TRIP 3

GUICHON CREEK BATHOLITH AND MINERAL DEPOSITS

FIELDTRIP GUIDEBOOKS

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JOINT ANNUAL MEETINGS
VANCOUVER B.C., APRIL 1977

LEADERS

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VANCOUVER, BRITISH COLUMBIA

FIELD TRIP NO. 3: GUIDEBOOK

GUICHON CREEK BATHOLITH AND MINERAL DEPOSITS

APRIL 27 - 29, 1977

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DAY 1: VANCOUVER TO CACHE CREEK

(W. J. McMillan, M. J. Osatenko)

Mileage

0.0 to 220.0 - It will be necessary to travel from Vancouver to the village of Cache Creek during the late afternoon and evening of April 27th. We will stay in Cache Creek overnight and travel to Highland Valley from there. No stops will be made on this leg of the trip but we will have travelled across the south tip of the Coast Plutonic Complex, through the Cascade Fold Belt and into the Intermontane Belt.

DAY 2: CACHE CREEK TO BETHLEHEM MINE

(W. J. McMillan, M. J. Osatenko)

We will leave Cache Creek at 0800 hours, make several stops to see various phases of the Guichon Creek batholith, spend some time at Valley Copper, then visit Bethlehem Mine in the afternoon.

Mileage

0.0 The village of Cache Creek lies within the Bonaparte Disturbed Zone. The Zone here crosses highly sheared ribbon cherts and black argillites of the middle Pennsylvanian to late Permian Cache Creek group. The Cache Creek group comprises 15,000 to 20,000 feet of chert, ribbon chert, argillite, limestone, andesite flows, agglomerate and tuff.

The highway cuts in and out of the Disturbed Zone for more than 20 miles south of Cache Creek. The Zone is marked by silicified, often pyritized areas which weather red, buff, yellow and white. Gossans are common in the Zone but no economic mineralization has been found associated with them.

Travelling southward rocks of the Cache Creek group crop out west of the highway and east of it to Bonaparte River valley. In the Bonaparte Valley, Cache Creek rocks are in fault contact with late Triassic to Jurassic volcanic and sedimentary rocks. Capping the hills and unconformably overlying the older rocks are lavas of Eocene age.

2.5 Follow the turnoff eastward toward the village of Ashcroft. Outcrops along the road are shales, siltstones and sandstones of the lower to middle Jurassic Ashcroft formation. These unconformably overly the Guichon Creek batholith (198 ± 8 m.y.) which cuts rocks of the Nicola group of Karnian (perhaps as young as Norian) age. Consequently the Batholith was probably intruded close to the end of the Triassic but before the Jurassic era began. By early Jurassic time it was already unroofed, at least locally, and shedding material into the Jurassic sedimentary basins.

7.0 Cross the Thompson River and pass alongside Ashcroft (Fig. 1).

Pleistocene sand and gravel deposits and several remnants of Pleistocene terraces can be seen along the valley walls. These sediments also form a thin veneer over Jurassic black siltstones and shales adjacent to the Highland Valley highway as we drive up the hill out of Ashcroft.

12.5 White weathering cliff exposures east of the highway are biotite quartz andesine porphyry of Eocene age. The outcrops are part of a small stock which cuts through Jurassic sedimentary rocks. Outliers of porphyritic lava derived from the stock unconformably overly the Jurassic rocks south and west of the stock.

13.0 Going around the Barnes Lake switchback, we pass into recrystallized basic volcanic rocks of the late Triassic Nicola group. The edge of the Guichon Creek batholith is exposed in the hills east of the highway and accounts for the metamorphism of the volcanic rocks.

to 15.0 - Along this stretch of road, Nicola volcanics underly it, granitic rocks crop out to the east and Jurassic sedimentary rocks to the west.

to 17.0 - Local outcrops of Jurassic sedimentary rocks occur. These are generally brown sandstones, siltstones and shales but local conglomerate beds are encountered. The conglomerates appear, here, to be stream bed deposits.

At mile 17 we enter the Guichon Creek Batholith. Details of the character of the Batholith are given in the enclosed paper: "Geology and Genesis of the Highland Valley Ore Deposits and the Guichon Creek Batholith".

The Batholith is concentrically layered with an older, more basic, finer grained border and successively younger, more acidic, coarser grained phases inward toward the core. We will examine the border zone (Hybrid Phase), an intermediate zone (Bethlehem Phase) and the core zone which is exposed at Valley Copper (Bethsaida Phase).

to 20.0 - Sporadic Hybrid Phase quartz diorite outcrops occur.

20.0 STOP 1 - Exposed in this outcrop are more or less equigranular quartz diorites of the Hybrid Phase. They are biotite- and hornblende-bearing with color index about 25. Mafics are generally fresh but may be chloritized. The host rock carries a variable number of fine to medium grained basic xenoliths. Some xenoliths have sharp borders and are evidently basic volcanic rocks, others have diffuse contacts, are recrystallized and have less certain origins. Much of the quartz has a bluish color and K-feldspar is fine grained and interstitial. Overall, the rock has a dark gray-green aspect. Halos of green, sericitic feldspar alteration occur around some north striking joints and several slickensided shear zones carry malachite. Medium-grained biotite quartz monzonite dikes and veinlets of calcite, quartz-epidote and chlorite cut the quartz diorite country rock.

to 25.0 - Although there is little outcrop, the highway is underlain either by small Tertiary grabens infilled with lavas and sediments or by quartz diorites of the Hybrid Phase.

to 30.0 - Outcrops along the highway are variably rocks of the Highland Valley (25 to 27.7, 28.5 to 30) or younger Bethlehem phases. These are granodiorites with color index generally ranging from 10 to 20 and medium to coarse grain size. Some varieties are porphyritic.

30.0 STOP 2 - Exposures are in cuts made for the highway and the Lornex tailings pipeline. The rocks are relatively leucocratic, with color index 8 to 10, generally coarse grained and somewhat porphyritic. Mafics are biotite and hornblende in approximately equal abundance. About two percent of coarsely crystalline poikilitic hornblende to one centimetre in long dimension are characteristic of rocks linked to the Bethlehem phase. These rocks have been assigned to the Skeena variety of the Bethlehem phase. They have characterisitics intermediate between those of typical Bethlehem and those of typical Bethsaida phase rocks. They are thought to be the result of intermixing at the contact when the Bethsaida magma was injected into the earlier but only partly solidified Bethlehem phase.

The rocks here are generally only weakly altered, although local argillic or sericitic and minor copper mineralization can be found adjacent to some joints. Mafics are generally fresh, though biotite may be chloritized, especially in the alteration halos.

30.5 Turnoff to Bethlehem Copper. The trace of the major north-trending Lornex fault crosses the highway near the turnoff. The fault has significant vertical and lateral movement components. Some movement is post-ore and the Lornex and possibly the Valley Copper deposits are truncated by the fault.

31.5 STOP 3 - We continue onward on the Highland Valley road, to the Valley Copper campsite. Little outcrop, save that at the portal, is exposed here, but remnants of dumps from three thousand feet of underground workings enable one to see rocks of the Bethsaida phase as well as alteration and mineralization as seen in the Valley Copper deposit.

The Bethsaida quartz monzonite here is leucocratic, coarsely crystalline and somewhat porphyritic. Biotite is the predominant mafic and color index is normally 5 to 8. Biotite, quartz and plagioclase form coarse subhedral to euhedral crystals in a fine to medium grained matrix of quartz, plagioclase and K-feldspar.

32.5 Bethlehem Turnoff again.

35.0 STOP 4 - Bethlehem Mine - depending on the time, we will have lunch at Valley Copper or here at the viewpoint overlooking Huestis Pit and Highland Valley. After lunch, we will visit the Mine office and the operation. The areas to be visited will be dictated by mining and weather conditions. A detailed description of the deposit is appended: Briskey: "Bethlehem Copper's Jersey, East Jersey, Huestis and Iona deposits."

48.0 If there is room in the Hotel, we will continue onward through Highland Valley and stay overnight at the town of Logan Lake; if not, we will return to Cache Creek. Expected arrival time 1700 hours.

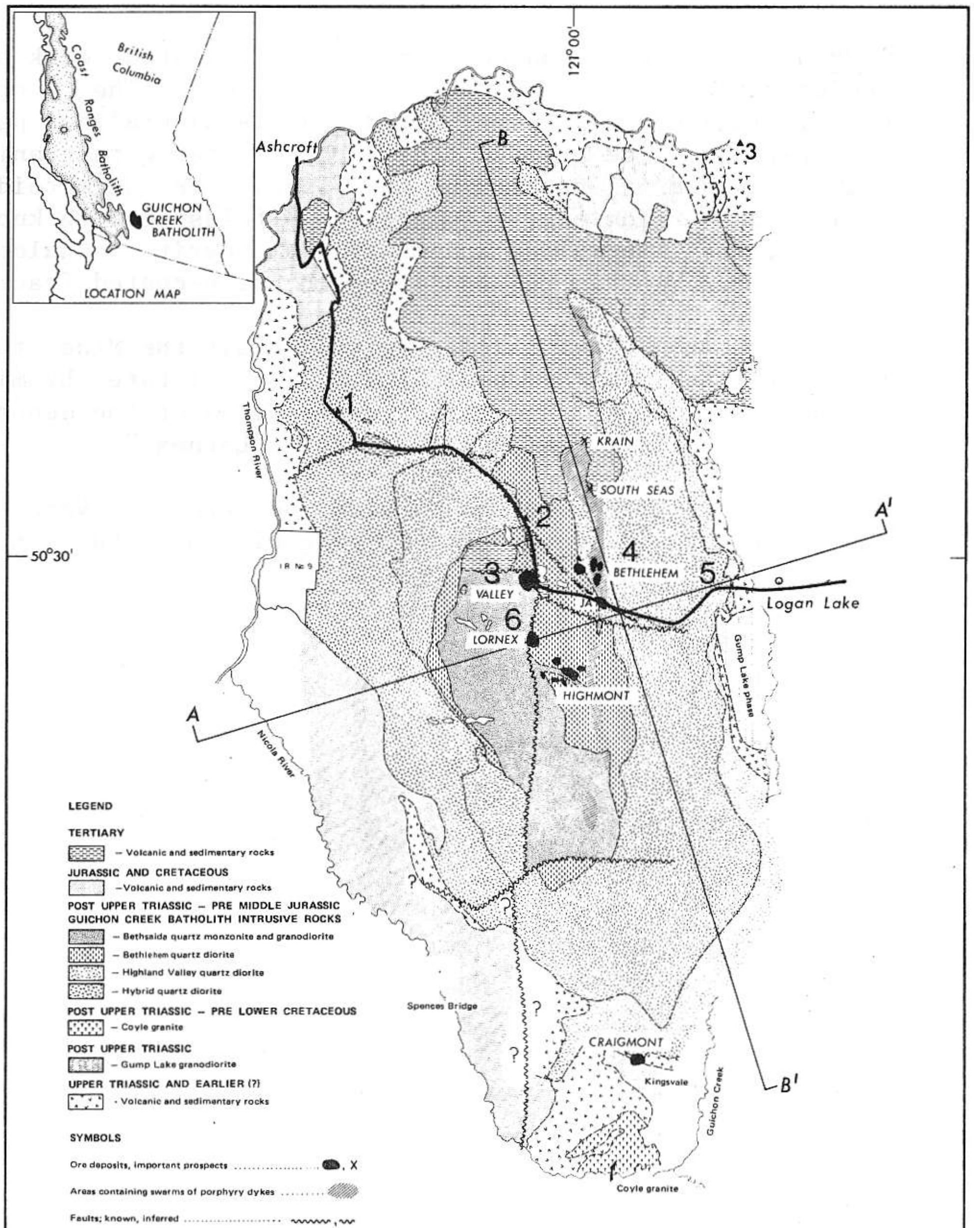


FIGURE 1

SIMPLIFIED GEOLOGY OF THE GUICHON CREEK BATHOLITH.

scale 0 4 8 miles

scale 0 8 16 kilometres

DAY 3: LOGAN LAKE OR CACHE CREEK TO LORNEX MINE AND RETURN TO VANCOUVER. DEPARTURE 0800 HOURS.

(W. J. McMillan, M. J. Osatenko)

Mileage

From Logan Lake

2.8 STOP 5 - A highway road cut consists of foliated, dark gray, medium grained Hybrid quartz diorite breccia. The outcrop is cut by plagioclase porphyry dykes and has mineralized pegmatoid segregations. The exposed face is brecciated with granitic and pegmatoid material separating the blocks. The pegmatoid segregations are predominantly quartz and K-feldspar with knots of epidote, some tourmaline and minor chalcopyrite. Chalcopyrite is also spottily distributed along chlorite-coated fractures.

(cumulate fragments)

11.0 STOP 6 - Lornex Mine Office. We will visit the Mine office, then the operation. The areas visited will be dictated by mining and weather conditions. A detailed description of the deposit is appended: Waldner, Smith and Wallis: "Lornex."

255.0 We will visit Lornex in the morning and return to Vancouver during the afternoon. Expected arrival time will be between 6 and 7 in the evening.

Geology and Genesis of the Highland Valley Ore Deposits and the Guichon Creek Batholith

W. J. McMillan,
Department of Mines & Petroleum Resources,
Victoria, B.C.

Introduction

THE HIGHLAND VALLEY porphyry copper district is situated 40 km southeast of Cache Creek and 54 km southwest of Kamloops (Fig. 1). The deposits which comprise the district lie within the late Upper Triassic Guichon Creek batholith. The batholith, which has a surface area of about 1000 km², is a semi-concordant domal body that is elongated slightly west of north. It intrudes sedimentary and volcanic strata of the Permian Cache Creek and Late Triassic Nicola groups and is unconformably overlain by sedimentary and volcanic strata ranging in age from Early Jurassic to middle Tertiary (Fig. 2).

Five major deposits, each of which is described in detail in this volume, occur in the Highland Valley district. These include two operating mines, Bethlehem and Lornex, and three potential mines, Valley Copper, Highmont and Bethlehem's J.A. deposit. Two other deposits, Krain and South Seas, which have similar grades, but smaller tonnage potential, have been extensively tested, and several other deposits, among them Ann Number 1 and Minex, have been delineated. The producing and potential producing mines and the Krain deposit are described in this volume. Numerous small, high-grade vein deposits are scattered throughout the district and several, e.g., OK (Alwin), Snowstorm and Aberdeen, are former producers. Aggregate ore reserves for the 65 km² (5 mi.²) central part of the Highland Valley district are expected to be almost two billion tonnes of 0.45 per cent copper equivalent — the major reserve of British Columbia. This figure includes known reserves from: Bethlehem (55 million tonnes of 0.47 per cent copper); Lornex (392 million tonnes of 0.411 per cent copper and 0.014 per cent molybdenite); Valley Copper (700 million tonnes of 0.48 per cent copper); Highmont (136 million tonnes of 0.285 per cent copper and 0.051 per cent molybdenite); and J.A. (260 million tonnes of 0.43 per cent copper and 0.017 per cent molybdenum). Reserves of smaller deposits are: Krain (15 million tonnes of 0.5 per cent copper); Ann Number One (48 million tonnes of 0.27 per cent copper); and Minex (36 million tonnes of 0.2 per cent copper). Mineralization is erratic in the South Seas deposit and there are no reliable tonnage estimates.

Regional Setting

The Guichon Creek batholith is one of a series of plutons which are associated and probably comagmatic with late Upper Triassic volcanic rocks of the Intermontane belt that form a northwest-trending zone

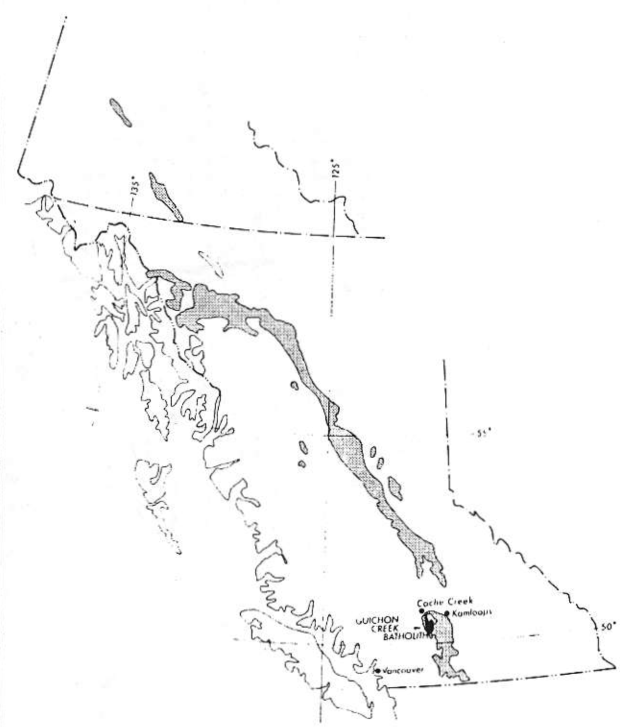


FIGURE 1 — Distribution of Late Upper Triassic volcanic rocks in the Canadian Cordillera.

extending from southern British Columbia into southwestern Yukon Territory (Fig. 1). These volcanic and associated plutonic rocks, which display both calc-alkalic and alkalic differentiation trends (Barr, Fox, Northcote and Preto, this volume; Preto, 1976), are interpreted to be products of island-arc volcanism (Gabrielse and Reesor, 1974). Furthermore, these volcanic rocks are presumed to have been derived from partial melting of subducted oceanic crust and it has been suggested that they were deposited on rocks of the Paleozoic Cache Creek Group which were part of the oceanic crust (Monger *et al.*, 1973). Cache Creek and Nicola rocks in the Highland Valley area are either in fault contact (Carr, 1962) or their contacts are ambiguous. Elsewhere, however, Cache Creek rocks were deformed and metamorphosed before Triassic time (White, 1959; Patterson and Harakal, 1974). For example, Triassic rocks unconformably overlie metamorphic rocks which are probably derived from rocks of the Cache Creek Group at Salmon River (Preto, 1964; Campbell and Okulitch, 1973). In other areas,

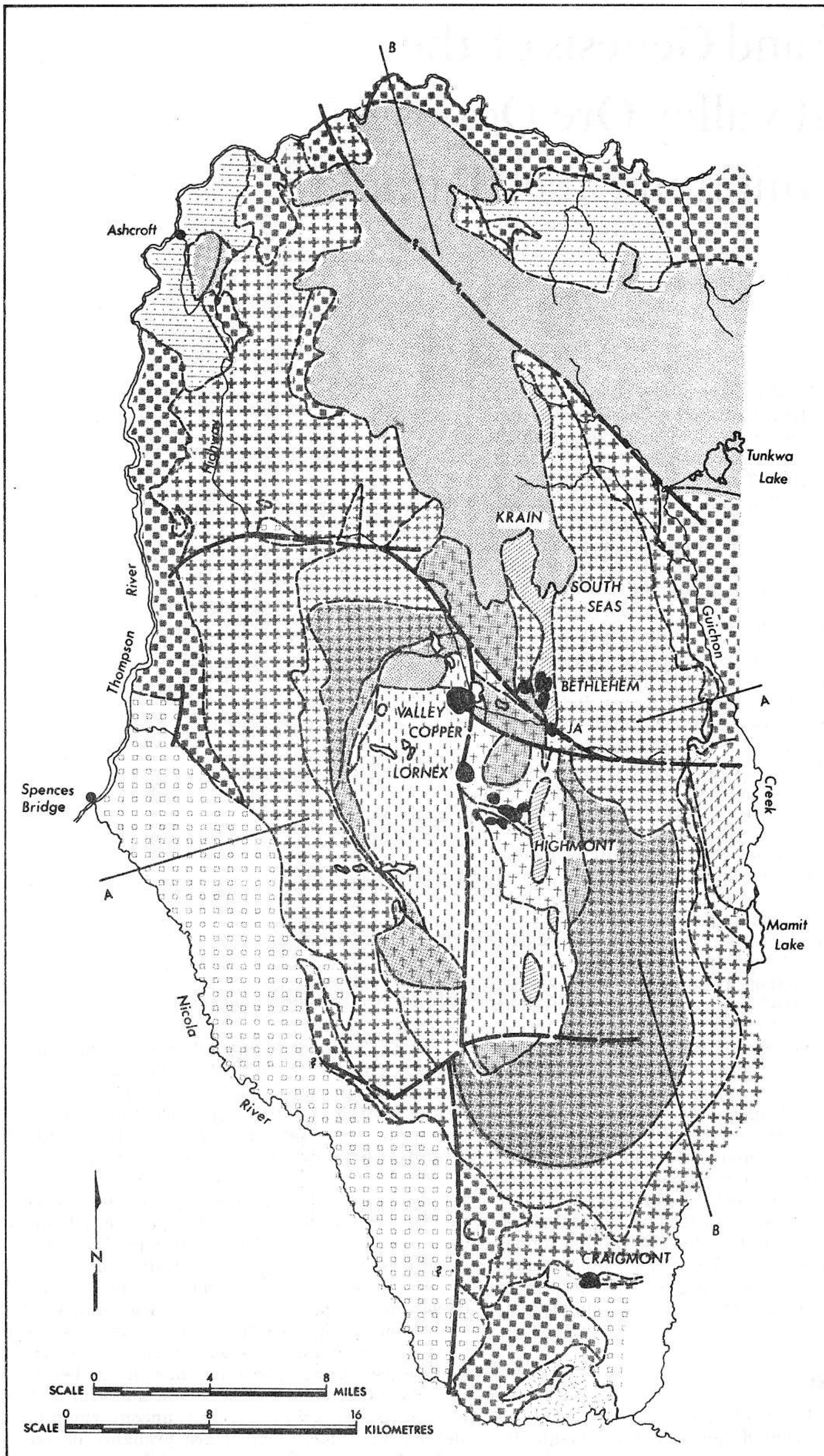


FIGURE 2 — Geology of the Guichon Greek batholith.

the contact appears conformable, but over-all it probably crosscuts units in the Cache Creek succession (Cockfield, 1948). Adjoining the Guichon Creek batholith on the west, rocks mapped as Cache Creek (Duffel and McTaggart, 1952) are lithologically similar to those of the Nicola Group and may have been mistakenly identified originally.

Cache Creek rocks appear to have been deposited in two volcanic arcs separated by a belt of oceanic rocks (Monger, 1972). Late Triassic rocks were apparently deposited in volcanic arcs and trenches or in trench-arc gaps (Price and Douglas, 1972, p. 21). In view of their depositional settings, it is reasonable to expect relationships between Cache Creek and Nicola strata in different areas to vary. For example, although no unbroken succession has been found, it is conceivable that sedimentation in some areas occurred continuously from Pennsylvanian through into Upper Triassic time, whereas in other areas deformation and metamorphism with accompanying uplift and erosion produced angular unconformities.

General Geology

The oldest rocks exposed adjacent to the Guichon Creek batholith are Cache Creek Group sedimentary and volcanic rocks of Permo-Carboniferous age that outcrop west of the batholith and west of the Thompson River (Fig. 2). These rocks include argillite, chert, conglomerate, grit, greywacke, tuff and some quartzite. Clasts in the conglomerates include well-rounded pebbles to cobbles of chert, cherty tuff and fine-grained igneous rock. Some zones within the Cache Creek Group are predominantly greenstone, with interlayers of chert, limestone and chert breccia.

Metamorphic rocks adjacent to the batholith, herein included in the Nicola Group, were formerly assigned to the Cache Creek Group (Duffel and McTaggart, 1952; Northcote, 1969). These include hornblende-plagioclase gneiss, schist, quartzite and hornfels that occur in a metamorphic halo ranging up to 500 metres in width. Near the batholith contact, mineral assemblages are typical of the hornblende hornfels facies; away from the contact, albite-epidote facies assemblages are normal. Porous impure sandstones have been extensively epidotized and impure limy strata converted to epidote skarn that may contain local pods and grains of chalcopyrite.

Upper Triassic rocks of the Nicola Group envelop the batholith and locally form roof pendants within it. Lithologically, Nicola rocks are similar to those of the Cache Creek Group, so that fossils are needed to distinguish between the two with confidence. Volcanic flows and breccias predominate at the north edge of the batholith, whereas sedimentary rocks are prominent constituents along the east, south and west edges.

Volcanic rocks in the Nicola Group are predominantly basalts and basaltic andesites. Locally, abundant volcanic breccias and agglomerates signal the former presence of volcanic centers. Most of the breccia fragments are lava, but some granitic fragments are found locally. The granitic clasts are typically quartz-feldspar porphyries, which do not resemble any of the phases of the Guichon Creek batholith. Sedimentary rocks include chert, siltstone, sandstone, greywacke, limestone, and volcanic conglomerate which grades to sedimentary volcanic breccia. Where sedimentary grains are large enough to be recognizable they are generally of volcanic provenance, although rare quartz porphyry and aplite pebbles occur in the conglomerates. Soft-sediment deformation structures, ball and pillow structures, cross-bedding, graded bedding and scour erosion structures occur in various siltstone, sandstone and greywacke beds. Pyrite is abundant in most of the noncalcareous sediments.

TERTIARY
VOLCANIC AND SEDIMENTARY ROCKS
CRETACEOUS (?)
VOLCANIC AND SEDIMENTARY ROCKS
JURASSIC
SEDIMENTARY ROCKS
INTRUSIVE ROCKS OF THE BATHOLITH
POST-BETHSAIDA DYKES
BETHSAIDA PHASE
POST-SKEENA DYKES AND PLUGS
SKEENA VARIETY
POST-BETHLEHEM DYKES AND PLUGS
BETHLEHEM PHASE *
HIGHLAND VALLEY PHASE
CHATAWAY VARIETY
GUICHON VARIETY
HYBRID PHASE
INTRUSIVE ROCKS OF UNCERTAIN AFILIATION
GUMP LAKE PHASE
COYLE "GRANITE"
UPPER TRIASSIC
VOLCANIC AND SEDIMENTARY ROCKS

SYMBOLS
BRECCIA BODIES .... ▲▲ OR
ORE DEPOSITS, IMPORTANT PROSPECTS x
AREAS WITH SWARMS OF PORPHYRY DYKES ....
FAULTS, MAPPED, INFERRED ....
SECTION LINES FOR GRAVITY PROFILES .... A — A

* DESIGNATION OF GRANITIC UNITS AS PHASES OR VARIETIES FOLLOWS THE USAGE OF NORTHCOTE, 1969.

LEGEND for Figure 2 — as well as Figs. 3, 4, 6, 7, 12 and 13.

Guichon Creek Batholith

The Guichon Creek batholith is a semi-concordant dome that is elongated slightly west of north. It consists of several nearly concentric phases which have sharp contacts locally, but are generally gradational (Fig. 2). Extensive K/Ar dating (Northcote, 1969) has shown that, within limits of analytical error, all phases began retaining argon at the same time, 198 + 8 m y ago. Geological data, however, indicate that the phases are progressively younger from the border of the batholith inward.

Various phases of the batholith have been distinguished on the basis of compositional and textural criteria and are established as formal names (Northcote, 1969), as follows.

1. The border, or Hybrid, phase is generally a fine- to medium-grained mafic-rich diorite or quartz diorite. Locally, it carries country-rock inclusions and, as a result of contamination, ranges from amphibolite to monzonite in composition.

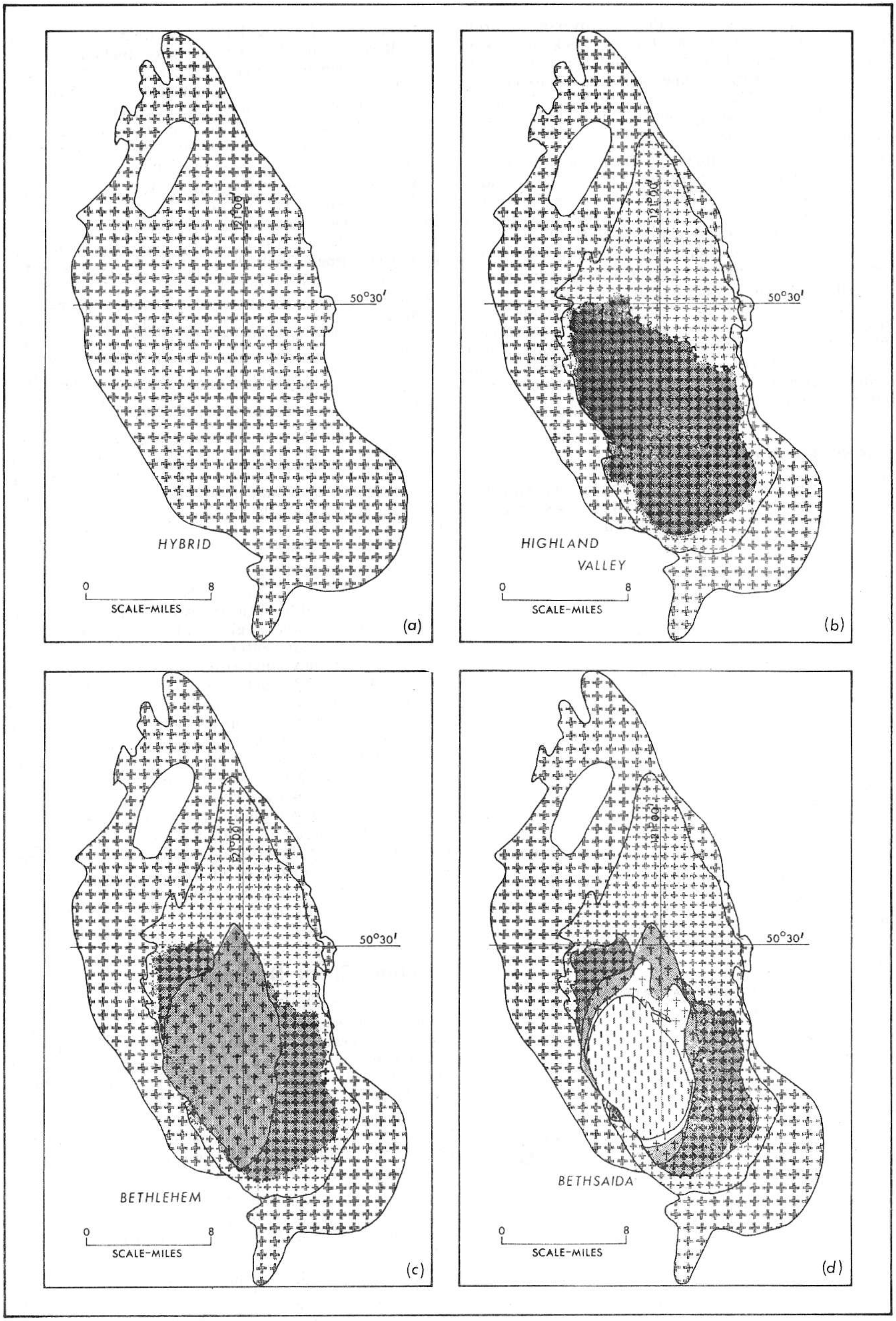


FIGURE 3 — Intrusive history of the batholith. (For legend, see Figure 2.)

2. The Highland Valley phase consists of the Guichon and Chataway varieties. The Guichon variety is quartz diorite to granodiorite that normally contains 15 per cent mafic minerals in unevenly distributed clusters of subhedral to euhedral crystals. The Chataway variety is largely granodiorite, but normally contains 12 per cent evenly distributed mafic minerals which form subhedral (blocky) crystals. In the Guichon variety the abundances of biotite and hornblende are roughly the same, but in the Chataway variety hornblende predominates. Intercalated contacts between the two varieties are common, but these are gradational and no chilling is evident.

3. The Bethlehem phase, which is also granodiorite, normally contains 8 per cent mafic minerals. It is characterized by several per cent of coarse-grained poikilitic hornblende crystals distributed irregularly in a matrix containing evenly distributed fine- to medium-grained mafic crystals. Quartz in these rocks is ameboid in shape.

In most areas of the batholith, the Bethlehem phase is in gradational contact with the younger Bethsaida phase. The borders of this contact zone are arbitrary, but rocks within it are fairly distinctive and are mapped as the Skeena variety. The Skeena variety is predominantly granodiorite. Mafic textures are similar to those of the Bethlehem phase, but over-all grain size is larger, mafic content is slightly lower, and quartz is coarse grained and subhedral to anhedral. Skeena granodiorite is abundant south of Highland Valley, where it is cut by the Gnawed Mountain dyke, an offshoot of the Bethsaida phase. In that area, it is probably underlain at shallow depth (1 to 2 km) by Bethsaida quartz monzonite.

4. The Bethsaida phase varies from quartz monzonite to granodiorite. It normally contains 6 per cent mafic minerals. Biotite, which forms coarse-grained euhedral books, predominates in the northern half of the pluton, but biotite and hornblende are equally abundant in the southern half.

A swarm of porphyry dykes which are younger than Bethlehem Granodiorite extends northward from Highland Valley and comprises a zone which includes the Bethlehem, South Seas and Krain deposits. Textural and chemical similarities (Briskey and Bellamy, this volume) suggest that many of these dykes are derived from the Bethlehem phase. South of Highland Valley, on the same trend, are dykes and small plugs of porphyry which cut the Skeena variety. At least some of these porphyries are offshoots of the Bethsaida phase and some, although they are apparently related to it, cut the Bethsaida phase.

Proceeding from the border to the center of the batholith, age, colour index, specific gravity and magnetic susceptibility normally decrease, whereas grain size and rock acidity increase.

Mineral showings of copper or copper and molybdenum are widely distributed within the batholith. However, all the large deposits are either associated with the dyke swarm north of Highland Valley or occur in or near the contact of the Bethsaida phase and related dykes. If the majority of the dykes north of Highland Valley are late differentiates from the Bethlehem phase, then mineralization at Bethlehem, South Seas and Krain is of post-Bethlehem, pre-Bethsaida age. In contrast, deposits in and south of Highland Valley all appear to be younger than Bethsaida-phase rocks. As outlined in the detailed papers in this volume, Highmont, Lornex and Valley Copper are definitely younger and the J.A. deposit is inferred to be. Thus, it is conjectured that the deposits north of Highland Valley which have copper but negligible molybdenum are older than the copper and copper-molybdenum deposits to the south. However, potassium-argon dating of hydrothermal minerals from the deposits gives dates which are virtually identical to those of the rocks of the batholith (Blanchflower, 1971; Dirom, 1965; Jones *et al.*, 1973).

INTRUSIVE HISTORY OF THE BATHOLITH

An attempt has been made to unravel the intrusive history of the batholith by restoring fault movements and by sequentially eliminating phases of it from youngest to oldest in light of their geological relationships. Figure 3 shows restored plan views of the batholith at various stages during its history. The intrusive process started with Hybrid-phase magma rising along a zone of structural weakness and spreading laterally when it reached a depth where it was able to shoulder aside overlying rocks — a depth roughly equivalent to the Cache Creek/Nicola contact. Some country rocks were assimilated and others at the batholith contacts were metamorphosed into the hornblende hornfels and albite-epidote hornfels facies. Flow alignment of plagioclase and mafic minerals in the Hybrid phase and Guichon variety as well as mineralogical evidence (Westerman, 1970) suggest that the magma was convectively overturning at that time. The restored plan of the batholith at the close of emplacement of the Highland Valley phase (Fig. 3b) indicates that the Hybrid and Highland Valley phases form a differentiation sequence from Hybrid phase to Guichon variety to Chataway variety.

The Bethlehem phase clearly crosscuts projected contacts of the Highland Valley and Hybrid phases (Fig. 3c). Contacts, which vary from gradational to sharp, probably indicate that the Bethlehem phase was intruded prior to complete crystallization of the Highland Valley phase. Plagioclase in the Bethlehem and Bethsaida phases has complex oscillatory zoning, in contrast to simple normal zoning of plagioclase of the early phases. Oscillatory zoning and crystallization of quartz before plagioclase indicate that higher volatile pressures existed in these younger magmas and also that the magmas were static (i.e., convective overturning did not occur) (Westerman, 1970).

The Bethsaida phase crosscuts rocks of the Bethlehem phase and forms dykes and small plugs in them (Fig. 3d). However, the narrow to wide expanse of Skeena-variety rocks of intermediate character indicates that the younger phase invaded the older before crystallization was complete. The Skeena variety probably represents intermixing of Bethlehem and Bethsaida magmas. Dyke swarms in the batholith and some oscillatory zoning of plagioclase are probably related to episodic release of volatiles accumulated during magmatic crystallization. Dykes north of Highland Valley, which are texturally and chemically similar to the Bethlehem phase, are probably late-stage offshoots of Bethlehem-phase magma; those south of Highland Valley, which have close textural affinity to the Bethsaida phase, are probably late-stage offshoots of the Bethsaida-phase magma. Despite the different ages inferred for these dyke swarms, they have the same trends and, taken together, comprise one elongate, north-striking zone (Fig. 2). This long-lasting zone of tension developed along what is now the eastern margin of the exposed part of the Bethsaida phase and extended northward.

GRAVITY MODELS

Gravity data from three detailed profiles (Ager, McMillan and Ulrych, 1972), together with density, magnetic and geological data, have been used to calculate models of the three-dimensional shape of the batholith (Fig. 4). In the models, the Highland Valley and younger phases are treated as one density unit and the Hybrid phase and country rock as a second unit. Therefore, only the Highland Valley/Hybrid contact shown on the figure is based on gravity data: all other contacts are inferred geologically. The gravity survey indicates that the batholith is a flattened, funnel-shaped body. The spout of the funnel underlies Highland Valley at more than 8 km depth and plunges about 80 degrees toward the northeast. The average depth to the base of the batholith below the present surface is about 6 km. The dyke-swarm zone lies above the "spout", and dyke emplacement may have been related to doming above the molten core and feeder zone of the batholith.

Post-Batholith Rocks

JURASSIC SEDIMENTARY ROCKS

A period of quiescence apparently followed emplacement of the batholith. Between cessation of Triassic volcanism and deposition of sediments in early Jurassic time, the batholith became a positive area in which erosion removed virtually all the Triassic cover from the granitic rocks. By early Jurassic time, granitic debris was being shed from the batholith into shallow marine basins along its north and west flanks. No volcanism accompanied the sedimentation.

The Jurassic sediments that now form the Ashcroft Formation range in age from Hetangian or Sinemurian to at least Callovian (Frebold and Tipper, 1969; Duffel and McTaggart, 1952; Frebold, pers. comm., 1972, 1973, 1975). For the most part, they uncomformably overlie Nicola strata, but also lap onto rocks of the border phase of the batholith. The Jurassic/Nicola contact has marked angular discordance where it is observed (McMillan, 1974).

Sedimentation occurred in structural depressions, both synclinal troughs (Duffel and McTaggart, 1952) and grabens, off the north and northwest flanks of the batholith. Basal conglomerate gives way upward in most areas to siltstone, shales and fine-grained sandstones. Locally, fetid bioclastic limestone bodies occur near the base of the succession (Carr, 1962; McMillan, 1974) and conglomerate beds are scattered throughout it.

CRETACEOUS VOLCANIC AND SEDIMENTARY ROCKS

Cretaceous rocks are exposed in a northwesterly trending belt that crosses the southwest flank of the batholith (Fig. 2). The belt includes rocks of the Spences Bridge Group of Aptian age and the Kingsvale Group of Albian age. Normally the two groups are conformable, but locally they are unconformable. The assigned ages are based on plant remains, but potassium-argon isotopic ages create some doubt. Kingsvale rocks near the Craigmont mine have yielded an age of 80 m y (Lowden, 1963) and rhyolite from rocks mapped as Spences Bridge Group has recently been dated at 48.7 ± 1.4 m y. The recent date indicates either that Tertiary volcanic rocks cut the Spences Bridge Group or that the Spences Bridge Group is not of Cretaceous age.

The Spences Bridge Group consists predominantly of pyroclastic rocks and andesitic to dacitic flows, but

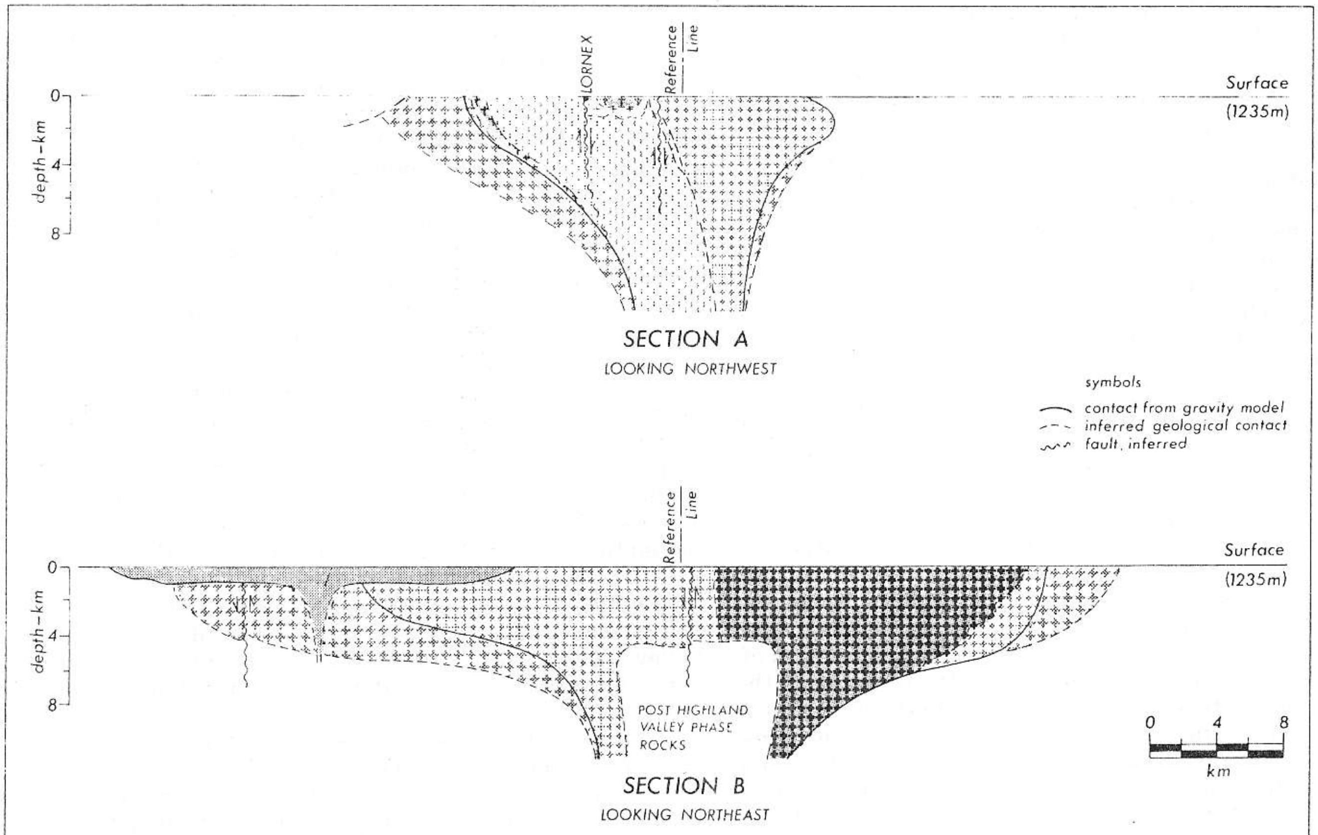


FIGURE 4 — Gravity profile models of the batholith. (For legend, see Figure 2.)

includes local water-lain tuff, rhyolite and basalt. Intercalations of sandstone, arkose or rare black shale occur toward the top of the succession. Only plant fossils have been found in the succession. Apparently the sediments were non-marine.

The Kingsvale Group has a basal member consisting either of a sequence of conglomerate, greywacke, arkose, sandstone and argillite or of agglomerate (Rice, 1948: Duffel and McTaggart, 1952). Pyroclastic breccias and varicoloured rhyolitic, andesitic and basaltic flows overlie the basal member.

TERTIARY ROCKS

Tertiary volcanic and sedimentary rocks unconformably overlie Jurassic and older rocks at the north end of the batholith. If sedimentary rocks occur, they normally form a basal member composed of conglomerates and sandy to muddy, poorly indurated sediments. Lava flows and volcanic breccias are intercalated with and overlie the sediments. Most of the lavas are dacitic to andesitic, but occasional flows are basalt or rhyolite. These rocks occur in basins that are typically fault-bounded, and they are important in the context of this paper because they overlie granitic rocks near the Krain deposit and along Highland Valley.

Tectonic Fabric of the Guichon Creek Batholith

The Guichon Creek batholith is oval in outline and elongated slightly west of north. Its average width is 20 km, its approximate length 65 km. Carr (1966) suggested that this elongation reflects the influence of deep-seated structures, and geological and gravity models support this interpretation (Ager, McMillan and Ulrych, 1973). Localization of Jurassic and Cretaceous depositional basins and the distribution of regional faults in the late Cretaceous to Tertiary interior basin and range fault zone (Eisbacher and Templeman-Kluit, 1972) may also have been controlled by older basement structures. The batholith is almost enclosed by long, narrow grabens (Fig. 5), and those along its northern and southern edges are filled with younger marine and continental sedimentary and volcanic rocks.

The batholith is also internally divided into segments by northerly and northwest to westerly striking faults. The major northerly structures are the Lornex and Guichon Creek faults; from north to south, the major northwesterly structures are the Barnes Creek. Highland Valley and Skuhun Creek faults (Fig. 6). Both fault sets played important roles in localizing mineralization. Large-scale tension features have orientations similar to those of the faults. The most striking of these are the northwesterly striking Gnawed Mountain dyke and the northerly striking zone of dyke swarms extending from just north of the Skuhun Creek fault to the Barnes Creek fault. These tensional features are closely associated with mineralization at the Highmont, J.A., Bethlehem, Krain and South Seas deposits.

The Lornex fault is well defined between Skuhun Creek and Highland Valley, where it truncates the Lornex deposit on the west and apparently truncates the Valley Copper deposit on the east. Geologic contacts along this segment of the fault show 5 to 6 km of cumulative right-lateral offset. The dip of the fault near Lornex varies from moderate to steep toward the west. Near Valley Copper, the trace of the fault down the south slope of Highland Valley sweeps eastward, which might mean that the dip there is steeply eastward. However, because drill results suggest that the fault splits into several strands south of Valley Copper it is possible that the strike, not the dip, may have changed. Drill results also show that the main strand of the fault dips steeply near Valley Copper (McMillan, 1971). Although lineaments and faults occur both north along the projection of the Lornex fault trace and east of it, the actual position of the main strand of the Lornex fault north of Highland Valley is uncertain because outcrop is sparse and Tertiary volcanic cover is extensive. South of Skuhun Creek, on the other hand, the extension of the fault is fairly well defined in spite of sparsely distributed outcrops. The Lornex fault "jogs" where it crosses Skuhun Creek, but it is uncertain whether the jog is an offset or whether the fault was refracted as it crossed the Skuhun Creek fault. Southward, the inferred fault trace nearly coincides with and probably influenced deposition along the eastern margin of the Spences Bridge Group. Relative effects of older rocks here are obscured by the younger cover, but downward movement on the west is inferred from the distribution of younger rocks.

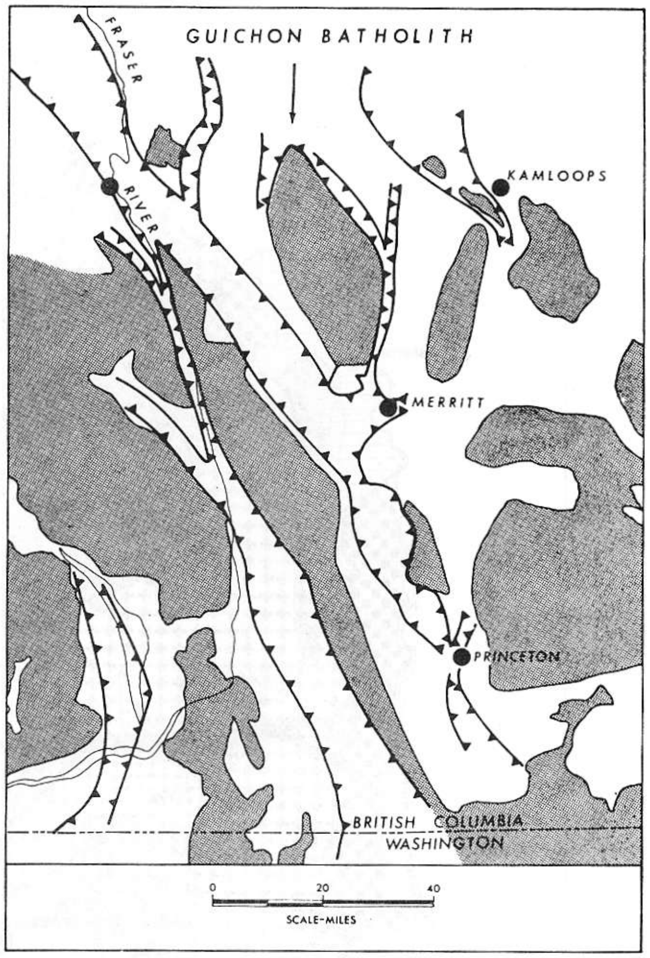


FIGURE 5 — Tectonic setting of the batholith.

The Guichon Creek fault is interpreted from geology as well as magnetic and topographic lineaments. The Gump Lake granite (Fig. 6) is evidently cut off by the fault on the east, and mercury showings occur along it near Tunkwa Lake and farther north. A lobe of granitic material east of the fault and east of the Craigmont mine apparently contains rocks which resemble those of both the Bethlehem phase and the Gump Lake granite (Christie, pers. comm., 1973). If this is correct, cumulative right-lateral movement on

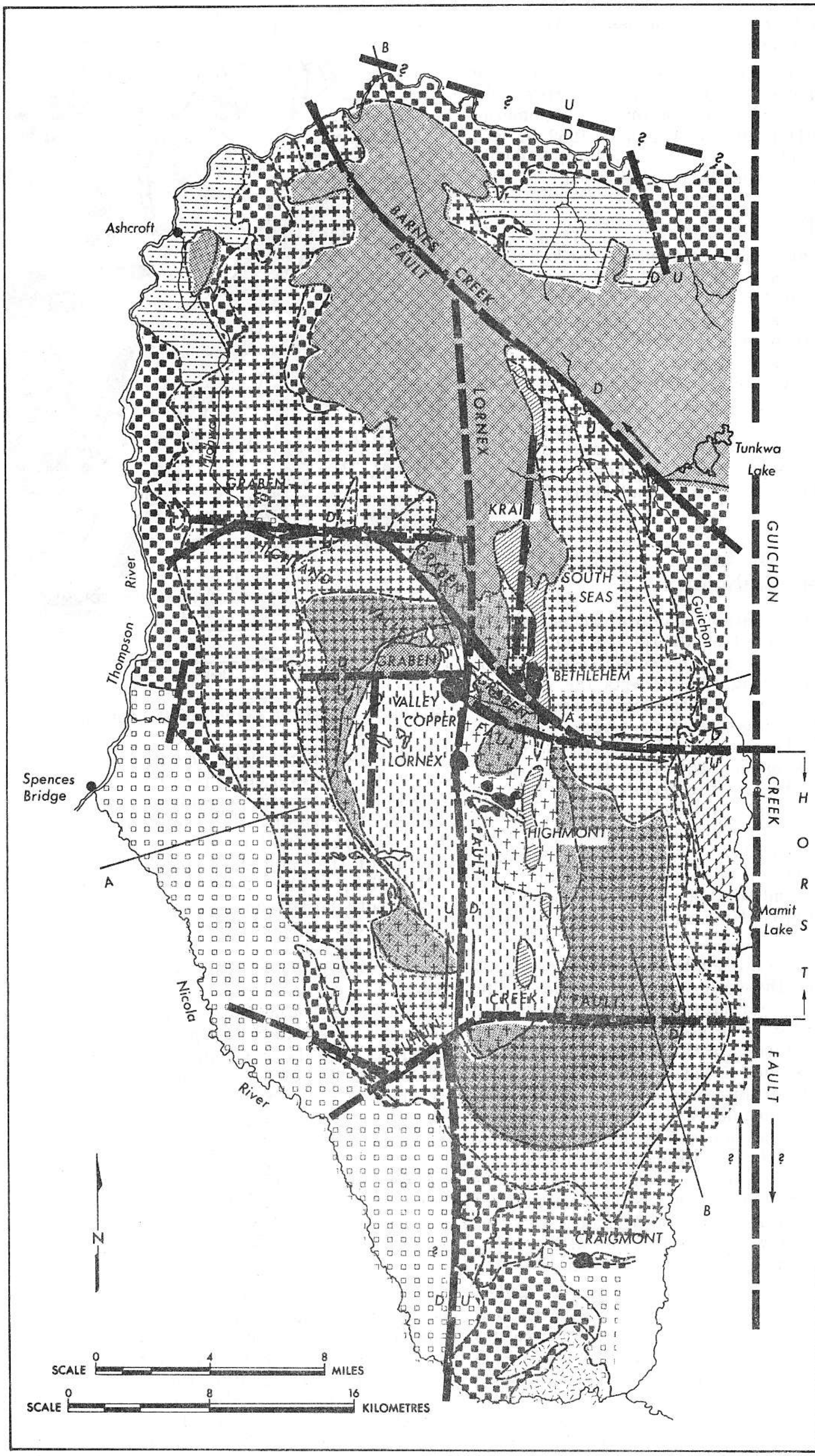


FIGURE 6 — Tectonic fabric of the batholith. (For legend, see Figure 2.)

the fault may be as much as 20 km. No mineralization of significance is known to be associated with this fault.

The area bounded by the Highland Valley and Skuhun Creek faults is apparently a horst. This interpretation is founded on the paucity of both older granitic and younger cover rocks within the area. Erosion appears to have stripped off the younger rocks and to have exposed deeper-level granitic rocks. Possibly this is a result of isostatic adjustment, because this area is underlain by a high percentage of the least dense rocks of the batholith. Remnants of Tertiary flows and dykes east of the Lornex fault and small stocks west of it suggest that Tertiary rocks formerly covered at least parts of the horst. Preservation of a wide area of Skeena Granodiorite (Fig. 4, Sect. A-A′) as well as characteristics of the ore deposits discussed later indicate that less cover was eroded from the area east of the Lornex fault and, therefore, it was less highly uplifted than the area west of the fault.

North of Highland Valley, another northwesterly striking fault is inferred to underlie Barnes Creek. Evidence for the fault includes topographic and magnetic lineaments as well as the disposition of Jurassic and Tertiary rocks northeast of Barnes Creek. The presence of depositional basins northwest of the fault during Jurassic and Tertiary times indicates downfaulting of that area. Poor outcrop and Tertiary cover rocks mask evidence of lateral offsets, but from restoration by first removing the cover, then projecting geological contacts, it appears that cumulative left-lateral movement occurred. Similar left-lateral movement is indicated for the Highland Valley fault, but little or no lateral movement is evident for the Skuhun Creek fault. Along Highland Valley, Tertiary movement produced a series of wedge-shaped grabens. Basins produced by the movement were subsequently infilled by sedimentary and volcanic rocks.

Data from various Highland Valley ore deposits suggest that the tectonic fabric of the batholith was established after intrusion of the Bethsaida phase, but prior to the formation of the deposits (several papers, this volume; McMillan, 1971; Hollister *et al.*, 1975). It is uncertain whether the strike-slip movement on the Lornex fault was initiated prior to ore deposition. If, as Carr (1967) speculated, the Valley Copper and Lornex orebodies were once joined, mismatched geological contacts indicate that lateral movement began before ore formation. However, the relationship between the orebodies and the fault at Lornex and Valley Copper is not simple. Aligning the two deposits does not produce coherent patterns of geology, grade, alteration or sulphide zoning. It is probable that Valley Copper formed at a deeper level under higher temperature conditions than Lornex, and this topic is discussed more fully later in the paper. In any case, there is strong evidence of post-ore lateral offset at Lornex (Waldner *et al.*, this volume).

Vertical movements on the faults apparently occurred periodically over a long time span. Grabens formed during Early to Middle Jurassic time localized sedimentation north of Barnes Creek and perhaps near Ashcroft. Vertical movements on the Lornex fault south of Skuhun Creek apparently controlled the eastern boundary of deposition of the Spences Bridge Group in Late Cretaceous or Early Tertiary time. Several localized Tertiary grabens formed in Eocene and possibly Oligocene time. Thus, the evidence available indicates sporadic movements, with both lateral and vertical components, beginning in Mesozoic or earlier time and continuing well into the Tertiary. In each episode, old faults were reactivated and few new faults appear to have formed.

Ore Deposits

GEOLOGICAL SETTING

The general geology of Highland Valley is shown in Figure 7 and geological features of the various deposits are summarized in Figure 8. The Krain and South Seas deposits are in Guichon Quartz Diorite that is laced with predominantly north-trending dykes. Mineralization at Krain is associated with a sheet-like body of granodiorite which, from its texture, is related to the Bethlehem phase. Most of the mineralization at South Seas is in a breccia pipe. The breccia consists largely of Guichon fragments, but also both carries and is cut by plagioclase porphyry and rhyolite porphyry. The breccia apparently resulted from explosive release of volatiles generated during crystallization of the rhyolite porphyry (Carr, 1966). Mineralization at Bethlehem Copper also occurs within the dyke swarm. There, however, it occurs in breccias and in closely fractured zones along and adjacent to the Guichon Quartz Diorite and Bethlehem Granodiorite contact. Guichon rocks are most closely fractured adjacent to digitations in the Bethlehem contact. Dykes and associated breccia bodies in the deposit cut Bethlehem and older country rocks. They were injected prior, during and after ore formation. Most are latite or dacite and virtually all are porphyritic.

The J.A. deposit also straddles the Guichon/Bethlehem contact and is cut by porphyritic dykes. However, it differs from deposits to the north because mineralization is closely allied to, but post-dates, a quartz monzonite porphyry stock that appears to be an offshoot from the Bethsaida Quartz Monzonite. Rocks of the stock closely resemble those of the composit Gnawed Mountain dyke, which is an offshoot of the Bethsaida. The Gnawed Mountain dyke is closely associated with the various Highmont deposits, Minex, Ann Number 1 and possibly Lornex. Country rock for the deposits south of Highland Valley is Skeena Granodiorite or Bethsaida Quartz Monzonite. Valley Copper lies entirely within Bethsaida Quartz Monzonite and has few associated dykes. Most of the dykes at Valley Copper are mineralized, but a few of similar composition are post-ore and there are a few much younger lamprophyre dykes (Jones *et al.*, 1972). Local breccia bodies occur both within the Gnawed Mountain dyke and adjacent to it. Although tourmalized breccia bodies are locally cut by sulphide mineralization, as for example at Minex and the southeast corner of Highmont's Number 1 zone, Reed and Jambor (this volume) conclude that sulphide deposition was largely completed before tourmalized breccias formed. No breccias have been found at Lornex or Valley Copper.

STRUCTURAL SETTINGS OF HIGHLAND VALLEY DEPOSITS

Almost all the sulphide mineralization in Highland Valley deposits is either in or closely associated with veins, fractures, faults or breccias. Fracture density was apparently the most important single factor influencing ore grades, although mineralized breccias are important at Bethlehem, South Seas and to a lesser extent at Highmont, and mineralized fault zones are significant local ore controls at Bethlehem. Grades are typically good where swarms of fractures occur and

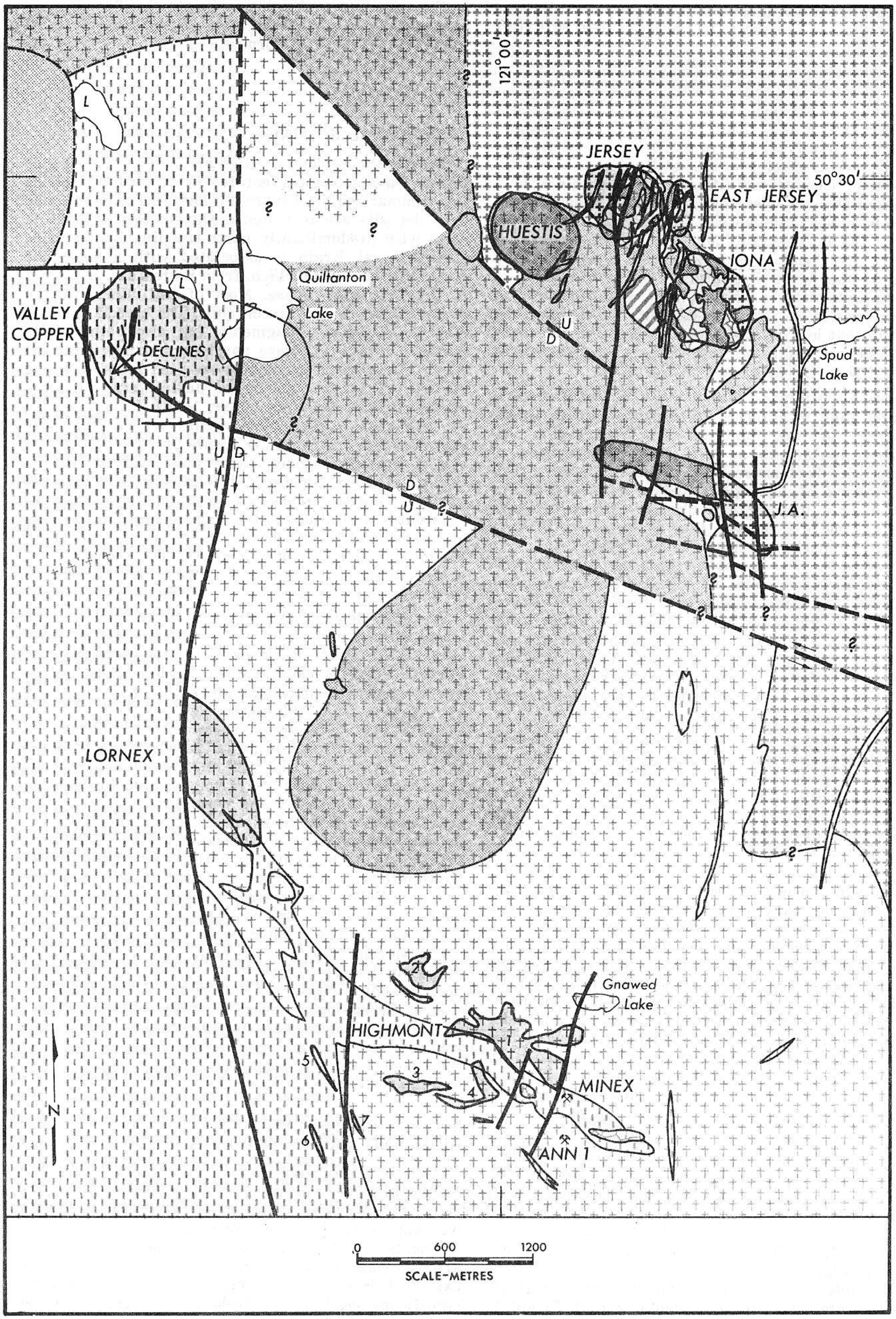


FIGURE 7 — Generalized geology of the Highland Valley area. (For legend, see Figure 2.)

better still where sets of fracture swarms overlap. At Bethlehem, northeast and lesser north-trending fracture sets at Valley Copper strike north-northwest and are elongated northeastward. In the Highmont area, ore grades occur where swarms of northeast- and northwest-trending fractures overlap in a general zone of fracturing adjacent to the Gnawed Mountain dyke (Bergey, *et al.*, 1971; Reed and Jambor, this volume). At Lornex, which occupies a closely fractured area at the contact of Skeena Granodiorite with Bethsaida Quartz Monzonite, north-northeast-, northeast- and east-trending mineralized fractures predominate and the best grades occur where all three sets overlap (Waldner *et al.*, this volume). The predominant fracture sets at Valley Copper strike north-northwest and east-southeast (McMillan, 1971), but the orebody occupies a shatter zone in which fractures are more evenly distributed than those in the other deposits.

ALTERATION AND VEINING

The following synopsis of the types of alteration and veining in Highland Valley deposits is based on work done by the writer, but also draws heavily on data on various properties presented in this volume by: Briskey and Bellamy; Christie; Reed and Jambor; and Waldner, Smith and Willis. The synopsis will begin with the distribution of quartz stockworks with associated silicic alteration, then consider potassic, phyllic, argillic, propylitic, and other alteration and veining types (Fig. 9). Subsequently, the sequences of alteration and veining will be considered.

Quartz Stockworks and Silicification

Silicification is important in areas with stockworks of quartz veins and veinlets without quartz and flakey sericite envelopes. Quartz in these stockworks is primarily fracture controlled, but also occurs as overgrowths on primary crystals and locally replaces the country rock. At Valley Copper (Osatenko and Jones, this volume), for example, the percentage of secondary quartz was estimated by subtracting the average background quartz content of the country rock. The 10 per cent secondary quartz contour thus estimated outlines the deposit; areas of greater than 0.5 per cent copper have 10 to 20 per cent secondary quartz.

Only Valley Copper and Lornex have significant quartz stockworks. That at Valley Copper occurs at bedrock surface in the southeast corner of the deposit and forms an elliptical dome-like zone which plunges northwestward (McMillan, 1971). Throughout the zone, quartz veins are on average less than 30 cm apart. This zone grades outward into the ore zone, where quartz veins are 60-150 cm apart, but is itself poorly mineralized. Like at Valley Copper, the quartz stockworks at Lornex form an elliptical dome with an axis apparently plunging northwestward; its apex was removed by erosion south of the ore zone, but the frequency of quartz veins at Lornex is lower. In most other Highland Valley deposits, quartz veins without quartz and flakey sericite envelopes are relatively abundant locally, but do not form significant zones.

Potassic Alteration

Potassic alteration characterized by deposition of hydrothermal biotite or hydrothermal K-feldspar is variably developed in Highland Valley deposits. At Valley Copper, moderately developed fracture-controlled K-feldspathic alteration occurs in the central, deeper part of the deposit. J.A. is the only other deposit with a coherent K-feldspathic alteration zone. There the carapace of the porphyry stock is flooded and veined by K-feldspar. However, the potassic zone at J.A. may be more closely allied to geological setting that to ore-forming processes. K-feldspathic alteration is also spottily developed at Lornex, but only hydrothermal biotite formed at Jersey and Highmont. This biotite is typically greenish brown in thin section and occurs either in veinlets or as crystal aggregates replacing primary mafic minerals. In the Jersey deposit, hydrothermal biotite is distributed throughout the central, better-grade zone. In contrast, the potassic zone at Highmont is very weakly developed, and only scattered biotite occurrences were noted at J.A., Valley Copper and Lornex.

Phyllic Alteration

In Highland Valley, phyllic alteration is characterized by fracture-associated zones or vein envelopes of quartz and flakey sericite (actually $2M_1$ muscovite). At Valley Copper, this alteration is widely and strongly developed throughout the ore zone. Phyllic alteration is a particularly important ore control at Valley Copper, because it is abundant and because much of the copper sulphide associated with it is bornite. At Lornex, phyllic alteration is important, but weaker. Areas where it is well developed are much more restricted, vein envelopes rather than quartz sericite zones predominate and the envelopes are often narrower than those at Valley Copper. At Highmont and J.A., phyllic alteration is generally weakly developed, although it is moderately abundant locally. At Highmont, according to Reed and Jambor (this volume), there is a fairly good correlation between phyllic alteration and areas of greater than 0.2 per cent copper equivalent. The average intensity of phyllic alteration decreases from Valley Copper to Lornex to Highmont and J.A.

Argillic Alteration

The term argillic alteration is used here to describe alteration of feldspars and locally mafic minerals to an assemblage typified by sericite and kaolinite with or without montmorillonite. This type of alteration occurs within the ore deposits and often extends significantly beyond the 0.3 per cent copper isopleth. Judging from data on the Jersey deposit, argillic alteration is significant down to 0.1 per cent copper (Briskey and Bellamy, this volume).

At Krain, argillic alteration occurs in the higher-grade core zone. In the Jersey deposit, argillic alteration encloses the potassic core zone and more or less coincides with a zone of epidote alteration. At J.A., moderate to intense argillic alteration occurs both in and south of the ore zone in and immediately north of the porphyry stock. Weak argillic alteration occurs more or less throughout the remainder of the orebody. Distribution of argillic alteration in the Highmont Number 1 zone is analogous to that at J.A., because it is moderate to intense both in and adjacent to the Gnawed Mountain dyke. At Highmont No. 1, argillic alteration is also moderate to intense in major fault zones and along the base of the mineralized zone. At Lornex, according to Waldner *et al.*, the orebody virtually coincides with the zone of moderate to intense argillic alteration and it, like the orebody, is truncated by the Lornex fault. The distribution of moderate to intense argillic alteration at Valley Copper, like that at Lornex, almost coincides with the distribution of ore. The most intense areas of alteration partially coincide

Deposit	Country Rock: Guichon	Bethlehem	Skeena	Bethsaida	Associated Dykes or Small Stocks	Associated Breccias
Krain	+	-	-	-	+	-
South Seas	+	-	-	-	+	+
Bethlehem	+	+	-	-	+	+
J.A.	+	+	-	-	+	-
Highmont	-	-	+	-	+	P
Ann # 1	-	-	+	-	+	-
Minex	-	-	+	-	+	+
Lornex	-	-	+	P	+	-
Valley Copper	-	-	-	+	P	-

Symbols: + abundant
P present but not volumetrically significant
- absent

FIGURE 8 — Synopsis of geological features of Highland Valley deposits.

	Valley Copper	Lornex	Highmont	J.A.	Bethlehem	Krain
Quartz Stockwork	S **	M-S	-	-	-	-
Potassic - Kfeldspar	M-S	VW	-	S	-	-
- Biotite	-	-	VW	VW	M	-
Phyllic	S	M-S	W	W	-	-
Argillic	S	M	W-M	W-M	W-M	W-M
Propylitic	W	W	M	M	M	M
Tourmaline	-	-	W	-	M	-

* see text for definition of usage of alteration terms

** S strong; M moderate; W weak; VW very weak; - negligable

FIGURE 9a — Distribution of alteration and vein minerals in Highland Valley deposits.

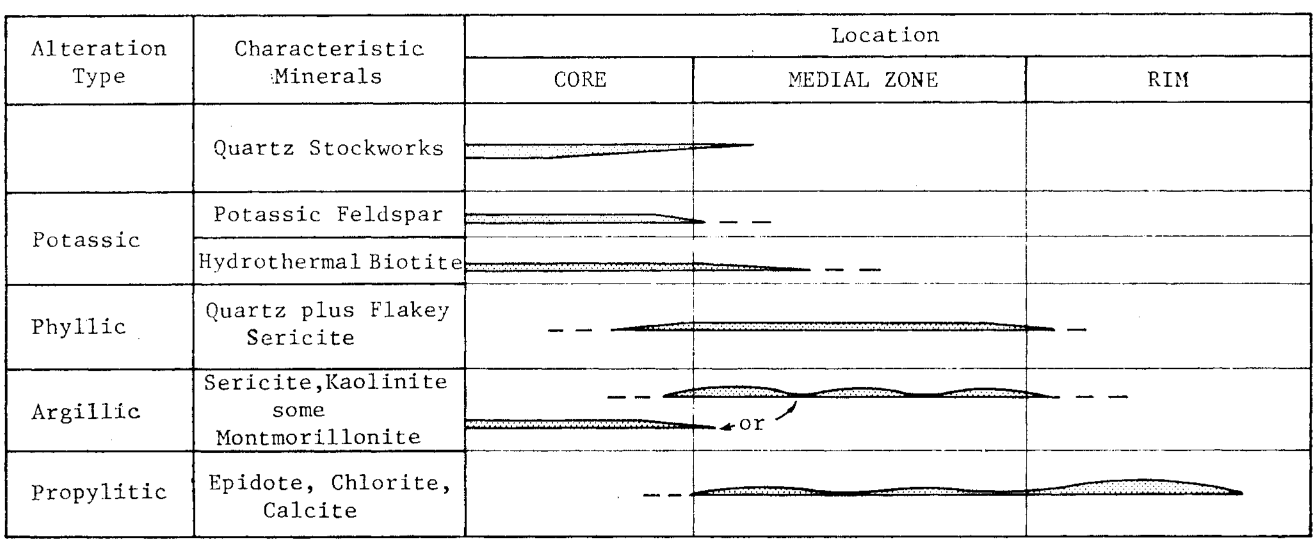


FIGURE 9b — Generalized alteration zoning of Highland Valley deposits.

with areas of greater than 0.5 per cent copper. At Valley Copper, kaolinite and sericite are abundant, but montmorillonite is uncommon.

Propylitic Alteration

Virtually all the Highland Valley deposits have propylitic alteration zones of varying width, location and intensity. In general, there is a gradation between propylitic and argillic alteration zones and in some deposits they overlap. In hand specimen, epidote has been used as the characteristic mineral of propylitic facies alteration. Chlorite is almost ubiquitous in all the deposits except Valley Copper, so it is not generally a useful facies indicator. Feldspars in propylitic zones are altered to sericite, carbonate and some clay minerals; mafic minerals are altered to chlorite and carbonate with associated epidote.

At Krain and Jersey, fairly well defined propylitic halos enclose the orebodies. In each, nearby rock is virtually fresh, but is cut by local fracture-coatings and veinlets of quartz, chlorite and epidote. At J.A. and Highmont, propylitic facies assemblages occur almost throughout the ore zones. At J.A., intensity of propylitic alteration is greater in the mafic-rich Guichon Quartz Diorite than in the Bethlehem Granodiorite country rock. At Lornex, there is a narrow propylitic alteration zone peripheral to the orebody. At Valley Copper, such alteration is weakly developed and ill-defined.

Tourmaline Distribution

At Bethlehem, South Seas and Highmont, tourmaline occurs in and near breccia bodies, where it forms crystalline aggregates, replaces clasts or replaces comminuted rock of the matrix. It is commonly associated with quartz, specularite, epidote, calcite, copper sulphides and occasionally with actinolite. At South Seas, specularite, quartz and chalcopyrite fill openings in the breccia and are generally slightly younger than quartz and tourmaline in the matrix. At Bethlehem and Highmont, quartz and tourmaline-bearing breccias are mineralized, but locally carry clasts mineralized with copper sulphides. Thus, some brecciation and associated tourmaline deposition occurred after the initiation of sulphide deposition.

Late-Stage Veining

Zeolite and calcite are locally intergrown with sulphide minerals or epidote in Highland Valley deposits, but typically they are younger. Zeolites occur primarily as veins and fracture coatings; less commonly they form pervasive alteration zones around fractures and zeolite veins. Most of the zeolite present is laumontite, but some stilbite and uncommon chabazite and heulandite occur. Zeolites commonly have intergrown calcite and occasionally have intergrown gypsum. Zeolites are common at Bethlehem and J.A., less common at Highmont and rare in the other deposits. Calcite also occurs without zeolite in veins and fractures in all the deposits. Generally calcite in this form is younger than zeolite. Gypsum, which is also largely post-zeolite, is abundant as veins and fracture fillings at J.A. and Valley Copper, occurs locally at Lornex and is reported from Highmont. Occasionally, fibrous gypsum fills vugs in main-stage quartz sulphide veins at the J.A. deposit. Anhydrite occurs in a similar setting in several deep drill holes at Valley Copper; consequently, fibrous gypsum at J.A. may be secondary after anhydrite.

Age Relationships of Alteration Types

Interpretations of age relationships of alteration types in Highland Valley vary from deposit to deposit. At Jersey (Briskey and Bellamy, this volume), ore fluids are thought to have moved upward and outward. Thus, formation of the potassic core and the fringing argillic and propylitic zones are interpreted to have been virtually synchronous. At J.A., there may have been a pre-ore weak stage of propylitic alteration. During the main stage of sulphide mineralization, phyllic with associated argillic alteration was followed by propylitic with associated argillic alteration. At Highmont, Reed and Jambor (this volume) indicate that there was an early phase of potassic alteration that was accompanied by propylitic alteration and followed successively by phyllic, argillic and additional propylitic alterations. They infer that most of the metals were introduced at the potassic stage of alteration. At Lornex, Waldner *et al.* (this volume) indicate that argillic alteration was initiated prior to main-stage sulphide mineralization and continued for a short time after it, that phyllic alteration and quartz stockwork formation occurred primarily during main-stage mineralization, and that propylitic alteration was later. At Valley Copper, the indicated sequence of alteration (Osatenko and Jones, this volume) is propylitic and then argillic, phyllic and potassic; quartz stockworks post-date potassic alteration. The various alteration types overlap in time and the main period of sulphide deposition occurred during the phyllic stage. In contrast, Reed and Jambor (this volume) argue that alteration sequences at Valley Copper and Lornex are like those at Highmont. In all cases, sequences are based on crosscutting features; however, disagreement remains. It seems likely that the discrepancies are caused in part by overlapping of alteration types, in part by variations related to distance from the source of hydrothermal solutions and in part by repetition of alteration types in response to changing temperatures or chemical compositions of the hydrothermal fluids. Zeolites in the deposits are predominantly later than sulphide deposition, and calcite and gypsum veins and fracture-fillings are younger still.

Sulphide and Oxide Zoning Of Highland Valley Deposits

In most Highland Valley deposits there is a fairly well developed metallic mineral zoning, but, because grades are structurally controlled, these patterns do not always correlate closely with grade distribution patterns. That is, although most of the deposits have zones in which bornite and then chalcopyrite and then pyrite are the predominant sulphide minerals, ore grades may or may not occur in a given zone (Fig. 10). At Krain, in the Jersey deposit, at Valley Copper and at Lornex, the core zones, which have better than average grades, are enriched in bornite relative to chalcopyrite. In contrast, only part of the bornite zones at J.A. and Highmont are of ore grade.

At Valley Copper and Jersey, sulphide zoning is almost concentric, although that at Valley Copper is complicated by superposition of younger chalcopyrite related to the central quartz stockwork. Inside the 0.3 per cent copper isopleth at Valley Copper, bornite abundance equals or exceeds that of chalcopyrite. Outside it, there is a narrow zone dominated by chalcopyrite and then a narrow, very weak pyritic halo. Pyrite in the halo is much less than 1.0 per cent. At Jersey, grades exceed 0.5 per cent copper in the bornite

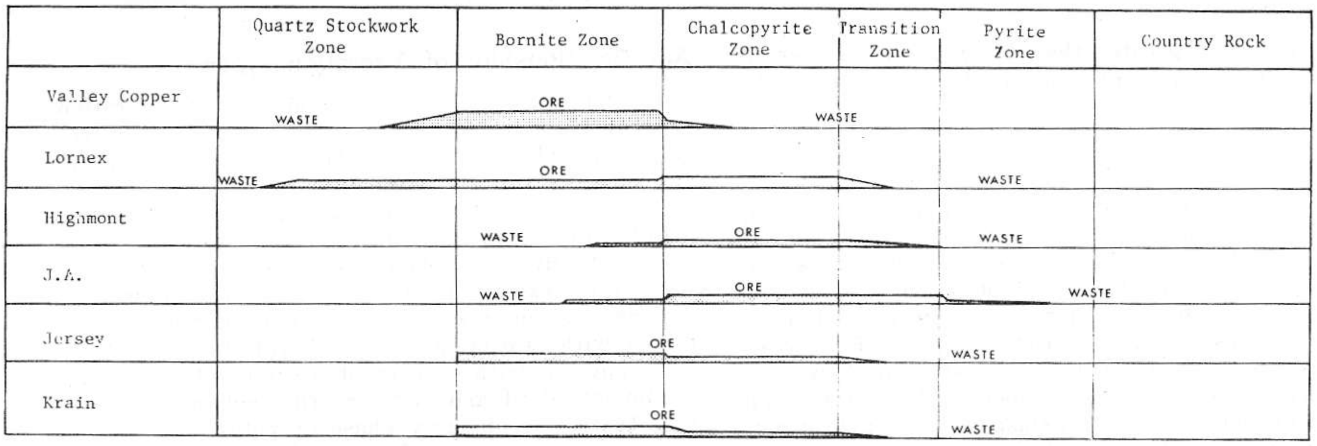


FIGURE 10 — Relationship between ore distribution and sulphide zoning in Highland Valley deposits.

zone and there are fringing chalcopyrite, pyrite and specularite zones. North of the orebody, the pyrite and specularite zones are discontinuous. At Highmont, Lornex, J.A. and Krain, sulphide zoning is not concentric. Zoning at Highmont is subparallel to the Gnawed Mountain dyke, that at Lornex is elongated and symmetric about either the quartz porphyry dyke or the structure along which it was emplaced, zoning at J.A. is related to the quartz monzonite porphyry stock and that at Krain is related to the quartz diorite porphyry stock.

Sulphide zones and alteration are not closely correlated. The bornite zones at Valley Copper and Lornex are in areas with phyllic and argillic alteration, those at Highmont and Jersey are associated with hydrothermal biotite, and those at J.A. and Krain are in areas with argillic alteration. Chalcopyrite zones generally are associated with argillic alteration, although those at J.A. and Krain partially overlap into the propylitic alteration zone. Pyritic zones generally have associated propylitic alteration.

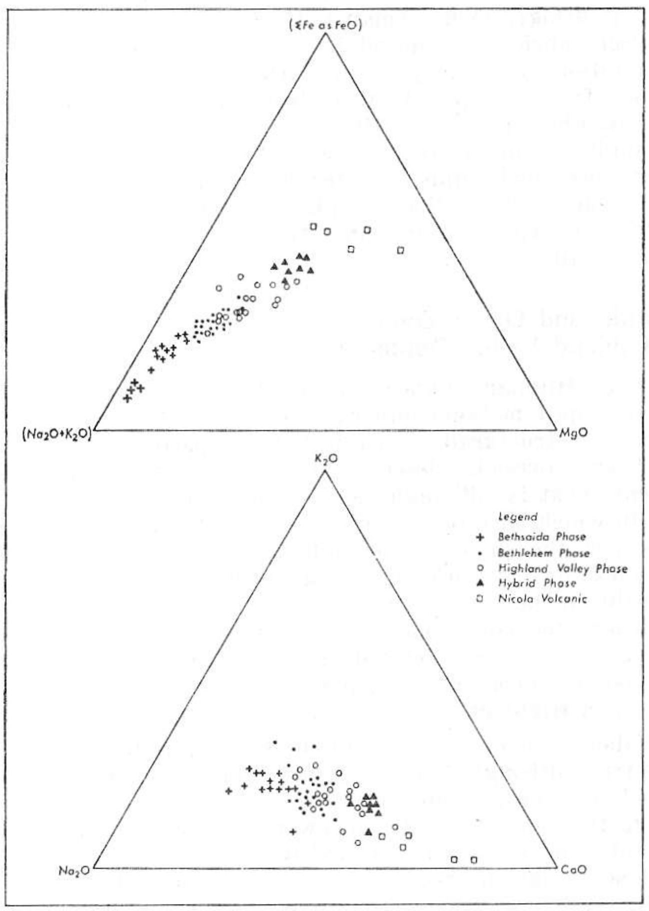


FIGURE 11 — Iron, magnesium and alkalies and AFM plots of chemical analyses of rocks of the Guichon Creek batholith.

Molybdenite contents and distributions vary widely in Highland Valley deposits. Molybdenite grade is below economically recoverable levels at Krain and Bethlehem, and slightly below that level at Valley Copper, but it is economically significant at J.A. and Lornex and is very important at Highmont. Molybdenum distribution in the deposits is similar, but not identical, to that of copper. Molybdenite occurs with quartz in veinlets in the central bornite zone at Krain, but it is generally monomineralic and in the chalcopyrite zone at Bethlehem. It occurs sparsely along the northern side of the orebody in the pyrite zone at Valley Copper, but at Lornex, J.A. and Highmont molybdenite is sparsely but widely distributed. Most molybdenite in these deposits occurs in quartz and sulphide veins. That at J.A. is most abundant in the zone with best copper grades, but it is also concentrated along the southern edge of the orebody near and in the stock. At Lornex, zones with grades exceeding 0.02 per cent molybdenum occur in both the bornite and chalcopyrite zones and locally extend out into the pyrite halo. The molybdenite and copper zones overlap considerably at Highmont, but the top of the molybdenite zone is below that of copper and its base extends below that of copper.

Geochemistry of the Batholith

Major element distribution in the Guichon Creek batholith was studied by Brabec (1971) and Olade (1974). They found that rocks of the batholith show normal calc-alkaline differentiation trends on both AFM and total iron, magnesium and alkalie plots (Fig. 11). Variations found are attributable to fractional crystallization of a diorite parent magma. However, on an alkali-lime plot, it is evident that differentiation resulted in sodium enrichment rather than more normal potassium enrichment. Differentiation of this nature is apparently typical for potassium-deficient magmas of trondhjemitic affiliation (Larson and Poldervaart, 1961; Taubeneck, 1967). In contrast, some porphyry dykes show evidence of potassium enrichment; Olade attributes these to high-level "phenomena" in cupola environments.

Two Nicola volcanic rocks analyzed by Brabec have contrasting compositions, but both are rich in iron

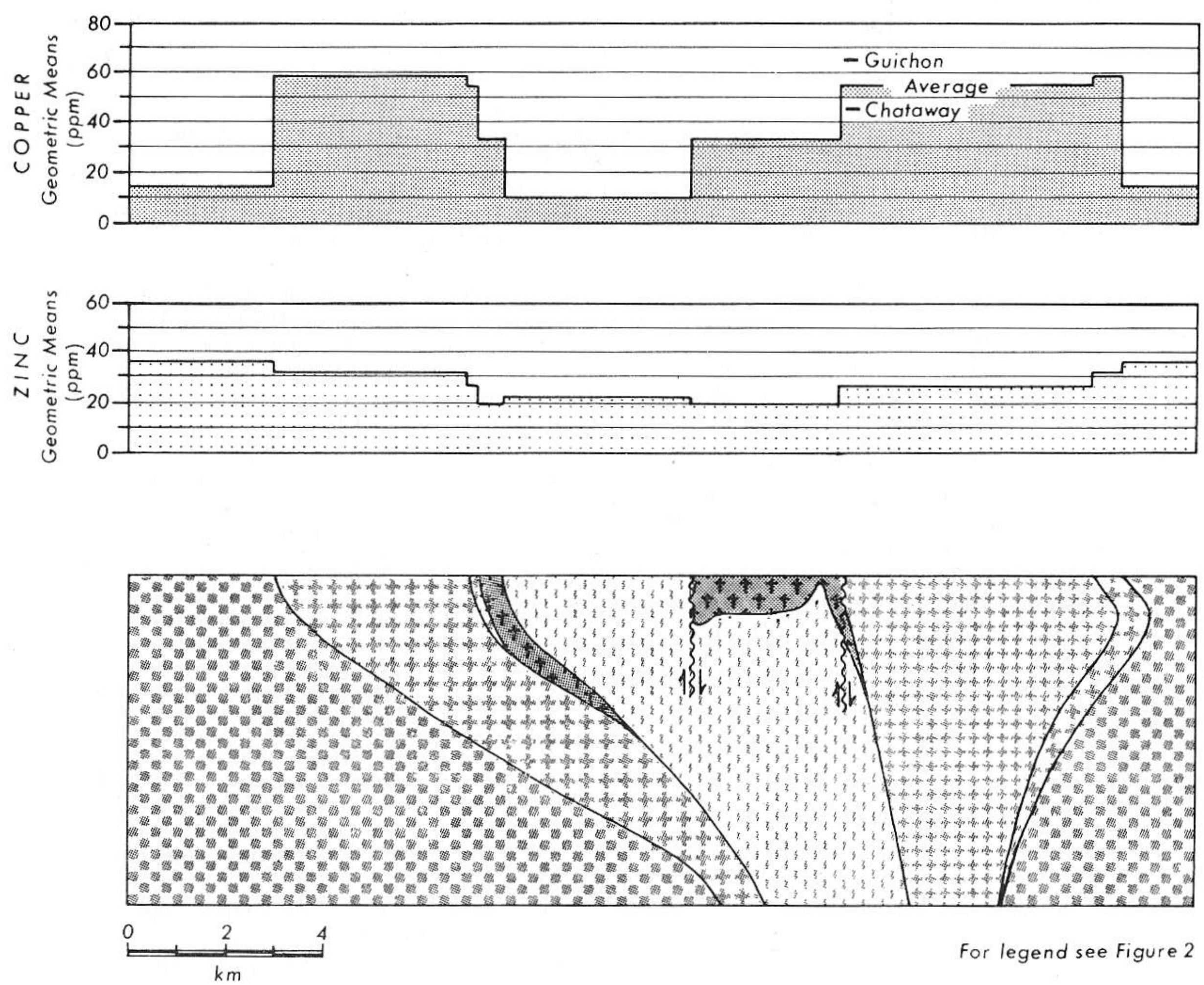


FIGURE 12 — Copper and zinc contents of various phases. (For legend, see Fig. 2.)

and calcium and poor in potassium. Five Nicola samples reported by Olade lie along differentiation trends for rocks of the Guichon Creek batholith (Fig. 11). It is possible, therefore, that these Nicola volcanic rocks and rocks of the Guichon Creek batholith were derived from the same source magma.

Minor element trends reported by Brabec and Olade are similar, despite the use of aqua-regia extraction by Brabec as opposed to total extraction by Olade. Only distributions of copper and zinc will be considered here. Both studies concluded that copper and zinc have different forms of occurrence. For example, the correlation with modal biotite abundance is not significant ($R = +0.23$) for whole-rock copper, but is significant ($R = +0.64$) for zinc (Brabec and White, 1971). It is likely that zinc in the rocks is predominantly in ferromagnesian silicates, whereas a significant proportion of the copper is in sulphide form (Brabec, 1971). Statistical plots of copper analyses (Brabec and White, 1971) show several populations of copper in the batholith. For further analysis, the data were divided into three populations: Hybrid phase, Highland Valley phase and younger rocks. Copper values within each population are apparently distributed lognormally and geometric means of copper content for each population and various phases of the batholith were calculated. These means show that older marginal phases are considerably richer in copper than younger more central phases (Fig. 12). Very wide ranges of values exist for copper analyses in all phases. Distribution of zinc values also suggests two populations of data, but populations that are distributed normally rather than lognormally. Zinc values have narrow ranges and decrease only slightly from the margin to the center of the batholith (Fig. 12).

There has been considerable speculation about the source of copper in porphyry copper deposits. One of the more popular hypotheses is that the metals are derived from associated intrusions. In the Guichon Creek batholith, all the major deposits are in close proximity to the contact of its youngest phase, the Bethsaida. This most felsic phase of the batholith is also the one with lowest background copper content (Brabec, 1971).

In intrusive bodies where fractional crystallization occurred, several studies indicate that the copper content of various phases increased during fractional crystallization until most of the magma was crystallized, then dropped dramatically. At Skaergaard, for example, the drop occurred when the intrusion was 90 per cent crystalline and coincided with the development of an immiscible sulphide phase (Wager and

Brown, 1967). In biotites from Laramide intrusions in Arizona (Graybeal, 1973), copper contents were apparently magmatically controlled. That is, copper content of biotites increased as the rocks evolved and became more felsic. However, in the productive core phases of the intrusions the copper content in biotites is lower. Graybeal concluded that these lowered values occurred because copper was fractionated into the melt when a hydrothermal phase evolved. In contrast, highest copper contents in biotites from the Boulder batholith are from the productive Butte quartz monzonite (Al-Hashimi and Brownlow, 1970), where copper values exceeding 200 ppm were interpreted to be of hydrothermal origin. In a microprobe study of copper distribution in igneous biotites near two porphyry copper deposits in Arizona, Banks (1974) found very low copper contents in both fresh igneous biotites and in hydrothermal biotites, but significant copper contents within transitional contact zones between biotite and chlorite. Apparently, copper was introduced with the chloritizing solutions. Banks concluded that high copper values reported from biotites represent hydrothermal copper in zones of incipient chlorite alteration. Thus, no agreement exists at this time regarding the significance of copper abundance in biotites, but in each of the cases cited a volatile or hydrothermal phase is interpreted to have influenced copper distribution.

In the Guichon Creek batholith, Brabec has shown that modal hornblende and biotite are not significantly correlated with whole-rock copper content. Thus, variations in copper content between border and central phases are not controlled by variations in mafic content. The geometric means of copper values (Brabec, 1971) increase from the border, Hybrid phase to the Guichon variety, decrease in the Chataway variety, decrease again in the Bethlehem phase and drop sharply in the Bethsaida phase. Possibly the beginning of the decrease in whole-rock copper content is related to the separation of a significant volatile phase in the magma. Copper in Highland Valley ore deposits, from this point of view, is derived from the magma and represents metals leached from the crystallizing magma by the associated volatile phase.

Other possible sources of metal considered for porphyry copper deposits include:
(a) leaching of wall rocks by convecting meteoric waters (White, 1968) or deuteric alteration (Putnam, 1972);
(b) assimilation of metal-rich country rock (Schau, 1970);
(c) generation of ore fluids from the same source area, but independent of the magma (Noble, 1970; Sillitoe, 1972; Olade, 1975).

In Highland Valley, wall-rock leaching is an unlikely metal source, because the fresh wall rocks are commonly metal-deficient. Furthermore, geochemical studies around the deposits do not show depletion halos, at least at the level of formation of the deposits (Olade, 1974; Osatenko and Jones, this volume). However, it is controversial whether rocks intruded by the batholith are or are not a likely source of copper. Christmas *et al.* (1969) list 100 ppm copper as average for Nicola volcanic rocks and Schau (1970) gives an arithmetic mean 75 ppm for 48 samples of basalt collected in an area 32 km east of the batholith. Brabec and White (1971) replotted Schau's data and calculated a geometric mean of only 35 ppm copper; furthermore, 11 Nicola samples collected adjacent to the batholith have a geometric mean of 15 ppm copper (Brabec, 1971). As a test of the assimilation hypothesis, Brabec analyzed contaminated rocks of the border, or Hybrid, phase of the batholith. He found no copper enrichment in them relative to other phases. When these data are all considered, derivation of copper in the batholith from the country rock seems unlikely.

Generation of metal-rich solutions from the same source area, but independently of the magma, was postulated by Noble in 1970. According to this hypothesis, the role of the magma is one of structural control. It provides channel ways for the mineralizing phase to facilitate its upward movement and provides sites which are chemically and structurally favourable for the ore deposition. Olade (1974, 1975) proposes this model for the origin of Highland Valley ore deposits. Derivation of the metal from rocks of the batholith is rejected by Olade, because the geochemical patterns observed are interpreted to resemble those of typical differentiated but unmineralized intrusions. Strontium isotope ratios (Christmas *et al.*, 1969), high K/Rb and Sr values and low Rb, K and Rb/Sr values (Olade, 1974) indicate that the batholith was derived from a deep-seated, upper mantle source. Olade argues that both the magma and metal-rich solutions were derived from metal-rieh subducted oceanic crust.

It is clear that the evidence available from Highland Valley and the present state of knowledge about metal distributions in granite rocks are consistent with the hypotheses of both Brabec and White, and Olade. However, one aspect of the evidence weighs in favour of derivation of the copper from the magma. The copper content of the Hybrid phase is lower than that of the Guichon variety of the Highland Valley phase (Fig. 12). That is, the early stages of crystallization differentiation resulted in copper enrichment, not depletion. Background copper in the Chataway variety is lower, and that of the Bethlehem and Bethsaida phases is much lower. In the younger phases there is evidence of a significant volatile phase. Quartz crystallization preceded plagioclase, there is complex feldspar zoning (Westerman, 1970), there are dyke swarms and explosion breccia bodies developed (Carr, 1966).

A rough calculation was made to see if copper "missing" from the Bethlehem and Bethsaida phases balanced that concentrated in the ore deposits. To make the calculations, it was necessary to assume average copper contents for the original magma and the combined felsic phases, the Bethlehem and Bethsaida. The initial value in the magma was assumed to equal that of the Hybrid phase (57 ppm). The Bethlehem and Bethsaida phases have roughly equal surface areas (Fig. 3d), so they are assumed to have roughly the same volume; hence the average value taken for the combined felsic phases was the average of their background values (21 ppm).

Highland Valley ore deposits carry roughly 10 million tonnes of copper metal. It is necessary to remove 36 ppm from roughly 100 cubic kilometers of the felsic phases to account for copper in the deposits. The felsic phases have an elliptical outline with an area of 40 square kilometers and if, for simplicity, one assumes the contacts are vertical, a depth of 2.7 kilometers is sufficient to supply the copper to produce the deposits. The estimated volume of the felsic phases is roughly double this calculated minimum volume; therefore, much more copper has been lost from the felsic phases than is needed to form the deposits.

Chemical and isotopic data clearly indicate that the Guichon Creek magma originated in the upper mantle. Furthermore, the large number of copper-molybdenum and copper deposits associated with the batholith and other intrusive bodies of similar age along the Nicola belt suggests strongly that the source material for these intrusions was metal-rich. However, none of the evidence accumulated to date is adequate to determine whether the source was metal-rich upper mantle material or subducted oceanic crust.

Geochemical Patterns of Highland Valley Deposits

Zonal arrangements of major and trace elements occur in Highland Valley ore deposits. Olade (1974) studied geochemical variations around the Valley Copper, Lornex, Highmont and J.A. deposits. Osatenko and Jones (this volume) conducted a detailed geochemical study of the Valley Copper deposit. Both studies found variations in chemical elements in the different alteration zones, and both found progressive changes from the edge to the center of deposits.

In general, lithophile elements, Ca, Na, Mg, Sr, Ba and Mn, decrease from the borders of deposits to their centers. At Valley Copper, the most depleted zone is characterized by phyllic alteration and less depletion occurred in zones of propylitic and argillic alteration. Osatenko and Jones report that argillic alteration locally extends more than 300 m beyond the 0.3 per cent copper isopleth. The writer also found that alteration of plagioclase to sericite and clay occurred well out into the country rock at the Lornex, Highmont and J.A. deposits. Geochemically, this alteration causes depletion in Na and Ca relative to background.

Other elements, notably Si, K, Rb, Fe and Ti, are enriched in the Valley Copper deposit. Highest K values occur in areas of vein sericitic alteration which correspond to areas of the best grade of mineralization. Copper is, of course, enriched and the border of the deposit is an assay boundary. Zinc and Mo form halos that are primarily outside the deposit and Mn forms a distinct halo roughly 300 m in width around it.

Olade reports similar elemental distribution patterns for the other Highland Valley deposits, although, in contrast to Osatenko and Jones, he reports Fe depletion in them. Olade found that potassic alteration zones were enriched in Rb, Ba, Si, K and S, but lost Ca, Mg, Fe, Na and Al. In general, Olade found that lithophile elements are controlled by alteration types and more or less coincide with alteration halos, whereas femic elements (Zn, Mn, Ti, V, Ni, Co, Fe and Mg) are largely controlled by primary lithology and hydrothermal redistribution of them is minor.

Sulphur, Cu and, locally, Hg and B distributions were interesting from the exploration point of view. Sulphur and Cu both formed halos up to 500 m wide around deposits, but the sulphur distribution was the more consistent. Mercury formed a broad halo around the J.A. deposit, but not around Valley Copper. Boron anomalies marked Lornex and Highmont, but boron was inconspicuous at Valley Copper and J.A. Rubidium and Sr distribution and Rb/Sr ratios also outlined some ore deposits. At Valley Copper and J.A., Rb contents were highest and Sr contents lowest in the potassic core zones, and contours of Rb/Sr at the 0.1 level broadly delineated both deposits (Olade and Fletcher, 1975).

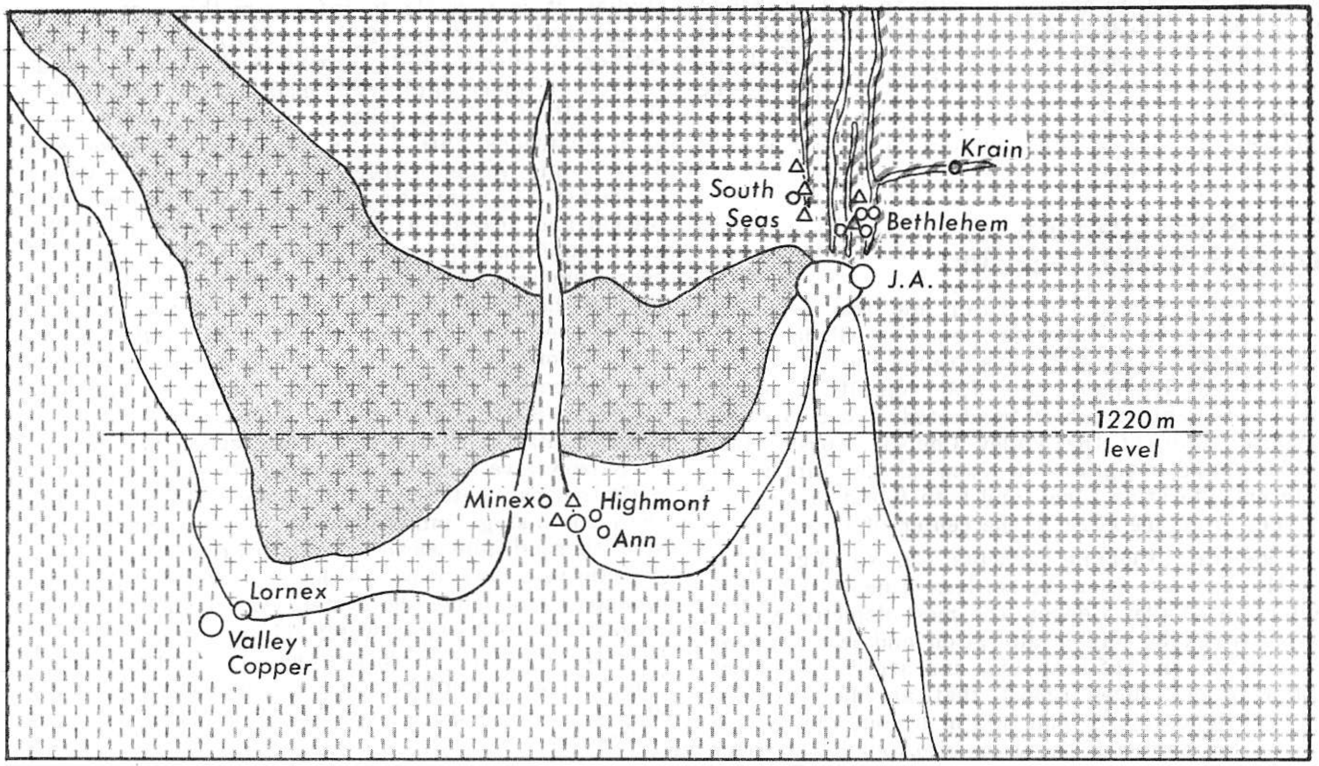
The Ore-Forming Fluids

From the character of hydrothermal veining and alteration, and various isotopic and fluid-inclusion studies, it is possible to infer something about the nature and variations of the ore-forming fluids. According to Olade (1974), argillic and sericitic alteration occur under slightly to moderately acidic conditions (pH 6), whereas potassic alteration requires less acid conditions (pH 7). In contrast, Osatenko and Jones (this volume) infer an initial pH at Valley Copper of 1.5, rising to 3 during main-stage mineralization and nearing 4 during potassic alteration. Regardless of absolute values, both sets of data argue for decreasing acidity with time. Isotopic data indicate that sulphur in the hydrothermal system had a mantle source (see also Christmas *et al.*, 1969). Sulphur and oxygen isotopic data (Jones, 1975) indicate that alteration temperatures increased from 260°C in the early stages of alteration to 480°C during the main stage of mineralization. These data also suggest that: during early pervasive sericitic alteration, 70 per cent of the hydrothermal water had an oceanic source; during early main-stage mineralization, 80 per cent of the hydrothermal fluid was of magmatic origin; and during gypsum vein deposition, 94 per cent of the water was oceanic. Presumably the system was quenched by the large influx of oceanic water. If, however, pervasive sericitic alteration is late stage (Reed and Jambor, this volume), a progressive decrease in temperature and increase in oceanic water content with time is indicated.

Fluid-inclusion data are few. However, Jones (1975) reported a few halite, sylvite and carbonate crystals as well as liquid CO_2 in some fluid inclusions. The fluid inclusions are small and occur along linear zones, which suggests that most are secondary. However, those containing solid phases or liquid CO_2 may be primary. Liquid CO_2 suggests pressures of formation in the range of 100 to 300 bars, which would occur at a depth of 1 to 2 km. Post-mineralization fluid inclusions from Lornex fall into groups at 200°C, 160°C and 120°C (Schmuck, 1974, pers. comm.).

Because alteration mineralogy in all the deposits is similar, because geologic settings are similar and because they occur in close proximity to one another, it may be presumed that the character of ore-forming fluids in all the deposits was similar. That being the case, the fluid would be a chloride brine, probably containing HCl, H_3BO_3, HF, H_2S, H_2SO_4 and other volatiles (Olade, 1974). It would be partly of deep-seated origin and be derived either from an upper mantle source or subducted oceanic crust. At least in part, it would be derived from the Guichon Creek magma by crystallization differentiation, although the metal and part of the hydrothermal fluid could be from a separate but similar source as the magma.

Alteration was initiated by the influx of hydrothermal magmatic fluids into structurally favourable areas. Initial intermixing with oceanic waters might be caused by the formation of a convective cell. Conversely, the oceanic water may already have been there. Proportions of magmatic and oceanic water and consequently temperature varied across the deposits (Osatenko and Jones, this volume) and temperature and water composition controlled alteration type and intensity (Taylor, 1974). Main-phase mineralization was dominated by upwelling magmatic fluids and this stage probably consisted of several waves of hydrothermal fluid of varying composition. As magmatic supply waned, oceanic water proportionally increased, which diluted and cooled the ore-forming brines. Finally, when oceanic water predominated, the hydrothermal system collapsed and mineralization ceased.



Expanded view of Highland Valley Area (Schematic)

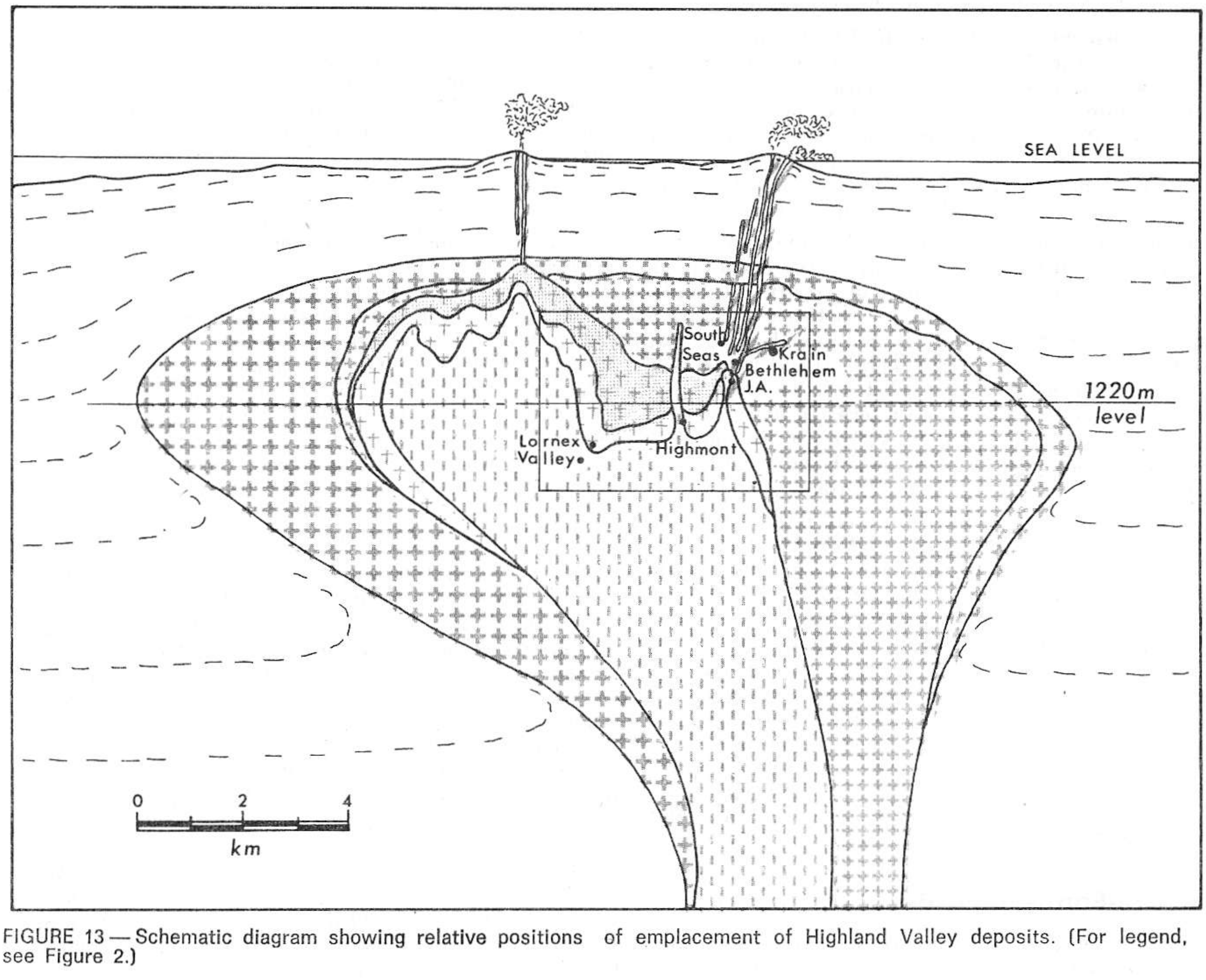


FIGURE 13 — Schematic diagram showing relative positions of emplacement of Highland Valley deposits. (For legend, see Figure 2.)

A Model of Highland Valley Porphyry Copper Deposits

Several aspects of the deposits were considered in order to categorize them with regard to depth and temperature of formation. With regard to emplacement depth, the first of the criteria considered was tectonic setting and character of the deposits: Valley Copper mineralization occupies a shatter zone with few dykes; Lornex ground is closely broken with local fracture swarms and contains one large and several smaller dykes; Highmont mineralization is controlled by fracture swarms and is associated with the Gnawed Mountain dyke; J.A. mineralization forms a northwest elongated zone, but is best in a closely fractured area north of the quartz-plagioclase aplite stock around the Bethlehem/Guichon contact; Bethlehem ore grades are controlled by fractures and faults and swarms of porphyry dykes occur; South Seas and Krain have associated porphyry dykes. In addition, Highmont and South Seas have areas of breccia which are sites of mineralization. The changes indicated represent depth of formation from deeper to shallower conditions in the following sequence: Valley Copper, Lornex, J.A., Highmont, Bethlehem and South Seas. The relative position of Krain is not certain, but, judging from present elevations, it probably formed at slightly shallower depth than South Seas.

The significance of molybdenite distribution is not certain. The high-level deposits — Bethlehem, South Seas and Krain — are poor in molybdenite, but so is Valley Copper. Lornex and J.A. have roughly equal molybdenum grades, but those at Highmont are more than twice as high. In general, deposits north of Highland Valley, interpreted to be older than those south of it, are molybdenum deficient. That is, relative age rather than emplacement level seems to be a principal control of molybdenum abundances.

The intensity and types of alteration comprise the second criterion considered. Only Valley Copper and J.A. have significant potassic feldspar alteration, and that at J.A. is more closely related to geologic setting than mineralization. Hydrothermal biotite occurs in several deposits, but is most significant in the core of the Jersey deposit and at Highmont. Phyllic alteration is strongly developed at Valley Copper, well developed at Lornex and occurs sporadically at J.A. and Highmont. Intensity of pervasive argillic alteration of feldspars decreases from Valley Copper to Lornex to Highmont to Jersey to J.A. to Krain. Similarly, X-ray analyses of these alteration assemblages indicate decreasing average sericite and clay abundances from Valley Copper to Lornex to Highmont to J.A. Propylitic alteration zones fringe Valley Copper, Lornex and Jersey, although chlorite alteration occurs throughout Jersey. Propylitic alteration extends well into the ore zones at Highmont, J.A. and Krain. Late-stage zeolite veining and alteration is prominent at Jersey and J.A., present at Highmont and occurs locally at Lornex. Based on these data, alteration intensity and inferred maximum temperature of alteration decrease in the following sequence: Valley Copper, Lornex, Highmont, Jersey, J.A. and Krain.

Based on compositions of biotite coexisting with magnetite and K-feldspar, Bean (1974) concluded that porphyry copper deposits with bornite formed at higher temperatures than those with only chalcopyrite. If this result is generalized somewhat, it becomes a fourth, albeit questionable, criterion, because bornite-to-chalcopyrite ratios can be used to infer relative formation temperatures for the deposits. Highland Valley deposits, from highest to lowest relative bornite-to-chalcopyrite abundance, are: Valley Copper, Lornex and J.A. No reliable estimates are available for Highmont and Bethlehem, but the ratios appear to be similar to that at Lornex.

Conclusion

Evidence summarized in the paper shows that although the deposits are broadly similar, they vary considerably in detail. Host rocks, alteration intensities and assemblages, and associated structural features all differ. Deposits north of Highland Valley appear to be older than those to the south, so age may also vary. The variations are thought to be related in part to depth of emplacement and in part to temperature of formation. Various Highland Valley deposits and prospects are thought to have formed in settings schematically illustrated in Figure 13. From hottest and deepest to shallowest and coolest, the deposits are tentatively placed as follows: Valley Copper, Lornex, J.A., Highmont, Bethlehem and South Seas, and Krain. The relative position of Highmont and J.A. is ambiguous. It is also evident from the data that although mineralization north of the Highland Valley is apparently intramagmatic, the most significant periods of mineralization were late magmatic events, events which post-date intrusion of the youngest major phase of the batholith.

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Bethlehem Copper's Jersey, East Jersey, Huestis and Iona Deposits

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Abstract

The Bethlehem porphyry copper deposits are near the center of the 200 m y old Guichon Creek batholith, which is a concentrically zoned calc-alkaline pluton that intrudes eugeosynclinal assemblages of the Permian Cache Creek and Upper Triassic Nicola groups. Four ore zones comprise the Bethlehem deposits considered in this article and are named the East Jersey, Jersey, Huestis and Iona deposits. The J.A. and Lake segment of the Valley deposits are considered in separate articles in this volume. Intrusive breccias, dacite and rhyodacite porphyry dykes, small masses of granite, granodiorite and porphyritic quartz latite, faults and fractures, and hydrothermal mineralization and alteration have been localized along the irregular intrusive contact that separates the older Guichon Granodiorite and younger Bethlehem Granodiorite phases of the batholith. Late-stage concentration of mineralizers in the dacite porphyry melt(s) were probably the source of hypogene metallization, which post-dates all intrusive rocks and breccias at Bethlehem. Important faults of post-breccia age strike north, northeast and northwest, and dip steeply. Detectable offsets are unusual.

Mineralization in the Bethlehem deposits includes variable amounts of chalcopyrite, bornite, pyrite, specularite and molybdenite; and white mica, chlorite, epidote, calcite, quartz, zeolites, secondary biotite and tourmaline. These minerals occur in veins, veinlets, fracture coatings, irregular blebs and disseminations.

The Bethlehem orebodies (especially the Jersey) exhibit metallic and non-metallic mineral zones. Peripheral zones of specularite and epidote, and intermediate zones of pyrite and white mica surround a central copper-rich core defined by relatively large amounts of bornite and secondary biotite. The mineralogy and arrangement of these zones suggest that the hydrothermal fluids responsible for mineralization and alteration moved upward and outward from the central core. Zones of secondary sulphide enrichment are not developed at Bethlehem, although the Iona orebody has mineable quantities of oxide ore (malachite).

The Bethlehem deposits (especially the Jersey orebody) generally possess geological, mineralogic and geochemical features consistent with those described for other porphyry deposits of western North America. However, in detail, they differ in the degree to which many of these features are developed. The more unique characteristics include: (1) an intrabatholith location; (2) a probable old age for mineralization (200 m y); (3) dominance of fracture-controlled copper mineralization; (4) mineralogic simplicity of the metallic constituents; (5) absence of lead, zinc and silver occurrences; (6) well-defined zonation of iron-bearing metallic minerals; (7) low total sulphide content (average < 2 per cent) and a paucity of pyrite (average < 1 per cent in the halo zone); (8) large bornite: chalcopyrite ratios (> 1) in the central copper-rich core; (9) molybdenite peripheral to the central parts of the ore zones; (10) association of chalcopyrite and bornite with epidote; (11) restriction of significant hydrothermal alteration to the ore zones; (12) scarcity of potassium-feldspar alteration; and (13) widespread post-metallization hydrothermal zeolites, especially laumontite.

Location

THE PROPERTY is located in south-central British Columbia on the north side of the Highland Valley at Lat. 50° 29.5′ N, Long. 120° 59′ W, N.T.S. 92I/7W. It lies approximately 32 km southeast of Ashcroft and 48 km southwest of Kamloops. Elevations vary from 1400 m to 1525 m.

History

Initial surface showings were discovered prior to 1896 and the original mineral claims were staked in the area in 1899. Sporadic interest was maintained in the prospect first by the B.C. Department of Mines, which drilled 8 holes in 1919, and then by several private companies which conducted various programs of surface and underground exploration.

In 1954, about 100 claims were staked by a syndicate. which later transferred these claims to the newly formed Bethlehem Copper Corporation Ltd. in early 1955. Surface trenching and bulk sampling followed, until an option agreement was completed with ASARCO. After 2½ years of work, ASARCO was forced to drop its options, but results proved sufficient for Bethlehem to begin an underground program to check the drilling results. An agreement was negotiated with Sumitomo Metal Mining Co. of Japan in 1960 to provide financing for a mill installation of 2700 tonnes per day and to purchase full production for a period of ten years. Plant construction commenced in the fall of 1961, with the project going on-stream in December, 1962. Five increases in plant size ensued and currently the mill has a rated capacity of 15,400 tonnes per day.

Production

Ore tonnages mined to December, 1974 (including stockpiled material) are as follows:

East Jersey	(1962-1965 and 1974)	3.384 million tonnes
Jersey	(1964-1972, 1973-1974)	28.656 million tonnes
Huestis	(1970-1974)	17.163 million tonnes
TOTAL	(1962-1974)	49.203 million tonnes

Reserves

The reserves available to the present mill as of December 31, 1975, based on a cutoff value of 0.25 per cent copper, were as follows:

Deposit	Tonnes	Grade
Huestis	7,430,000	0.45 per cent copper
Iona	12,050,000	0.47 " "
Jersey	31,640,000	0.46 " "
TOTAL	51,120,000	0.461 " "

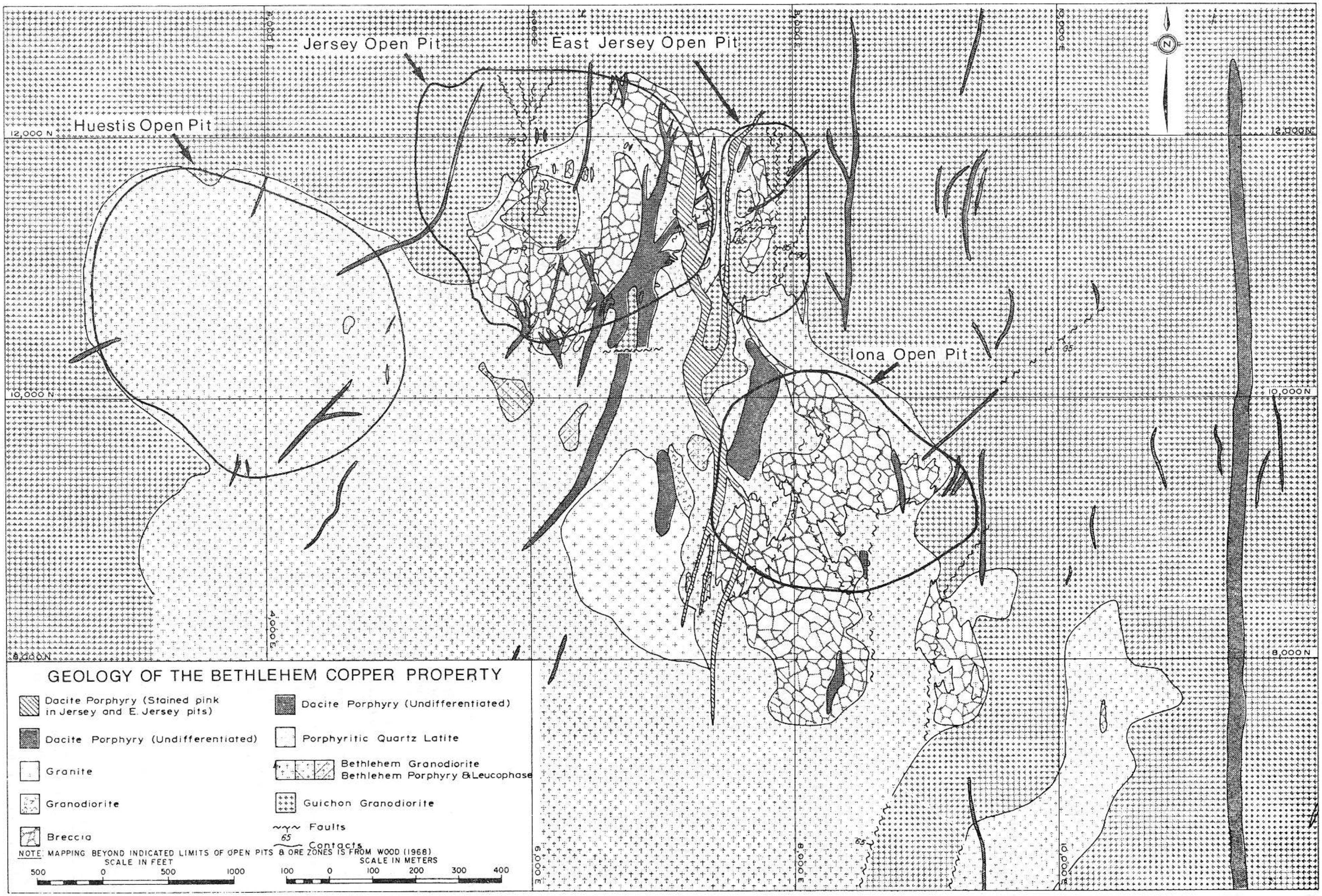

FIGURE 1 — Geology of the Bethlehem property.

Geologic Setting

The Bethlehem porphyry copper deposits are near the center of the 200 m y old Guichon Creek batholith (see location map, this volume), which for the past decade has been the subject of considerable study (see Northcote, 1969; McMillan, 1971, 1972, this volume; Hylands, 1972; Ager and others, 1972; Field and others, 1974; and Jones, 1974). The batholith is a concentrically zoned calc-alkaline pluton, which is interpreted to be shaped like a flattened funnel, the spout of which underlies Highland Valley and plunges 80 degrees to the northeast (Ager and others, 1972). The average thickness of the batholith is 6 km, increasing to more than 22 km over the central root zone (Ager and others, 1972). Major intrusive phases become progressively younger and change in composition inward from a border of gabbro, through quartz diorites and granodiorites, to a core of granodiorite or quartz monzonite. The batholith intrudes eugeosynclinal assemblages of the Permian Cache Creek and Upper Triassic Nicola groups. Sedimentary rocks of Middle and Upper Jurassic age, and volcanic and sedimentary rocks of Lower Cretaceous and Tertiary age, unconformably overlie the batholith.

The first comprehensive geologic investigations of the Bethlehem property were by White and others (1957) and Carr (1960, 1966). After mining began in 1962, these studies were supplemented with observations by mine personnel, including Coveney (1962), Coveney and others (1965), and Ewanchuk (1969). In 1966-67, Wood (1968) conducted a geologic and mineralogic study of the property. Most recently, the deposits have been re-examined and briefly described by McMillan (1972) and Hylands (1972). The present report incorporates: information obtained from a program of detailed and reconnaissance mapping and sampling carried out by J. A. Briskey* during the summers of 1970-73 as part of a detailed geological, mineralogical and chemical study of the Bethlehem area and particularly the Jersey orebody; field observations and detailed mapping by H. G. Ewanchuk in the East Jersey orebody; and detailed studies of outcrops and drill core in the Iona mineralized zone by J. R. Bellamy. Because the present investigation is not yet completed, this paper should be regarded as a progress report.

Lithology

The Bethlehem deposits formed along an irregular intrusive contact separating two major phases of the Guichon Creek batholith (Fig. 1). Rocks of the younger Bethlehem phase form a digitated northward-elongated apophysis that is intrusive into rocks of the older Guichon phase. This apophysis apparently followed the north-trending zone of structural weakness that subsequently localized the intrabatholith porphyry dyke swarm, which transects the property (McMillan, this volume). Intrusive breccias, dacite and rhyodacite porphyry dykes, small masses of granite, granodiorite and porphyritic quartz latite, faults and fractures, and hydrothermal mineralization and alteration have been localized along digitations in the contact of the apophysis. Mining operations removed thin cappings of Guichon Granodiorite from parts of the Huestis, Jersey and East Jersey orebodies. These cappings indicate that the current level of exposure is near the roof of the apophysis. Although not shown in Figure 1, between 50 and 60 per cent of the property is mantled by glacial deposits.

*J.A. Briskey's participation in this portion of the Bethlehem study occurred during his tenure as a graduate student in the Department of Geology at Oregon State University, and prior to his employment by the U.S. Geological Survey.

GUICHON AND BETHLEHEM GRANODIORITES

The Guichon Granodiorite may gradationally approach quartz diorite in composition (Tables 2 and 3). It is typically a medium crystalline hypidiomorphic granular rock composed of plagioclase feldspar (46-60%)*, quartz (15-25%), orthoclase (8-16%), hornblende (5-10%), biotite (1-10%) and minor augite. Orthoclase and quartz are interstitial and commonly show pronounced reaction boundaries with plagioclase feldspar. Mafic minerals are of uniform size and distribution.

The Bethlehem Granodiorite normally is a medium-crystalline hypidiomorphic granular rock that may grade into quartz dioritic and porphyritic varieties. Representative samples (Tables 2 and 3) contain plagioclase feldspar (53-65%), quartz (16-25%), orthoclase (5-16%), hornblende (2-22%) and biotite (0.5-6%). Phenocrysts of plagioclase feldspar, poikilitic hornblende and quartz (eyes) are common in the porphyritic varieties. Orthoclase and usually quartz are interstitial, and may display reaction boundaries with plagioclase feldspar. Uneven size and distribution of mafic minerals in Bethlehem Granodiorite distinguishes it from Guichon Granodiorite. White and others (1957) and Wood (1968) mapped a leucocratic subphase of the Bethlehem Granodiorite (see Fig. 7). It is characterized by alteration of mafic minerals to actinolite and absence of orthoclase, and occurs exclusively within the normal Bethlehem. Guichon and Bethlehem granodiorites are separated by a steeply dipping sharp but irregular intrusive contact along which Bethlehem Granodiorite may display weak chill textures. Scarce xenoliths of Guichon in Bethlehem have been reported from the East Jersey pit (Wood, 1968) and Iona mineralized zone (White and others, 1957). Other contact features include quartz veinlets, which are present in both rock types, and the development of incipient foliation in Bethlehem Granodiorite.

A small north-trending intrusion in the bottom of the Jersey pit is tentatively called Bethlehem porphyry (Figures 1 and 2). Although superficially similar in appearance to Bethlehem Granodiorite, it possesses a definite porphyry texture. The rock is a dacite, which contains plagioclase feldspar (50-60%), quartz (25-35%), hornblende and biotite (5-10%), and orthoclase (0-10%). Phenocrysts, up to 7 mm in the largest dimension, include plagioclase feldspar, quartz (eyes), hornblende and biotite. The groundmass, which comprises 25 to 35 per cent of the rock, consists of a mosaic of quartz and plagioclase feldspar, with variable small amounts of orthoclase, hornblende and biotite. Although the age of the Bethlehem porphyry is unknown, it has been mapped as a subphase of Bethlehem Granodiorite. Contacts of the porphyry are sharp and steeply dipping where it intrudes the Guichon. It locally exhibits a weak foliation and (or) a slight decrease in crystallinity to this contact. As suggested in a later section, the Bethlehem porphyry may be genetically related to the source of the hydrothermal fluids that formed the Jersey orebody.

*Volume per cent unless otherwise indicated. Where unaccompanied by percentage estimates, minerals will be listed approximately in order of decreasing abundance.

PORPHYRITIC QUARTZ LATITE

Irregularly shaped intrusions of porphyritic quartz latite occur in the southeast and west-central parts of the Jersey pit (Fig. 2) and in a slump block on the east wall of the Huestis pit (Fig. 1). This rock is fine to medium crystalline hypidiomorphic porphyritic, and contains plagioclase feldspar (40-50%), quartz (25-30%), orthoclase (25-30%) and hornblende and biotite (2-5%). Phenocrysts, up to 4 mm in the largest dimension, comprise plagioclase feldspar, quartz (eyes), biotite and hornblende. The groundmass, which constitutes approximately 50-60 per cent of the rock, is composed primarily of finely crystalline, saccharoidal quartz and interstitial orthoclase. Contacts between porphyritic quartz latite and Guichon or Bethlehem granodiorites are generally shap; however, a contact with the Bethlehem in drill core was gradational over several centimeters. Porphyritic quartz latite may rarely contain small xenoliths of Bethlehem, and locally exhibits a weak foliation within 6 mm of sharp contacts. Contacts are vertical or dip steeply to the west.

IGNEOUS BRECCIAS

Occurrences of breccia are widespread at Bethlehem, and are also found at the nearby Trojan and Highmont properties. They occur locally within the north-trending zone, characterized by swarms of porphyry dykes, in the central part of the Guichon Creek batholith (McMillan, this volume). At Bethlehem, breccias are associated with all but the Huestis orebody (Fig. 1). The southern extent of the main Iona breccia has not yet been determined, however its northern extension and a smaller parallel roofed breccia extend northward into the East Jersey pit. Exploratory drilling has intercepted several small breccia bodies at depth in the southeast part of the Iona zone. All of the Bethlehem breccias are near the contact between Guichon

TABLE 1 — Features of Metallic Mineral Zones in the Jersey Pit[1]

Zone	Dominant Metallic Mineral(s)	Total Sulphides	Bn/Cp	Py/Cp	Fe/Cu	S/Metal
Bornite core (bn-cp)	Bn	1-2%	≥ 1	$\ll 1$	<0.4	<0.4
Outer margin of bornite core to inner margin of pyrite halo (cp-bn)	Cp	1-3%	<1	$\ll 1$	>0.4	<0.4
Pyrite halo (py-cp)	Py + Cp	1-5%	$\ll 1$	~ 1	~ 2.5	~ 0.8
Specularite zone (sp-cp)	Sp	$<1\%$	$\ll 1$	$\ll 1$	>2.5	$\ll 0.4$

(1) The ratios of Fe:Cu and S:metal are calculated in terms of weight per cent of the indicated metallic mineral assemblages; other values are volume per cent.

TABLE 2 — Modal Analyses

	1[1]	2	3	4	5	6	7	8
Quartz	14.9	17.2	26.0	20.1	19.0	15.9	30.1	22.8
Primary K-feld.	9.4	9.6	—	—	6.7	9.7	—	—
Plagioclase feldspar	60.1	48.7	26.8	23.0	63.4	53.4	32.8	14.9
(An content, x = sodic)	(34)	(38)	(x)	(x)	(32)	(35)	(28)	(x)
Augite	0.6	0.6	—	—	—	—	—	—
Hornblende	8.6	5.0	—	3.6	7.8	10.0	—	—
Primary biotite	5.0	7.9	3.6	—	1.3	1.4	—	—
Opaques	1.0	1.7	3.4	4.0	0.2	0.7	1.0	0.8
Accessories[2]	0.4	1.2	0.9	0.6	0.4	1.5	0.6	0.7
Epidote group	—	1.3	0.8	1.9	0.8	0.6	5.2	1.2
Chlorite	—	0.3	20.8	3.6	0.6	0.8	2.2	3.3
Carbonate	—	—	—	0.3	—	—	0.8	0.8
F.c.a.p.[3]	—	5.0	16.0	35.8	—	4.4	12.4	35.8
White mica	—	1.5	1.7	—	—	1.6	14.6	1.7
Secondary biotite	—	—	—	7.1	—	—	—	3.1
Secondary K-feld.	—	—	—	—	—	—	—	14.5
Points counted	500	800	500	800	500	800	500	800
Grid spacing (mm)	?	1.0	?	1.0	?	1.0	?	1.0

	Coords. (m)	Elev. (m)
(1) 1: Unaltered Guichon Granodiorite (Wood, 1968)	—	—
2: Unaltered Guichon Granodiorite	3804N 1844E	1504
3: Altered and mineralized Guichon Granodiorite (Wood, 1968)	Jersey Pit	—
4: Altered and mineralized Guichon Granodiorite	3496N 1939E	1341
5: Unaltered Bethlehem Granodiorite (Wood, 1968)	—	—
6: Unaltered Bethlehem Granodiorite	2164N 2347E	1387
7: Altered and mineralized Bethlehem Granodiorite (Wood, 1968)	Jersey Pit	
8: Altered and mineralized Bethlehem Granodiorite	3548N 1978E	1341

(2) Accessories include: apatite, sphene, rutile and zircon.
(3) Finely crystalline alteration products include: white mica and small amounts of kaolinite, montmorillonite and carbonate.

and Bethlehem granodiorites, but only locally are these two rock types separated by breccia. The breccias are preferentially localized within Bethlehem Granodiorite, and none have been found entirely within the Guichon. Bodies of breccia tend to be anastomosing, steeply dipping masses with a northerly elongation. With increasing depth, they commonly decrease in size and some pinch out. Mining operations and drilling to date have exposed breccia to depths of over 300 m.

Breccia fragments include Guichon and Bethlehem granodiorites, dacite porphyry, porphyritic quartz latite and silicic aplite. Guichon fragments ordinarily predominate. Breccias in the Iona ore zone are virtually enclosed in Bethlehem Granodiorite, but clasts are predominantly of Guichon granodiorite. Fragments of dacite porphyry are widely distributed in the breccias, but are abundant only in the breccia mass on the northeast wall of the Jersey pit. Pink stained dacite porphyry has not been found as a component of the breccias. Clasts of porphyritic quartz latite are abundant in and near gradational contacts between intrusions of this rock type and breccia, but occur sporadically elsewhere. The diameters of many clasts are between 1 and 20 cm. Their shapes range from angular to rounded, but those which are subangular to subrounded predominate. Rounding appears to have resulted from corrasion during transport, and rarely from corrosion by hydrothermal fluids or dacite porphyry magma. Blocks of included dacite porphyry may be markedly tabular, and suggestive of prebrecciation sheet fractures or joints.

Comminution of entrained fragments has resulted in a cataclastic matrix, reflecting the mineralogic composition of the host rocks. Broken and crushed crystals of plagioclase feldspar and quartz, with or without smaller amounts of orthoclase, hornblende and biotite, compose most of the matrix. Where comminution was more intense, crystal fragments are mixed with, or grade into, fine-grained rock "flour". The matrix is usually compact, but irregular vugs up to 30 cm in length are not uncommon. Finely crystalline biotite and chlorite are widely distributed throughout the breccia matrix, and locally predominate over all other matrix components. Biotite is particularly abundant in the upper parts of the Iona breccias. Tourmaline is a widespread but minor constituent of the breccia matrix. In some upper parts of the Iona breccias, porous granular quartz, commonly intergrown with finely to coarsely crystalline aggregates of tourmaline, encloses the breccia fragments. This quartz does not normally replace the fragments, so that it probably filled open spaces in a loosely consolidated breccia. Induration of the breccia, either as the result of or following deposition of this quartz, preceded the formation of later sulphide-filled fractures that crosscut both matrix and fragments alike. Breccia fragments in a matrix that closely resembles some of the dacite porphyries have been observed in two small, isolated areas. Reaction between this matrix and many of the fragments is indicated by contacts that are corroded and gradational over as much as 8 cm. Where unaffected by corrosion, contacts between the fragments and cataclastic matrix are generally sharp. Lineations caused by the subparallel alignment of matrix components are conformable to fragment faces, and are attributed to either flowage or compaction, or both.

Contacts between breccia masses and host rock are usually steep. They may be sharp or gradational over as much as several meters. Many of the well-defined contacts show fingers or embayments of breccia extending into the surrounding country rock. Breccia contacts in the Iona zone may coincide with shear zones, which are common along the tops of protrusions of Bethlehem Granodiorite that extend up into the breccia from below. Although restricted zones of horizontal fracture sheeting are present in the upper parts of some Bethlehem breccias, their vertical counterparts have not been observed in either the breccias or their adjacent host rocks. In general, there is little evidence of severe fracturing in host rocks adjacent to the breccia masses.

The north elongation of the breccia bodies probably reflects control by the same structural weaknesses that localized the parallel-trending Bethlehem Granodiorite

TABLE 3 — Chemical(1) and Trace-Element(2) Analyses

	1	2	3	4	5	6	7	8
SiO_2	61.44	62.37	60.35	62.32	62.91	64.33	67.51	65.75
TiO_2	0.48	0.69	0.78	0.70	0.55	0.51	0.48	0.44
Al_2O_3	17.43	16.27	18.67	16.15	16.42	16.79	15.76	17.32
Fe_2O_3	1.46	2.39	1.60	1.76	3.26	2.37	1.06	0.78
FeO	4.19	2.56	4.56	2.45	3.06	1.54	3.04	1.27
MnO	0.09	0.08	0.06	0.08	0.06	0.08	0.04	0.03
MgO	2.48	2.34	2.29	2.64	1.10	1.37	0.95	0.90
CaO	5.27	4.88	2.67	4.83	6.09	4.73	3.33	2.72
Na_2O	3.99	3.93	2.99	3.84	2.88	4.60	4.50	4.99
K_2O	1.99	2.35	1.12	1.20	1.32	1.66	0.69	2.25
H_2O^+	0.81	1.13	4.63	2.32	1.64	0.97	1.70	2.04
H_2O^-	0.20	0.05	0.11	0.19	0.44	0.04	0.59	0.23
P_2O_5	0.16	0.11	0.14	0.11	0.09	0.15	0.12	0.08
	99.99	99.15	99.97	98.59	99.82	99.14	99.77	98.80
Elements — parts per million(3)								
Ag	1	−1	2	−1	1	−1	1	−1
Cu	95	150	9900	4900	420	55	3900	1400
Mo	3	4	54	−1	3	−1	4	10
Pb	25	10	30	10	35	10	50	10
Zn	30	30	25	35	20	50	25	15

(1)Standard wet chemical analyses by Dr. Ken-ichiro Aoki, 1966 and 1974, Tohoku Univ.
(2)Trace-element analyses by Rocky Mountain Geochemical Laboratories, 1973, Salt Lake City, Utah. Molybdenum determined colorimetrically; others determined by atomic absorption. Silver digested by aqua regia with an acetate buffer; others digested by hot perchloric acid.
(3)Minus sign (—) means "less than".

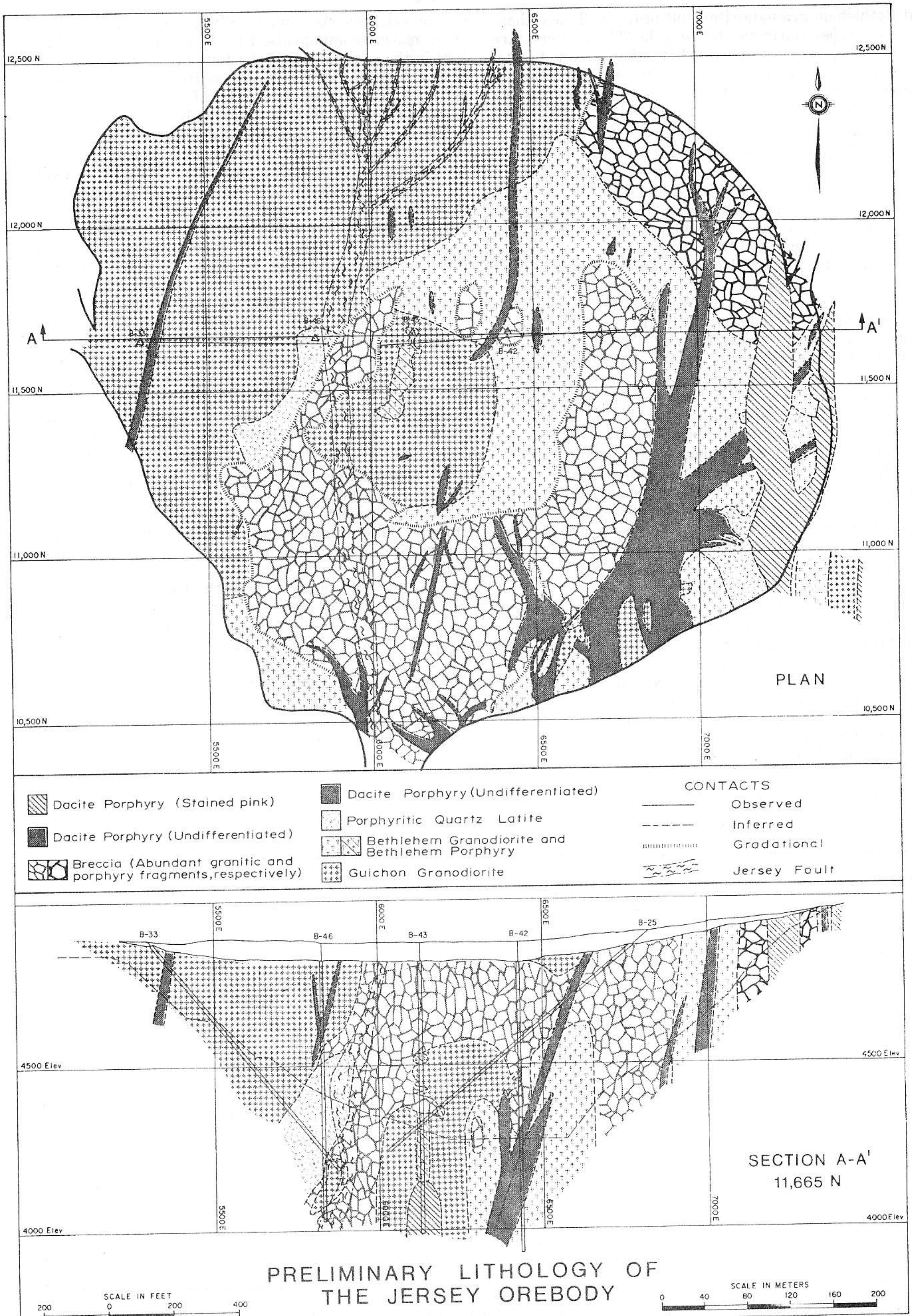

FIGURE 2 — Geological plan and section of the Jersey deposit.

apophysis, major faults and emplacement of porphyry dykes. The major faults, as now exposed, do not appear to have exerted either spatial or structural control over the emplacement of the breccia masses. Moreover, all of these faults exhibit movement younger than breccia consolidation. Alternatively, it is possible that breccia intrusion along pre-existing fault zones largely obliterated these zones and that later shearing along currently exposed major faults may have resulted from renewed displacement along these older structures. The localization of breccia dykelets in small gouge zones on the southeast wall of the Jersey pit suggests some local fault control of breccia emplacement. The coincidence of a few breccia contacts with shear zones in the Iona orebody may also be interpreted as a structural control, or as the result of breccia compaction.

GRANODIORITE AND GRANITE

An oblong mass of granodiorite is exposed west of the Iona zone (Fig. 1). The rock is predominantly medium crystalline hypidiomorphic granular, but gradational increases in the size of plagioclase feldspar or biotite crystals locally render the texture porphyritic. The principal minerals are plagioclase feldspar (45-55%), quartz (30-35%), orthoclase (15-20%), biotite (3%) and rare hornblende. This granodiorite is distinguished from the Bethlehem Granodiorite by the near absence of hornblende, larger and more abundant crystals of quartz, and the presence of biotite phenocrysts. This granodiorite apparently intrudes the Bethlehem, but contacts with the older rocks are not exposed. Wood (1968) reported the presence of orthoclase stringers in the granodiorite and suggested that they were derived from a nearby aplitic granite intrusion that is also exposed west of the Iona zone (Fig. 1).

Dykelets compositionally and texturally similar to the granite intrusion are widespread elsewhere in the Guichon and Bethlehem granodiorites as well as in the breccias, although these dykelets may or may not be related to the larger mass of granite. Textures in the granite body and dykelets are finely to medium crystalline allotriomorphic granular (aplitic) or porphyritic. Graphic intergrowths of quartz and orthoclase or plagioclase feldspar are common and locally cryptocrystalline spherulites are present. Typical constituents are orthoclase (50-60%), quartz (30-50%), sodic plagioclase feldspar (5-20%) and biotite (0-3%). Phenocrysts, where present, are plagioclase feldspar. The proportion of plagioclase feldspar to orthoclase increases in the northern part of the main granite mass and locally the composition approximates a quartz monzonite. Contact relationships of this pluton as described by previous investigators are contradictory and the critical outcrops are now obscured by mining operations. White and others (1957) described marginal chilling in Bethlehem Granodiorite adjacent to granite, whereas Wood (1968) described granite chilled against granodiorite and Iona breccia. Although the interpretation by Wood (1968) is favoured, the apparent conflict would be resolved had the granite mass formed by temporally distinct intrusions, as is consistent with observed compositional and textural variations. Further evidence indicating multiple ages of granite emplacement is the presence of small aplitic granite dykelets chilled against Guichon and Bethlehem granodiorites and breccia, and their presence as fragments or within fragments in breccia.

DACITE PORPHYRY

Dykes of dacite porphyry exposed on the Bethlehem property (Figs. 1 and 2) are part of a north-trending swarm. The swarm is 34 km long and the Bethlehem deposits occur midway along its length. Dykes are spaced irregularly across the 5- to 10-km width of the swarm, and average one dyke every 100 to 300 m (Carr, 1960). At Bethlehem, the dykes are clearly of several ages. They predate and are probably coeval with ore deposition. They also predate and postdate brecciation, and although the individual relationships have not been satisfactorily distinguished, more than one age of post-brecciation dyke emplacement has been recognized. Most dykes are less than 15 m wide, but some are as much as 60 m. The prevailing trend is northerly, but a significant number strike northeasterly. Dips are normally within 20 degrees of vertical. The large dyke at the east margin of the area (Fig. 1) is texturally distinct and probably not closely related to the others on the property.

Dacite porphyry is characterized by phenocrysts of plagioclase feldspar (50-70%), hornblende (2-5%) and quartz (0-3%), set in a finely crystalline groundmass composed of a mosaic of anhedral to subhedral quartz, plagioclase feldspar, minor hornblende and variable small amounts of orthoclase. Where the orthoclase content is relatively high, these rocks may approximate rhyodacite in composition. Phenocrysts of plagioclase feldspar occur as roughly equant subhedra and euhedra 3 to 5 mm in the largest dimension. Quartz phenocrysts normally form rounded "eyes" up to 3 mm in diameter, but square cross sections are not uncommon and bipyramidal crystals may be present. Subhedral and euhedral phenocrysts of poikilitic hornblende, ordinarily replaced by aggregates of epidote, reach a maximum length of about 10 mm. Samples of typical porphyry contain 50 to 70 per cent phenocrysts, except at finely crystalline margins. In the vicinity of the Jersey and East Jersey pits, the plagioclase feldspar of a late dacite porphyry dyke has been stained pink, presumably by the presence of finely crystalline hematite. Although similar in texture and mineralogy to other dacite porphyry, this particular dyke (Figs. 1 and 2), even where it is not stained, can usually be recognized by the higher content (5-10%) and larger size (up to 5 mm) of its quartz phenocrysts. Finely crystalline orthoclase occurs sporadically in the groundmass.

Dykes of dacite porphyry intrude older lithologies, including breccias and other dacite porphyries. Contacts are sharp, highly irregular and steeply dipping, and have finely crystalline margins that range from several to more than 100 cm in thickness. The margins of some dykes contain inclusions of breccia. These contact features imply that the breccias were lithified prior to emplacement of at least some of the dacite porphyry dykes. Moreover, a gradational contact occurs between breccia and a mass of leucocratic dacite porphyry immediately south of the East Jersey pit (see Fig. 1 and Wood, 1968). Fragments of similar porphyry also occur in breccia on the south wall of the Jersey pit. Although other dacite porphyry fragments are also present in the Bethlehem breccias, this is the only exposed mass with a demonstrable pre-breccia age of formation.

Genesis of Breccias and Porphyries

The association of breccias and porphyries with copper mineralization at Bethlehem was stressed by

Carr (1960, 1966) and Wood (1968). Wood (1968) proposed that the breccias formed primarily as intrusion breccias caused by magma stoping along the leading edges of the Bethlehem Granodiorite intrusion. However, several characteristics of the breccias would preclude such an origin. These features include: (1) numerous fragments of Bethlehem Granodiorite and those of younger porphyritic quartz latite and dacite porphyry; (2) the occurrence of breccia elsewhere than at the contact between the Guichon and Bethlehem phases; (3) the absence of Bethlehem Granodiorite as matrix material; and (4) the paucity of xenoliths in Bethlehem Granodiorite.

Carr (1966) postulated that impermeable chilled rinds formed around porphyry magmas that were intruded into cold, well-fractured country rocks so that the volatiles released during later stages of crystallization were impounded. "Explosive" release of these volatiles and consequent brecciation occurred when increasing internal pressures exceeded the confining pressures imposed by the host rocks.

A mechanism involving the rapid release of confined volatiles from crystallizing dacite porphyry magma is believed to best explain the formation of the Bethlehem breccias. However, the scarcity of pre-brecciation porphyry masses and the comparatively small number of porphyry fragments in the breccias indicate that the major episode of porphyry magma intrusion followed, rather than preceded, breccia formation.

The Bethlehem breccias are interpreted to have originated in the upper parts of the magma chamber(s) that produced the dacite porphyry dykes. Similarities in texture and mineralogy between the porphyries and Bethlehem Granodiorite suggest a related source. After initial intrusion of minor pre-brecciation porphyries, a relatively large hydrous vapour bubble(s) may have formed in the upper part of the porphyry magma chamber(s). Norton and Cathles (1973) postulated that such a bubble may form when coalescing, upward-migrating water exsolved from a magma is trapped and contained by the cooled rind of the pluton. Several features of the Bethlehem breccias suggest that subsequently, in contrast to the simple collapse mechanism of breccia formation proposed by Norton and Cathles (1973), fracturing of the cooled rind and adjacent wall rocks permitted the rapid escape of this bubble, with consequent brecciation in a fluidized system as proposed by Reynolds (1954). Features which imply forceful (intrusive) breccia emplacement, rather than collapse, include: (1) the transgressive nature of breccia contacts (Fig. 1), particularly in the Jersey pit (Fig. 2); (2) the occurrence, below Bethlehem Granodiorite roof rocks, of breccia containing predominately Guichon fragments; (3) the heterogeneous distribution of fragment types; (4) the presence of abundant cataclastic matrix, including interstitial rock "flour"; and (5) the rounded shapes of many fragments. Rapid escape of contained volatiles would have abruptly enhanced crystallization of the adjacent dacite porphyry melt, thus causing the formation of a second chill rind, which may have trapped much of this melt. However, small quantities of magma probably escaped at this time to form those few areas where the breccia contains porphyry matrix. After compaction and consolidation of the breccias, additional pulses of magma injection, withdrawal and (or) crystallization accompanied by fracturing and faulting may have broken the second chill rind and permitted the injection of porphyry magma. Repeated tapping of this magma would explain the multiple ages of dacite porphyry emplacement. A significant portion of the relatively small quantity of porphyry fragments in the breccia were probably derived from the initial chilled rind.

The various breccia masses may be the by-products of several vapour bubbles, or of a single vapour bubble that escaped along several channelways. Pressures necessary to cause an "explosive" release of trapped volatiles may have resulted simply from their accumulation in a restricted water-rich magma or from subsequent injection of magma originating at depth in the crystallizing batholith. McMillan (personal communication, 1972) believes that magma surges did occur during emplacement of at least the later phases of the Guichon Creek batholith.

Regardless of mechanisms, brecciation and most porphyry intrusions were accompanied and (or) followed by widespread and intense fracturing and associated hypogene mineralization and alteration, which presumably was accomplished by fluids and mineralizers derived from late-stage concentration in the dacite porphyry magma chamber(s).

Faults

Numerous faults and zones of closely spaced fractures at Bethlehem have exerted varying degrees of control on the emplacement of porphyry dykes, intrusive breccias and hydrothermal alteration-mineralization (Figs. 1 and 2). Faults are arbitrarily divided into major and minor types on the basis of gouge zone thicknesses of greater or less than 1 m, respectively. Most of the major faults trend north. They occur in the east-central part of the Huestis pit, the west-central part of the Jersey pit (Jersey fault), the east-central part of the East Jersey pit (East Jersey fault) and the central part of the Iona zone. Dips are vertical or steep to the west, although that of the Iona fault is unknown, but inferred to be steep. Horsetail patterns are displayed by the East Jersey fault at the north and south ends of the Jersey pit and by the Jersey fault on the north wall of the Jersey pit. Although McMillan (1971; personal communication, 1975) has "weak" evidence that the Jersey fault extends 1.7 km southward to the J.A. orebody, it is not known to extend north of the Jersey pit. Major faults of other orientations are less common, but several strike northeastward and dip steeply to the southeast. A few of the major faults have northwest trends, particularly in the Iona ore zone, but their extent is not known. Numerous minor faults are subparallel and adjacent to the major faults; most strike northward, although others strike northeast and northwestward and a few strike eastward.

Many of the faults cut the Bethlehem breccias. Although they may have been partly synchronous with dacite porphyry dyke injection, most have evidence of later movement. However, offsets have been detected at only three faults. Recent drilling between the East Jersey and Iona ore zones has confirmed 60 to 90 m of apparent left-lateral displacement of breccias and copper mineralization along a northeast-trending fault (Fig. 1). A dacite porphyry dyke in the East Jersey pit has undergone 12 m of apparent left-lateral offset along a northeast-trending splay of the East Jersey fault. Immediately south of the Jersey Pit, Wood (1968) mapped a dacite perphyry dyke with 38 m of apparent right-lateral offset along an east-trending fault.

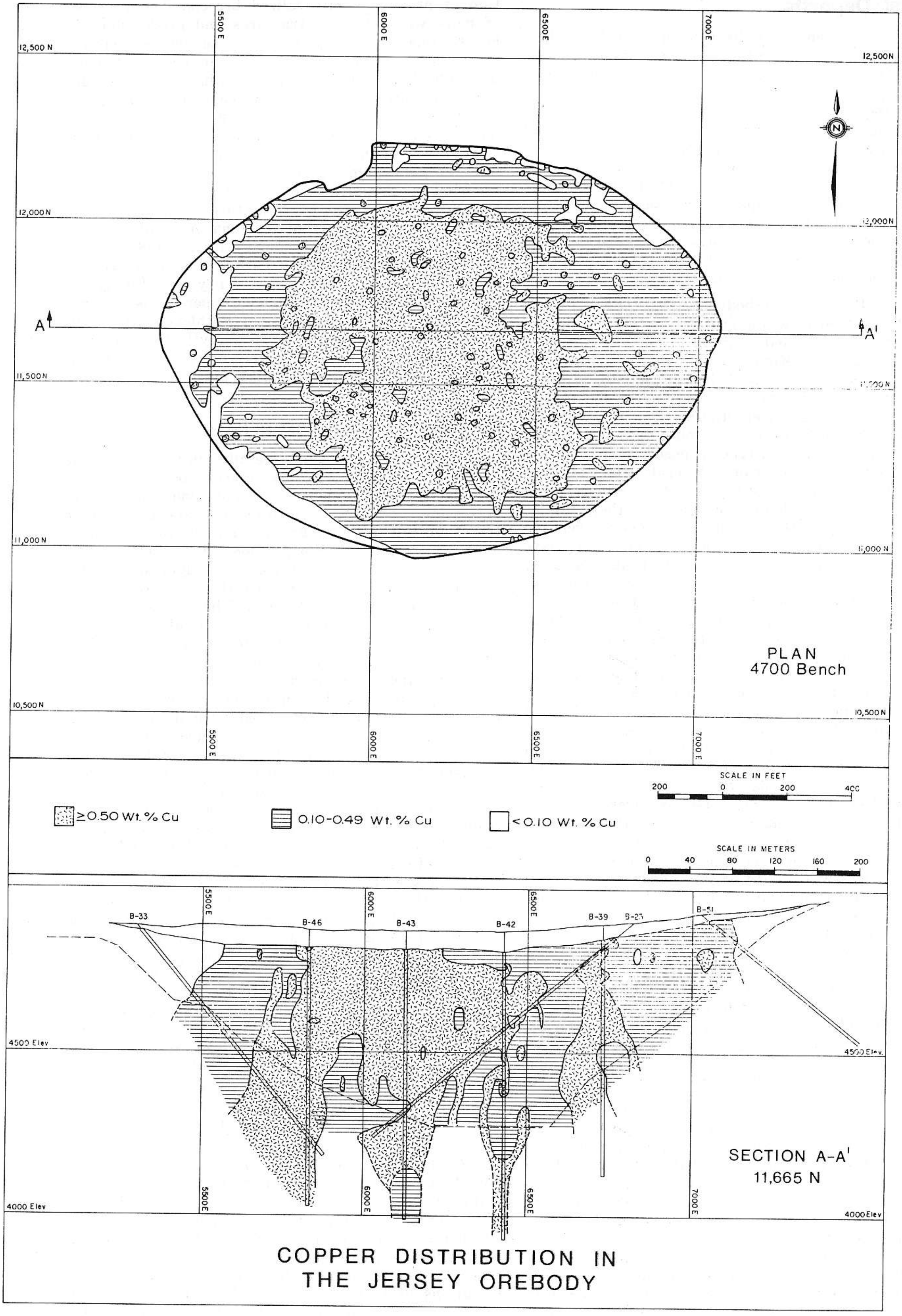

FIGURE 3 — Copper distribution in the Jersey deposit.

Mineral Deposits

Common epigenetic minerals on the Bethlehem property include white mica, chlorite, epidote, calcite, quartz, zeolites, chalcopyrite, bornite, pyrite, specularite, geothite, malachite, secondary biotite, tourmaline and molybdenite. These minerals occur in veins, veinlets, fracture coatings, irregular blebs and disseminations. Veinlets, fracture coatings and disseminations predominate. Veins, which are defined to be greater than 2.5 cm in width, contain variable proportions of specularite; quartz, calcite, epidote, chalcopyrite, bornite, pyrite and tourmaline. They occur in a zone peripheral to the central parts of the Jersey and Huestis orebodies, but, in contrast, they are more centrally located in the East Jersey and Iona ore zones.

The four Bethlehem orebodies are outlined in Figure 1. A detailed plan view and cross section of the Jersey orebody was constructed from blast-hole assays and is shown in Figure 3. Mineralization in the Jersey orebody is concentrically zoned; the central core of high-grade copper metallization is surrounded by a peripheral zone of progressively diminishing copper grade. At depth, the high-grade core splits into downward-extending roots. All rock types exposed within the ore zone predate mineralization. Mineralization is commonly higher in grade and more uniformly distributed in the breccias, which probably reflects their higher initial porosity and their greater frangibility relative to surrounding granitic host rocks. Major faults have only a minor and probably secondary influence on over-all ore disposition. Although these structures locally provided channel ways for ore deposition and seepage of mineralizing fluids into the peripheral vein system, they do not appear to have been a primary control of copper metallization in the central part of the orebody (Fig. 3). Pods of sheared copper sulphides in faults indicate post-ore movement, but nowhere has displacement been sufficient to offset the outline of the ore zone. The Jersey and Huestis orebodies are roughly oval in plan. In contrast, the East Jersey and Iona deposits are elongate northward, reflecting control by breccias and major shear zones. The East Jersey orebody has been described by several authors, including Coveney (1962), Coveney and others (1964), and Ewanchuk (1969). The orebody is composed of multiple, narrow, northerly trending ore shoots that dip steeply westward. Most of these bodies occur within breccia and commonly coincide with shear zones. Copper mineralization in the Iona ore zone is chiefly confined to the breccias, but these are unevenly mineralized. Zones of weak mineralization are interpreted to be areas where the breccias were tightly consolidated and resisted fracturing. Moreover, fragments and wall rock of the Bethlehem phase in the breccia are usually only weakly mineralized, whereas the reverse is true for the more mafic Guichon variety. Consequently, rock composition has influenced the distribution of copper metallization, a characteristic also observed in the Jersey orebody.

The intimate spatial association of copper mineralization with the emplacement of late-stage plutonic phases of the Guichon Creek batholith suggests a close temporal relationship as well. Copper-bearing fractures are numerous throughout the breccias, and crosscut both fragments ahd matrix alike. Thus, the main episode of metallization must have postdated breccia consolidation. However, several occurrences of brecciated sulphides suggest that minor amounts of mineralization may have preceded breccia formation and (or) there was some local, late-stage re-brecciation of previously mineralized breccia. The presence of more widely spaced fractures and proportionately lower grades of ore in some of the dacite porphyry dykes that postdate brecciation may indicate that either mineralization or fracturing, or both, largely preceded this late period of dyke emplacement. Bornite and chalcopyrite in joints in pink-stained dacite porphyry indicate that copper sulphide deposition continued beyond, or began after, the cooling of this youngest unit. A potassium-argon age of 199 ± 8 m y was reported by Dirom (1965), White and others (1967), and Northcote (1969) on a mixture of magmatic and hydrothermal biotite from the Iona ore zone (Dirom, 1965). This age is in agreement with the 198 ± 8 m y age for the Guichon Creek batholith (see Northcote, 1969), and 202 ± 4 and 198 ± 4 m y ages for hydrothermal sericite from the Valley Copper deposit (Jones and others, 1973), 6 km west of Bethlehem. However, because of the relatively large analytical uncertainty (± 8 m y), the Iona sample may not be a reliable indicator of the age of mineralization.

HYPOGENE METALLIC MINERALS

The common hypogene metallic minerals on the Bethlehem property are chalcopyrite, bornite, pyrite, specularite and molybdenite. Minor amounts of magnetite and chalcocite are also present, and microscopic traces of tetrahedrite, galena and possibly linnaeite have been reported (Wood, 1968; White and others, 1957). Trace analyses for copper, molybdenum, zinc, lead and silver are included with the whole-rock chemical analyses shown in Table 3. The consistently low values for silver, lead and zinc, particularly between "unaltered" and equivalent altered and mineralized lithologies, further emphasize the simplicity of the metallic mineral assemblage. Specularite is present in minor amounts as disseminations, but usually occurs in veins and veinlets associated with quartz, calcite, epidote, chalcopyrite, bornite and rarely tourmaline. Chalcopyrite, bornite and pyrite are present in veins; however, veinlets and fracture coatings of these sulphides and of molybdenite predominate in the ore zone. Disseminated finely crystalline sulphides that replace primary and secondary mafic minerals adjacent to mineralized fractures are common, but quantitatively subordinate to fracture-controlled mineralization. The following are customary mineral associations: chalcopyrite with chlorite, bornite, pyrite, quartz, secondary biotite, epidote and calcite; bornite with chalcopyrite, chlorite, secondary biotite, quartz and calcite (in veins); and pyrite with chlorite, chalcopyrite, epidote, calcite and quartz. The combined abundances of bornite and chalcopyrite within the ore zones rarely exceed 2 per cent by volume. Concentrations of pyrite in the halo zones are normally less than 1 per cent, although locally they reach 5 per cent. Molybdenite is sporadically distributed and commonly peripheral to the central parts of the ore zones. Occurrences may be monomineralic or associated with chalcopyrite, quartz and bornite in veinlets or less commonly in quartz stockworks.

Distributions of specularite, pyrite, chalcopyrite and bornite in the Jersey pit (Fig. 4) were determined using quantitative visual estimates obtained from (1) microscopic examination of 560 hand samples, (2) detailed logging of core from five diamond drill holes and (3) field investigations. Specularite occurrences are peripheral to those of pyrite and the distributions of both these minerals form crudely concentric zones about a bornite-rich core. The outer

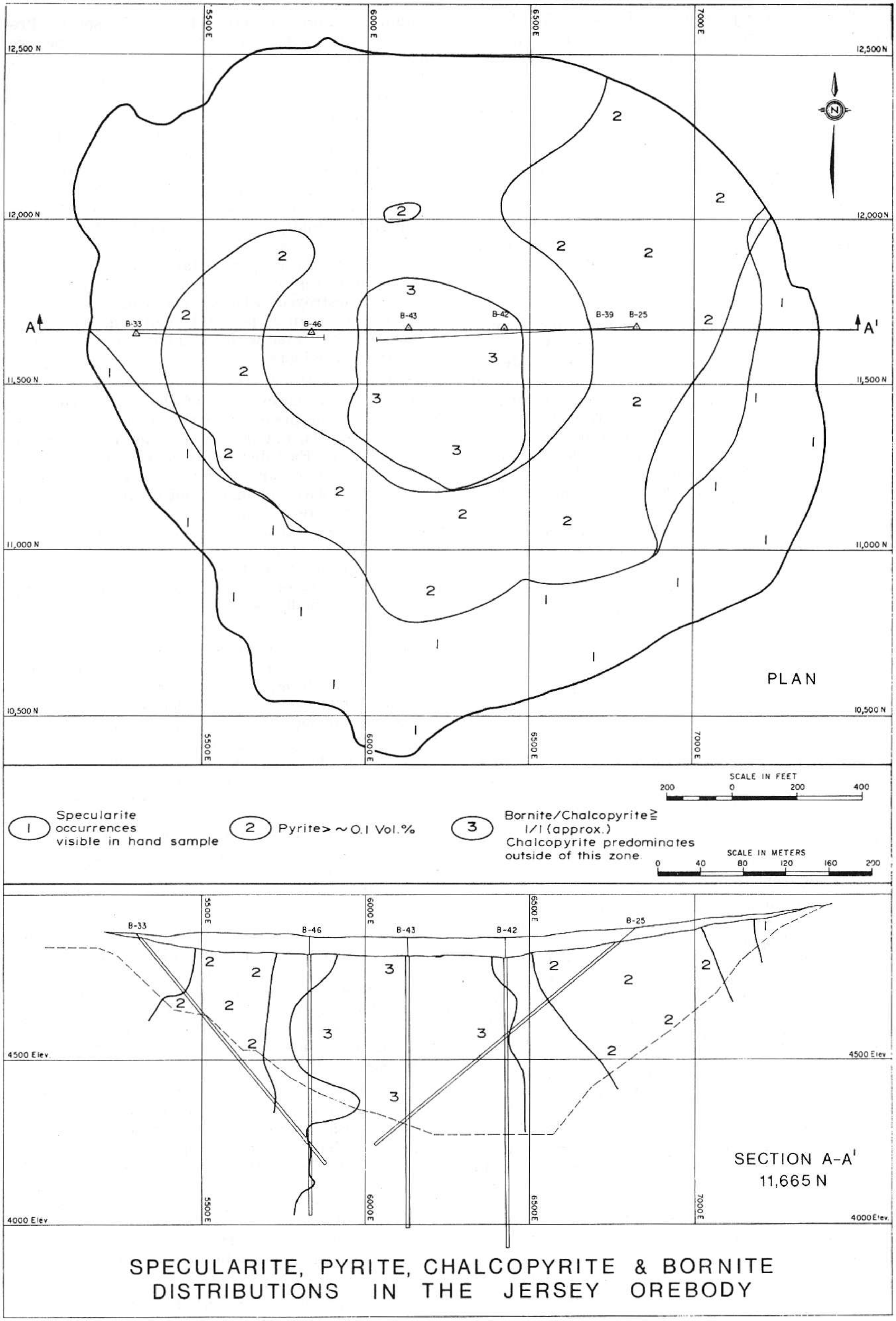

FIGURE 4 — Metallic mineral distribution in the Jersey deposit.

zone of low-grade copper mineralization (Fig. 3) approximately coincides with the pyrite halo, and the high-grade core is largely contained within the bornite-rich central zone. Chalcopyrite is present throughout the deposit and is most abundant within the outer limits of the pyrite zone. Reconnaissance work suggests similar zonal patterns in the Huestis orebody and that peripheral specularite also occurs around the Iona ore zone. Comparative data are not available for the East Jersey orebody. Mineralogic and chemical variations between the hypogene metallic mineral zones in the Jersey pit are shown in Table 1. Features of particular interest are: (1) high bornite:chalcopyrite ratios in the bornite-rich core; (2) low total sulphide content; and (3) a well-defined zone of specularite beyond the pyrite halo.

Several features of the Bethlehem porphyry (Fig. 2) may imply a close genetic relationship to the source of the hydrothermal fluids that formed the Jersey orebody. These are: (1) increase in the amounts of secondary biotite, copper sulphides (especially bornite) and quartz (veinlets) in Guichon Granodiorite host rocks near contacts with Bethlehem porphyry; (2) central position of the porphyry with respect to zoning of metallic and alteration minerals (c.f. Figs. 2, 3, 4 and 5); (3) paucity of fractures in the porphyry relative to surrounding rocks; and (4) presence of disseminated copper sulphides in the porphyry that apparently are spatially unrelated to fractures.

HYPOGENE NONMETALLIC ALTERATION AND VEIN MINERALS

Common hypogene nonmetallic minerals include white mica, chlorite, epidote, calcite, quartz, zeolites, secondary biotite, and tourmaline. Smaller amounts of kaolinite, albite, actinolite, montmorillonite, secondary potassium feldspar, rutile and prehnite are also present. Scheelite and possible alunite were reported by White and others (1957). In addition to the vein-type occurrences of hypogene minerals previously described for the Bethlehem property, alteration selvages in host rocks adjacent to faults, joints and fractures commonly contain quantities of white mica, chlorite, calcite and some epidote. The selvages are ordinarily 1 m or less in width, but are as much as 30 m wide adjacent to major faults.

Epidote is most abundant at the outer margins of the Jersey and Huestis orebodies. The approximate distributions of epidote and secondary biotite in the Jersey pit are shown in Figure 5. The distributions form a roughly concentric zonal pattern, with epidote peripheral to a central biotite-rich core. Most vein occurrences of hypogene minerals are contained within the epidote zone, and the majority of these are confined to the specularite-rich portion (Fig. 4). Epidote is rare in the Iona breccias, but is common in adjacent host rocks. It is also common throughout the East Jersey ore zone. Epidote is usually found in veins, veinlets and coating fractures, and as disseminations replacing calcic plagioclase feldspar and primary mafic minerals. Where disseminated, it may compose up to 20 per cent of the host rock; however, amounts between 1 and 10 per cent are typical. Epidote is normally associated with chlorite, white mica, calcite, quartz, specularite, chalcopyrite and pyrite. The association with chalcopyrite and, less commonly, bornite is unusual in porphyry copper deposits and may represent a late-stage or retrograde mineralization event.

The term "white mica" as used in the text of this report includes all optically unidentifiable, finely crystalline alteration products of feldspars. Preliminary X-ray diffraction studies indicate the presence of sericite and small amounts of kaolinite and montmorillonite in this material. White mica is widespread in all but the most unaltered rocks of the Jersey and Huestis orebodies. Significant quantities of white mica roughly coincide with areas of greater than 0.1 weight per cent copper, even though zonal distributions are not obvious (Fig. 3). In the Iona zone, white mica is predominantly restricted to breccias and pervades host rocks only near areas of quartz flooding. Reconnaissance studies of the East Jersey orebody indicate that white mica alteration accompanies significant copper metallization. White mica preferentially replaces orthoclose, which is usually completely destroyed, whereas plagioclase feldspar is typically more than 20 per cent unaltered. White mica is generally associated with small but variable amounts of calcite and epidote.

Secondary biotite in the Jersey orebody is largely restricted to the lower parts of the bornite-rich core zone. It is widespread in near-surface localities of the Iona breccias, but is only a minor constituent in the Huestis and East Jersey ore zones. Although some secondary biotite occurs in veinlets and fracture coatings, most replaces primary biotite and hornblende, secondary chlorite and actinolite, and breccia matrix. Breccias may contain as much as 50 per cent secondary biotite, whereas other rock types seldom have more than 15 per cent. Quantities between 3 and 8 per cent are representative of most biotite-rich areas. Secondary biotite is usually associated with chlorite, bornite and chalcopyrite.

Chlorite is the first alteration mineral encountered at the outermost margins of the mineralized zones. Epidote and white mica become common closer to the orebodies. Chlorite occurs as replacements of primary biotite and hornblende, breccia matrix, and secondary actinolite, biotite and epidote, and also as veinlets. The local abundance of chlorite is predominantly controlled by rock type, although the mineral is present throughout the deposits. Within mineralized zones and in rocks other than breccia, chlorite typically composes 5 to 15 per cent of a sample. Breccias having a chloritic matrix may contain as much as 25 per cent chlorite. Chlorite is normally associated with epidote, chalcopyrite, bornite, pyrite, secondary biotite, and calcite.

Calcite is common in the peripheral vein assemblages. It is also abundant in veinlets, some of which are post-ore age, where it may be associated with zeolites. Moreover, calcite is a nearly ubiquitous alteration product of plagioclase feldspar and, less commonly, hornblende. Calcite is ordinarily associated with white mica, epidote, chlorite, quartz, chalcopyrite, pyrite, specularite and bornite.

Quartz is the predominant constituent of veinlets that are locally abundant in the central parts of the Huestis and Easy Jersey orebodies and the bornite-rich core of the Jersey orebody, and is also a common component of the peripheral vein assemblages. As previously mentioned, quartz is an abundant constituent of the matrix in breccias of the Iona zone. These occurrences of quartz are monomineralic or are components of assemblages that also include bornite, chalcopyrite, calcite, epidote, specularite, pyrite and tourmaline.

Black schlorlitic tourmaline has widespread but erratic distribution. It is present both within, and marginal to, all the ore zones, but is abundant only

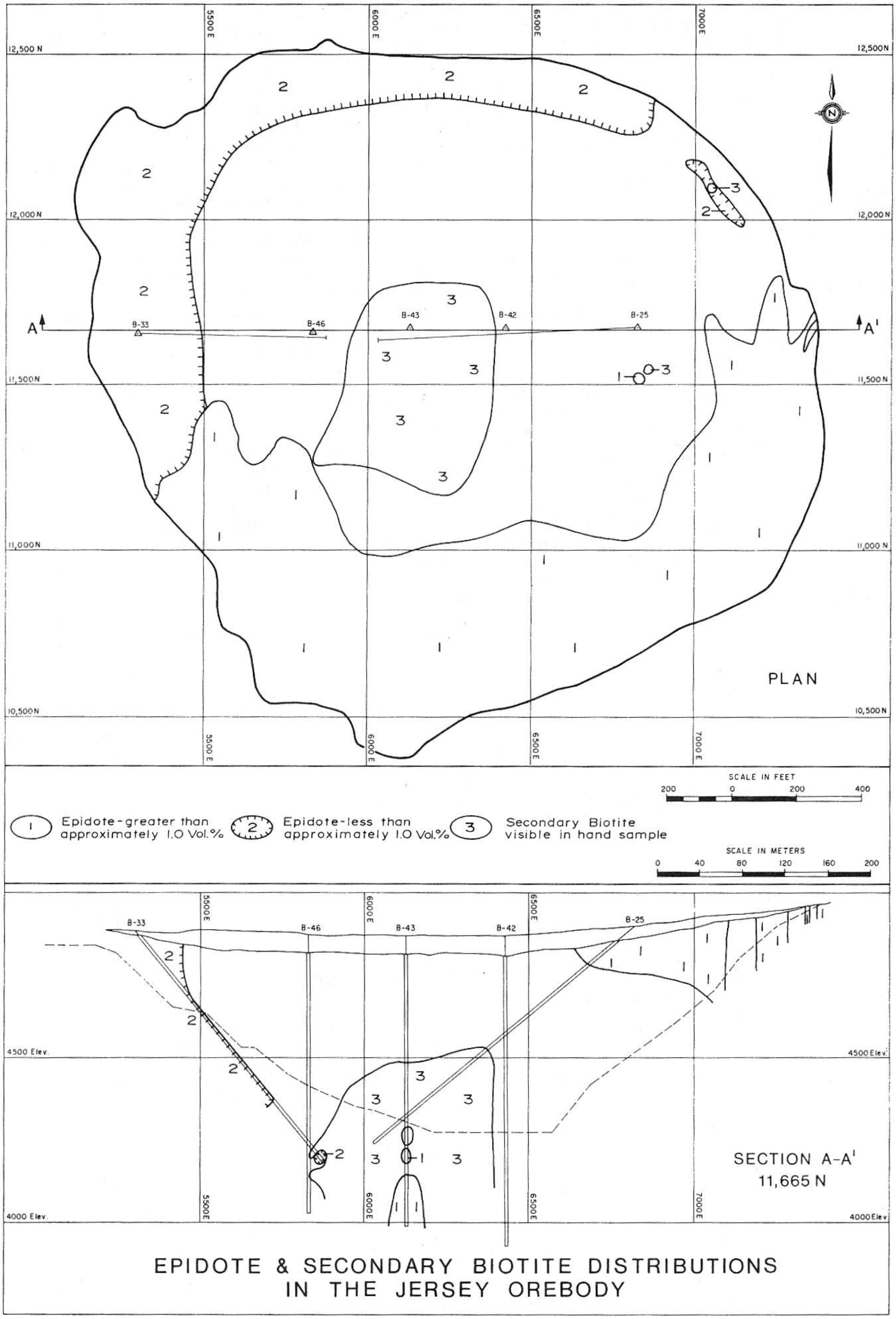

FIGURE 5 — Epidote and secondary biotite distribution in the Jersey deposit.

in breccias of the Iona zone that have a quartz-rich matrix. Tourmaline occurs as crystalline aggregates intergrown with quartz, as replacements of small breccia fragments and breccia matrix in veinlets, as veins and fracture coatings, and rarely as rosettes in gouge zones. It is predominantly associated with quartz, epidote, chalcopyrite, calcite, actinolite and specularite.

The presence of the zeolites laumontite, stilbite, heulandite and chabazite has been confirmed by X-ray diffraction studies. Numerous veinlets of laumontite that generally contain smaller amounts of calcite, stilbite and heulandite crosscut all rock types and hypogene mineralization. They are ubiquitous in all four ore zones. Veinlets of stilbite are abundant, and stilbite and rarely chabazite encrust vugs in the south breccia of the Jersey pit. Post-ore zeolites, especially laumontite, are interpreted to be low-temperature products deposited during cooling and collapse of the Bethlehem hydrothermal system(s).

Zonal development of hydrothermal alteration in the Jersey orebody (Fig. 5) is similar to that described for most porphyry copper deposits. Distributions of epidote and secondary biotite in the Jersey orebody outline propylitic and potassic alteration zones respectively (samples 4 and 8, in Tables 2 and 3). The intervening area, dominated by white mica, is probably equivalent to a mixed zone of phyllic and argillic alteration (samples 3 and 7, in Tables 2 and 3). The potassic zone is atypical because of the near absence of secondary potassium feldspar (sample 8 is the only known occurrence). Significant hydrothermal alteration is restricted to the immediate area of the orebody and only the epidote zone and associated chlorite extend beyond the limits of conspicuous copper sulphide mineralization.

OXIDATION AND SUPERGENE ENRICHMENT

Minerals identified from the zones of oxidation at Bethlehem include geothite, hematite, malachite, manganese oxides, chrysocolla, azurite, cuprite, native copper and ferrimolybdenite. Possible occurrences of powellite and erythrite were reported by White and others (1975). Although the effects of oxidation are largely surficial (less than 20 m deep), its distribution and intensity is controlled by structure. The shattered southern third of the Iona ore zone is strongly oxidized and total oxidation of sulphides is common to depths exceeding 100 m. Open fractures may be stained by limonite for considerable distances below the zone of oxidation. Assays for copper are relatively unchanged between zones of sulphide and oxide ore in the Iona orebody, and this consistency reflects the scarcity of pyrite and the relative abundance of carbonate, both of which effectively inhibited the migration of copper. Minute quantities of supergene chalcocite and covellite occur in surficial exposures and drill core, but there is no zone of secondarily enriched ore.

Comments

At Bethlehem, hypogene mineralization probably began during the later stages of post-brecciation porphyry dyke emplacement and continued beyond the cessation of this period of intrusive activity. If hydrothermal mineralization proceeded upward and outward from the bornite-rich core of the ore zones, as the arrangement of alteration zones probably indicates, the deposition of metallic minerals may have begun with the precipitation of sulphide assemblages having low iron-to-copper ratios (i.e. bornite:chalcopyrite $\leqslant 1$) from fluids initially low in both iron and sulphur. However, hydrothermal alteration of primary mafic minerals may have increased the availability of iron with increasing distance from the bornite-rich core. This would favour lower bornite-to-chalcopyrite ratios and eventually the formation of pyrite. Subsequent depletion of sulphur could have sufficiently decreased its fugacity relative to that of oxygen to the extent that remaining iron was deposited primarily as specularite (Meyer and Hemley, 1967). Alternatively, the relatively rapid transition from sulphide- to oxide-dominated assemblages may have resulted from the mixing of magmatically derived fluids with oxygenated ground water. Faults, joints and fractures in the peripheral vein system would have provided favourable channel ways for the intermingling of magmatic fluids with ground water, and might account for the restriction of most occurrences of specularite to these structures. The possible role of ground water is currently being investigated through studies of fluid inclusions and light, stable isotope distributions.

The Bethlehem orebodies generally possess geologic, mineralogic and geochemical features that are similar to those described for other porphyry copper-molybdenum deposits of western North America (e.g. Creasey, 1959, 1966, 1972; Burnham, 1962; Titley and Hicks, 1966; Meyer and Hemley, 1967; Sutherland Brown, 1966; Lowell and Guilbert, 1970; Rose, 1970; James, 1971; De Geoffroy and Wignall, 1972; and Field and others, 1974). However, in detail the Bethlehem deposits, especially the Jersey orebody, differ in the degree to which many of these features are developed. Distinctive characteristics of Bethlehem include: (1) an intrabatholith location; (2) relatively old mineralization (200 m y); (3) dominance of fracture-controlled copper mineralization; (4) mineralogical simplicity of the metallic constituents; (5) absence of lead, zinc and silver occurrences; (6) well-defined zonation of iron-bearing metallic minerals; (7) low total sulphide content (average < 2 per cent) and sparse pyrite (average < 1 per cent in the halo zone); (8) high bornite-to-chalcopyrite ratios ($\geqslant 1$); (9) molybdenite peripheral to the central parts of the ore zones; (10) association of chalcopyrite and bornite with epidote; (11) restriction of significant hydrothermal alteration to the ore zones; (12) scarcity of potassium feldspar alteration; and (13) widespread presence of post-metallization zeolites, especially laumontite.

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Lornex

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Abstract

The Lornex copper-molybdenum deposit is situated in the Highland Valley of British Columbia, 42 kilometers southeast of Ashcroft. This zoned, structurally controlled, porphyry deposit is entirely within Skeena Quartz Diorite. The host rock, a variety of the Bethlehem phase of the Upper Triassic Guichon Creek batholith, is intruded by a pre-mineral quartz porphyry dyke. The dyke trends northwesterly and is most prominent in the southern portion of the ore zone. The Lornex fault, a north-striking and west-dipping regional structure, is the northwestern boundary of the orebody and separates the host rock from younger, virtually barren Bethsaida Granodiorite west of the orebody.

The ore zone is approximately 1900 meters long and 500 meters wide, and geological interpretations suggest that the orebody plunges 30 to 40 degrees toward the northwest. Mineralization is fracture controlled and commonly occurs as fracture coatings or veins. The major sulphides, in order of abundance, are chalcopyrite, bornite, molybdenite and pyrite.

These sulphide minerals and hydrothermal alteration zones are distributed in a roughly concentric pattern. The bornite core is surrounded by a zone of chalcopyrite and molybdenite mineralization; pyrite is peripheral. Phyllic and pervasive argillic alterations occupy the ore zone and propylitic alteration occurs in the peripheral zone of pyrite and lower copper grades. Intensity of hydrothermal alteration increases with fracture density and sulphide content.

The Lornex orebody is considered to have formed at the intersection of regional structures. Tectonic stresses developed conjugate shears at this intersection which were subsequently mineralized by the injection of hydrothermal fluids. Reactivation of stresses caused rupture, displacement and tilting of the mineralized zone along the Lornex fault. Minor faulting and fracturing of the mineralized zone occurred after relaxation of major tectonic forces.

Location

THE LORNEX copper-molybdenum deposit is located in the interior plateau of British Columbia on the southern slope of the Highland Valley — Lat. 50° 27′ N, Long. 121° 03′ W, NTS 92I/6E. The original surface of the orebody is about 1550 meters above sea level. The property is 42 km by road southeast from Ashcroft and 72 km by road from Kamloops.

History

Copper mineralization was discovered in bulldozer trenches by Egil Lorentzen in 1964. Mr. Lorentzen formed Lornex Mining Corporation, and in 1965, under agreement with Lornex, Rio Tinto Canadian Exploration Limited began an investigation of the property. A program of geochemical, induced polarization, magnetometer and geological surveys was implemented. The IP survey outlined two zones where chargeabilities were in excess of twice mean background (i.e. chargeabilities in excess of 5 milliseconds). Subsequent diamond drilling of the anomalous zones returned encouraging copper grades. A total of 26,200 meters of surface diamond drilling and 27,000 meters of percussion drilling were completed by 1967. An underground bulk sampling program and a small open pit provided feed for a pilot mill at 90 tonnes per day. The mine was put into production in the spring of 1972 by Lornex Mining Corporation Limited, which is controlled by Rio Algom Mines Limited.

The developed orebody contained an estimated 266 million tonnes of mineable ore averaging 0.427 per cent copper and 0.014 per cent molybdenum at a cutoff grade of 0.26 per cent copper and a waste-to-ore ratio of 1.2:1. During the period from 1973 to 1974, an additional 20,700 meters of diamond drilling was completed. Drill-indicated reserves, within a single open pit, as of December 31, 1974, were estimated to be 425 million tonnes of proven ore grading 0.412 per cent copper and 0.014 per cent molybdenum at a 0.26 per cent copper cutoff grade and a 2:1 waste-to-ore ratio.

The mill was designed to process 34,500 tonnes of ore per day. Actual throughput, however, has been such that, for planning purposes, the mill capacity is now rated at 43,500 tonnes per day.

Regional Geology

The Lornex ore deposit occurs within the composite, concentrically zoned, Upper Triassic, Guichon Creek batholith (see McMillan, this volume).

The batholith, which is approximately 65 kilometers long and 30 kilometers wide, trends in a north-northwesterly direction. The batholith has been divided into four phases, which are compositionally and texturally distinguishable. From oldest to youngest, the phases are as follows.

1.) The Hybrid phase is peripheral and is generally a mafic-rich quartz diorite to diorite in composition.
2.) The Highland Valley phase consists of the Guichon and Chataway granodiorites.
3.) The Bethlehem phase is generally granodiorite, but the Skeena variety, the host rock for the orebody, is a medium- to coarse-grained quartz diorite.
4.) The central Bethsaida phase is coarse-grained granodiorite to quartz monzonite.

The batholith intrudes sedimentary and volcanic rocks of the Permian Cache Creek Group and Late Triassic Nicola Group.

Middle Jurassic sedimentary rocks and Cretaceous volcanic and sedimentary rocks unconformably overlie the batholith. The orebody and most of the batholith were mantled with a veneer of Pleistocene glacial deposits.

Structural zones transect the Guichon Creek batholith and are considered to be the result of regional tectonic stresses which created a series of block faults (Carr *et al.*, 1970). Predominant trends in the batholith are north, northwest and, to a lesser extent, east and northeast. According to McMillan, (pers. comm., 1974), the Lornex orebody is located in a horst bounded on the north by the Highland Valley fault and on the south by the Skuhun Creek fault. The horst is cut by the north-striking Lornex fault. This regional fault forms the contact between the Bethsaida and Bethlehem phases in the vicinity of the Lornex orebody and truncates mineralization in the ore zone. Cumulative movement on this west-dipping fault is apparently right lateral and reverse (McMillan, pers. comm., 1974).

Geology of the Ore Deposit

The Lornex copper-molybdenum deposit is approximately 1900 meters long, 500 meters wide and plunges northwesterly to a depth in excess of 750 meters (below 850 m A.S.L.). The ore deposit is mantled by 2 to 75 meters of overburden, which gradually thins eastward from a maximum depth in Award Creek Valley, the surface expression of the Lornex fault.

The orebody occurs within Skeena Quartz Diorite, a slightly porphyritic, medium- to coarse-grained rock (Fig. 1). It consists of quartz (20%), plagioclase (50%), orthoclase (10%), biotite (5-10%) and hornblende (5-10%), with accessory sphene, apatite, zircon and magnetite. Quartz occurs interstitially in subhedral grains that show undulatory extinction. Plagioclase is twinned and exhibits oscillatory zoning, with crystal cores of about An_{30-35}. Orthoclase is interstitial and perthitic. Biotite is subhedral to euhedral. Hornblende is irregular anhedral and commonly has a poikilitic texture.

A pre-mineral quartz porphyry dyke (Fig. 1), which is probably related to the Bethsaida phase (McMillan, pers. comm., 1974), trends northwesterly through the Highmont property and into the Lornex orebody.

Contacts of the dyke are indistinct because of silicification and sericitization of adjoining Skeena Quartz Diorite. The dyke is presumed to have intruded one of a series of structural zones parallel to Highland Valley (Bergey *et al.*, 1970). Quartz phenocrysts normally compose 20 to 25 per cent of the dyke and plagioclase phenocrysts occur locally. The grey aphanitic matrix is composed of 60 to 70 per cent plagioclase (An_{40}) and 10 per cent quartz.

AGES OF ROCK TYPES AND MINERALIZATION

All phases of the Guichon Creek batholith have been dated at 198 ± 8 m y (Northcote, 1969), however geologic evidence indicates that relative age decreases from the periphery to the core. Hydrothermal alteration products from the Lornex orebody were dated at 190 ± 4 m y (Jones *et al.*, 1974). This and geological evidence indicates that Lornex mineralization is slightly younger than the youngest intrusive phase of the batholith.

STRUCTURE

Mineralization at Lornex is controlled by fracture density and distribution. Mineralized and post-mineral fractures were formed during at least three periods of deformation. In order to facilitate the study of more than 11,000 structural measurements from the Lornex pit, a computerized stereo-plot program was utilized. This program plots poles to planes on a lower-hemisphere, equal-area net. As illustrated in Figure 3a, contoured plots of per cent density indicate three major attitudes for copper-molybdenum veins: N22°E/55°SE, N64°E/57°SE and N90°E/58°S. Certain of these veins are dominant in distinct zones of the orebody. The N22°E-striking veins are common in the northern zone, whereas the N90°E-striking veins are concentrated in the south and southeast zones. In the central and western zones there is an overlap of all three vein attitudes, which results in a greater concentration of veins and high copper grades (Fig. 2).

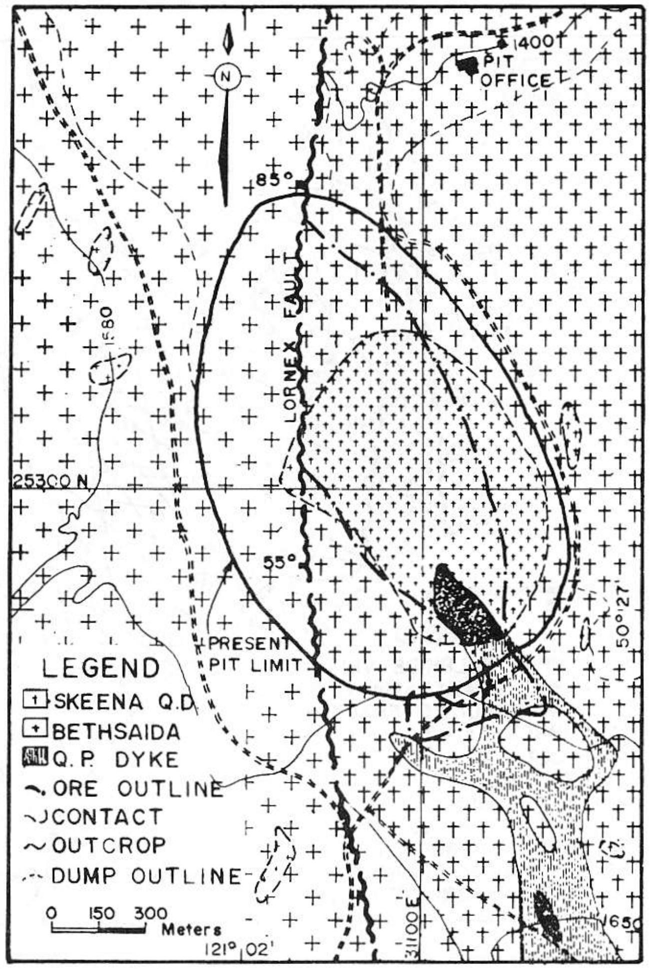

FIGURE 1 — General geology of the Lornex deposit.

Two post-mineral fracture systems have been recognized in the open pit. One system of faults and fractures trends N86°W/52°S to N88°W/62°S and N21°E/46°SE to N32°E/54°SE (Fig. 3b and 3c), sub-parallel to the N22°E- and N90°E-striking copper-molybdenum veins. A second system which offsets the first has three dominant trends:

Fractures	Faults
1.) N68°W/69° S W	N63°W/57° S W
2.) N44°W/66° S W	
3.) N 8°W/68° W	N 8°W/64° W

Where faults cut vein mineralization, displacements are from 1 centimeter to 2 meters.

In summary, three distinct structural systems, one mineralized and two unmineralized, have been recognized in the orebody. They are, from oldest to youngest:

(1) mineralized fractures striking N22°E, N64°E and N90°E;

(2) post-mineral faults and fractures which strike N88° to 86°W and N21°E to N32°E;

(3) faults and fractures which strike N68° to 63°W, N44°W and N8°W.

The most prominent structural feature is the Lornex fault, illustrated in Figures 1 and 2a. It has been exposed by mining and intersected by diamond drill holes. The fault truncates the northwestern part of the ore deposit and juxtaposes Bethsaida Granodiorite and Skeena Quartz Diorite in the vicinity of the orebody.

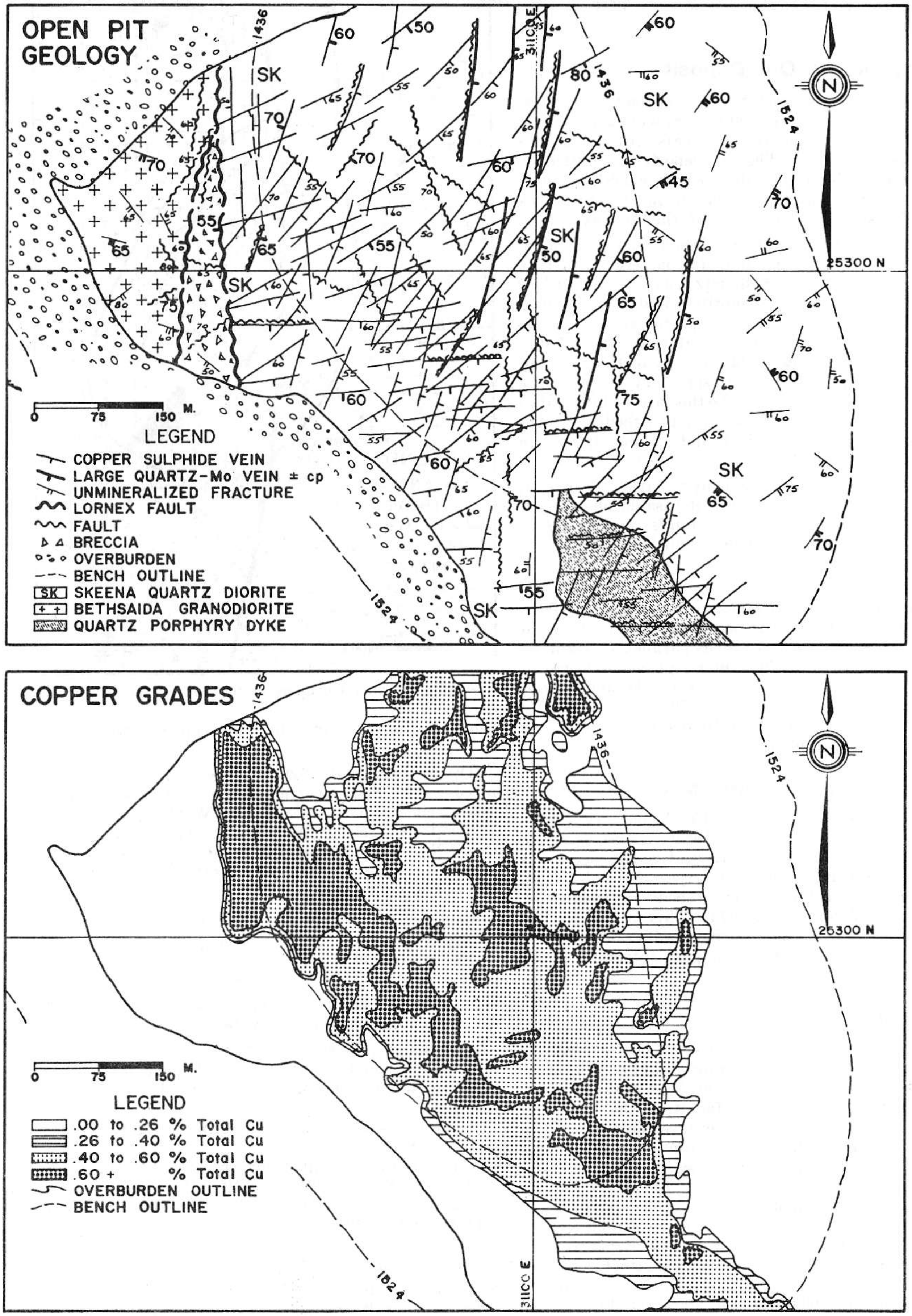

FIGURE 2 — Composite maps of 1436-m and 1524-m benches, illustrating: (a) structural geology and (b) copper-grade distributions.

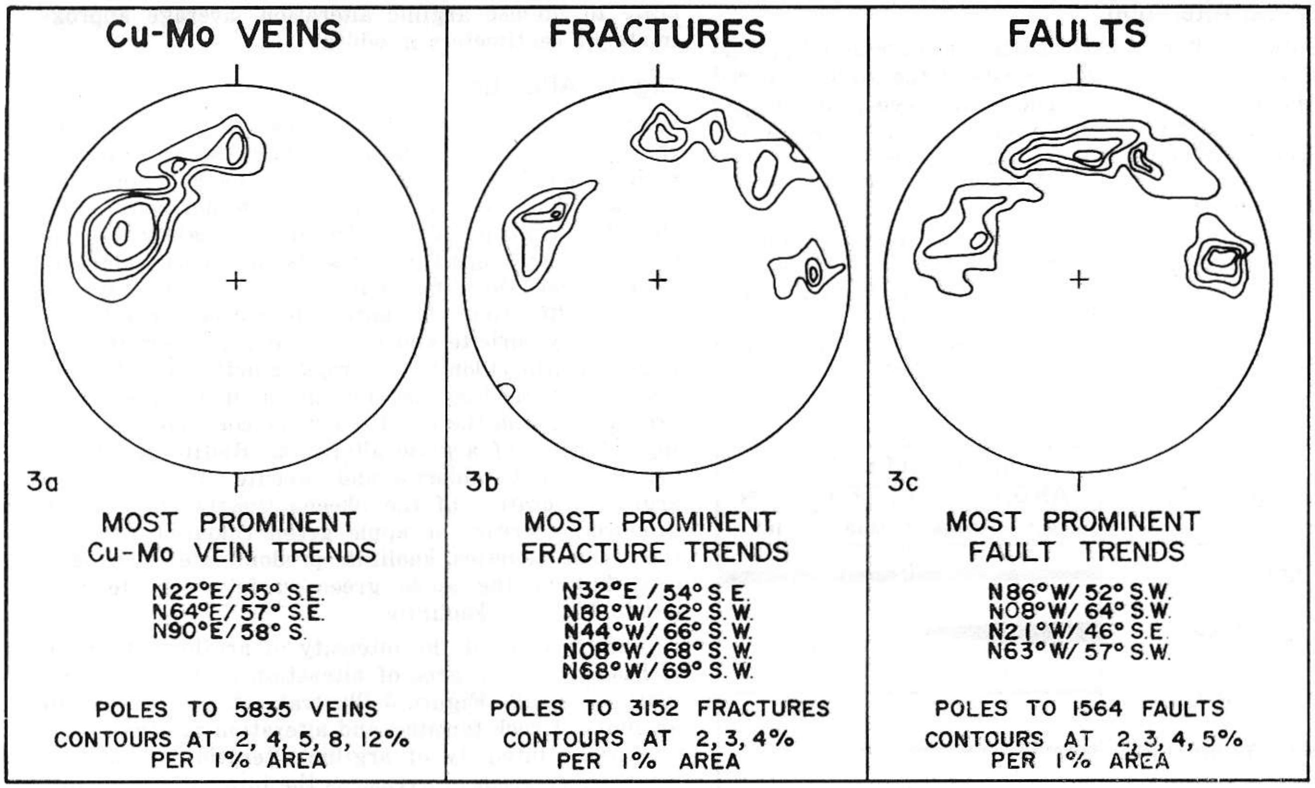

FIGURE 3 — Lower-hemisphere, equal-area stereographic projections of structures mapped in the open pit.

The fault strikes northerly and dips 55 to 85 degrees westward. In general, the dip is least in the south and steepens toward the north. Black gouge, which forms on the footwall of the fault zone, varies in thickness from 10 centimeters to 1½ meters. Mylonite, which forms discontinuous pods 1 to 50 meters wide in the hanging wall of the fault zone, has been exposed in the pit over a strike length of 75 meters.

MINERALIZATION

The predominant hypogene sulphide minerals, in order of abundance, are chalcopyrite, bornite, molybdenite and pyrite. Minor amounts of sphalerite, galena, tetrahedrite and pyrrhotite also occur. Total sulphide content averages 1 to 1.5 weight per cent in the ore zone, but gradually decreases from the central part of the orebody toward its periphery. Common gangue minerals include quartz, calcite, epidote, hematite, magnetite and gypsum.

Sulphide mineralization occurs primarily as fracture fillings with quartz and as fracture coatings. Only an estimated 5 per cent of the total bornite, chalcopyrite and pyrite mineralization occurs as disseminations or as partial replacements of mafic constituents of the host rock. Veins average 5 to 15 millimeters in width, but vary in width from a hairline to more than a meter. The larger veins, some of which have been mapped along strike lengths of over 200 meters, are commonly composed of quartz, molybdenite and chalcopyrite. Molybdenite may occur as rosettes in vuggy quartz veins, but normally occurs as thin laminae in banded quartz veins. Kimura and Drummond (1968) describe similar veins at Endako and suggest that repetitive pulses of mineralization occurred along these types of vein structures. Molybdenite veins more than a meter in width are prominent on the eastern side of the orebody (Fig. 2a). Post-ore faults are prevalent along these veins.

An erratic band of late-stage gypsum occurs at elevations below approximately 1100 meters (Fig. 7b). The gypsum is generally at a higher level on the fringe of the orebody and deeper in its center. Gypsum mineralization is post-ore and occurs in veins 5 to 10 millimeters thick.

Trace-element studies of the orebody, surrounding rocks and the Lornex fault zone indicate anomalous values of several elements. Anomalously high amounts of Zn, Ag and Bi and, according to Olade (1974), Pb, Mn, Hg, Cd and Ca exist in the Lornex fault where it truncates the orebody. Zinc values as high as 1200 ppm have been determined from analyses of Lornex fault gouge. Sphalerite and discontinuous pods of massive pyrite occur in the Lornex fault zone, but chalcopyrite, bornite and molybdenite have not been observed. Assays of over 70 ppm Bi in the fault are probably due to the presence of bismuthinite, which was identified by microprobe analyses of copper concentrate. The orebody is enriched in B, Ti and V, but anomalously low in Mn, Sn and Ba.

HYDROTHERMAL ALTERATION

X-ray diffraction (McMillan, pers. comm., 1974), megascopic and microscopic studies were conducted to classify intensities and types of hydrothermal alteration. Four types of alteration — potassic, phyllic, argillic and propylitic — which are related to quartz and sulphide mineralization have been recognized. A fifth type of alteration, silicification, is not detailed, because the zone of silicification appears to be related to the pre-mineral quartz porphyry dyke.

This dyke appears to be weakly affected by the other hydrothermal alterations, in contrast to the Skeena Quartz Diorite host, which was very susceptible.

Potassic Alteration

Potassic alteration is erratically distributed and no well-defined potassic zone exists at the levels explored in the Lornex orebody. The hydrothermal K-feldspar that does exist is found as veins that average approximately 5 millimeters in width.

Phyllic Alteration

Phyllic alteration in the orebody consists of quartz-sericite envelopes. A grey mixture of quartz and sericite commonly forms borders on quartz-copper sulphide and quartz-molybdenite veins within the argillic alteration zone (Fig. 10a & b). These envelopes, which commonly form sharp boundaries with pervasive moderate to intense argillic alteration, average approximately 3 centimeters in width.

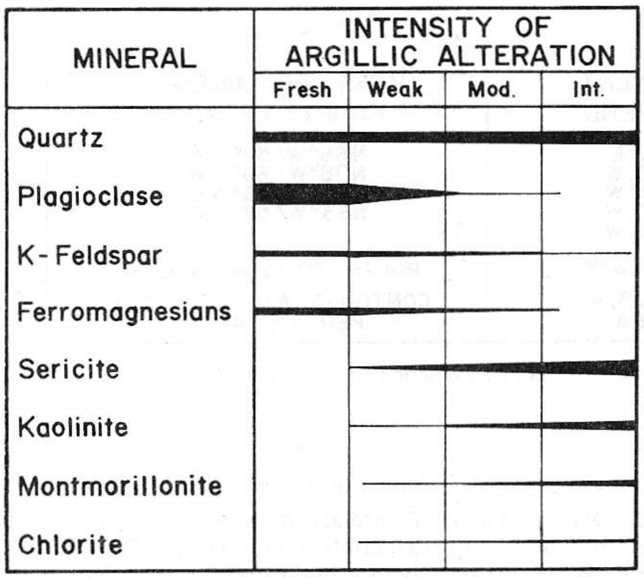

FIGURE 4 — Abundance of minerals which define zones of varying intensity of argillic alteration.

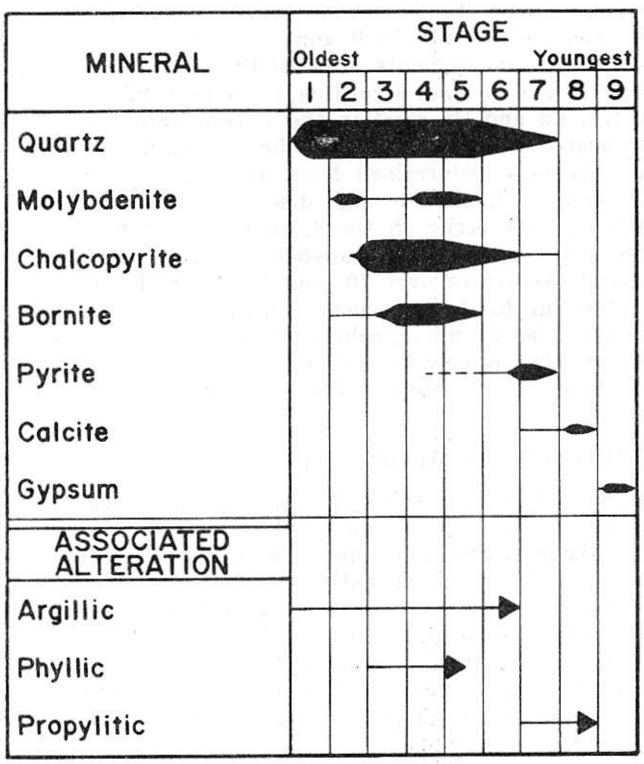

FIGURE 5 — Paragenetic sequence and relative abundance of mineralization and related hydrothermal alteration.

Argillic Alteration

Argillic alteration, which is pervasive throughout the ore zone, is characterized by the presence of quartz, sericite, kaolinite, montmorillonite and chlorite. Sericite and kaolinite, with minor montmorillonite and chlorite, form pseudomorphs after plagioclase. The cores of the plagioclase crystals are more intensely altered than the rims, but in the intense stage of argillic alteration the entire plagioclase crystal is replaced by sericite and clays. Kaolinite, sericite and minor montmorillonite also replace orthoclase. In contrast to plagioclase, the alteration of these crystals progresses from the rim toward the core with increasing intensity of argillic alteration. Biotite and hornblende alter to chlorite and sericite. The pervasive argillic alteration of the Skeena Quartz Diorite has produced a cream or apple green coloured rock. In the cream varieties, kaolinite predominates over sericite, but in the apple green variety sericite predominates over kaolinite.

Classification of the intensity of argillic alteration is based on the degree of alteration of feldspars and mafic minerals. Figure 4 illustrates the variations in amounts of rock-forming and alteration minerals with increasing intensity of argillic alteration. Generally, total copper grades increase as the intensity of argillic alteration increases.

Propylitic Alteration

Propylitic alteration is also pervasive and is peripheral to the argillic alteration. The typical propylitic alteration assemblage consists of epidote (zoisite), chlorite and carbonates (calcite), with minor sericite and hematite. Epidote and calcite are most common as veins. Quartz and orthoclase are fresh, but plagioclase, which has a fresher appearance than in the argillic alteration zone, alters to calcite and epidote with minor amounts of sericite and chlorite. Mafic minerals alter to chlorite, calcite and sericite, with minor hematite and epidote.

PARAGENESIS AND ZONING

Relative ages of mineralization have been determined from crosscutting relationships, such as are illustrated in Figures 10a & b, polished-section exsolution features and vein zoning. The stages of mineralization and the related alteration types for each stage are illustrated in Figure 5. Quartz is ubiquitous in all but the two youngest stages of mineralization. Molybdenite occurs in stages 2 to 5, but is most abundant in stages 4 and 5.

Copper mineralization is generally confined to stages 3, 4 and 5. Pyrite mineralization is insignificant in the ore zone. It is probable that calcite veining associated with propylitic alteration is an alteration product rather than a late-stage product of hydrothermal fluid fractionation, but no definite relationship has been determined. The final stage of mineralization, gypsum, has no associated alteration. The concave line below the 1200-meter elevation on Figure 7b is the gypsum line.

Concentric horizontal (Fig. 6) and vertical (Fig. 7a and b) zonal distributions of principal sulphides and major hydrothermal alteration phases are evident at Lornex. Sulphide and alteration zones plunge northwesterly at 30 to 40 degrees and terminate abruptly against the footwall of the Lornex fault. Bottoms of

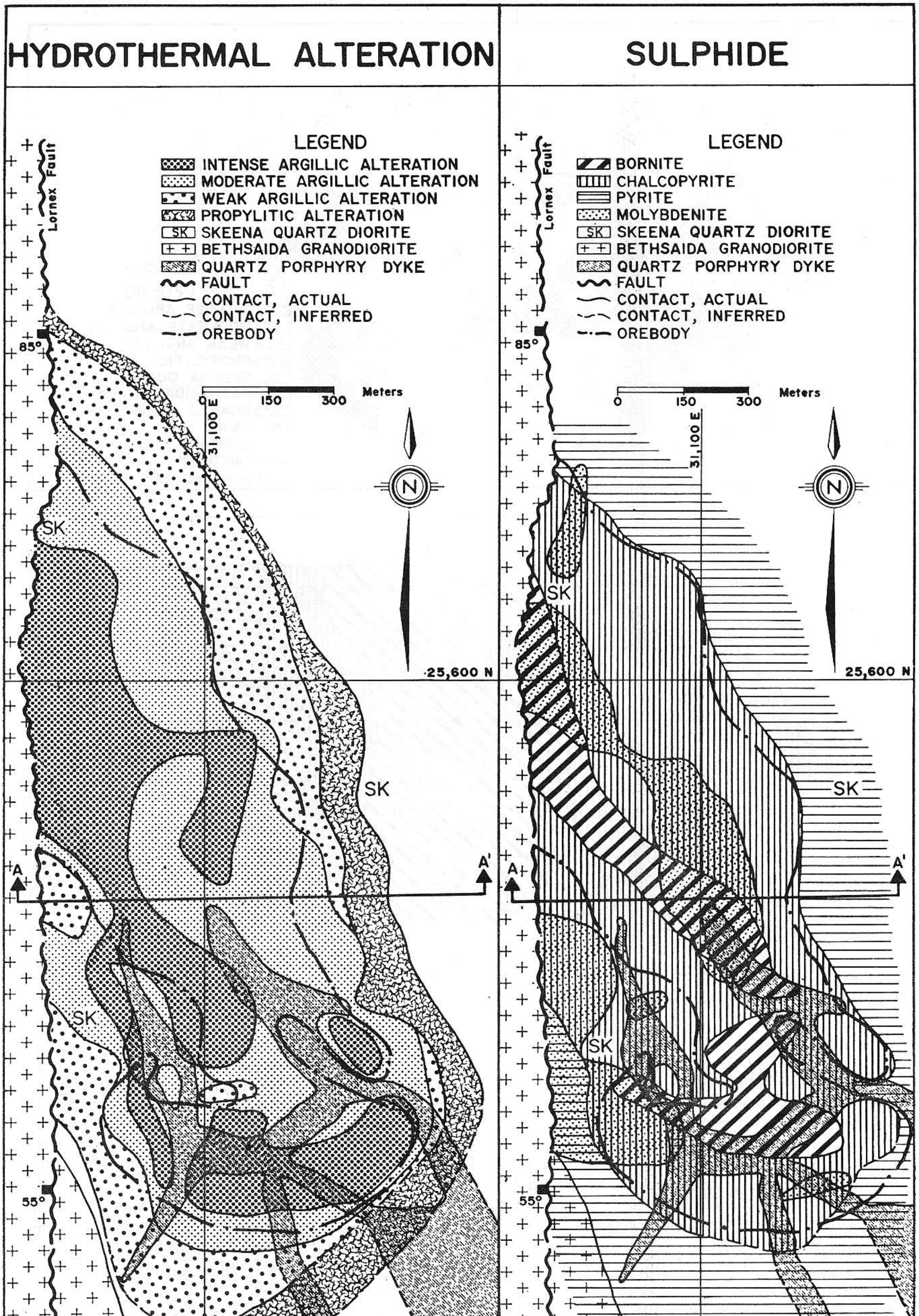

FIGURE 6 — Hydrothermal alteration and sulphide mineral zoning at the 1370 level.

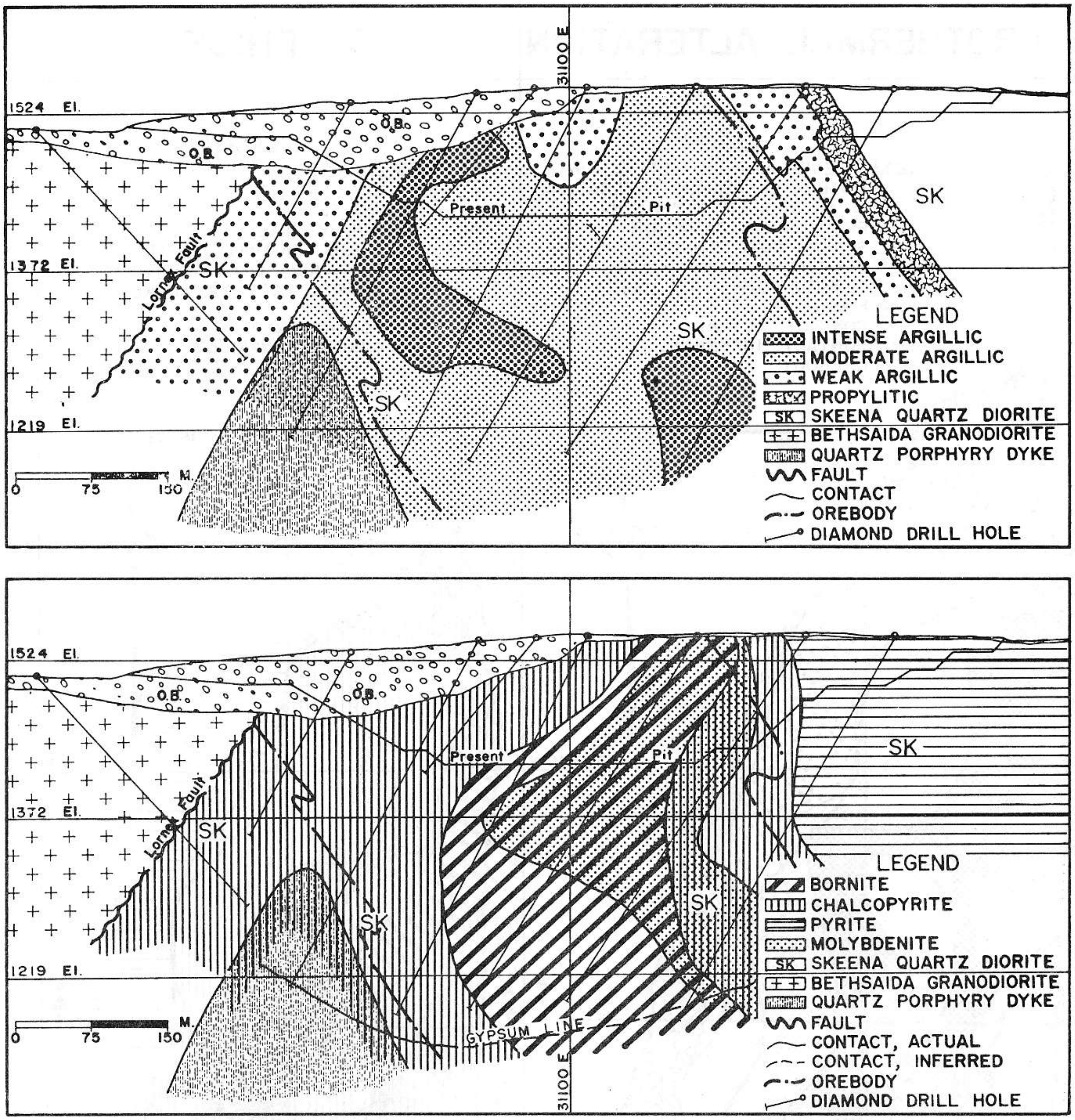

FIGURE 7 — Section A-A', looking north, showing: (a) zonation of hydrothermal alteration and (b) sulphide mineralization.

zones have been determined in the south-central portion of the orebody and have been interpreted in the northern part. The shallow depth of the zones in the south-central area coincides with the highest level of quartz porphyry dyke intrusion.

Weak hydrothermal alteration and the relatively low sulphide content in the dyke may be due in part to both the very fine grained nature of the dyke matrix and the halo of silicified rock surrounding the dyke, which may have impeded access of hydrothermal fluids to the dyke.

The sulphide zones illustrated in Figures 6 and 8 are defined as follows:

Bornite Zone: bornite > chalcopyrite > pyrite
Chalcopyrite Zone: chalcopyrite > bornite > pyrite
Pyrite Zone: More than 0.05% pyrite and total copper $\leq$ 0.26% Cu.
Molybdenite Zone: molybdenum $\geq$ 0.02% Mo.

Total sulphide content averages 1 to 1½ per cent in the bornite, chalcopyrite and molybdenite zones, but only ¼ to ½ per cent in the pyrite zone. According to Olade (1974), an increase in pH could cause the sulphide zonation, if the rate of decrease of copper, caused by deposition of copper sulphide, was less than the rate of decrease of H^+ activity caused by hydrothermal alteration.

The alteration maps (Figs. 6 and 7a) illustrate zones of pervasive argillic and propylitic alteration. The argillic alteration has been divided into three degrees of intensity, as defined in Figure 4. A marked zone of phyllic alteration is not shown on the maps, but generally coincides with zones of moderate to intense argillic alteration.

The following general statements regarding the mineral and alteration zoning of the orebody can be

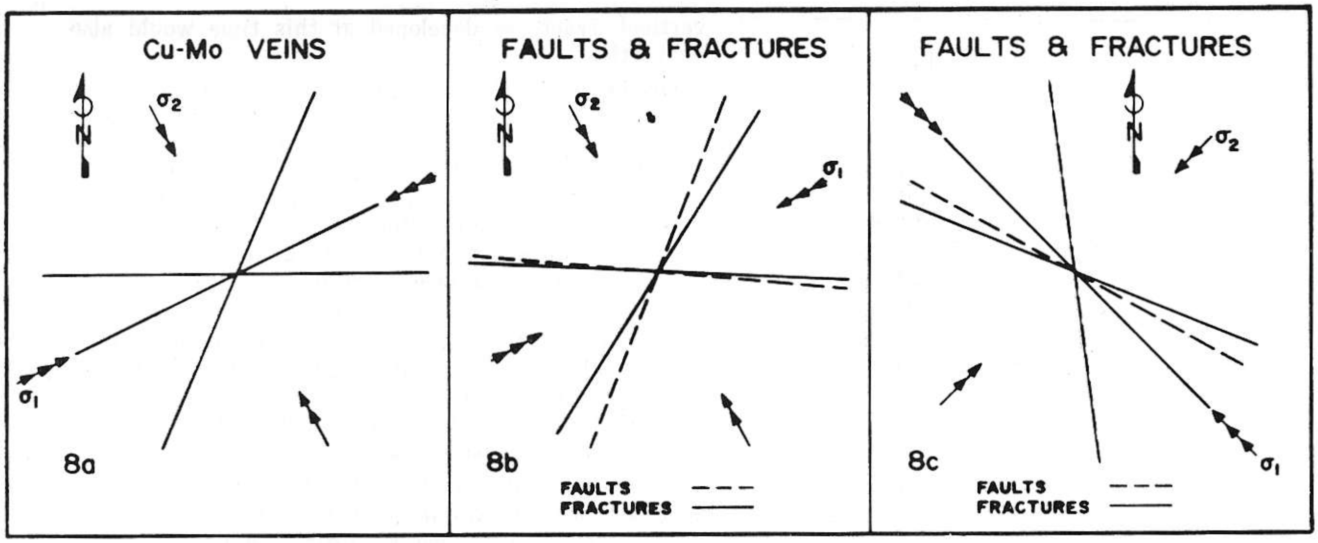

FIGURE 8 — Interpreted principal stress directions and structures developed during the three periods of deformation.

made.

(1) The principal sulphides form a concentric pattern, with bornite in the center, chalcopyrite outside bornite, and a molybdenite zone overlapping portions of the bornite and chalcopyrite zones. Pyrite forms a halo around the ore zone.

(2) Copper grades and total sulphide content decrease outward from the core of the orebody to its periphery.

(3) Sulphide and alteration zones are deep in the north and shallow in the southern portions of the orebody, indicating a 30- to 40-degree northwest plunge to the orebody.

(4) Zones of moderate to intense argillic alteration correspond to grades higher than 0.26 per cent copper and a total sulphide content greater than 1 per cent.

(5) The propylitic alteration zone which occurs on the margin of the orebody is associated with sub-economic copper grades, with the pyrite zone and with a total sulphide content of less than one-half of 1 per cent.

WEATHERING AND SUPERGENE CHARACTERISTICS

The oxide zone averages only 3 to 30 meters in thickness and contains only minor amounts of recoverable copper sulphides. It is thickest on the west side of the orebody and thins toward the east. The depth of the zone is irregular, apparently controlled by local fracture density. Malachite is the predominant copper mineral in the oxide cap, but azurite, cuprite, chalcocite, covellite and native copper are common. Limonite and pyrolusite are also abundant in this zone. No molybdenum oxide minerals have been identified. Enrichment in the oxide zone is not economically important, although a discontinuous layer of chalcocite, averaging about 5 to 10 centimeters thick, occurs at the oxide-sulphide interface.

Genesis of the Ore Deposit

The interpretation of the genesis of the orebody has been based on the following criteria.

(1) The age of 198 ± 8 m y for the batholith and 190 ± 4 m y for the mineralization.

(2) The intersection of the Lornex fault and the zones of weakness along which the quartz porphyry dyke intruded.

(3) Truncation of the Skeena Quartz Diorite and the ore zone by the Lornex fault.

(4) The interpreted right-lateral and reverse movement on the Lornex fault.

(5) Sulphide mineralization occurs primarily as fracture infillings.

(6) The N22°E/55°SE, N64°E/57°SE and N90°E/58°S orientations of copper-molybdenum veins.

(7) The density and spatial distribution of veins in the orebody.

(8) The presence and orientation of two post-mineral structural systems. Faults and fractures in the first set strike N26°E and N87°W. The youngest faults strike N65°N and N8°W; fractures strike N44°W.

(9) The relative ages of mineralization and related hydrothermal alteration.

(10) Hydrothermal alteration is weaker and sulphide content is less in the quartz porphyry dyke, relative to the Skeena Quartz Diorite.

(11) The concentric, zonal distribution of sulphides and hydrothermal alteration.

(12) The interpreted 30- to 40-degree northwest plunge of the ore deposit.

Emplacement of the Lower Jurassic Guichon Creek batholith into Permian and Triassic rocks of the Cache Creek and Nicola groups appears to have been controlled by major, deep-seated zones of weakness (Carr and McMillan, 1970).

The Lornex fault may be the rejuvenated supracrustal expression of one of these deep-seated structures. The quartz porphyry dyke, probably related to intrusion of the Bethsaida phase, was emplaced along a northwest-trending zone of weakness which intersects the Lornex fault.

Figure 9 illustrates the proposed genetic model of the orebody, as described below.

Pre-mineral tectonic stresses are thought to have formed a conjugate shear system at the intersection of the Lornex fault and the quartz porphyry dyke. Maximum principal stresses from the east-northeast and west-southwest produced the fracture pattern illustrated in Figure 8a. These shear fractures strike N22°E and N90°E, and extension fractures strike N64°E. Assuming that the principle stresses were vertical, fractures developed at this time would also be vertical.

Ore-bearing, hydrothermal fluids, which may have developed as a late-stage fractionation of the magma that formed the batholith, migrated along the fractures. The result was an epithermal ore deposit with a concentric zonal distribution of sulphide minerals and hydrothermal alteration (concentric rings in Fig. 9). The bornite-rich central core has associated phyllic and moderate to intense argillic alteration.

Successively outward is a chalcopyrite zone with phyllic and moderate to intense argillic alteration, and a peripheral zone of pyrite mineralization with associated weak argillic and propylitic alteration. A zone of high total sulphide content developed in the zone of most intense fracturing (stippled area on Fig. 9).

Following mineralization, it is thought that regional stresses, with maximum principal stresses from the east-northeast and west-southwest, produced further

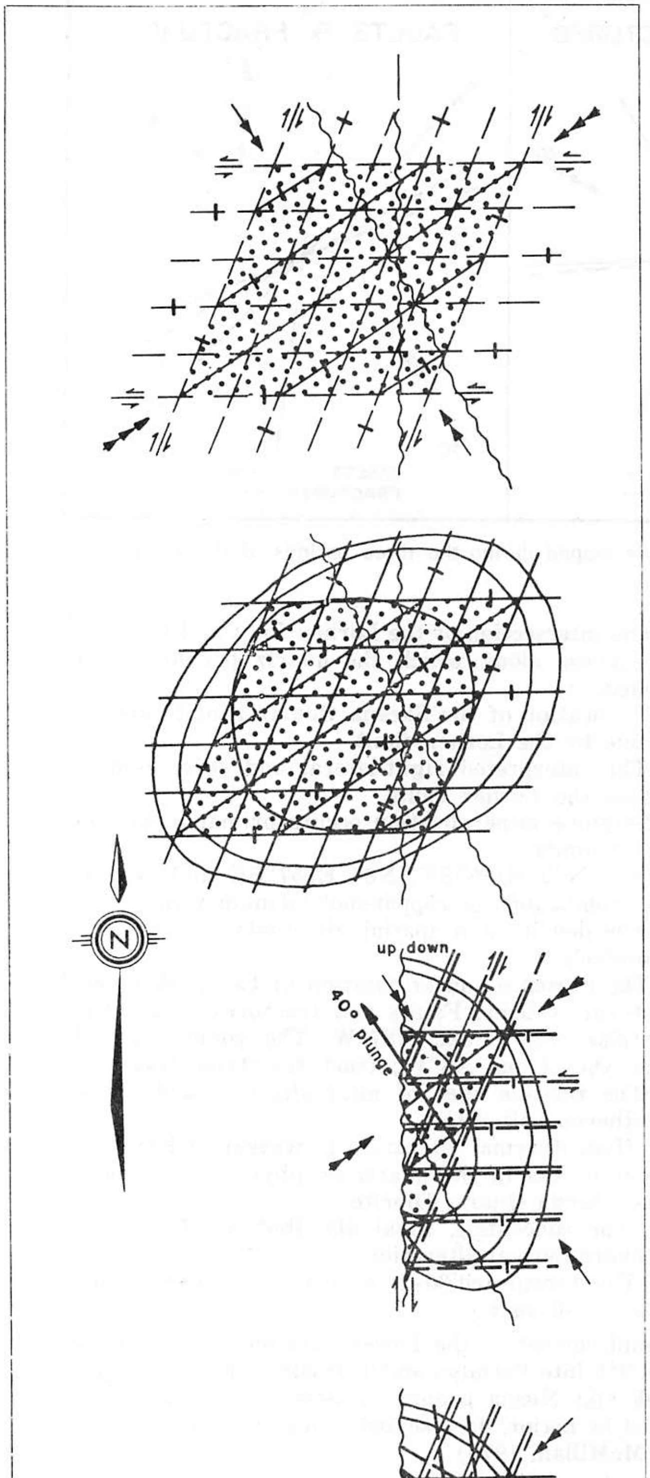

FIGURE 9 — Schematic plans illustrating the interpreted genesis of the orebody.

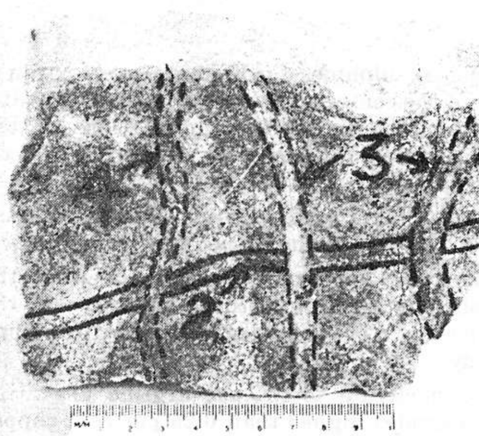

FIGURE 10a — A stage 2 quartz-molybdenite vein with associated argillic alteration is cut by stage 3 quartz-chalcopyrite-molybdenite veins with associated phyllic alteration and a stage 4 quartz-chalcopyrite-bornite vein with associated phyllic alteration.

FIGURE 10b — **Left Sample** — A stage 3 quartz-chalcopyrite vein with associated phyllic alteration is cut by a stage 4 quartz-chalcopyrite-bornite vein with associated phyllic alteration. A stage 5 (or stage 6) vein composed of quartz-chalcopyrite with minor bornite and molybdenite and associated argillic alteration cuts the stage 3 and 4 mineralization. **Right Sample** — A stage 4 (or 3) quartz-chalcopyrite vein with minor bornite and associated phyllic alteration cuts argillic alteration associated with a barren, stage 1 quartz vein and a stage 2 quartz-chalcopyrite-molybdenite-bornite vein.

shearing subparallel to and along N22°E- and N90°E-striking veins (Fig. 8b). It is probable that, during this period of deformation, apparent right-lateral displacement took place on the Lornex fault. Apparently, the Lornex orebody (the portion east of the fault) was tilted down in the north and relatively up in the south at this time. This 30- to 40-degree tilt is invoked to explain why mineralized fractures now dip in a southerly direction and why sulphide and alteration zones plunge northwesterly.

A late-stage deformation produced by maximum principal stresses, oriented from the northwest and southeast, developed a conjugate shear set (Fig. 8c). Conjugate shears are oriented N65°N and N8°W, and extension fractures strike N65°W. Displacements related to this period of deformation are generally minor.

Pleistocene glaciation and other geomorphological processes developed the present oxide cap and cover of glacial, fluvial and lacustrine sediments.

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