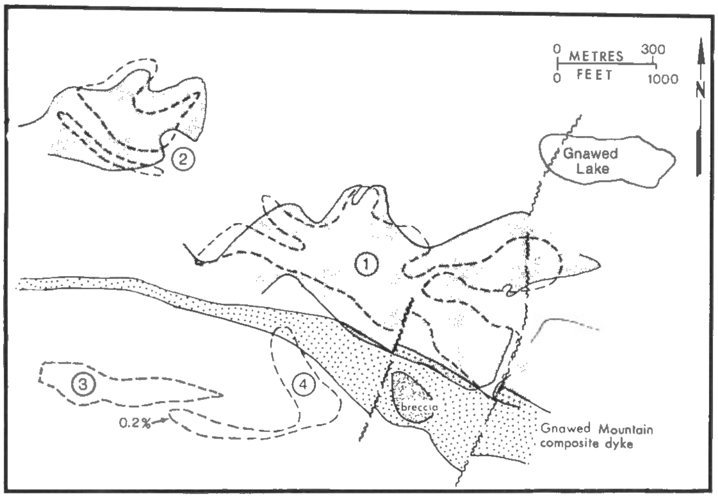


Figure 24a. Distribution of hydrothermal biotite (shaded) at Highmont Nos. 1 and 2 deposits. Dashed outlines are isopleths for 0.2 per cent copper-equivalence at surface. (Adapted from Reed and Jambor, 1976).

intense, pervasive retrograde alteration which has affected the potassic zone much more extensively than at Highmont or Valley Copper. Despite the widespread retrograde alteration at Lornex, hydrothermal biotite relicts persist through most of the deposit and constitute a mappable potassic zone as shown in Figure 24b. The boundaries for the biotite and copper-molybdenum zones almost coincide in the northern part of the deposit. However, thin section studies indicate that, prior to retrograde alteration, the original biotite halo was slightly larger. Along the eastern side of the deposit, biotite alteration extended outwards about 100 m from its present position. On the western side of the Lornex fault, Bethsaida rocks opposite the Lornex orebody are devoid of potassic alteration.

REGIONAL PATTERNS OF SULPHIDE ZONING AND BIOTITE ALTERATION

The term region here denotes the area encompassing Highmont, Lornex, Valley Copper, and their adjoining properties as shown in Figure 25. Fracture density is the dominant ore control at all deposits in the region, and highest metal grades occur where mineralized fractures are most abundant. Thus, the contours for metal grades cut across the patterns established for sulphide species. Such transections are particularly evident at Highmont.

Detailed sulphide zonal patterns for the Highmont, Lornex, and Valley Copper deposits are given in Figures 3, 4, and 11; sulphide ratios for areas adjacent to the deposits are shown in Figure 25. Projection of sulphide zonal patterns outward from the known deposits is commonly difficult because datum points are few, and sulphides at these sites are sparse. However, there are some indications that the sulphide minerals have a regional pattern additional to the local patterns at the deposits.

The regional distribution of biotite alteration is shown in Figure 26. Hydrothermal biotite data for the Highmont No. 1 and No. 2 deposits (Fig. 24a) are from Reed and Jambor (1976), who noted that this type of alteration is present also in the Nos. 3 and 4 deposits south of the Gnawed Mountain dyke. No hydrothermal biotite alteration was found in the Sheba drillholes shown in Figure 26; therefore, the biotite zone at the eastern boundary of Highmont either dies out or swings south.

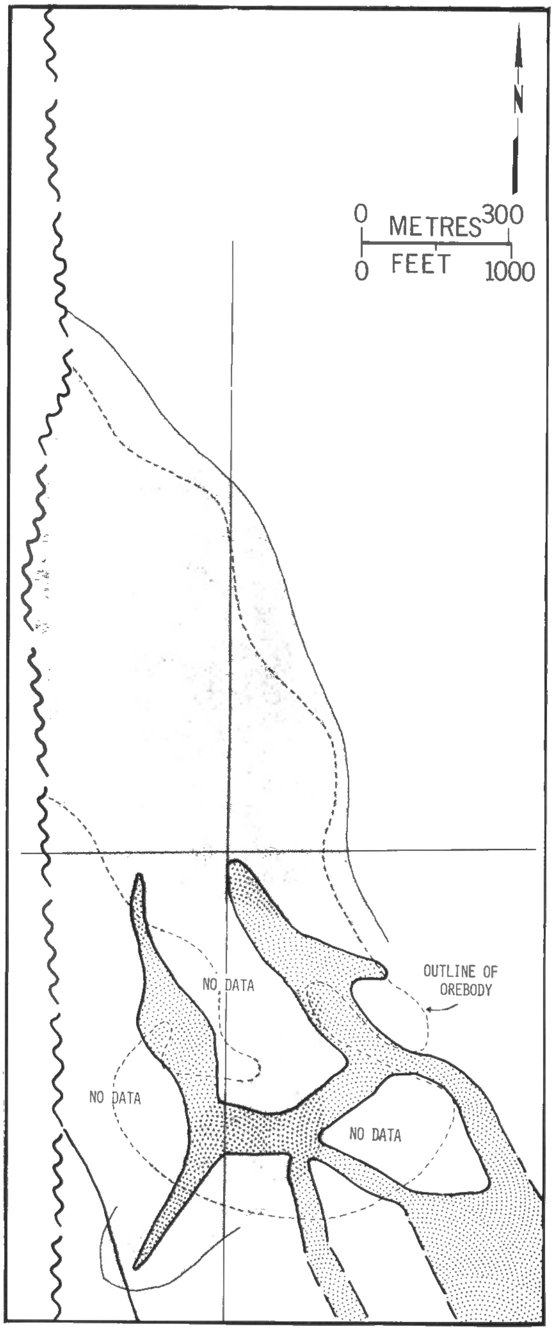


Figure 24b. Distribution of hydrothermal biotite (shaded areas) at Lornex. Base-map features are as given in Figure 4.

In the northern part of the region, the large biotite aureole at Valley Copper is not closed off completely. The outer limit of hydrothermal biotite is well-defined in drillholes directly west of the deposit. To the southwest, however, biotite alteration gradually wanes, but does not terminate. Instead, this part of the Valley Copper halo seems to extend into a large protuberance at the western side of the property (Fig. 26). The intensity of biotite alteration is extremely weak in most of this area, but seems to increase toward an untested area in the lobe. The increase suggests that a biotite zone separate from that of Valley Copper may be present, and that the two haloes have merged.

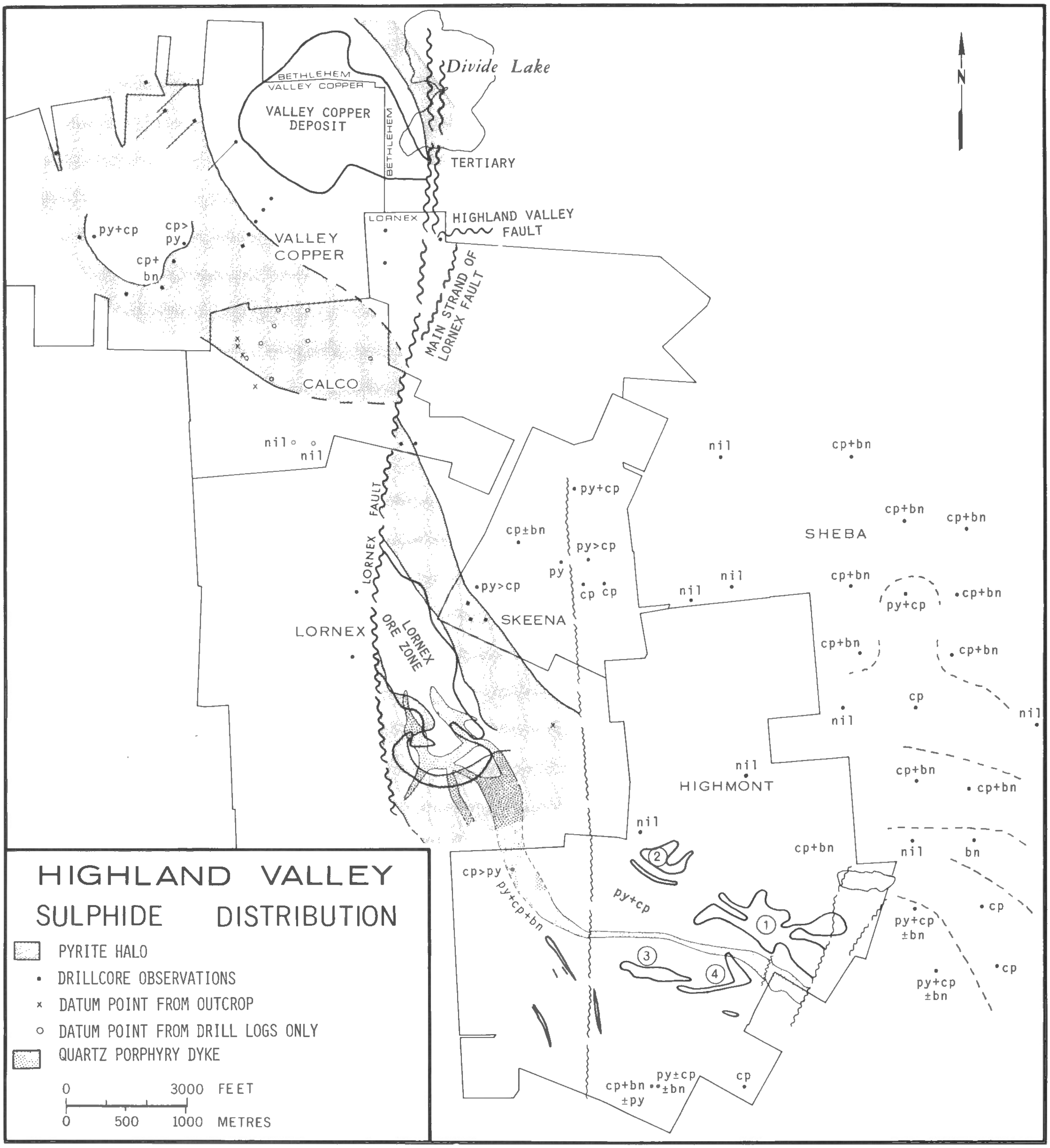


Figure 25. Regional sulphide distribution in the southwestern part of Highland Valley. Details for the Nos. 1 to 4 Highmont deposits are given in Figure 3, and the Lornex ore zone and Valley Copper deposit are shown in Figures 4 and 11. Sulphides in the Sheba drillholes are mostly at, or close to, background levels. The zone of chalcopyrite + bornite northeast of Highmont No. 1 deposit is based on results from several drillholes in this area. In the almost circular, unshaded area approximately 1 km southwest of the Valley Copper deposit, pyrite decreases and copper sulphides increase; this area is considered to merit further exploration. The offset part of the Lornex ore zone is interpreted to abut the western side of the labelled "main strand" of the Lornex fault. The position of the main strand is not known exactly, but it is interpreted to be east of the drillhole near the Highland Valley fault. Dots represent the collar sites of drillholes.

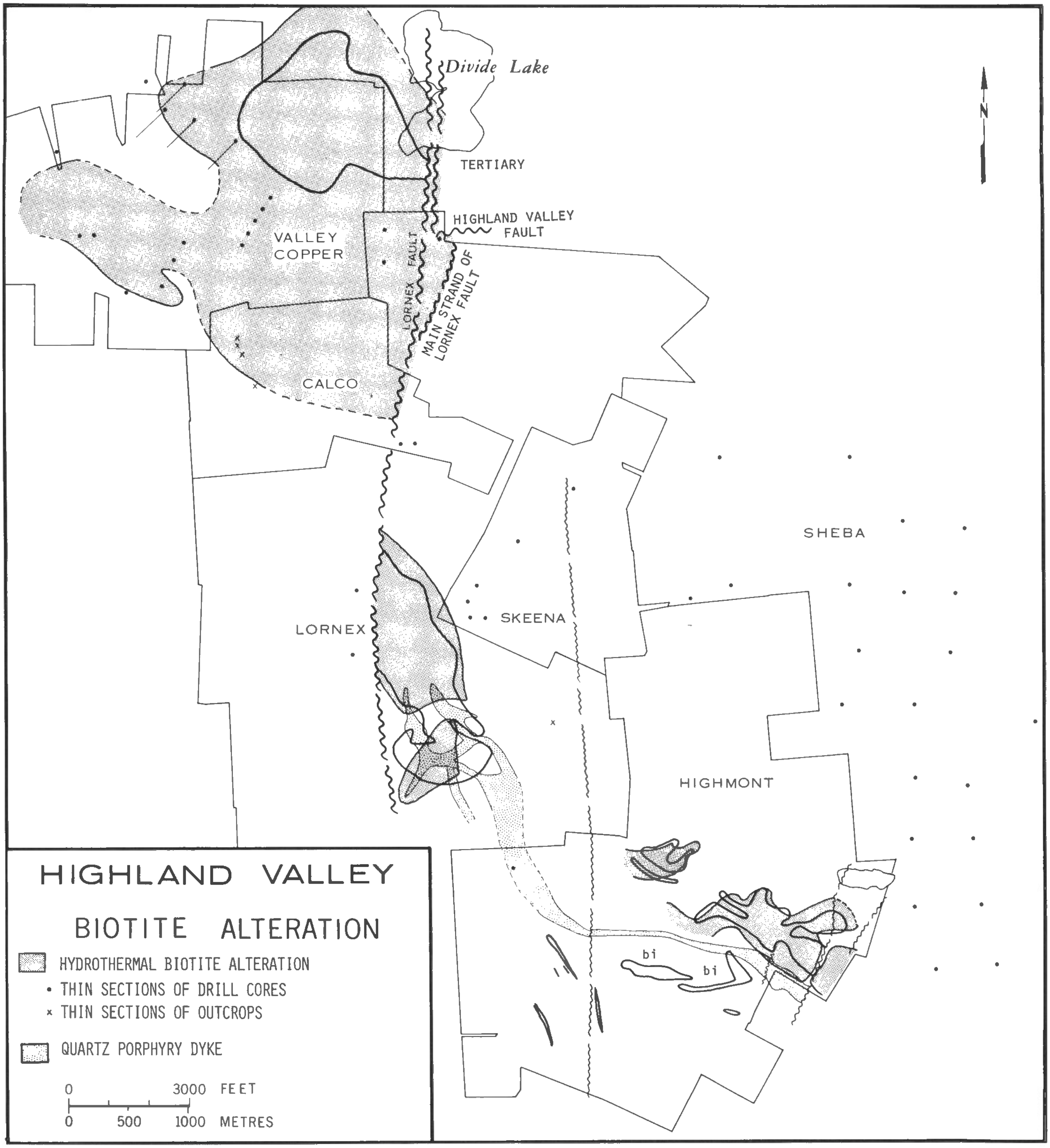


Figure 26. *Regional distribution of hydrothermal biotite alteration in the southwestern part of Highland Valley. Data for Highmont are from Reed and Jambor (1976), who noted that hydrothermal biotite (bi) is present also in the sulphide deposits south of the porphyry dyke which extends to Lornex. Biotite alteration at the Lornex and Valley Copper deposits is shown in Figures 20 and 24. Dots represent the collar sites of drillholes.*

With respect to the proven deposits, K-feldspar alteration decreases from Valley Copper to Lornex to Highmont. The intensity or original hydrothermal biotite alteration decreases in the same sequence, so that there is a well-defined correlation between copper grades and the intensity of potassic alteration in these deposits.

LORNEX FAULT

The Lornex fault bisects the region and truncates the northwestern part of the Lornex orebody. The dip of the fault ranges from 55 to 85° west (Fig. 4). McMillan (1971, 1976) has postulated that movement along the fault was right-lateral and reverse. The amounts of pre-ore versus post-ore movements have not been established, but geological contacts along this segment of the fault indicate a cumulative right-lateral offset of 5 to 6 km (McMillan, 1976).

Although the Lornex fault has been well-defined by drilling and mining at Lornex (Waldner et al., 1976), the character of the fault at Valley Copper is known less well. From drillholes examined in the present study, it is concluded that the fault is split in the northern part of the region and that, at Divide Lake, at least three major splays are present. The westernmost splay passes through the bottoms of drillholes 69-48 and L-19 and a second major splay is slightly farther east (Fig. 11). Both splays dip steeply westward and intersect the Valley Copper orebody, but the footwalls of both contain substantial copper mineralization.

Near the Bethlehem-Lornex property boundary south of Divide Lake, Lornex vertical drillhole 104 (Fig. 27) intersected quartz plagioclase porphyry which is hydrothermally altered and contains sparse pyrite and chalcopyrite. The hole bottomed in a major fault. The continuity of copper mineralization across the two aforementioned splays, and the projected continuity of the porphyry dyke (Fig. 7) indicate that, if the movement which offset the Lornex orebody was mainly strike-slip, then nearly all of the translation must have occurred along a splay east of the collar of drillhole 104. The regional distributions of potassic alteration and sulphide zoning (Figs. 25, 26) confirm that significant horizontal offset did occur; therefore, the third splay (east of drillhole 104) must be the major strand of the Lornex fault. The apparent offset of the alteration and sulphide zones is right-lateral, in agreement with the sense of offset indicated by regional mapping of the batholith by the British Columbia Department of Mines and Petroleum Resources. Post-ore offset is discussed in detail below, but its apparent horizontal displacement is about 3 km whereas the regional offset is indicated to be about 5-6 km; the difference could be an indication of the magnitude of pre-ore movement, but 2 to 3 km of pre-ore horizontal offset does not provide matching geological contacts to account for the Skeena host rock of the Lornex deposit versus the Bethsaida host rock of Valley Copper. Thus, movements other than horizontal were apparently involved; according to Waldner et al. (1976), the pre-ore movement of the Lornex fault was right-lateral and reverse.

As the porphyry deposits and Guichon Creek batholith have identical ages within the limits of error of potassium-argon determinations (Northcote, 1969; Jones, 1975), and as the ore deposits apparently formed before the batholith had cooled (Reed and Jambor, 1976), the pre-ore offset must have been almost contemporaneous with ore deposition. Pre-ore movement on the Lornex fault has been postulated to be one of the two main structural components in generating the mineralized fractures at Lornex and Valley Copper (Allen and Richardson, 1970; McMillan, 1971; Hollister et al., 1975; Waldner et al., 1976).

Tertiary Fault Basin

South of Divide Lake, along and just east of the Bethlehem-Indian Reserve Boundary (Fig. 27), a series of drillholes intersected only Tertiary sediments with minor volcanics. Drillhole L-18 by Bethlehem at the southeastern corner of its property also intersected similar rock. McMillan (1971), in a detailed study of this area, concluded that deposition occurred in a Tertiary basin bounded by the north-striking Lornex and easterly-striking Highland Valley faults. McMillan (1971) stated that the Tertiary rocks near this intersection were more than 300 m thick. Minor modifications are suggested here in order to accommodate the present writers' interpretation of the Lornex fault.

The western boundary of the Tertiary basin must lie between the main strand of the Lornex fault and the two, more westerly splays which cut the Valley Copper deposit. Therefore, the main part of the Tertiary boundary must be in contact with the deposit along a third, almost vertical splay. In order to incorporate Bethlehem drillhole L-18, the third splay must branch eastward of the other two splays (Fig. 27).

The easterly-striking Highland Valley fault is the southern boundary of the Tertiary basin (McMillan, 1971). The drillhole data indicate that the Highland Valley fault in this area must lie barely north of Lornex drillhole 104, near which it intersects the main strand of the Lornex fault (Fig. 27). As this intersection marks the edge of the Tertiary basin, the northerly projection of the Lornex main strand must have been displaced downwards, so that it now lies beneath the 300 m thickness of Tertiary sediments.

The Highland Valley fault is interrupted at the Lornex splays and its westward projection does not appear in drillholes on Valley Copper ground. Thus, early or pre-ore formation of the Highland Valley fault and subsequent pre-ore northward displacement by the Lornex fault could have occurred (Hollister et al., 1975). The movements involved in the formation of the Tertiary basin therefore could have been mainly vertical adjustments along the older fault zones.

Post-Ore Offset Along the Lornex Fault

Proof that major post-ore offset did occur along the Lornex fault is the truncation of the Lornex orebody and the juxtaposition of hydrothermally unaltered Bethsaida rocks against the western side of the ore zone. North of Lornex, at Divide Lake, the continuation of substantial sulphide mineralization on both sides of the western splays of the Lornex fault indicates that large strike-slip movements did not occur in this specific area. Therefore, post-ore offset must have taken place largely, or wholly, along the main eastern strand.

The outer limit of the pyrite halo north and east of the Lornex orebody is well-defined in drillholes. The small pyrite-chalcopyrite Victor deposit (McMillan, 1975) in the main north-trending fault on the Skeena property (Fig. 23) is not correlative with the porphyry-deposit aureole. The pyrite halo and copper zone abutting the eastern side of the Lornex fault have a total length of approximately 3000 m along the fault. A matching total length of the halo on the western side of the fault requires that the halo extend northwards to the top of Divide Lake. However, no drillhole data are available to establish the northern pyrite boundary in this area. In order to have contiguous inner and outer southern boundaries of the pyrite halo, apparent right-lateral translation of approximately 2400 to 3100 m must have occurred.

Displacement along the Lornex fault is evident also from the relative positions of the hydrothermal biotite haloes at the fault (Fig. 26). The amount of offset is approximate because the limits of biotite alteration near the fault are not

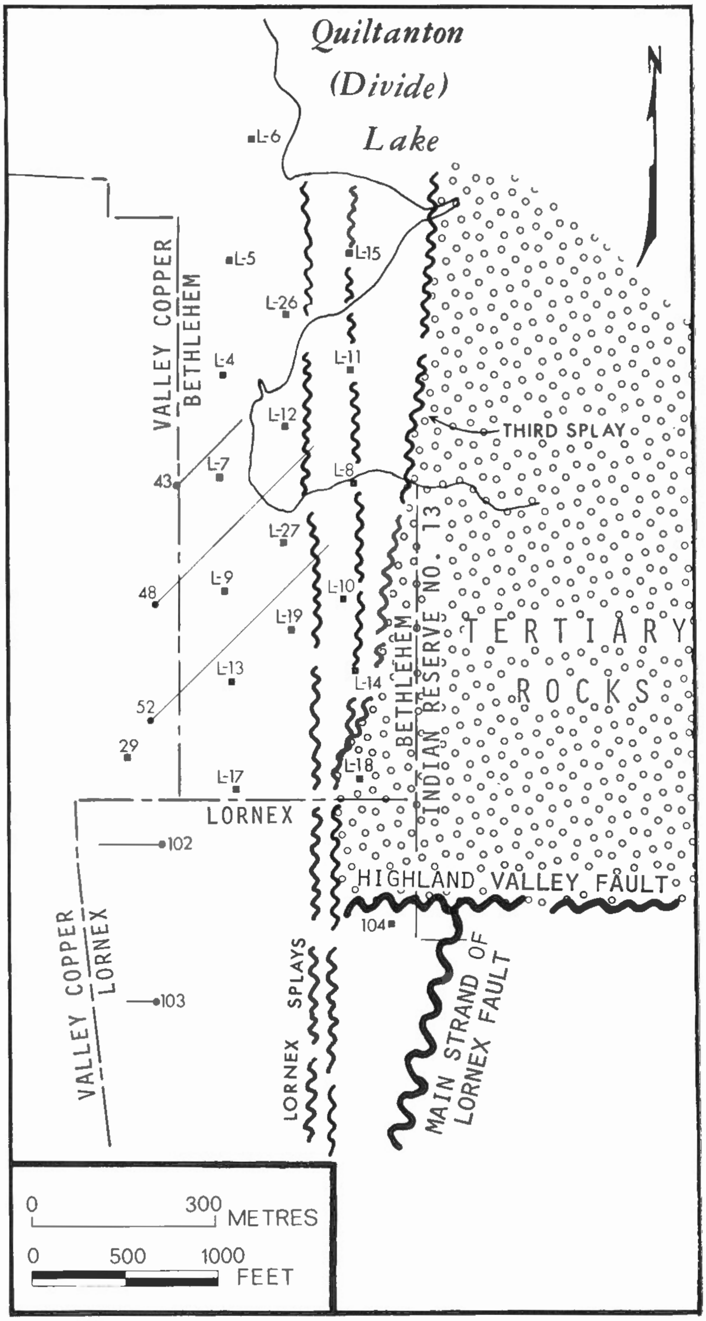


Figure 27. Major faults at the southeastern margin of the Valley Copper deposit. The two most westerly splays of the Lornex fault dip westward and have mineralized footwalls; an associated third splay is interpreted to be the boundary between Tertiary rocks on the east (including drillhole L-18) and the Guichon Creek batholith on the west. The Highland Valley fault is north of drillhole 104 and is the southern boundary of the Tertiary basin. The main strand of the Lornex fault is an unknown distance east of drillhole 104, and its northerly continuation has been offset by the Highland Valley fault.

located precisely. For example, the northern biotite boundary at Lornex is shown as close to the Lornex orebody (Fig. 26), and is based on the observed presence of hydrothermal biotite in a drillhole at this site. The boundary line which marks the absence of hydrothermal biotite is therefore some metres north of this site, where no holes have been drilled. However, the inference from the microscopic character of the biotite is that the boundary line is not more than 300 m north. The northern limit of biotitization at Valley Copper can be deduced similarly; the boundary line trends southeasterly at Divide Lake and intersects the projected main strand of the Lornex fault south of the lake. To have a contiguous northern boundary of the potassic zone, right-lateral translation must have been of the same order of magnitude as that required for juxtaposition of the pyrite halo.

The Valley Copper-Lornex Relationship

That the Valley Copper and Lornex orebodies formed as two separate and unique entities is evident from their differences in metal grades, sulphide zonal patterns, alteration characteristics, and numerous other features. The almost concentric character of the Valley Copper ore zone and sulphide shells is alone convincing evidence that this deposit had its own, predominantly isolated hydrothermal system. Although the Lornex orebody was apparently fed from a separate source and most of the deposit apparently had its own hydrothermal circulatory system, the northwestern end of its sulphide zones seems to have overlapped the Valley Copper deposit.

The offset segment of the Lornex orebody is interpreted to occur approximately 900 m south of Divide Lake, at the northwestern corner of the Lornex property and abutting the western side of the labelled "Main Strand of Lornex Fault" (Figs. 26, 27). The segment is considered to be the terminal part of the deposit and is shown as the zone of "bn>cp" south of the Valley Copper deposit (southeastern corner of Fig. 11). Bornite and chalcopyrite-rich parts of the segment should extend to the west of drillhole 104, and for a considerable distance southwest of it. The area of intense barren quartz veining and pervasive silicification, which has its focal point at the southeastern end of the Valley Copper deposit, may mark the confluence of part of the Lornex and Valley Copper hydrothermal systems.

Restoration of the biotite alteration zones and sulphide zones to their original positions shows that their boundaries do not match exactly (e.g., Fig. 28). A much better fit could have been obtained by redrawing the dashed contacts on the Calco property (Figs. 25, 26). The contacts shown are the original versions which led to the fault interpretation presented in this paper. Although the Valley Copper and Lornex deposits are considered to have formed at the same depth in the batholith, a precise match of alteration and sulphide zones across the Lornex fault would occur only if the post-ore movements on the fault were mainly or wholly strike-slip. Indications that movements may have been more complex are as follows: (1) Waldner et al. (1976) concluded that the Lornex deposit has undergone a 30 to 40° post-ore tilt, with the north end down relative to the south. The tilt was invoked to explain why mineralized fractures now dip in a southerly direction and why sulphide and alteration zones plunge northwesterly. (2) McMillan (1976, p. 93) concluded that less cover, including Tertiary rocks, was eroded from the area east of the Lornex fault and, therefore, it was uplifted less than the area west of the fault. (3) For the southern part of the Lornex-Valley Copper pyrite halo, the amount of pyrite east of the Lornex fault exceeds that west of it. If strike-slip movements alone were involved in offsetting the haloes, sulphide abundances should be equal on both sides of the fault.

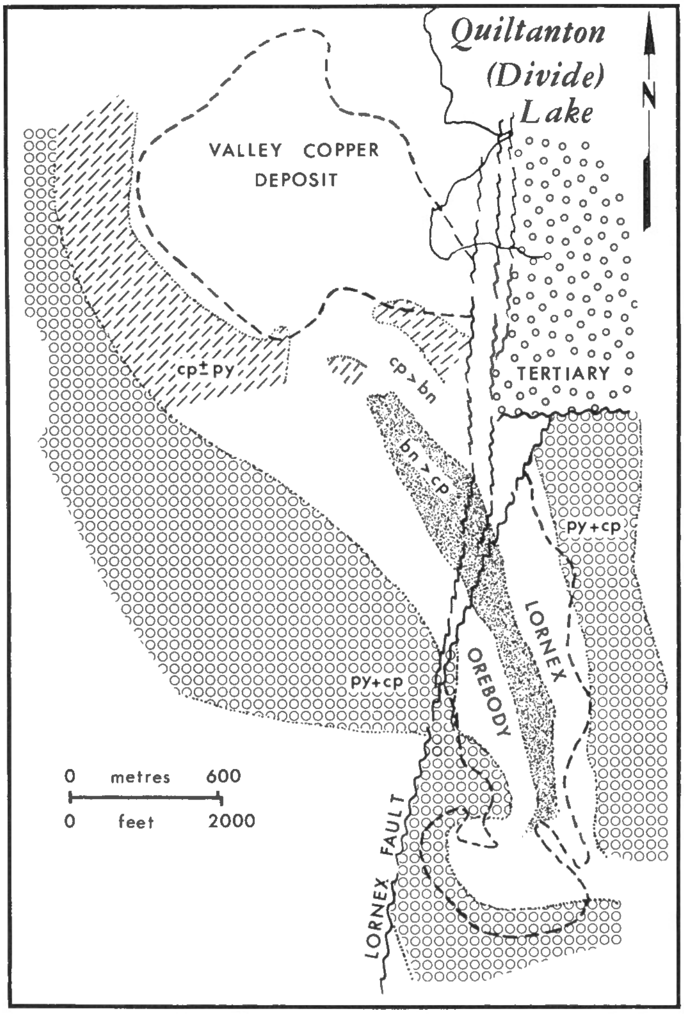


Figure 28. Possible configuration of sulphide zones across the Lornex fault, with schematic restoration attained by moving the Lornex orebody approximately 2600 m north along the main strand of the Lornex fault. The shape of the bornite zone west of the fault is not known. All faults bordering the Tertiary basin are assumed to have been active after displacement of the orebodies.

The Gnawed Mountain Porphyry

The pre-ore Gnawed Mountain composite dyke extends from Highmont to the southern end of the Lornex deposit, whereupon it ramifies (Fig. 24), and apparently does not reach the Lornex fault. Reed and Jambor (1976) noted that, at Highmont, smaller quartz plagioclase porphyry dykes seemed to have a close temporal and genetic association with the Gnawed Mountain Porphyry. These quartz plagioclase porphyry dykes are of the same type that occurs at Valley Copper (Fig. 7). The dykes at Valley Copper are arcuate, and the two largest are west and south of the deposit. Only the latter has been interpreted to continue to the Lornex fault, but both may represent the westernmost offshoots of the Gnawed Mountain Porphyry.

RELATIVE AGES AND DEPTHS OF EMPLACEMENT

Relative ages of the deposits

Based on a faulting theory for Highland Valley, Hollister et al. (1975) postulated that Highmont is the oldest, the Bethlehem group of deposits intermediate in age, and Lornex-Valley Copper the youngest of the Highland Valley deposits. In contrast, McMillan (1976) pointed out that mineralized porphyry dykes which may be older than the Bethsaida phase of the batholith occur in deposits north of Highland Valley, and he conjectured that these northern deposits (e.g., the Bethlehem group) may be older than the southern deposits (Highmont, Lornex, Valley Copper). The postulated youngest age for Lornex-Valley Copper mineralization was reiterated by Seraphim and Hollister (1976) without reference to the contrary data presented by McMillan (1976) and Jambor (1976).

The relative age of sulphide deposition at Highmont was discussed in a previous section. Sulphides at Highmont are post Gnawed Mountain Porphyry, and they continued to be deposited after intrusion of quartz plagioclase porphyry dykes. The dykes are also cut by very minor pre-mineral pink aplite dykes which are rarely more than 1 m wide. A few of these aplites also occur at Lornex and at Valley Copper, where they have the same age relation with the sulphides.

Tan-coloured felsite porphyry dykes at Valley Copper may have been intruded during the waning stages of mineralization (Osatenko and Jones, 1976). Some of these dykes are sparsely mineralized whereas others are unaltered and contain sericite-veined Bethsaida fragments. The lone tan felsite dyke noted at Highmont has been hydrothermally altered and therefore is concluded to be pre-mineral.

Reed and Jambor (1976) pointed out that post-ore laumontite apparently formed before the Guichon Creek batholith had cooled completely, and that this zeolite cuts sericite-sulphide veinlets at Highmont and Lornex. Thus the late-stage magmatic events, sulphide deposition, and post-ore veining were apparently closely related, but none provides a basis for age distinction among the Lornex, Valley Copper, and Highmont deposits, all of which may have formed contemporaneously.

Relative depth of emplacement

The presence of dykes and breccias, and the character and degree of fracturing were interpreted by McMillan (1976) to reflect relative depths of formation of the deposits. The sequence established by McMillan is, from deepest to shallowest, Valley Copper, Lornex, Highmont.

The present writers have emphasized the close association of the Gnawed Mountain (quartz porphyry) dyke with the Highmont and Lornex deposits. Bedrock surface at Lornex is only 100-150 m lower than that at Highmont and the present positions of the sulphide bodies probably reflect their relative depths of formation. We concur with McMillan's (1976) suggestion of shallower emplacement of the Highmont deposits because their sulphide zones "bottom out", i.e., the roots of the Highmont sulphide zones are shallower than those of Lornex. The shallow roots and absence of well-defined vertical zonation of hydrothermal alteration at Highmont are two features which should not be dismissed simply on grounds that the deposits are of low grade (cf. Carson and Jambor, 1974).

Lornex, unlike Highmont, shows good vertical zonation in that well-defined potassic alteration at depth becomes progressively obscured upward and gives way to a predominance of phyllic, argillic, and propylitic alterations. The main part of the Lornex copper zone does not bottom out; thus the vertical dimension of Lornex exceeds that at Highmont, and the erosional surface at Lornex is in a definable upper part of the deposit.

The proposal by McMillan (1976) that Valley Copper was formed at a deeper level than Lornex is considered to be more tenuous. The quartz porphyry at Lornex represents a large volume of dyke rock, but dykes at Valley Copper are both more numerous and more varied than at Lornex.

Differences in character and degree of fracturing may be more a reflection of local pore fluid pressures and proximity to major faults than a measure of depth of formation. Vertical zonation of alteration minerals at Valley Copper is well-defined and downward progression into a less altered potassic core occurs at about the same depth in the alteration zoning as at Lornex. The present writers conclude that Valley Copper and Lornex were formed at about the same level.

Gypsum lines

Gypsum and anhydrite are too sparse to form a mappable unit at Highmont, but these minerals are abundant at Valley Copper. The initial appearance of gypsum down the Valley Copper drillholes is not erratic but occurs at a fairly constant topographic elevation that can be projected from hole to hole to form a "gypsum line". Below this "line" gypsum is common; the line was found by Jambor and McMillan (1976) to also mark the boundary at which rocks with weak or negligible argillic alteration are separated from intensely argillized rocks; the latter are confined largely to the upper part of the deposit. The above authors concluded that the gypsum veins were formed during a late-stage influx of non-magmatic water which reacted with the calcium and sulphate released from primary feldspars and anhydrite during argillic alteration.

If the Valley Copper and Lornex deposits formed contemporaneously, and overlapped, the late-stage influx of nonmagmatic water should have been at approximately the same elevation, particularly where the alteration haloes for the two deposits overlapped. According to Jambor and McMillan (1976), the gypsum line at Valley Copper is at the 1000-1100 m elevation; at Lornex, the gypsum line is at about the 1100 m elevation in the centre of the deposit (Waldner et al., 1976) and about 100 to 150 m higher at the sides of the orebody. The approximate coincidence of the gypsum lines may be an indication that the deposits were at about the same depth when post-ore gypsum veining took place.

Bedrock surface at Valley Copper is irregular and dips steeply toward the floor of Highland Valley. The copper zone is highest at the southwestern part of the deposit at about the 1300 m elevation. Bedrock surface at Lornex averages about the 1500 m elevation. Thus, if the deposits formed at the same level, the upper part of Valley Copper was eroded at least 200 m more than Lornex.

Dry versus wet deposits

Lowell and Guilbert (1970) and Guilbert and Lowell (1974) have suggested that the Highland Valley deposits may be examples of porphyries in a deep-seated environment, and that they may be examples of "dry" deposits characterized by relatively low sericite and pyrite contents. Although the above authors (1970) cautioned that "wet" and "dry" terms were casual, they subsequently (1974, p. 107) characterized the Highland Valley deposits as follows: "The paucity of hydrous minerals, textures and mineralogies of silicate assemblages, low total-sulphide-to-copper ratios, and relatively narrow pyrite haloes of the Highland Valley mineralization and alteration are those of a low-sulphur, low-volatile, relatively "dry" system........".

We continue to visualize Valley Copper as a very "wet" deposit because it has an abundance of hydrous minerals which are especially represented by intense argillic alteration (Jambor and McMillan, 1976; Jambor and Delabio, 1978). Also worthy of note is that the Valley Copper pyrite halo, although weak, is extremely broad. Although abundant pyrite and intense sericite alteration may be characteristic of most "wet" deposits, the absence of voluminous pyrite does not characterize a "dry" deposit. For example, Granisle and Morrison (Carson and Jambor, 1974, 1976) have well-developed pyrite haloes, but have very little sericitic alteration.

Sericitic alteration may reflect "wetness" from magmatically derived volatiles, from an influx of non-magmatic fluids, or from a combination of both. Textures formed by crystallization at the potassic stage of alteration, or at the K-feldspar and K-mica reaction boundary (Hemley and Jones, 1964) are indications of what has happened early in the formation of the hydrothermal aureole. Subsequent crystallization at the phyllic stage of alteration may occur in wet or dry conditions, and pervasive argillic alteration may occur in extremely wet conditions in which pyrite has long since ceased to crystallize. It is interpreted that, if hydrothermal alteration at Valley Copper was initially dry, it subsequently became wet.

Concluding remarks

McMillan's (1976) model of the Guichon Creek batholith and his positioning of the porphyry deposits indicate that the deposits may have been emplaced at a depth of 4 to 5 km. Although low in pyrite, the deposits in other aspects do not fit well into depth-of-alteration models. However, the deposits do conform well with the concept of progressively evolving hydrothermal systems in which early potassic alteration is overprinted by other hydrothermal alteration facies. In the initial stages of this study, the Highland Valley deposits were thought to be quite "different" from other porphyries; the detailed studies have shown that these "batholithic" deposits have substantial variations in shape and in the extent and intensity of their hydrothermal assemblages. However, the Highland Valley deposits are not much different in that their evolution seems to have been along trends common to many, if not most, porphyry deposits.

EXPLORATION APPLICATIONS

Despite the extensive retrograde alteration which has affected the early-formed potassic assemblage in the region, remnant hydrothermal biotite is widespread in the known ore deposits. The distribution of hydrothermal biotite has a well-defined correlation with the copper zones, and the intensity of biotite alteration is correlative with copper grades: intensity declines in the sequence Valley Copper, Lornex, Highmont. Moreover, the character of the biotite at each deposit also changes systematically from the ore zone outward, and reflects progressive declines in intensity of potassic alteration and copper grades. These traits are considered to constitute valid criteria for assessing exploration possibilities in the Highland Valley.

Within the study region two targets which merit investigation have been delineated (Jambor and Beaulne, 1977). The first of these, south of Quiltanton (Divide) Lake and west of the Lornex fault, is interpreted to be the offset segment of the Lornex orebody (Fig. 28). The second target, slightly more than 1000 m southwest of the edge of the Valley Copper ore zone, is a largely untested area (Fig. 25) with a southern rim of weak, but persistent, hydrothermal biotite.

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