010159

May 31, 1975

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Dear Bill:

Here, at long last, is the first draft of the Bethlehem porphyry copper deposits paper. I hope that next time I will be a better judge of how long such a project will take. Your patience has been nothing short of incredible, and you have my sincere appreciation. Your comments are expected and will be gratefully considered. The sections concerning location (p. 7), history (p. 8), and "enviornmental considerations" (p. 48) have been left for the Bethlehem staff, and with the exception of my own name I have not attempted to arrange or specify authors. I presume that Henery and John Bellamy will be coauthors, but beyond that I have left the matter to Henery's discretion. After you have had an opportunity to review the manuscript, return it to me and I will rewrite it incorporating your suggestions along with those of the Bethlehem staff and various other reviewers. I have taken the liberty to send a copy of the paper to W.J. Moore of the U.S. Geological Survey and to A.W. Rose of the Pennsylvania State University. Both men are experienced in the study of porphyry copper deposits, and I am certain that our paper will benefit significantly from their comments also. Because the contributions of these various people are yet unknown, I have left the acknowledgments section of the manuscript blank. It can be written more conveniently at a later date. Erik Anderson informs me that he has sent you copies of the five figures. I have made some revisions in these and have enclosed part of a letter I sent to Erik concerning them. Other minor revisions have been made exclusively on the figures and are not mentioned in the letter. I hope that the majority of the paper meets with your approval, and I will, in any case, look forward to receiving your comments.

Best regards, Joe

Re: Revisions to Figures

(1) Add north arrows to each Figure

(2) Because we do not have geological information for diamond drill holes B-39 and B-51, they should be removed from Figures 2, 4, and 5. However, assays are available for these drill holes and, although they are not necessary, they may be left on Figure 3.

(3) The section line A-A' in Figures 2-5 must be moved to 11,665N. This line (11,665N) contains the drill holes used to construct the cross-sections, and does not correspond to the geology of the 11,000N section. Unless this change is made the reader will not be able to properly correlate the plan and cross-sectional views.

(4) Make the following revisions to Figure 1: (1) construct outlines of the Huestis, Jersey, East Jersey and Iona orebodies; (2) cut the Guichon overlay pattern from around the names of the ore zones in order to improve legibility; (3) add the following sentence to the legend: "Mapping beyond indicated limits of open pits and ore zones is from Wood (1968)".

(5) Because of the necessity of reduction for publication it will not be possible to show the three varieties of contacts indicated for Figure 2. Therefore, I recommend than a solid line be used for all contacts.

(6) Show the locations of the drill holes on the plan view in Figure 3.

(7) If convenient, it would be more consistent with the zoning displayed by Figure 4 to represent the distribution of pyrite with the numeral 2, and that of specularite with the numeral 1. The positions of the words "PYRITE" and "SPECULARITE" might also be reversed in the title of Figure 4.

(8) These and other changes are shown in red on the Figures.

Draft no. 1
5/31/75

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Geology of the Bethlehem Porphyry Copper Deposits, Highland Valley, British Columbia

by Joe A. Briskey

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BIOGRAPHY

Joseph A. Briskey Jr. was born May 5, 1946 in Tillamook, Oregon. He received his Bachelor of Science degree in 1968 from the Department of Geology at Oregon State University, where he is currently working toward a doctorate in economic geology. Previous employment includes: geologic field assistant for the U. S. Geological Survey, research and teaching assistant for the Department of Geology at Oregon State, and geologic consultant for base metal exploration in western Idaho.

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ABSTRACT

The Bethlehem porphyry copper deposits are near the center of the 200 m. y. Guichon Creek Batholith, which is a concentrically zoned calc-alkaline pluton that intrudes eugeosynclinal assemblages of the Cache Creek (Permian) and Nicola (Upper Triassic) Groups. Along the irregular intrusive contact that separates the older Guichon granodiorite and younger Bethlehem granodiorite phases of the batholith, have been localized intrusive breccias; dacite and rhyodacite porphyry dikes; small masses of granite, granodiorite, and porphyritic quartz latite; faults and fractures; and hydrothermal mineralization and alteration. Late-stage concentration of mineralizers in the dacite porphyry melt(s) were probably the source of hypogene metallization, which was imposed on all intrusive rocks and breccias at Bethlehem. Major faults of post-breccia consolidation age strike north, northeast, and northwest, and dip steeply. Detectable offsets are usually rare.

Mineralization includes variable amounts of chalcopyrite, bornite, pyrite, specularite, and molybdenite; and white mica, chlorite, epidote, calcite, quartz, zeolites, secondary biotite, and tourmaline, which occur in veins, veinlets, stringers,

irregular blebs, and disseminations. Although the Iona orebody has mineable quantities of oxide ore (malachite), zones of secondary sulfide enrichment are not developed at Bethlehem. Distributions (especially in the Jersey orebody) of metallic and nonmetallic minerals exhibit peripheral zones of specularite and epidote, and intermediate zones of pyrite and white mica, which 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 that produced mineralization and alteration moved upward and outward from the central core.

The Bethlehem deposits (especially the Jersey orebody) generally possess geologic, mineralogic, and geochemical features that are consistent with those described for other porphyry-type 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 sulfide content (average < 2 percent) and especially pyrite (average < 1 percent in the halo zone); (8) large bornite:chalcopyrite ratios (> 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; (13) decreasing K_2O/Na_2O ratios as the central parts of the ore zones are approached; and (14) widespread presence of post-metallization hydrothermal zeolites, especially laumontite.

LOCATION

(Bethlehem staff)

Lat. and Long., N. T. S. Sheet, Elevation, brief geographic description (Figure showing location and topography.

HISTORY

(Bethlehem staff)

Discovery: Significant persons, dates, and methods.

Ownership:

Production: Record, plant size, bench height, etc.

Reserves with stripping ratios where these have been published, if not, some indication whether large or small.

GEOLOGY

The Bethlehem porphyry copper deposits are near the center of the 200 m.y. 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 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 12 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. The batholith intrudes eugeosynclinal assemblages of the Cache Creek (Permian) and Nicola (Upper Triassic) 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 notably 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 (1) 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; (2) field observations and detailed mapping by H. G. Ewanchuk in the East Jersey orebody; and (3) 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 (see Fig. 1). Granodioritic rocks of the younger Bethlehem phase (to the south and west) form a digitating, north-south elongate apophysis into those of the older Guichon phase (to the north and east). This intrusive activity occurred where the north-northwest striking contact between these two phases intersected the north-trending structural weakness that later localized the intrabatholith porphyry dike swarm shown by McMillan (this volume). Along this lobate contact have been localized intrusive breccias; dacite and rhyodacite porphyry dikes; small masses of granite, granodiorite, and porphyritic quartz latite; faults and fractures; and hydrothermal mineralization and alteration. Mining operations removed thin cappings of Guichon granodiorite from parts of the Huestis, Jersey, and East Jersey orebodies. These cappings suggest that the current level of exposure is near the roof of the apophysis. Though not shown in Figure 1, between 50 and 60 percent of the area is mantled by glacial deposits.

Guichon and Bethlehem Granodiorites

The Guichon granodiorite intrusion may gradationally approach quartz diorite in composition. It is typically medium crystalline hypidiomorphic granular, and composed of quartz (15-25%)[1], orthoclase (8-16%), plagioclase feldspar (46-60%), minor augite, hornblende (5-10%), and biotite (1-10%). 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 intrusion is medium crystalline hypidiomorphic granular, but may grade into quartz dioritic and porphyritic varieties. Representative samples contain quartz (16-25%), orthoclase (5-16%), plagioclase feldspar (53-65%), hornblende (2-22%), and biotite (0.5-6%). Phenocrysts of plagioclase feldspar, poikoilitic 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

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[1] Volume percent unless otherwise indicated. Where unaccompanied by percentage estimates, minerals will be listed approximately in order of decreasing abundance.

leucocratic subphase of the Bethlehem granodiorite (see Fig. 1). It is characterized by alteration of mafic minerals to actinolite, absence of orthoclase, and occurs exclusively within the normal Bethlehem granodiorite. Guichon and Bethlehem granodiorite are separated by a sharp, steeply dipping, irregular, intrusive contact, along which Bethlehem granodiorite may display weak chill textures. Scarce xenoliths of Guichon granodiorite 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 (see Figs. 1 and 2). Although superficially similar in appearance to Bethlehem granodiorite, it is medium crystalline hypidiomorphic inequigranular as it possesses a definite porphyritic (porphyry) texture. The rock is compositionally a dacite, which contains quartz (25-35%), orthoclase (0-10%), plagioclase feldspar (50-60%), and hornblende and biotite (5-10%). Phenocrysts, up to 7 mm in the largest dimension, include plagioclase feldspar, quartz (eyes), hornblende, and biotite. The groundmass, which comprises 25 to 35 percent of the rock, consists of a mosaic of quartz and plagioclase feldspar, with variable smaller 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 Guichon granodiorite. It may exhibit a weak foliation and (or) a slight decrease in crystallinity adjacent 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.

Porphyritic Quartz Latite

Irregularly shaped intrusions of porphyritic quartz latite occur in the southeast and west-central parts of the Jersey pit (see Fig. 2), and in a slump block on the east wall of the Huestis pit (see Fig. 1). This unit is fine to medium crystalline hypidiomorphic porphyritic, and contains quartz (25-30%), orthoclase (25-30%), plagioclase feldspar (40-50%), 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 percent of the rock, is composed primarily of finely crystalline, saccharoidal quartz and abundant interstitial orthoclase. Contacts between porphyritic quartz latite and Guichon and Bethlehem granodiorite are generally sharp; however, a contact with Bethlehem granodiorite in drill core appeared to be gradational over several centimeters. Porphyritic quartz latite may rarely contain small xenoliths of Bethlehem granodiorite, and may exhibit a weak foliation within 6 mm of sharp contacts. Contacts dip vertically or steeply to the west.

Igneous Breccias

Occurrences of breccia are widespread at Bethlehem, and are also found at the nearby Trojan (5 km north), and Highmont (8 km south) properties. They form a north-trending zone that is within, and parallel to, the porphyry dike swarm in the Guichon Creek Batholith. In the Bethlehem area, the breccias are associated with all of the orebodies except the Huestis (see Fig. 1). The southern limits of the main Iona breccia have not yet been determined. Its northern extension, and a smaller, parallel, roofed breccia, extend into the East Jersey pit. Exploratory drilling has intercepted several small breccia bodies at depth below the present land surface in the southeast part of the Iona zone. All of the Bethlehem breccias are near the contact between Guichon and Bethlehem granodiorite; however, these two rock types are not usually separated by breccia. Moreover, the breccias appear to be preferentially localized in Bethlehem granodiorite, and none have been found exclusively contained within Guichon granodiorite. Bodies of breccia tend to be irregularly shaped, steeply dipping masses with a north-south elongation. With increasing depth they commonly become more restricted in size and some appear to pinch out. Mining operations and drilling to date have exposed breccia to depths of over 300 m.

Breccia fragments include Guichon and Bethlehem granodiorite, dacite porphyry (discussed below), porphyritic quartz latite, and silicic aplite. Those of Guichon granodiorite ordinarily predominate. Breccias in the Iona ore zone are almost exclusively confined to Bethlehem granodiorite, although clasts are predominantly those of Guichon granodiorite. Fragments of dacite porphyry are widely distributed in the Bethlehem breccias, but they are abundant only in the breccia mass on the northeast wall of the Jersey pit. Pink-stained dacite porphyry (discussed below) has not been found as a component of the breccias. Clasts of porphyritic quartz latite are abundant near gradational contacts between intrusions of this rock type and breccia, but occur sporadically elsewhere. Diameters of many clasts are between 2 and 15 cm. Shapes of the breccia fragments range from angular to rounded, but those with subangular to subrounded shapes 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 has been 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 particularily 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, biotized cataclastic matrix is absent, and porous granular quartz, commonly intergrown with finely to coarsely crystalline aggregates of tourmaline, encloses the breccia fragments. Because this quartz does not normally replace the fragments, it probably filled open spaces in a loosely consolidated breccia. Induration of the breccia, either during or following deposition of this quartz, took place prior to the formation of later sulfide-filled fractures that cross-cut both matrix and fragments alike. Breccia fragments contained in a matrix that closely resembles some of the dacite porphyries has been observed in two small, isolated areas. Reaction between this porphyry matrix and many of the included fragments is indicated by contacts that are corroded and gradational over as much as 8 cm. Where unaffected by corrosion, contacts between fragments and cataclastic matrix are 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 that apparently are intrusive into the surrounding country rock. Contacts of the breccia in the Iona zone may coincide with shear zones. They 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-south elongation of the breccia bodies probably reflects control by the same structural weaknesses that localized the parallel-trending Bethlehem granodiorite apophysis, major faults (see above and below), and emplacement of porphyry dikes. The major faults as presently exposed do not appear to have exerted a spatial or structural control on the emplacement of the breccia masses. Moreover, all of these faults exhibit post-breccia consolidation movement. However, it is possible that breccia intrusion along pre-existing fault zones largely obliterated these zones, and that post-breccia consolidation shearing along the major faults may have resulted from renewed displacement along these older structures. The localization of breccia dikelets 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 (see Fig. 1). The rock is predominantly medium crystalline hypidiomorphic granular, but gradational increases in the size of plagioclase feldspar or biotite crystals may locally render the texture porphyritic. The principal minerals are quartz (30-35%), orthoclase (15-20%), plagioclase feldspar (45-55%), rare hornblende, and biotite (3%). Although this granodiorite closely resembles the Bethlehem granodiorite, it is distinguishable by the near absence of hornblende, larger and more abundant crystals of quartz, and the presence of biotite phenocrysts. The granodiorite appears to intrude Bethlehem granodiorite, but contacts with the older rocks have not been found. Wood (1968) reported the presence of orthoclase stringers in the granodiorite, and suggested that they had been derived from an adjacent granite.

Granite is exposed west of the Iona zone (see Fig. 1) and dikelets of compositionally and texturally similar material are widespread elsewhere in the Guichon and Bethlehem granodiorites and breccia. These dikelets may or may not be related to the larger mass of granite. Textures 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. Granite is typically composed of quartz (30-50%), orthoclase (50-60%), sodic plagioclase fledspar (5-20%), and biotite (0-3%). Phenocrysts, where present, are of plagioclase feldspar. The proportion of plagioclase feldspar to orthoclase increases in the northern part of the main granite mass and the pluton approximates quartz monzonite in composition. Contact relationships 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) found granite chilled against granodiorite and Iona breccia. Although the interpretation by Wood (1968) is favored, the apparent conflict would be resolved had the granite mass formed by temporally distinct intrusions as is consistent with observed compositional and textural variations.

Dacite Porphyry

Dikes of dacite porphyry exposed on the Bethlehem property (see 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. Dikes are spaced irregularly across the 5 to 10 km width of the swarm, and average one dike every 100 to 300 m (Carr, 1960). At Bethlehem the dikes are clearly of several ages, both pre- and post-brecciation; and although the individual relationships have not been satisfactorily differentiated to date, more than one age of post-brecciation dike emplacement has been recognized. Widths of the dikes are as much as 60 m, but most are less than 15 m. The prevailing trend is northerly with a noticeable northeasterly component. Dips are normally within 20 degrees of vertical. The large dike at the east margin of the area (see Fig. 1) is texturally distinct and probably not closely related to the others on the property.

Dacite porphyry is characterized by phenocrysts of quartz (0-3%), plagioclase feldspar (50-70%), and hornblende (2-5%) 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. The orthoclase content of these rocks is variable, and where high they may approximate rhyodacite in composition. Phenocrysts of plagioclase feldspar occur as roughly equant subhedra and euhedra, 3 to 5 mm in the largest dimension. Those of quartz formed rounded (by partial resorption) "eyes" up to 3 mm in diameter; however, square cross-sections are not uncommon, and euhedral, bipyramidal crystals are also present. Subhedral and euhedral phenocrysts of poikoilitic hornblende, ordinarily replaced by aggregates of epidote, reach a maximum length of about 10 mm. Samples of typical porphyry contain 50 to 70 percent phenocrysts, except at finely crystalline margins. In the vicinity of the Jersey and East Jersey pits, the plagioclase feldspar of a late dacite porphyry dike has been stained pink; presumably by the presence of finely crystalline hematite. Although similar in texture and mineralogy to other dacite porphyry, this particular dike (see Figs. 1 and 2) where unstained 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.

Dikes of dacite porphyry intrude older lithologies, including breccias and other dacite porphyries. Contacts are sharp, highly irregular, steeply dipping, and are defined by finely crystalline margins that range from several to more than 100 cm in thickness. Moreover, the margins of some dikes contain inclusions of breccia. These contact features imply that the breccias had been lithified prior to emplacement of the dikes. A gradational contact between breccia and a mass of leucocratic dacite porphyry immediately south of the East Jersey pit (see Fig. 1) was described by Wood (1968). Fragments of this porphyry have also been identified in the breccia on the south wall of the Jersey pit. Although other dacite porphyry fragments are present in the Bethlehem breccias, this is the only mass with a demonstrable prebreccia age of formation.

Genesis of Breccias and Porphyries

The association of breccias and porphyries with copper sulfide mineralization at Bethlehem has been 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) their occurrence elsewhere than at the contact between Guichon and Bethlehem granodiorite; (3) absence of Bethlehem granodiorite as matrix material; and (4) the paucity of xenoliths in Bethlehem granodiorite.

Carr (1966) has postulated that impermeable chill-zone rinds, formed after intrusion of porphyry magmas into cold, well-fractured country rocks, served to impound the volatiles released during later stages of crystallization. "Explosive" release of these volatiles, and consequent brecciation, occurred when the 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 prebrecciation porphyry masses and the comparatively small number of porphyry fragments in the breccias, suggest that the major episode of porphyry magma intrusion did not precede breccia formation.

Tentatively, the Bethlehem breccias are believed to have originated in the upper parts of the magma chamber(s) that produced the dacite porphyry dikes. Similarities in texture and mineralogy between the porphyries and Bethlehem granodiorite suggest a related source. After the initial intrusion of minor prebrecciation porphyries, a relatively large hydrous vapor bubble may have formed in the upper part of the porphyry magma chamber(s). Norton and Cathles (1973) have postulated that such a bubble may form when coalescencing, 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, and with consequent brecciation by a fluidized system as proposed by Reynolds (1954). Features which imply forceful (intrusive) breccia emplacement include: (1) the transgressive nature of breccia contacts as previously described and as illustrated from general outcrop patterns in the area (see Fig. 1) and especially in the Jersey pit (see Fig. 2); (2) the occurrence, below Bethlehem granodiorite roof rocks, of breccia containing predominately Guichon granodiorite fragments; (3) the heterogeneous distribution of fragment types; (4) 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 possibly causing the formation of a second chill rind, which may have trapped much of this melt. However, small quantities of magma may have escaped at this time to form those few areas where the breccia appears to contain porphyry matrix. After compaction and consolidation of the breccias, additional pulses of magma injection, withdrawal, and (or) crystallization that was 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. The relatively small quantity of porphyry fragments in the breccias may be related to the limited emplacement of porphyry magma prior to brecciation, and with some fragments possibly derived from the chilled rind. The various breccia masses may have formed with the escape of volatiles from several vapor bubbles, each associated with a separate porphyry magma chamber, or from volatiles derived from a single vapor bubble that escaped along separate channel ways from a common magma source. Pressures necessary to cause an "explosive" release of trapped volatiles may have resulted either 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 intrusion were 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 dacite porphyry magma.

Faults

The Bethlehem area shares a feature common to most porphyry-type deposits in that structural effects manifest by numerous faults and zones of closely spaced fractures have exerted varying degrees of control on the emplacement of porphyry dikes, intrusive breccias, and hydrothermal alteration-mineralization (see Figs. 1 and 2). Faults are arbitrarily subdivided into major and minor types on the basis of gouge zone thicknesses of greater or less than 1 m, respectively. The major faults are north-trending and are found in the east-central part of the Huestis pit, the west-central part of the Jersey pit (Jersey fault), east-central part of the East Jersey pit (East Jersey fault), and central part of the Iona ore zone (see Figs. 1 and 2). Dips are vertical or steep to the west, although that of the Iona ore zone fault is presently unknown but probably 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 evidence for extending the Jersey fault 1.7 km south to the J. A. orebody, it is not known to extend north of the Jersey pit. Other major faults are less common and usually strike northeast, and dip steeply to the southeast. A few of the major faults have northwest trends, particularily in the Iona ore zone, but little is currently known about them. Numerous minor faults have formed subparallel and adjacent to the major faults, especially to the north-south trending set. Minor faults that strike to the northeast and northwest are also common, whereas those that strike east-west are relatively uncommon.

Many of the faults mentioned above cross-cut the Bethlehem breccias. Although they may have been partly synchronous with dacite porphyry dike injection, most appear to have formed later. Detectable offsets are rare on most faults. However, recent drilling in the East Jersey and Iona ore zones has confirmed the apparent left lateral displacement of breccia masses and copper mineralization between these areas (see Fig. 1). A northeast-trending fault separating the two ore zones with 60 to 90 m of apparent left lateral offset could account for this displacement. A dacite porphyry dike 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 porphyry dike having 38 m of apparent right lateral offset along an east-west striking fault. Evidence of significant movement on other faults has not been found.

Mineral Deposits

Common epigenetic minerals on the Bethlehem property include: white mica, chlorite, epidote, calcite, quartz, zeolites, chalcopyrite, bornite, pyrite, specularite, goethite, malachite, secondary biotite, tourmaline, and molybdenite. These minerals occur in veins (fault, joint, and fracture fillings 2.5 cm or greater in width), veinlets, stringers, irregular blebs, and disseminations. Veinlets, stringers, and disseminations are most abundant. Vein occurrences characterized by variable proportions of specularite, quartz, calcite, epidote, chalcopyrite, bornite, pyrite, and tourmaline, are peripheral to the central parts of the Jersey and Huestis orebodies. In contrast, the veins 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 representing 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 grade of ore. At depth the high grade core splits into downward extending roots. All rock types exposed within the ore zone predate mineralization. However, metallization is commonly higher in grade and more uniformly distributed in the breccias. This difference probably reflects the ease with which the consolidated breccias were fractured relative to surrounding granitic host rocks. The apparent lack of ore control by the Jersey and other major faults (see Fig. 3) is noteworthy. 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. Pods of sheared copper sulfides indicate post-ore movement, but nowhere has the displacement been sufficient to offset the outline of the ore zone. The Jersey and Huestis orebodies appear to be roughly oval in plan. In contrast, the East Jersey and Iona deposits are elongate north-south, and reflect control by parallel-trending breccias and, less commonly, major shear zones. The East Jersey orebody has been described by several authors including Coveney (1962), Coveney and others (1964), and Ewanchuk (1969). Copper metallization in the Iona ore zone is chiefly confined to the breccias, which tend to be 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 Bethlehem granodiorite are usually only weakly mineralized, whereas the reverse is true for Guichon granodiorite.

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 cross-cut both fragments and matrix alike. Thus, the main episode of metallization must have postdated breccia consolidation. The presence of more widely spaced fractures and proportionately lower grades of ore in some of the late post-brecciation dacite porphyry dikes collectively suggest that either mineralization or fracturing, or both, commenced during this period of dike emplacement. Bornite and chalcopyrite fill joints in pink-stained dacite porphyry, therefore indicating that copper sulfide deposition continued beyond, or began after the cooling of this youngest unit. A potassium-argon age determination of hydrothermal biotite from the Jersey pit is expected to approximate 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.

Hypogene Metallic Minerals

The common hypogene metallic minerals on the Bethlehem property are essentially chalcopyrite, bornite, pyrite, specularite, and molybdenite. Minor amounts of chalcocite and magnetite 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, except for minor disseminations, usually occurs in peripheral veins where it is associated with quartz, calcite, epidote, chalcopyrite, bornite, and tourmaline. Although chalcopyrite, bornite, and pyrite are present in veins, veinlets and stringers of these sulfides and molybdenite predominate in the ore zone. Disseminated occurrences of finely crystalline sulfides resulting from replacement of primary and secondary mafic minerals adjacent to mineralized fractures are common, but quantitatively subordinate to fracture controlled mineralization. Chalcopyrite, bornite, and pyrite customarily have the following 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 percent by volume. Concentrations of pyrite in the halo zones are normally less than 1 percent, although locally they may reach 5 percent. The distribution of molybdenite is sporadic and is commonly peripheral to the central parts of the ore zones. Occurrences are ordinarily monomineralic or associated with chalcopyrite in veinlets and rarely in quartz stockworks.

Distributions of specularite, pyrite, chalcopyrite, and bornite in the Jersey pit (see 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 their distributions form crudely concentric zones about a bornite-rich core. The outer zone of low grade copper mineralization (see 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. Although reconnaissance work suggests similar zonal patterns in the Huestis orebody, and peripheral specularite in the Iona ore zone, comparable 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, relative to many porphyry copper deposits, are: (1) high bornite:chalcopyrite ratios in the bornite-rich core; (2) low total sulfide content; and (3) a well-defined zone of specularite beyond the pyrite halo.

Several features of the Bethlehem porphyry (see Fig. 2) may imply a close genetic relationship to the source of the hydrothermal fluids that formed the Jersey orebody. These features are: (1) increase in the amounts of secondary biotite, copper sulfides (esp. bornite), and quartz (veinlets) in Guichon granodiorite host rocks with proximity to contacts with Bethlehem porphyry; (2) central position with respect to zoning of metallic and alteration minerals (cf. Figs. 2, 3, 4, and 5); (3) lack of fractures relative to surrounding rocks; and (4) presence of disseminated copper sulfides that apparently are unrelated to fracture-controlled deposition.

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 sometimes epidote. The selvages are ordinarily 1 m or less in width, but may be as much as 30 m wide adjacent to major structures such as the Jersey fault.

Epidote occurs primarily 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. They display a roughly concentric zonal distribution with epidote peripheral to a central biotite-rich core. Most vein occurrences of the hypogene minerals are contained within the epidote zone, and the majority of these are confined to the specularite-rich portion (see Fig. 4). Epidote is rare in the Iona breccias, but is common in adjacent host rocks and throughout those of the East Jersey ore zone. Epidote is usually found in veins, veinlets, and stingers; and as disseminations replacing calcic plagioclase feldspar and primary mafic minerals. It may compose up to 20 percent of the host rock; however, amounts between 1 and 10 percent 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 this report includes all optically unidentifiable, finely crystalline alteration products of feldspar. Preliminary X-ray diffraction studies indicate the presence of small amounts of kaolinite and montmorillonite in the white mica. It is widespread in all but the most unaltered rocks of the Jersey and Huestic orebodies. Although zonal distributions are not obvious, significant quantities of white mica roughly coincide with areas of greater than 0.1 weight percent copper (e.g. Fig. 3). In the Iona zone, white mica appears to be predominantly restricted to breccias, and does not noticeably pervade host rocks except near areas of quartz flooding (see above). Reconnaissance studies of the East Jersey orebody indicate that it accompanies significant copper metallization. The preponderance of white mica occurs as an alteration product of feldspar. It preferentially replaces orthoclase, which is usually completely destroyed, whereas plagioclase feldspar is typically more than 20 percent unaltered. White mica is generally associated with small but variable amounts of calcite and epidote.

Secondary biotite in the Jersey orebody appears to be largely restricted to the lower parts of the bornite-rich core. It is widespread in near surface localities of the Iona breccias, but is present only in minor amounts in the Huestis and East Jersey ore zones. Although some secondary biotite occurs in veinlets and stringers, most of it replaces primary (esp. biotite) and secondary mafic minerals, and breccia matrix. Breccia may contain as much as 50 percent secondary biotite, whereas other rock types do not ordinarily have more than 15 percent. Quantities between 3 and 8 percent are representative of most biotite-rich areas. It 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 with increasing proximity to the orebodies. Chlorite usually occurs either as replacements of primary and, less commonly, secondary mafic minerals and breccia matrix, or in veinlets. Although it is present throughout the deposits its local abundance is predominantly controlled by rock type. In rocks other than breccia, chlorite typically composes 5 to 15 percent of a sample. Breccias having a chloritic matrix, such as that in the south part of the Jersey pit (see Fig. 2), may contain as much as 25 percent chlorite. It is normally associated with epidote, chalcopyrite, bornite, pyrite, secondary biotite, and calcite.

Calcite is common in the vein-type assemblages mentioned earlier, and in post-ore zeolite veinlets. Moreover, calcite and white mica are ubiquitous as replacements of plagioclase feldspar or, less commonly, hornblende. Calcite also occurs in veinlets. It is ordinarily associated with white mica, epidote, chlorite, quartz, chalcopyrite, pyrite, specularite, and bornite.

Quartz is a common component of the peripheral vein assemblages, and is the predominant constituent of veinlets that are locally abundant (1 to 20 percent of the rock) in the central parts of the Huestis and East Jersey orebodies, and the bornite-rich core of the Jersey orebody. As previously mentioned, quartz is an abundant constituent of the matrix in breccias of the Iona zone. These occurrences of quartz may be monomineralic or assemblages that also include bornite, chalcopyrite, calcite, epidote, specularite, pyrite, and tourmaline.

Black schorlitic tourmaline has an erratic and widespread distribution. It is present within, and marginal to, all of the ore zones, but is abundant only in those areas of quartz-rich matrix in breccias of the Iona zone. Tourmaline occurs as crystalline aggregates intergrown with quartz; as replacements of small breccia fragments and matrix; in veinlets, veins, and stringers; and rarely as sunbursts 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 have been confirmed by X-ray diffraction studies. Numerous veinlets of laumontite that may contain smaller amounts of calcite, stilbite, and heulandite cross-cut all rock types and hypogene mineralization. They are ubiquitous in all four ore zones. Veinlets of stilbite are abundant, and stilbite and rarely chabazite incrust vugs in the south breccia of the Jersey pit. Post-ore zeolites, especially laumontite, are interpreted to be low temperature retrograde 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. The intervening area, dominated by white mica, is probably equivalent to a mixed zone of phyllic (± argillic) alteration. The potassic zone is distinctive because of the near absence of potassium feldspar. Significant hydrothermal alteration is restricted to the orebody, and only the epidote zone extends beyond the limits of conspicuous copper sulfide mineralization.

Ternary AKF diagrams have been used to relate whole-rock chemistry to the mineralogy and thermal environment of hydrothermal alteration (Creasey, 1959, 1966, 1972; Burnham, 1962; Meyer and Hemley, 1967; and Rose, 1970). Ideally, samples in which the component minerals approached thermodynamic equilibrium will plot within fields, or on tie lines that correspond to those minerals. The AKF compatibility diagram shown in Figure 6 is a slight modification of that given by Rose (1970) for biotite-orthoclase type (potassic) and quartz-sericite type (phyllic) alterations. Two samples each of "unaltered" Guichon and Bethlehem granodiorite (see Tables 2 and 3) have been plotted on Figure 6. In accordance with their primary mineralogy, these samples plot in or near the potassium feldspar - biotite field. The more mafic character of Guichon granodiorite is reflected in its displacement toward higher F values, and lower A and K values, relative to Bethlehem granodiorite. Two samples each of altered and mineralized Guichon and Bethlehem granodiorite (see Tables 2 and 3) from the Jersey pit have also been plotted on Figure 6. Correlations between the chemistry and mineralogy of these altered rocks are complicated by the difficulty of optically identifying the finely crystalline alteration products of

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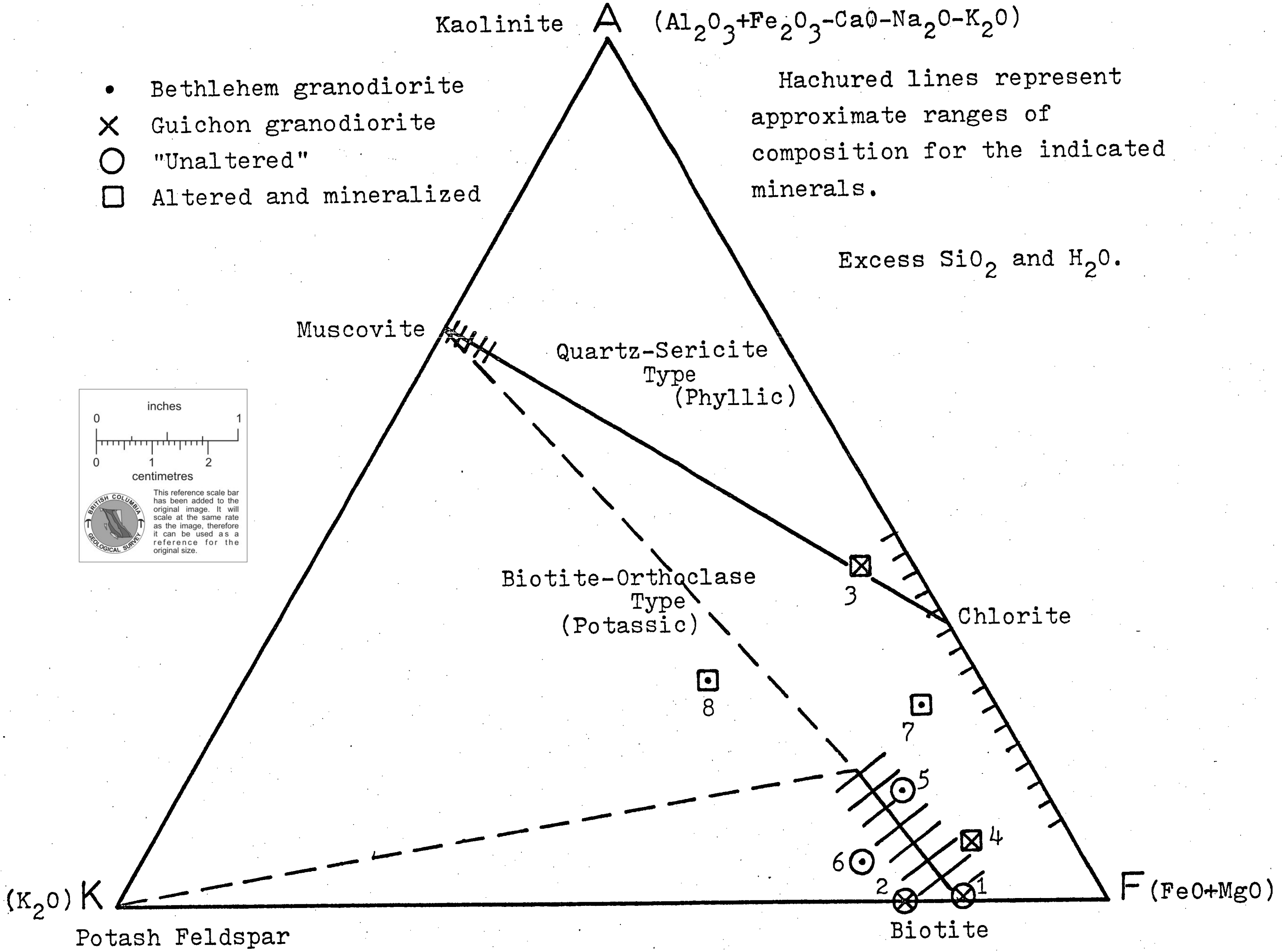
Figure 6
AKF diagram for alteration minerals common in porphyry copper deposits.



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feldspar. Nonetheless, most of this material appears to be white mica. Samples 3 and 7 are from areas of phyllic alteration, and samples 4 and 8 are from the potassic core; however, sample 8 contains secondary potassium feldspar, and thus is not entirely representative of this central biotite-rich zone. Samples 3 and 8 plot in the fields for phyllic and potassic alteration respectively, and therefore are in agreement with their observed alteration mineralogies. Samples 4 and 7 are anomalous and merit further discussion.

Sample 7 plots in the potassic alteration field, but contains neither potassium feldspar nor biotite. Sample 4 has unexpectedly low A and K values when considered with respect to its high content (35%) of finely crystalline alteration products of feldspar. These discrepancies are most readily explained by (1) the inadequacy of the AKF diagram to represent partially altered rocks, and (2) the presence of alteration minerals (for example calcite and sodium-rich white mica) not considered in the construction of AKF diagrams. Partially altered rocks that have not undergone extensive metasomatism must necessarily plot near their unaltered equivalents. Consequently, more significance may be attached to the general trend of partially altered samples relative to their background equivalents, than to whether or not they plot in fields that correspond to their alteration mineralogy. Sample 7 is displaced toward the field of phyllic alteration relative to its unaltered equivalents. Moreover, altered rocks containing calcite and (or) sodium-rich mica would plot at unusually low A and K values on Figure 6. Some calcite is included in the modal analyses of Table 2, and additional small quantities are suspected as finely crystalline products of plagioclase feldspar alteration. If the plotted positions of samples 4 and 7 were corrected for as little as 2 percent calcite, their A values would each increase by 15 percent. The inferred presence of sodium-rich white mica has not yet been confirmed by X-ray diffraction study. However, the unexpectedly low A and K values and high Na_2O and low K_2O contents of samples 4, 7, and 8 suggest that sodium-rich mica may be present. In addition, these samples do not contain enough sodic plagioclase feldspar (see Table 2) to account for their high Na_2O values.

The typically low K_2O/Na_2O ratios of altered rocks from the Jersey orebody are unusual for porphyry copper deposits, where, according to Meyer and Hemley (1967, p. 210) "Almost invariably, the ratio of potassium to sodium increases toward sulfide ore." However, Meyer and Hemley (1967, Fig. 6.7, p. 215) show the potential compatibility of the relatively high sodium assemblage, potassium mica-albite-sodium mica. Low K_2O/Na_2O values are not incompatible with potassic (i.e. biotite-orthoclase type) alteration. Recent work by Moore and Czamanske (1973), and Beane (1974), have confirmed the phlogopitic composition of secondary biotite from potassic zones of porphyry copper deposits. Moreover, the data of Meyer and Hemley (1967, Fig. 6.8, p. 216) indicate that phlogopite will form at relatively low potassium concentrations provided that pH and magnesium concentrations are sufficiently high.

Oxidation and Supergene Enrichment

Minerals identified from the zones of oxidation at Bethlehem include goethite, hematite, malachite, manganese oxides, chrysocolla, azurite, cuprite, native copper, and ferrimolybdenite. Possible occurrences of powellite and erythrite have been reported by White and others (1957). Although the effects of oxidation are largely surficial (less than 10 to 20 m deep), its distribution and intensity is controlled by structure. The shattered southern one-third of the Iona ore zone is strongly oxidized and total oxidation of sulfides 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 sulfide 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 have been observed in surficial exposures and drill core, but there is no zone of secondarily enriched ore.

"Environmental Considerations"

(Bethlehem Staff)

SUMMARY AND CONCLUSIONS

The Bethlehem porphyry copper deposits are near the center of the 200 m.y. Guichon Creek Batholith, which is a concentrically zoned calc-alkaline pluton that intrudes eugeosynclinal assemblages of the Cache Creek (Permian) and Nicola (Upper Triassic) Groups. The orebodies formed along an irregular intrusive contact separating two major phases of the batholith. Granodioritic rocks of the younger Bethlehem phase form a digitating, north-south elongate apophysis into those of the older Guichon phase. This intrusive activity occurred where the north-northwest striking contact between these two phases intersected the north-trending structural weakness that later localized the intrabatholith porphyry dike swarm. Along this lobate contact have been localized intrusive breccias; dacite and rhyodacite porphyry dikes; small masses of granite, granodiorite, and porphyritic quartz latite; faults and fractures; and hydrothermal mineralization and alteration. Tentatively, the Bethlehem breccias are believed to have formed by a fluidized system, which resulted from the rapid release of volatiles from a hydrous vapor bubble(s) derived from either shallow porphyry magmas or a deeper magma chamber that fed pre- and post-brecciation dacite and rhyodacite porphyry dikes. Late-stage concentration of mineralization in this melt were probably the source of hypogene metallization imposed on all intrusive rocks and breccias at Bethlehem.

Major faults strike north, northeast, and northwest, and dip steeply. Faults are post-breccia consolidation in age, and although they may have been partly synchronous with porphyry dike injection, most appear to have formed later. Detectable offsets are usually rare.

Hypogene mineralization probably began during the later stages of post-brecciation porphyry dike emplacement and continued beyond the cessation of this period of intrusive activity. Substantial but variable amounts of chalcopyrite, bornite, pyrite, specularite, and molybdenite; and white mica, chlorite, epidote, calcite, quartz, zeolites, secondary biotite, and tourmaline occur in veins, veinlets, stringers, irregular blebs, and disseminations. These minerals are concentrically distributed with respect to copper mineralization in the Jersey and Huestis orebodies. The central high grade core is surrounded by a peripheral zone of lower grade metallization, and with depth splits into downward extending roots. The East Jersey and Iona deposits are elongate north-south, and reflect control by parallel-trending breccias and major shear zones. Specularite occurrences are peripheral to those of pyrite and their distributions form crudely concentric zones about a bornite-rich core. Chalcopyrite is present throughout. Distributions of epidote and secondary biotite outline propylitic and potassic alteration zones respectively. Epidote is peripheral to the central biotite-rich core, and the intervening area, dominated by white mica, is probably equivalent to a mixed zone of phyllic (± argillic) alteration. The potassic zone is distinctive because of the near absence of potassium feldspar. Significant hydrothermal alteration is restricted to the orebody, and only the epidote zone extends beyond the limits of conspicuous copper sulfide mineralization. Post-ore zeolites, especially laumontite, are interpreted to be low temperature and (or) retrograde vein constituents that were deposited during the cooling and collapse of the hydrothermal system(s).

If hydrothermal mineralization proceeded upward and outward from the bornite-rich core, as the arrangement of alteration zones would suggest, the deposition of metallic minerals may have begun with the precipitation of sulfide assemblages having low iron:copper ratios (bornite:chalcopyrite ≥ 1) from fluids initially low in both iron and sulfur. However, the availability of iron may have increased with increasing distance from the bornite-rich core as a consequence of hydrothermal alteration of primary mafic minerals, thus favoring lower bornite:chalcopyrite ratios and eventually the stabilization of pyrite. Subsequent depletion of sulfur may have sufficiently decreased the fugacity of sulfur relative to that of oxygen to the extent that the remaining iron was deposited primarily as specularite (see Meyer and Hemley, 1967). Alternatively, this relatively rapid transition from sulfide 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 favorable channel ways for the intermingling of these fluids and ground water, and would 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 zone of oxidation is largely surficial (less than 10 to 20 meters deep), and only the Iona orebody has mineable quantities of oxide ore (malachite). Supergene chalcocite and covellite are locally present in small amounts but there is no zone of secondarily enriched ore.

The Bethlehem orebodies generally possess geologic, mineralogic, and geochemical features that are consistent with those described for other porphyry-type copper-molybdenum deposits of western North America (e.g. Creasey, 1959, 1966, 1972; Burnham, 1962; Titley and Hicks, 1966; Meyer and Hemley, 1967; Brown, 1969; 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. 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) 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 sulfide content (average < 2 percent) and especially pyrite (average < 1 percent in the halo zone); (8) large bornite:chalcopyrite ratios (≥ 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; (13) decreasing K_2O/Na_2O ratios toward the central parts of the ore zones; and (14) widespread presence of post-metallization zeolites, especially laumontite.

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Table 1: Features of Metallic Mineral Zones in the Jersey Pit[1]

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

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[1] The ratios of Fe:Cu and S:metal are calculated in terms of weight percent of the indicated metallic mineral assemblages; other values are volume percent.

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 (An content, x=sodic)	60.1 (34)	48.7 (38)	26.8 (x)	23.0 (x)	63.4 (32)	53.4 (35)	32.8 (28)	14.9 (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

[1]

	Coords. (m.)	Elev. (m.)
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.

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

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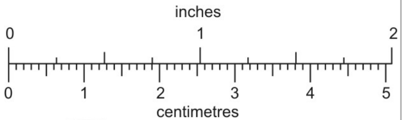
[1] Chemical analyses by Dr. Ken-ichiro Aoki, 1966 and 1974, Tohoku, Univ.

[2] Trace element analyses by Rocky Mountain Geochemical Laboratories, 1973, Salt Lake City, Utah.

[3] Minus sign (-) means "less than"

Figure 6. AKF diagram for alteration minerals common in porphyry copper deposits. Solid line separates the two alteration types distinguished by Rose (1970). Dashed lines indicate some of the possible equilibrium assemblages.



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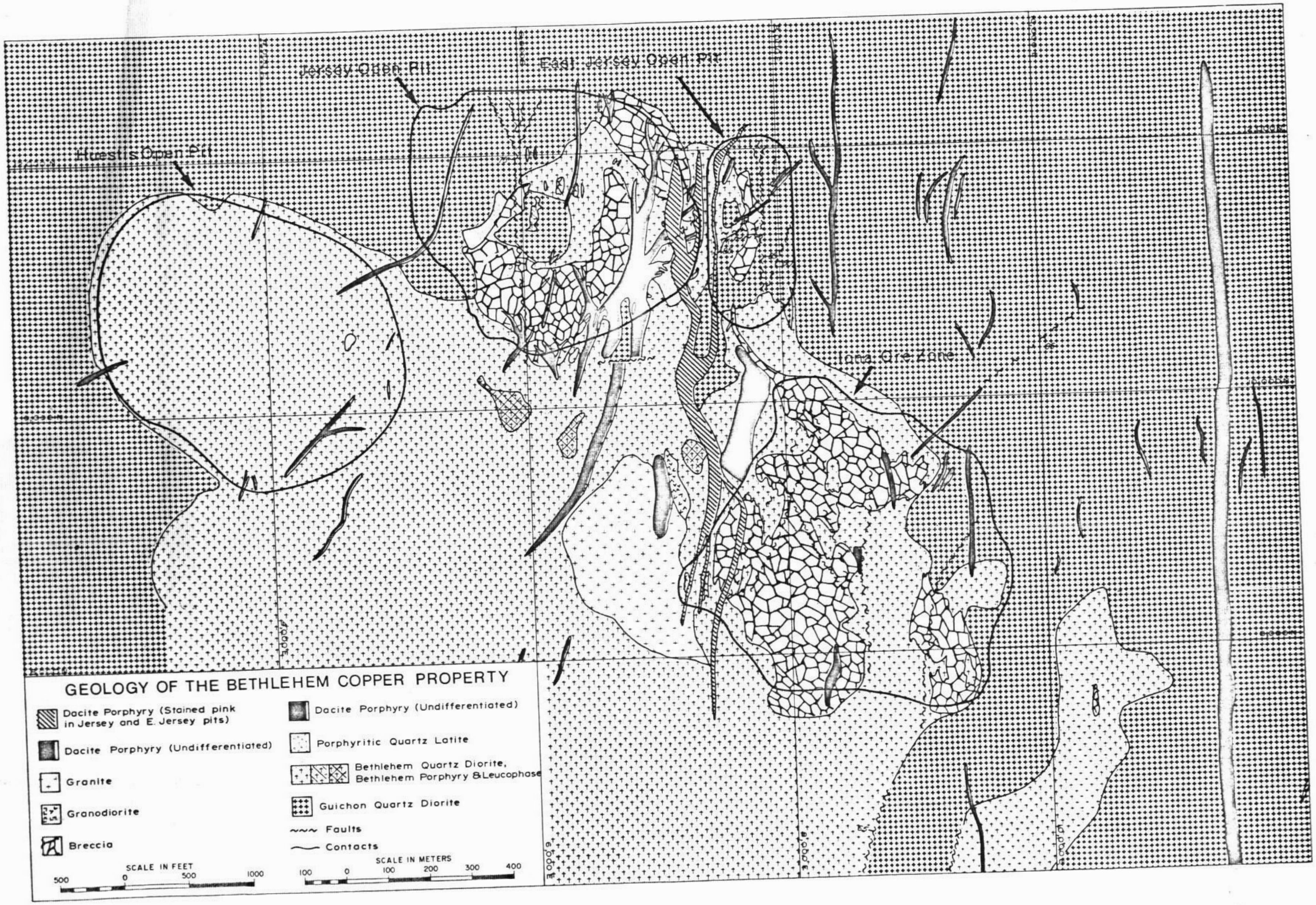
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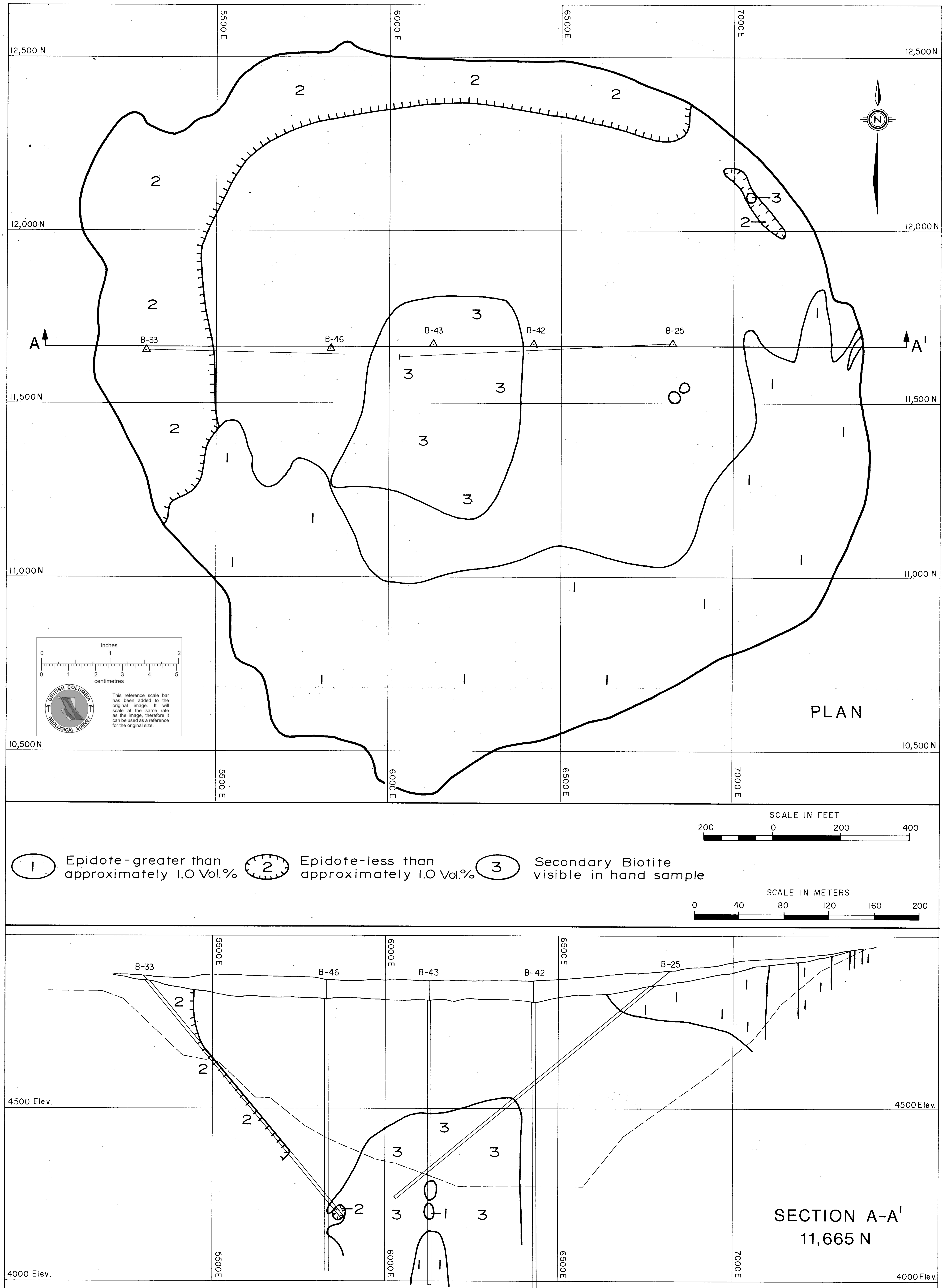

EPIDOTE & SECONDARY BIOTITE DISTRIBUTIONS IN THE JERSEY OREBODY

FIG. 5