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MINERALOGY, SULPHIDE-SILICATE ZONAL RELATIONSHIPS, AND ECONOMIC SIGNIFICANCE OF HYDROTHERMAL ALTERATION AT THE PORPHYRY COPPER DEPOSITS OF THE BABINE LAKE AREA, B.C.

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ABSTRACT

Porphyry copper deposits in the Babine Lake area, including the Granisle and Bell orebodies, are associated with Tertiary biotite plagioclase porphyry intrusions. Detailed studies of seven deposits, ranging in grade from <0.1% to +0.5% copper, have shown that all have similar zonal patterns of sulphides and hydrothermal alteration minerals. The normal outward progression is from biotite-chalcopyrite to chlorite-carbonate-pyrite. An intervening quartz-sericite zone of variable intensity may be present. The higher-grade Babine copper deposits have a core, consisting of bornite plus chalcopyrite, that is closely associated with the most intense hydrothermal biotitization. The outward progression from the bornite-bearing core is to chalcopyrite ± pyrite → pyrite ± chalcopyrite → pyrite ± pyrrhotite (the pyrite halo). Lower-grade deposits lack central bornite zones and have relatively weak pyrite haloes.

Electron microprobe analyses of biotite phenocrysts show that they contain an average of 4.3% TiO_2 whereas hydrothermal biotites average 2.8% TiO_2. At Granisle, MgO in secondary biotites decreases from an average of about 17% in the ore zone to less than 15% in the pyrite halo. Deep brown, coarse-grained, sugary-textured hydrothermal biotites are associated with relatively strong copper mineralization; greenish and/or fine-grained hydrothermal biotites are indicative of weak copper mineralization. It is concluded that economic and sub-economic deposits can be distinguished from one another by thin section studies because the size and grade of each copper zone corresponds with the areal extent and quality of hydrothermal biotite. This relationship between the quality of potassic alteration and the intensity of copper mineralization also seems to be applicable to most non-Babine porphyry copper deposits.

Introduction

More than a dozen porphyry copper deposits, all related to Tertiary biotite feldspar porphyry intrusions, are known to occur in the northern Babine Lake area of British Columbia (Figure 1). Seven hydrothermally altered areas, six of which contain centrally-located copper zones, are described in this paper (Figure 2). Although numerous published alteration studies are available, few have been concerned with sub-economic deposits and in none has there been an attempt to define the characteristics that might serve to distinguish low-grade copper occurrences from potentially economic ones. Most of the Babine Lake area copper zones are of sub-economic grade, but two (Granisle and Bell) are presently being mined. In four of the others, the over-all copper grades decrease from 0.4-0.45% Cu (Morrison) to 0.05-0.1% Cu (Nakinilerak). The seventh zone, South Newman, contains only traces of copper.

The Granisle and Bell deposits each contains 50 to 100 million tons of ore averaging about 0.5% copper, including considerable tonnages of +0.6% copper in higher-grade core zones. Production at Granisle (Granisle Copper Limited) is 14,000 tons per day from a pit designed for the ultimate mining of 88 million tons with an over-all average grade of 0.44% copper. At Bell (Noranda Mines Limited) production is 10,000 tons per day from a pit optimized to produce 50 million tons of 0.51% copper. Molybdenum in these deposits is less than 0.01% and is not recovered.

Interest in this study began in 1968 when, on the basis of mapping and extensive thin section studies of several properties, one of the present authors (D.J.T.C.) outlined the general zonal alteration pattern in which each copper deposit is contained within a zone of hydrothermal biotite that is in turn surrounded by a zone of chloritic alteration. It was found that

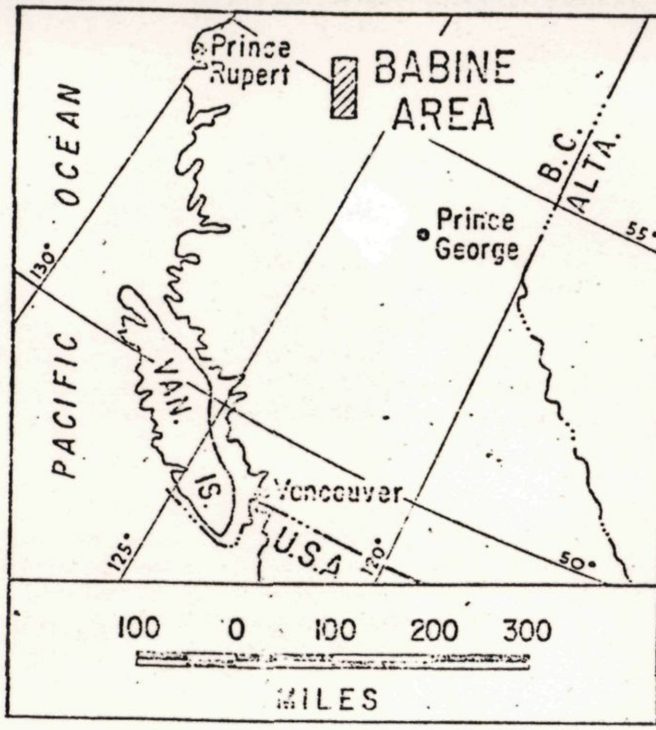

Figure 1 - Location of the Babine Lake area.

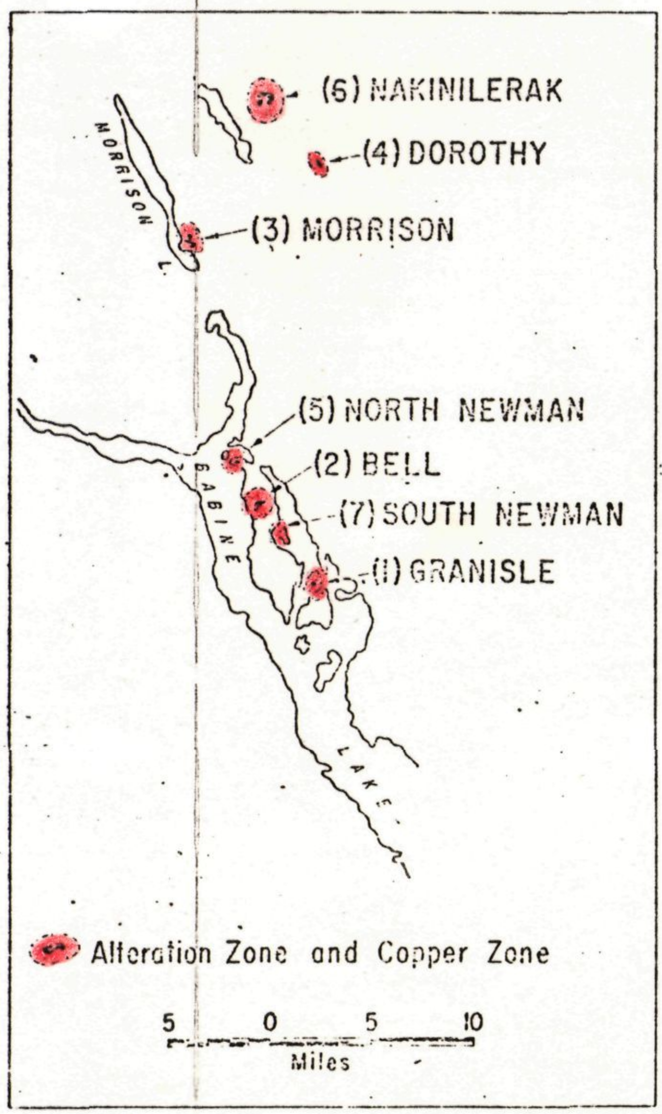

Figure 2 - Location of the seven hydrothermal alteration haloes described in this paper.

the areal extent and type of biotite in each hydrothermal biotite zone are related to the economic potential of the contained copper deposit. Because the biotite zones are larger and better-exposed than the copper deposits, the exploration applications, both at the reconnaissance and drilling stages, were readily apparent. Therefore, further mineralogical and chemical studies were made by the second author (J.L.J.), in order to verify and extend the initial conclusions. Granisle was selected as a model for the most thorough inspection because it appeared to possess all the important alteration features and had not been studied in detail previously. In this paper, Granisle is discussed at length first, and the other deposits are described more briefly in the numerical order shown in Figure 2. This order is one of decreasing copper grades.

Most rock exposures within and surrounding the seven alteration zones were examined by the authors. Four of the zones were mapped in detail. Extensive diamond drilling has been carried out by mining companies on the six copper-bearing alteration zones. All drill core was made readily available and, in addition to surface exposures, provided good sample coverage. Approximately 1000 thin sections and polished thin sections, and 150 polished sections, were studied under the microscope. Numerous microprobe analyses were made of several key mineral species, and several hundred trace element analyses were done on rock samples from four alteration zones. Fourteen chemical analyses were made of rocks from Granisle. The analytical data are too numerous to present in full here, but will be published in their entirety in the near future (Jambor, 1973). Figure 3 shows sample coverage for four of the zones studied.

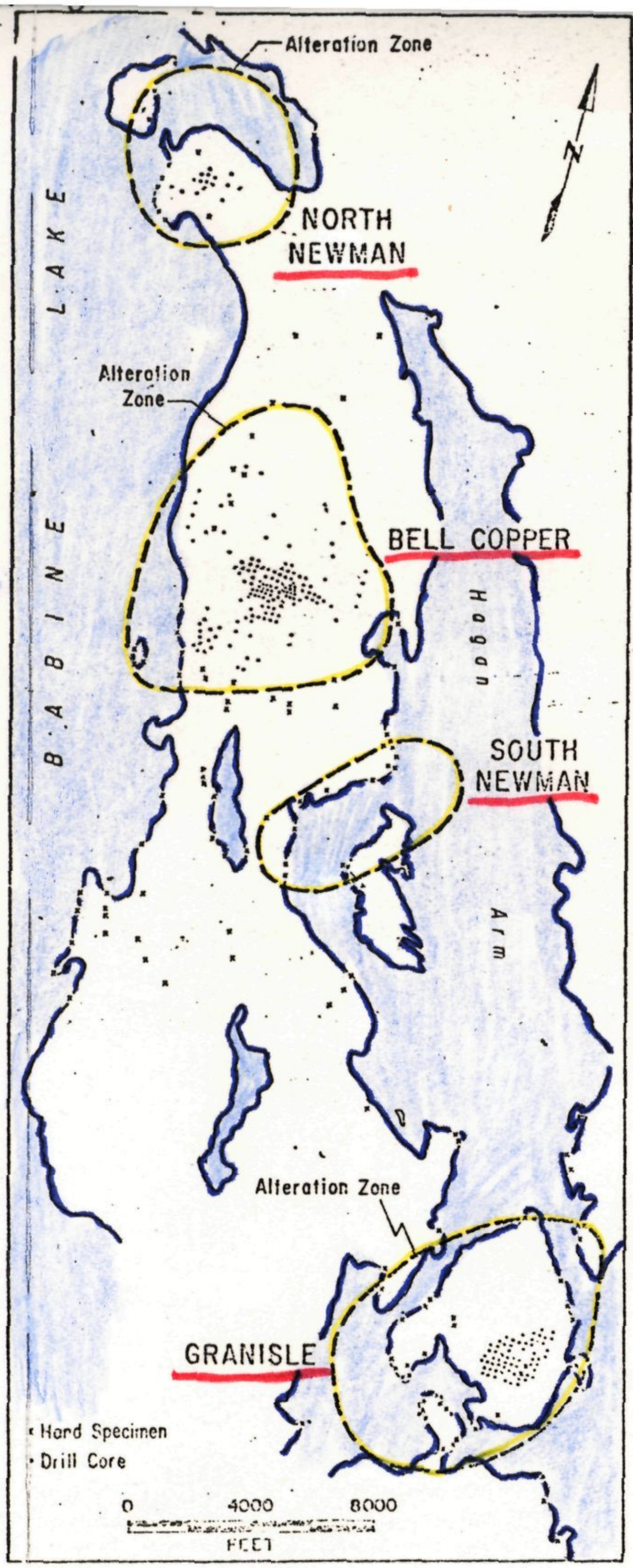

Figure 3 - Distribution of samples, analyzed by microscopic and/or chemical methods, at four of the alteration haloes. Many additional exposures, both within and between the alteration zones, were also mapped.

Regional Geology

The general geology of the Babine Lake area (Figure 4) has been summarized by Carter (1972). All the porphyry copper deposits and prospects in the area are related to small biotite plagioclase porphyry intrusions of early Eocene age (51.2±2 million years; Carter, 1972). This type of porphyry is known locally and informally as "BFP" (biotite feldspar porphyry) and will be referred to as such in this paper. Host rocks for the BFP intrusions are mainly Jurassic Hazelton Group andesitic, dacitic, and rhyolitic flows, plugs(?), and fragmentals, and marine siltstones, sandstones, and conglomerates that are mainly of volcanic derivation. Late Triassic sedimentary and volcanic rocks have been identified in the southwestern part of the map-area, and continental sediments believed to belong to the Cretaceous Sustut Group have been preserved within two linear grabens in the northeast.

Major faults trending north-northwest appear to have been the loci of emplacement of the Tertiary intrusions. Subsidiary northeast-trending faults may also be present. The rocks are gently to moderately folded along north-northwesterly axes.

The BFP intrusions are of various shapes — stocks, dykes, and possibly sills. They have a distinctive light to dark grey and white speckled appearance and are characterized by ¼-5 mm phenocrysts of biotite, plagioclase, and hornblende in a fine-grained to aphanitic matrix of the same minerals plus quartz and K-feldspar. Extensive differences in the appearance of BFP result from highly variable grain sizes and phenocryst contents, and the effects of several types of hydrothermal alteration. Fresh BFP compositions straddle the boundary between quartz diorite and granodiorite. Many of the intrusions, including those at Granisle (Kirkham, 1971) are multiphase. Breccias, believed by the authors to include both intrusive varieties and

Fig. 4

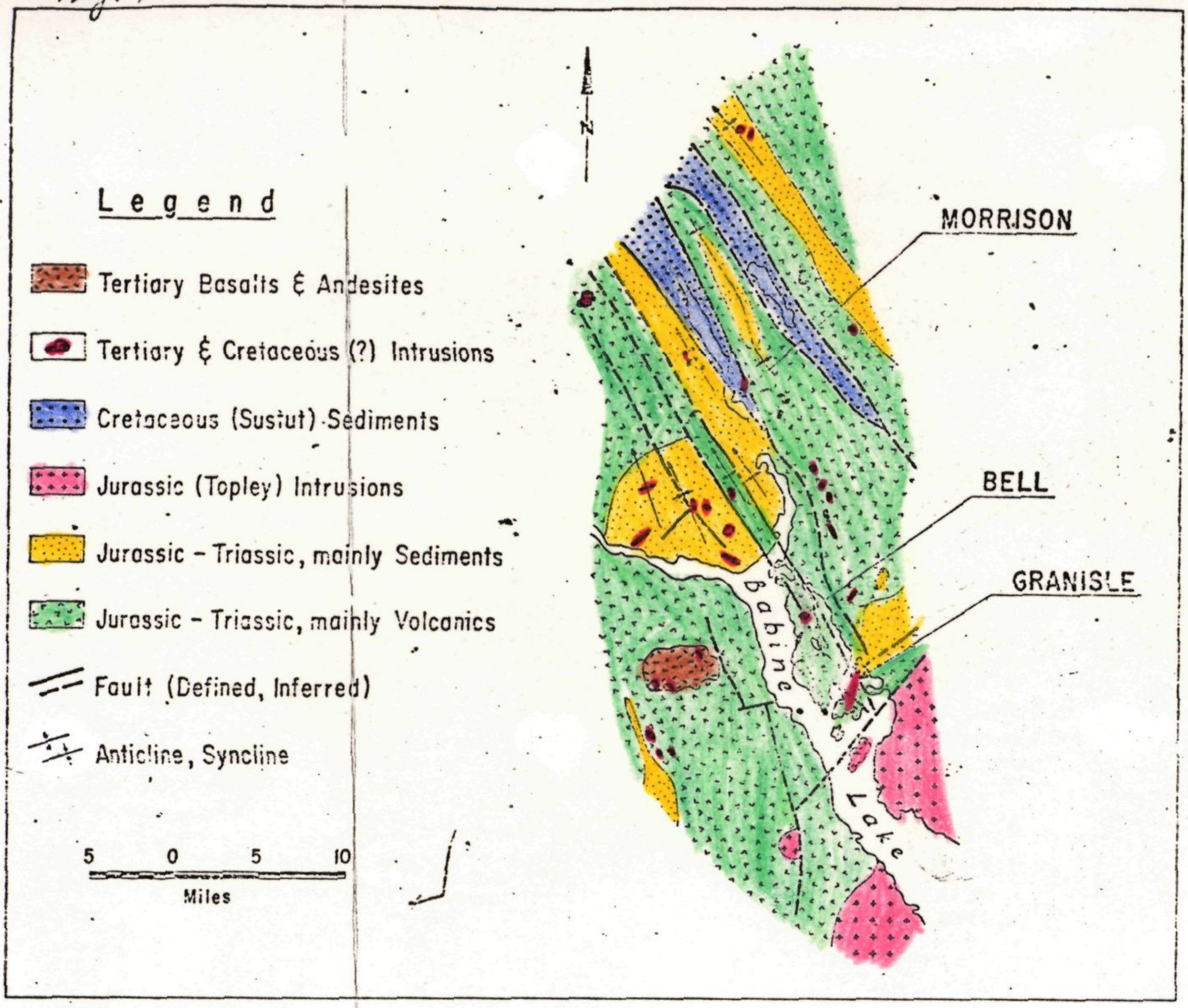

Figure 4 - Geology of the Babine Lake area (modified after Carter and Kirkham, 1969, with minor additions and deletions).

diatremes, are known to be present at Granisle, Bell, and Dorothy.

The copper-bearing zones range from a few hundred to a few thousand feet in diameter. They are centrally-located within much larger elliptical or circular areas of hydrothermal silicate alteration, and are also encircled by annular pyrite haloes. The main copper mineral, chalcopyrite, occurs both disseminated and as fracture-fillings in BFP, and to a lesser extent, in the adjacent country rocks. Bornite is important in the central portions of the higher-grade deposits. Limited supergene enrichment, with the formation of secondary chalcocite and covellite, has occurred only at Bell. However, the commercial exploitation of this deposit, as well as Granisle, is dependent on protore.

Alteration Terminology

Propylitic, argillic, phyllic, and potassic commonly appear in the literature as terms used to describe zones or mineral assemblages formed by hydrothermal alteration. In a recent comprehensive study of porphyry copper deposits, Lowell and Guilbert (1970) defined the following assemblages:

propylitic: chlorite-calcite-epidote-adularia-albite

argillic: quartz-kaolin-montmorillonite-chlorite-biotite

phyllic: quartz-sericite-pyrite with less than 5% kaolin, biotite, or K-feldspar

potassic: introduced or recrystallized K-feldspar and biotite, with minor sericite and highly variable but persistent and generally minor amounts of anhydrite.

The above alteration assemblages occur typically in the same sequence in porphyry copper deposits; the outward progression is from a potassic core to a peripheral propylitic zone. According to Lowell and

Guilbert, the phyllic (quartz-sericite-pyrite) zone is the principal ore-bearer in most porphyry deposits. In the Babine Lake area, however, phyllic zones are in general not well-developed and the ore is closely associated with secondary biotitization. Alteration has therefore been mapped on the basis of biotite, quartz-sericite, and chlorite-carbonate assemblages. These correspond approximately to the potassic, phyllic, and propylitic alterations, but the latter terminology has not been used.

GRANISLE (1)

Introduction

The geology of the Granisle copper deposit and of McDonald Island has been described by Carter (1966, 1972) and by Fahrni (1967). The deposit, which contains 50-100 million tons grading about 0.5% copper, is associated with a Tertiary dyke-like body of BFP intruded into mafic and felsic volcanics and minor sediments of the Lower Jurassic Hazelton Group. Copper mineralization occurs mostly, though not exclusively, in the BFP, both as disseminated grains and fracture fillings. The limits of the ore zone and the distribution of the associated alteration zones are shown in Figure 5. Alteration has affected all rock types for about 5000 feet outward from the orebody, but there has been some minor degree of dependence (particularly in areas of weak alteration) on the texture and composition of the affected rock. Thus, in places, fine-grained, mafic-poor, salic flows are relatively free of chloritic or biotitic alteration whereas adjacent hornblende-bearing BFP contains these alterations. On the other hand, the salic rocks are generally more readily sericitized. What is significant, however, is that varied rock types do not contain contrasting alteration assemblages, *i.e.* the variation in

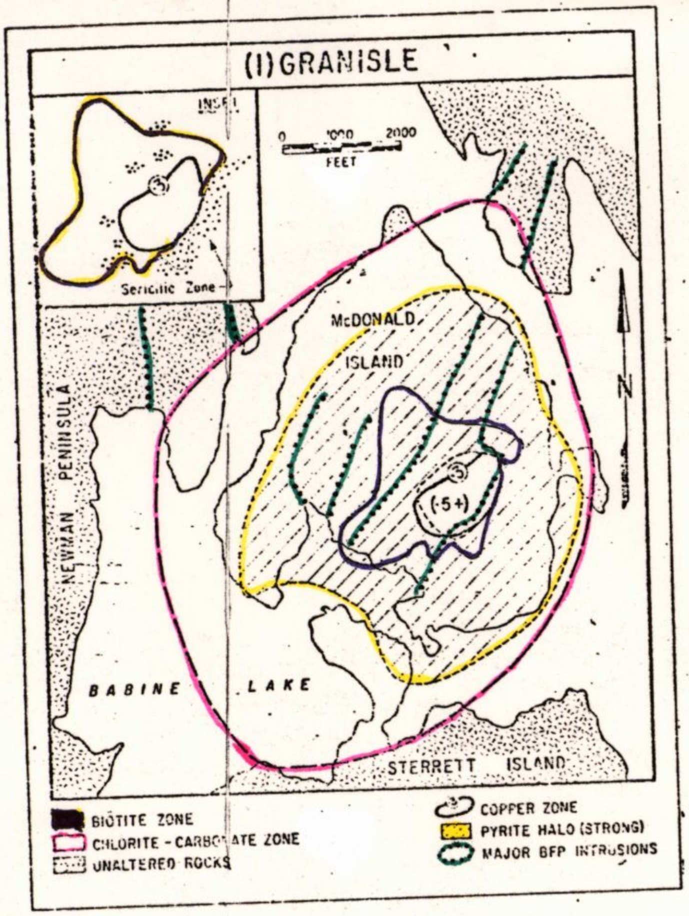

Figure 5 - Granisle alteration zones. The inset shows the areas of sericitic alteration (stippled).

response is one of abundance rather than mineralogy. Wherever possible, BFP was favoured for describing and mapping the alteration zones because (1) it is the principal host to copper mineralization; (2) it occurs in all deposits, both as major centrally-located bodies and peripheral dykes and sills; (3) it is less variable, in composition and texture, than other associated rocks; (4) amphibole phenocrysts seem to be particularly sensitive to alteration and BFP is the principal bearer of this mineral.

More than one hundred diamond drill holes, as well as most surface exposures, were examined and sampled for this study. The distribution of the specimens used for microscopic and/or chemical studies is shown in Figure 3.

Unaltered BFP

Unaltered BFP is a medium to dark grey speckled rock containing ¼ to 5 mm phenocrysts of biotite, zoned plagioclase, and hornblende in a fine-grained to aphanitic matrix of the same minerals plus quartz and K-feldspar (Figures 6, 7). Phenocrysts of quartz are present but uncommon; K-feldspar phenocrysts are extremely rare.

Microprobe scanning of the matrices of numerous BFP samples indicates that the matrices are quite variable in composition, straddling the boundaries between quartz diorite, granodiorite, and quartz monzonite. However, over-all BFP compositions, including phenocrysts, are quartz dioritic or granodioritic. Chemical analyses of two samples of unaltered BFP from outside the Granisle alteration zone are given in Table 1.

Plagioclase phenocrysts are normally zoned and generally vary from oligoclase to andesine. Maximum and minimum anorthite compositions encountered in microprobe analyses of several crystals were An_{74} (core) and An_{22} (rim) respectively. The plagioclases contain from 1.5% to 3.3% orthoclase in solid solution.


8
Pc
Pc
0 mm 0.5
9
cb
ch
7
Pc
Pc
0 mm 0.5
10
0 mm 0.5

Figure 6 - Hand specimen of BFP from Granisle showing crude layering, disseminated black biotite phenocrysts, and partial alignment of white plagioclase phenocrysts.

Figure 7 - Unaltered BFP, from outside the Granisle alteration halo, showing fresh phenocrysts of biotite (Bi), plagioclase (Pc), and hornblende (Hb) in a fine-grained matrix of the same minerals plus quartz and K-feldspar.

Figure 8 - BFP from the outer chlorite-carbonate zone at Bell. Plagioclase (Pc) fresh to partly replaced by sericite and carbonate, hornblende (Hb) completely replaced by carbonate (black, including minor opaque material) and chlorite, biotite (Bi) partly replaced by sericite and carbonate along cleavages.

Figure 9 - Altered hornblende phenocryst in BFP from the Granisle outer chlorite-carbonate zone. The complete replacement of amphibole phenocrysts by chlorite (ch) and carbonate (cb) marks the outer limit of the chlorite-carbonate zone.

Figure 10 - Chlorite-carbonate pseudomorph of a large amphibole phenocryst in BFP from the Morrison chlorite-carbonate zone.

Figures 7-10: photomicrographs, plane polarized light.

Microprobe analyses of hornblende phenocrysts in BFP are given in Table 2, and the results obtained from biotite phenocrysts are briefly discussed further below.

Chlorite-carbonate zone

The boundary between unaltered rock and the outer edge of the chlorite-carbonate zone is gradational and difficult to precisely define. For the Granisle halo, the dividing line between "unaltered" and hydrothermally altered" BFP was considered to be marked by the complete replacement of hornblende phenocrysts. Thus, as seen in thin sections, the initial alteration is the pseudomorphism of hornblende by mixtures that consist predominantly of chlorite and carbonate (Figures 8, 9, 10). Most of the carbonate in this fringe zone is calcite but, contrary to the initial indications (Carson and Jambor, 1971), dolomite and siderite are also present in some cases. In rocks lacking primary mafic constituents, the principal manifestation of the initiation of porphyry alteration is the presence of higher-than-normal amounts of carbonate. Epidote is present in many rocks, but its distribution and abundance are erratic. In all rocks the chief opaque minerals are magnetite and hematite.

Progressing inward toward the ore zone, the amount of carbonate replacement increases and the principal opaque mineral is pyrite (see Figure 5 and later discussion). BFP and other rocks in the main part of the chlorite-carbonate zone commonly have a pale green "bleached" appearance that was thought, in the initial field work, to represent strong clay alteration. Microscopic studies have shown, however, that the effect results predominantly from the presence of carbonate. Intense clay alteration is largely confined to faults. Dispersed clay alteration is largely confined to plagioclase phenocrysts. About 25 X-ray powder diffraction patterns of material from phenocrysts consistently indicated that the clay mineral present is kaolinite. Although the kaolinite is not restricted to a particular alteration zone, occurrences seem to be more numerous at the outer edge of the biotite zone, regardless of whether the zonal change is from biotite to quartz-sericite, or from biotite to chlorite-carbonate..

Alteration effects on BFP in a complete cross-section of the chlorite-carbonate zone may be briefly summarized. The fine-grained mixtures that form amphibole pseudomorphs at the halo fringes give way inwards to coarse chlorite pseudomorphs (Figures 11, 12). Blue and grey chlorite interference colours in the outermost reaches of the zone change inwards to green and brown. Primary biotite phenocrysts persist through all of the alteration zones and the orebody, but seem to have been partly susceptible to replacement in the outer and middle parts of the chlorite-carbonate zone. Although pseudomorphism of the biotite by chlorite or sericite has been observed, partial replacement of plagioclase by sericite or carbonate minerals that have penetrated along cleavage planes and compositional zones (Figure 13,14) is more common. Within the chlorite-carbonate zone, plagioclase phenocrysts show progressively more alteration towards the orebody; in the outer part of the halo only minor carbonate veining and flecking by sericite and carbonate are present, but towards the ore zone increased clouding and turbidity is general. The fine-grained BFP matrix in the chlorite-carbonate zone seems to have been less affected than the phenocrysts. At the outer extremities of the zone, matrix replacement is for the most part limited to disseminated patches of carbonate. Toward the ore zone, however, the matrix in many cases contains substantial amounts of chlorite, carbonate, sericite, pyrite, kaolinite, and quartz. This assemblage seems


11
Pc
Bi
Bi
ch
ch
0 mm 0.5
12
ch
ch
ch
13
14
15
ka
16

Figure 11 - BFP from the central part of the Morrison chlorite-carbonate zone showing coarse chlorite (ch) pseudomorphs after hornblende, unaltered biotite phenocrysts (Bi), plagioclase (Pc) partly altered to sericite and clay, and pyrite (opaque).

Figure 12 - BFP, from the Morrison chlorite-carbonate zone, showing the stability of biotite phenocrysts (Bi) relative to those of hornblende, the latter being completely chloritized (ch).

Figure 13 - Zoned plagioclase phenocryst partly replaced by sericite and clay along cleavages and compositional zones. From BFP in the outer part of the Granisle biotite zone. Crossed nicols.

Figure 14 - BFP in the inner part of the Granisle chlorite-carbonate zone showing zonal replacement of plagioclase by sericite and clay.

Figure 15 - BFP in the inner part of the Bell chlorite-carbonate zone showing kaolinite (ka) and carbonate (cb) pseudomorph of plagioclase adjacent to unaltered biotite phenocryst (Bi).

Figure 16 - BFP from the Morrison biotite zone showing a kaolinite pseudomorph of plagioclase, with original compositional zoning partly preserved by carbonate (black). Figures 11, 12, 14-16: plane polarized light.

to overlap, or partly overlap, the propylitic, argillic, and phyllic zones of Lowell and Guilbert (1970).

Sericite-quartz zone

Some of the Babine Lake properties show a direct transition from the outer chlorite-carbonate to an inner biotite zone; in others there is an intervening sericitic zone. The sericitic zone may contain abundant quartz (as at Bell Copper) and variable, minor amounts of clay, but neither is always present. X-ray powder diffraction patterns almost invariably indicate that the sericite is $2M_1$ muscovite and the clay is kaolinite.

Neither clay nor quartz is profusely developed at Granisle, but sericite accompanied by abundant carbonate is present as a partial ring around the deposit. This sericitic zone (Figure 5, inset) lies within the pyrite halo rather than the ore zone; it is well-developed along the eastern margin of the biotite zone and copper deposit but seems to be weak or absent along the northwest and west. However, a lack of exposures or drill holes in these areas make this interpretation uncertain.

BFP from the sericitic zone typically has both the phenocrysts and matrix extensively replaced by fine-grained muscovite. Sericitization that is present in the chlorite-carbonate zone is generally confined to phenocrysts or is dispersed in minor amounts in the matrix.

Biotite zone

In delineating the boundaries of the chloritic, sericitic, and biotitic zones, it must be borne in mind that priority in the present study has been given to biotite. In other words, rocks containing secondary biotite were placed in a biotite zone regardless of the other minerals present.

The inward progression from the chlorite-carbonate (or, in some cases, sericitic) zone into the centrally-located biotite zone is marked by the appearance of secondary biotite that, if abundant, is characteristically fine-grained and commonly greenish. Chlorite and carbonate do not disappear — both persist to the centre of the deposit in variable but much smaller amounts.

The orebody is located entirely within the biotite zone, and the texture, colour, abundance, and composition of secondary biotite change as the orebody is approached. These characteristics also seem to vary within the orebody, being dependent on the grade (intensity) of copper mineralization. Some typical textures of secondary biotite are shown in Figures 17 - 20. At Granisle, secondary biotite in the main part of the ore zone is microscopically dark brown; material that has replaced amphibole is relatively coarse-grained, generally sugary-textured, and is accompanied by abundant fine-grained shreddy biotite disseminated in the rock matrix. The colour, sugary-textured pseudomorphs and aggregates, and accompanying finer-grained matrix biotite, when combined, are indicative of the highest intensity of biotitization. Only in this environment are the primary biotite phenocrysts altered to secondary biotite, and even in this case the phenocrysts are usually only partly replaced at the edges. In places with lower copper grades, but still within the ore zone, there is a decrease in the amount of matrix biotite, i.e. a correspondingly higher proportion of the mica is present as amphibole pseudomorphs. The biotitized BFP in the Granisle pit megascopically has the fresh, black, unbleached appearance of unaltered mafic-rich igneous rock.

Outside the orebody, there is a decrease in the abundance of biotite. Although green biotite can be found throughout the biotite zone, it is abundant only in the outer fringes of the biotite halo. Outer fringe secondary biotite has commonly been extensively replaced by chlorite (Figure 17);

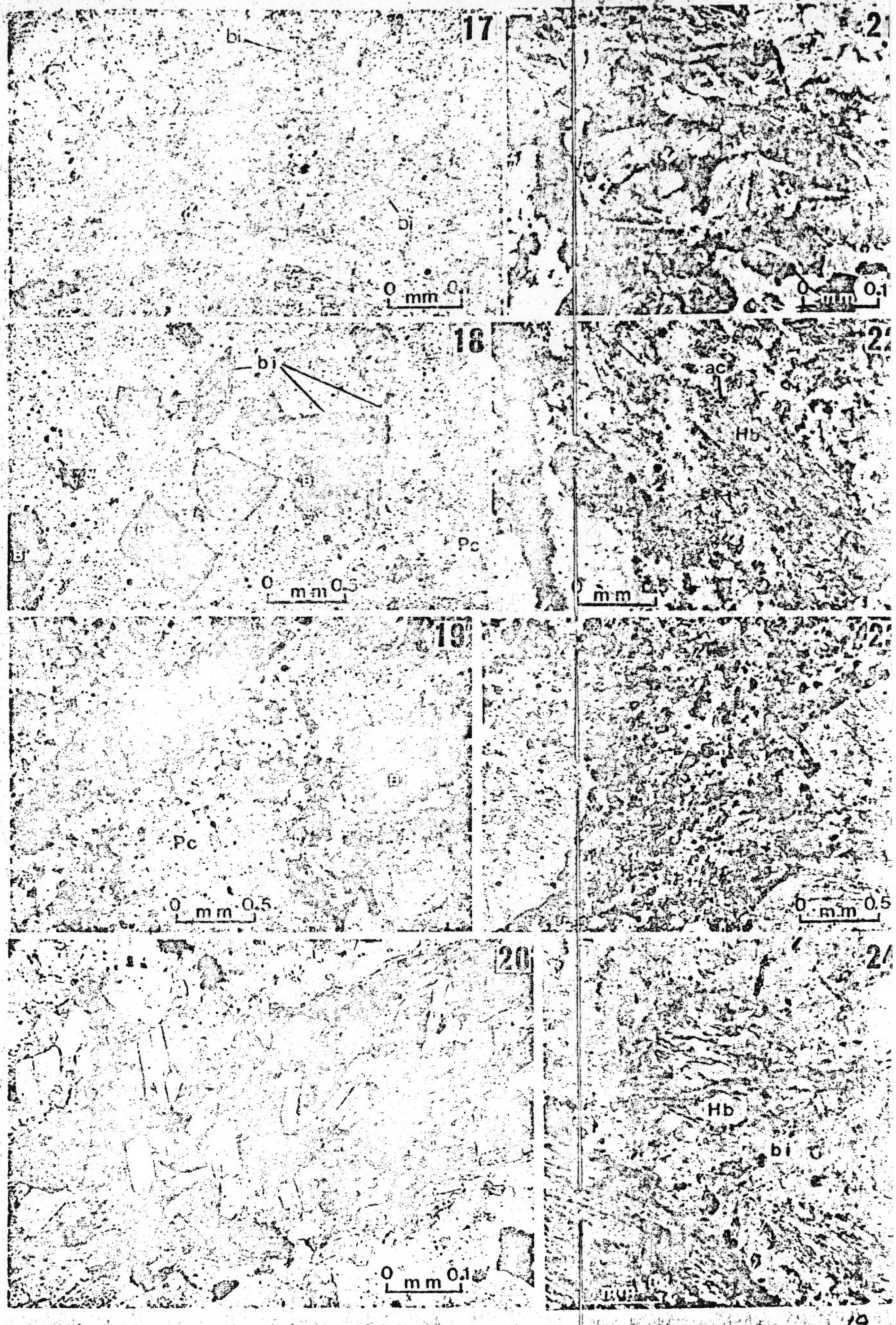
17
bi
bi
0 mm 0.1
0 mm 0.1
18
bi
Pc
0 mm 0.5
ac
Hb
0 mm 0.5
19
Pc
0 mm 0.5
0 mm 0.5
20
0 mm 0.1
Hb
bi

Figure 17 - Weakly biotitized hornblende phenocrysts in BFP from the outer fringe of the biotite zone at Granisle. Fine-grained, greenish-bro biotite (bi), typical "fringe" material, has replaced the phenocrys rims; chlorite (ch) has replaced the central portions.

Figure 18 - Weakly biotitized BFP from the Dorothy property showing fine-grain biotite (bi) restricted to pseudomorphs of hornblende and absent in the matrix. Phenocrysts of biotite (Bi) and plagioclase (Pc) are largely unaltered.

Figure 19 - Strongly biotitized BFP from the highest grade part of the Morrison copper zone. Coarse, sugary-textured brown hydrothermal biotite replaced hornblende and is scattered throughout the matrix. Phenocrysts of biotite (Bi) and plagioclase (Pc) are largely unaltered. Opaques are sulphides.

Figure 20 - Enlargement of the "sugary-textured" secondary biotite forming the pseudomorph of the hornblende phenocryst shown in Figure 19.

Figure 21 - Relatively coarse chlorite sheaves in a veinlet cutting BFP in the Morrison biotite zone. Crossed nicols.

Figure 22 - Hornblende phenocrysts (Hb) and secondary amphibole (ac) in BFP from the Morrison biotite zone. The fine-grained secondary amphibo occurs as veinlets, as rims that partly replaced the phenocrysts,an as grains disseminated in the matrix.

Figure 23 - BFP from Morrison showing disseminated sulphides and secondary amphibole in the matrix. Plagioclase phenocrysts are largely unaltered.

Figure 24 - Amphibole phenocryst (Hb) partly replaced by a rim of hydrothermal biotite (bi). From BFP in the Morrison biotite zone.

in addition to the microscopically observable chloritization, electron microprobe analyses suggest that chlorite interlayers with biotite are present.

Hydrothermal K-feldspar is a minor mineral at Granisle, and is restricted to the central (+0.3% Cu) portion of the biotite zone. The limited abundance of the mineral has precluded its use as an indicator of copper mineralization in the Babine Lake area.

Pyrite halo

A well-developed pyrite halo surrounds the Granisle orebody (Figure 5). Our field and laboratory studies, including sulphur analyses, indicate that the pyrite halo is annular, with maximum abundances of the mineral being reached in the sericitic and innermost part of the chlorite-carbonate zones. Although variable, the quantity of pyrite in this area is estimated to average about 10 per cent by volume. The typical appearances of disseminated and fracture-filling pyrite, both of which occur throughout the halo, are shown in Figures 25 and 26. Individual disseminated grains average less than 0.5 mm in diameter, but these are commonly clustered into larger aggregates. Most pyrite stringers are from 0.5 mm to 2 mm wide.

Mineralogical Data

In the preceding sections the distribution and general character of the alteration assemblages that surround the Granisle ore zone were discussed. Compositional data on the most important minerals occurring within these assemblages, as well as a description of additional but less abundant or diagnostic minerals, are given below.

Biotite compostions

Electron microprobe analyses were done on 84 biotites from 18 sample sites at Granisle. TiO_2 analyses are illustrated in Figure 29. The 34 analyses of phenocrysts in BFP are from 12 sample sites and the 50 analyses of secondary biotites are from 14 sites. The results of the microprobe study are summarized as follows:

1. Appreciable compositional variation in biotite phenocrysts in BFP may occur within a single thin section.

2. Biotite phenocrysts are readily distinguished from almost all secondary biotites at Granisle simply on the basis of TiO_2 contents (Figure 29). The average weight per cent TiO_2 in the phenocrysts is 4.3 (only one analysis in 34 is less than 4.0); in the secondary biotites the average TiO_2 is 2.8 per cent (only in 2 of the 50 analyses is TiO_2 greater than 4.0 per cent).

3. Titanium in secondary biotites is highest in the ore zone and decreases outwards; ore zone material averages about 3.2% TiO_2 whereas the biotites in the pyrite halo average about 2.7%.

4. MgO in secondary biotites decreases from an average of about 17% in the ore zone to less than 15% in the pyrite halo.*

5. Ore zone biotites are characterized by deficiencies in tetrahedral Al. Thus, even though biotites throughout the whole of the biotite zone have similar total iron contents, those in the ore zone contain more iron in the ferric state. This condition is correlative with, and supported by, the pattern found for MgO (point 4, above).

6. Microscopically greenish hydrothermal biotites have lower TiO_2 contents than brown hydrothermal biotites. The common presence of Al in excess of tetrahedral requirements also suggests that ferric iron is low in greenish biotites. The presence of lower ferric iron and the more common occurrence of the greenish mica at the fringes of the ore zone and in the pyrite halo is in accord with point 5 above.

The results of the microprobe analyses thus indicate that there is an over-all zonal pattern to the compositional variations in the hydrothermal biotites. It would appear that, with respect to biotite crystallization, the outer parts of the alteration halo were in a more reduced state than the site occupied by the present ore zone.

*A similar Mg variation in secondary biotites in the Bingham district, Utah, has been reported recently by Moore and Czamanske (Econ. Geol., vol. 68, pp. 269-280 [1973]).

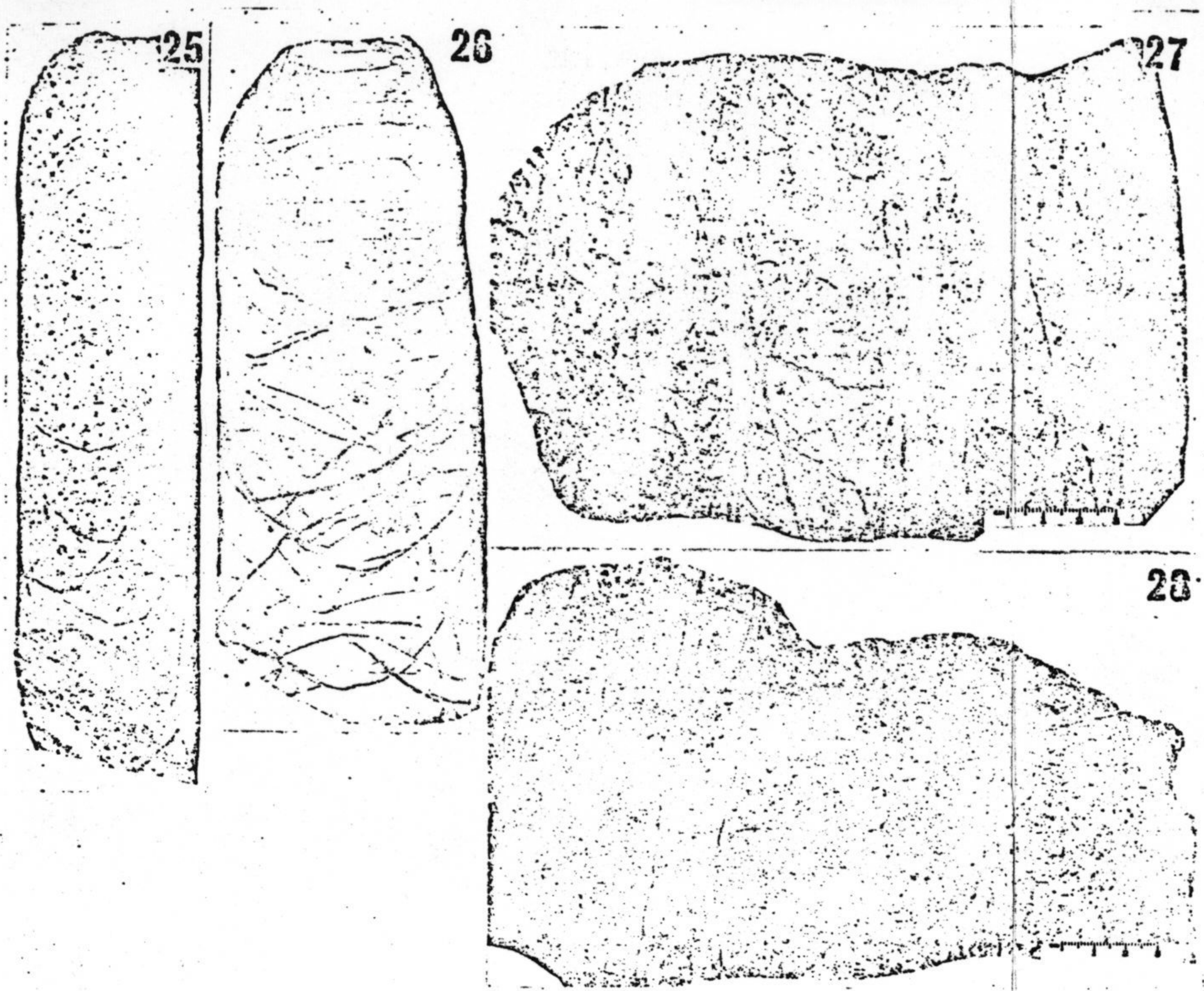

Figure 25 - Volcanic rock from Granisle pyrite halo showing dark disseminated pyrite, in some cases accompanied by chlorite and carbonate in clots. Smaller amounts of pyrite occur in stringers.

Figure 26 - Fine-grained sedimentary rock from the Granisle pyrite halo showing intense pyritization mainly along fractures.

Figure 27 - Intensive quartz veining typical of much of quartz-sericite zone and orebody at Bell Copper.

Figure 28 - Breccia from Bell containing only a few quartz stringers, but grey areas throughout the rock show the almost complete flooding by silica.

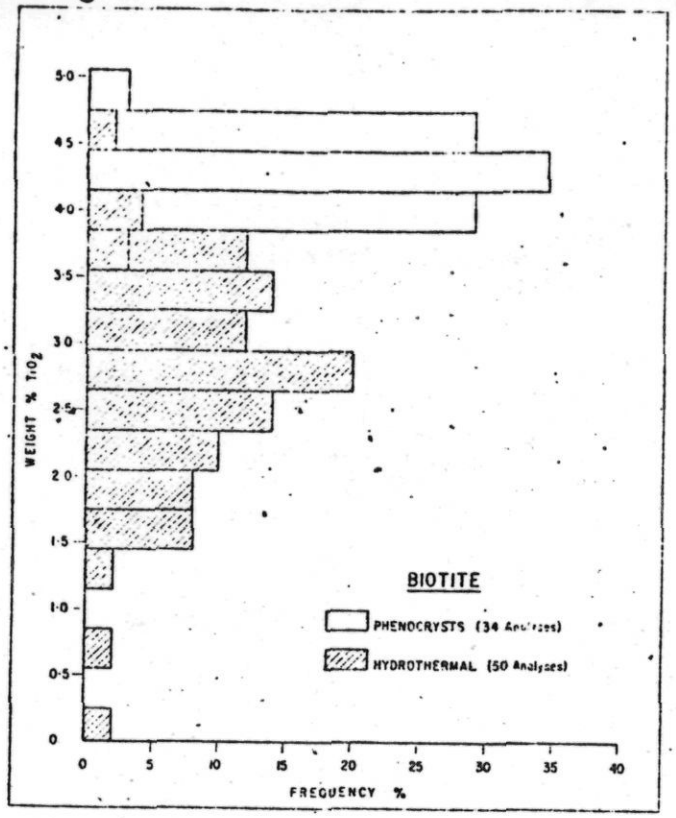

Figure 29 - Results of electron microprobe analyses of Granisle primary and hydrothermal biotites, showing the higher TiO_2 contents of the phenocrysts.

K-feldspar

Hydrothermal potassic feldspar is present in very minor amounts in the 0.3% copper zone at Granisle and other Babine area porphyry copper deposits. The mineral at Granisle is pinkish and occurs mostly with quartz in fractures generally <0.5 mm in width. Rare K-feldspar is also present as euhedral crystals, averaging about 2 mm in length, that line open fractures and cavities in BFP. Most K-feldspar occurs in the southern and southeastern part of the ore zone, where fractures and small cavities in the host rock matrix are lined with K-feldspar and partly filled with granular aggregates of magnetite, chalcopyrite, well-crystallized dark green chlorite, and a few scattered euhedral crystals of rutile. In a few places coarse K-feldspar occurs with quartz, chalcopyrite, and partly chloritized coarse books of hydrothermal biotite. Partial K-feldspar replacement of BFP plagioclase phenocrysts and the matrices of volcanic host rocks has been observed, particularly along the eastern side of the ore zone, but such occurrences are minor relative to biotitization.

X-ray powder diffraction patterns of the secondary K-feldspars indicate that they are usually of the "orthoclase" (monoclinic) type and have anomalous cell dimensions. Microprobe analyses (Table 3) show that the compositions are variable, with some containing appreciable amounts of sodium. Some K-feldspar veinlets also contain isolated grains of sodic plagioclase intergrown with the K-feldspar.

Chlorite

Chlorite occurs in variable amounts throughout the ore and associated alteration zones. The mineral is only a minor constituent in the biotite halo, where it characteristically occurs as well-crystallized sheaves (Figure 21) with green and brown interference colours. This habit also persists in the innermost part of the chlorite-carbonate zone, but here much of the chlorite is present as well-developed pseudomorphs after amphibole (Figures 11, 12). With increasing distance from the ore zone, the green and brown interference colours give way to blues and greys, the grain size decreases, and there is a general absence of well-developed sheaves. X-ray powder diffractions patterns indicate that the well-crystallized material from the biotite halo is predominantly or exclusively the IIb polytype whereas in the outer part of the chlorite-carbonate zone some ill-defined mixtures are present and chlorite polytypes are not exclusively IIb. These variations strongly suggest that the chlorites may vary in composition outward from the orebody, a situation perhaps analogous to that described above for biotite. Although microprobe analyses of 9 chlorites (Table 4) failed to show any obvious trend, this may be due to the small number of samples analyzed, or to the variable compositions and reactivities of the host rocks.

In the 4 samples in which both vein and non-vein (matrix) chlorite pairs were available, veinlet chlorite consistently contains the higher iron. If veinlet material represents the culmination of chlorite deposition, the trend toward iron enrichment may reflect decreasing temperatures.

Carbonates

The presence of abundant secondary carbonates is one of the most prominent manifestiations of hydrothermal alteration in some of the Babine porphyry copper deposits. Calcite, siderite, and minerals in the dolomite-ankerite series occur in all deposits and were identified initially by staining thin and polished thin sections with alizarin red (Warne, 1962). X-ray powder diffraction patterns were also made from material extracted from the sections under a petrographic microscope. Fifty five semi-quantitative electron microprobe analyses of samples from 12 different sites at Granisle showed that carbonate compositions within a single thin section are highly variable, that ankerite is abundant and almost all dolomites are ferroan (~ 5% FeO), and that manganese is generally low (< 1%), but ranges as high as ~5% in ankerite-dolomite.

Microscopic studies have indicated that the central part of the Granisle orebody is almost free of carbonate alteration and that the very minor amount of carbonate present is predominantly or exclusively calcite. The mineral occurs as patches and small veinlets in plagioclase phenocrysts rather than being associated with the mafic constituents. As the intensity of biotitization decreases outwards, carbonate increases and commonly becomes the most abundant non-sulphide alteration mineral in the pyrite halo. Calcite, siderite, and ankerite-dolomite occur as finely disseminated grains and as coarser grained anhedral aggregates both in the matrix and in plagioclase phenocrysts. Selective replacement of calcium-rich zones in plagioclase phenocrysts is commonly extensive rather than patchy and, unlike the ore zone occurrences, carbonate is commonly associated with chlorite and biotite pseudomorphs of amphibole phenocrysts. Most "bleached" rocks that megascopically appear to have been altered largely to clay minerals have been found, upon microscopic examination, to contain relatively minor clay in comparison to carbonate. A decrease in carbonate accompanies the outward weakening of the pyrite halo, and eventually there is a transition into unaltered rock. In summary, therefore, the overall pattern of carbonate alteration at Granisle is one in which a very weak calcitic core associated with the ore zone passes outward into very strong multi-carbonate alteration that decreases in intensity toward the outer fringes of the chlorite-carbonate zone.

Sulphides

The inward progression at Granisle from pyrite to chalcopyrite, to bornite plus chalcopyrite, is "classical" for porphyry copper deposits and need be commented on only briefly. Only within the higher-grade parts of the 0.3 per cent copper zone is bornite commonly found. Thus bornite and chalcopyrite are relatively abundant in the main part of the ore zone, but chalcopyrite alone accounts for the copper values in the lower-grade and marginally-economic to sub-economic parts of the deposit.

Although pyrite stringers have been observed within the 0.3% copper zone at Granisle, nearly all polished sections of ore lack disseminated pyrite. Chemical analyses show that the ore zone is characterized not only by its high copper content, but also by relatively low sulphur abundances that reflect the general absence of iron sulphides. With the exception of the northeastern side of the deposit, the boundary of the 0.3% copper zone marks the appearance of abundant pyrite (Figure 5). Along the eastern and southern sides of the deposit, individual drill holes commonly contain sections of chalcopyrite-rich ore-grade material alternating with pyritic waste, thus further demonstrating the general antipathetic relationship between abundant pyrite and ore-grade copper mineralization.

Other than pyrite, chalcopyrite, and bornite, additional sulphides are sparse. Minute amounts of chalcocite(?) and covellite have been observed in polished sections. Small amounts of molybdenite occur in fractures and as individual grains disseminated in the host rocks. This mineral occurs both in the ore zone and in the adjoining portion of the pyrite halo. Gold and silver are recovered from the concentrates, but a mineral source was not observed. Marcasite was found in several polished sections, some of which are of material from the pyrite halo, and others from the ore zone. Galena and sphalerite associated with pyrite and marcasite are abundant in the quartz-dolomite-calcite vein at the southwestern shore of the island, and have also been observed in minor quanitities in a few small (< 1 cm) carbonate veins elsewhere in the chlorite-carbonate zone. Kirkham (R.V. Kirkham, personal communication) reports the occurrence of some drusy quartz carbonate veins with galena and sphalerite, cutting the copper-bearing stockwork i the ore zone.

Pyrrhotite was seen only in polished sections, where it occurs in small rounded blebs in pyrite. Although not abundant, the fact that the pyrrhotite was seen in samples from more than a dozen sites suggests that the mineral is relatively widespread. Most observed pyrrhotite occurrences are from the inner part of the pyrite halo, possibly due to polished section sample coverage.

Gypsum and anhydrite

Although it has not been found in large quantities, gypsum is nevertheless relatively widespread. It was identified in 21 drill holes within both the ore-bearing and pyritized parts of the biotite halo. The mineral occurs typically in white to colorless, relatively coarse-grained veinlets 1-3 mm wide. Anhydrite was identified in only one drill hole (at 816 feet): it is associated with gypsum and traces of bassanite ($CaSO_4 \cdot \frac{1}{2} H_2O$) and seems to have crystallized in small disseminated pockets throughout the BFP matrix.

Of the 21 sites at which gypsum was noted, 10 are outside the 0.3% copper zone, but within approximately 500 feet of its margin. The depth of the occurrences ranges from 233 to 1710 feet. Although the mineral seems to be more common at depths greater than 450 feet, no definite systematic pattern was found. As implied above, however, all occurrences are within the biotite zone.

Kaolinite

In comparison to biotite, chlorite, sericite, and carbonate at Granisle, kaolinite is relatively uncommon. In most cases the mineral is associated with plagioclase phenocrysts, either along microscopic fractures in the crystal interiors, or as a partial replacement of specific zones in the phenocrysts. Kaolinization is present in the biotite, quartz-sericite, and chlorite-carbonate zones, but is rare in the ore zone.

Other minerals

Tourmaline is widspread but not abundant in some Babine deposits. It is present in very minor amounts at Granisle. Epidote is present as an alteration mineral in all the Granisle zones, but the paucity and scattered nature of the occurrences prevented an allocation to a specific alteration assemblage. Rutile is common throughout the alteration halo. Anhedral granular aggregates and clusters of subhedral crystals of this mineral have in many cases clearly formed from the breakdown of disseminated primary ilmenite and spinels. Very fine-grained turbid rutile aggregates also seem to have originated from the titanium that was present in replaced primary biotite and amphibole. In addition to such secondary material, euhedral to anhedral grains of the mineral have been noted in a few quartz-carbonate-sulphide veinlets.

Small amounts of apatite occur as a primary accessory in BFP, and some has also crystallized as a hypogene phase that was introduced with the hydrothermal alteration and sulphide mineralization. Some bornite-rich pockets at Granisle contain pale green euhedral apatite crystals having a basal diameter of up to 2 mm. Rare pockets and veinlets of very coarse-grained hydrothermal biotite intergrown with apatite crystals up to 15 mm in diameter have been observed in the central part of the orebody. Less conspicuous but more abundant, are anhedral grains associated with quartz and carbonate in microscopic cavities in BFP, and in veinlets of these minerals. A single microprobe analysis of such material indicated that the mineral is a fluorapatite comparable to that described from Durango, Mexico, by Young et al. (1969). The Granisle apatite contains only slightly less fluorine and more chlorine than the Mexican mineral. Although the distribution and abundances of apatite at Granisle have not been studied in detail, the impression obtained is that the mineral is most prolific in the ore zone and bordering portion of the pyrite halo.

Celestite, $SrSO_4$, is present in minor veinlets in several drill holes in the ore zone and adjacent parts of the pyrite halo. Although the sulphate has been found in narrow, tight calcite veinlets to depths as much as 746 feet, the typical association is with euhedral drusy calcite in open fractures. In these the calcite is coated either with white acicular celestite bundles up to 5 mm in length, or with pale blue to colorless euhedral celestite crystals up to 2 mm in length.

Barite, $BaSO_4$, was found only in the southernmost part of the ore zone, but it is unlikely that occurrences are restricted to this area. At a depth of 878 feet in one drill hole, subhedral barite crystals up to 2 mm in length are intergrown with dolomite in dolomite-quartz-calcite veinlets. In most other occurrences the barite is present in open fractures as platy aggregates stained red with hematite.

Three hand specimens obtained at the Granisle mine office contain cristobalite that occurs as fine-grained, pulverent white coatings, and as yellowish, waxy, clay-like coatings on well-crystallized sulphides in fractures. The associated minerals are quartz, carbonates, pyrite, marcasite, chalcopyrite, and in one case, abundant molybdenite.

Magnetite and hematite veinlets occur both in the ore zone and pyrite halo. Carter (1972) reported that magnetite and specularite are common in the northern half of the ore zone. A magnetic survey of Granisle was reported by Fahrni (1967) to have yielded an anomaly centered upon the highest grade part of the orebody.

In addition to magnetite, small amounts of andalusite and corundum were formed by contact metamorphism of the volcanics on the eastern side of the deposit. Supergene effects are minor and have not been systematically studied; jarosite, brochantite, siderotil, rozenite, and cyanotrichite were identified in the few samples examined.

new paragraph

Trace Element Studies

Approximately 125 Granisle rock samples were analyzed for Cu, Mo, Pb, Zn, Ag, Hg, S, Rb, Sr, and Ti. Seventeen samples were also analyzed for Au and Se. The generalized results obtained for zinc are shown in Figure 30. A distinct zinc low (<50 ppm) coincides with the Granisle orebody whereas several anomalously high values occur in the outer part of the pyrite halo. The high zinc sample from southwestern McDonald Island has $>10,000$ ppm Zn. This sample is from the original mineral showing, a narrow vein that consists predominantly of sphalerite, pyrite, marcasite, and minor galena in quartz and dolomite. Such zinc-rich veins at the peripheries of pyrite haloes are characteristic of many porphyry copper deposits.

Copper values exceeding 200 ppm are confined to the ore zone and innermost part of the pyrite halo. Molybdenum has a similar distribution, but with fewer high values (>10 ppm) in the pyrite halo. Gold is highest in the ore zone, but Pb, Ag, and Hg do not show well-defined patterns. These and additional results for Granisle, North and South Newman, Bell, and Dorothy will be given in detail in another paper (Jambor, 1973).

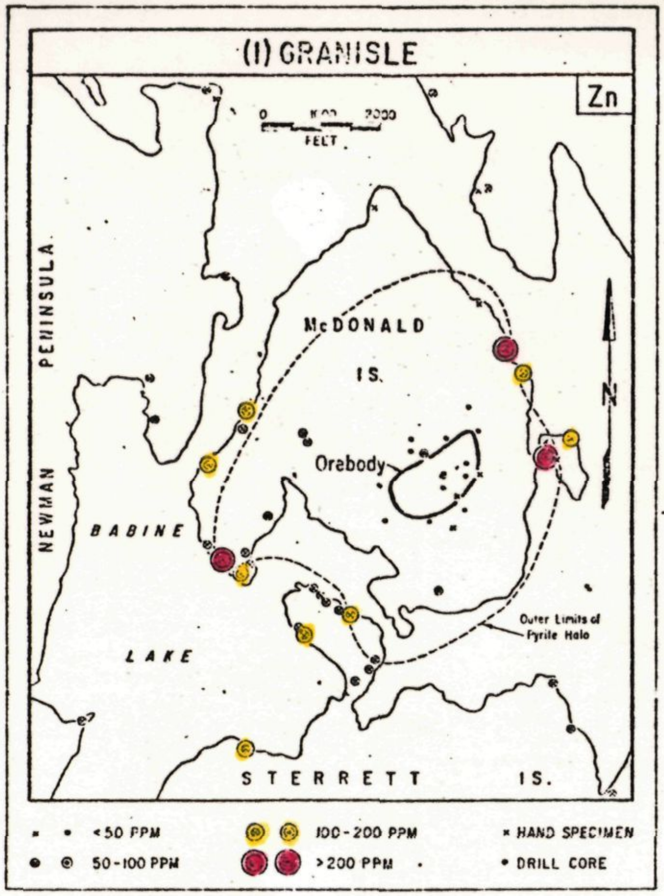

Figure 30 - Zn (ppm) in Granisle rocks. High values are concentrated at the outer limits of the pyrite halo.

BELL COPPER (2)

Introduction

The location and general geological setting of the Bell deposit are shown in Figures 2 and 4. The orebody contains 50-100 million tons of ore averaging about 0.5% copper, and has a higher grade (~0.7% Cu) pipe-like core approximately 500 feet in diameter. Ore-grade material is known to extend to a depth of at least 2500 feet.

The geology of the Bell deposit has been described by Carter (1966, 1972) and Bell (1970). The geological relationships are similar to those at Granisle in that copper mineralization is associated with a Tertiary BFP intrusion emplaced in Mesozoic sediments and volcanics.

Alteration

The alteration halo at Bell is about the same size as that at Granisle — approximately 10,000 feet by 8,000 feet (Figure 31). The orebody is surrounded by a well-developed pyrite halo approximately 6500 feet in diameter. The central ore-bearing area is relatively low in pyrite, and therefore the shape of the halo is annular. The average content of pyrite in the halo is about 10%, but it varies from approximately 5% to 25% in different localities. Pyrite occurs both as disseminations and fracture-fillings. Maximum quanitities probably occur in the central part of the halo where fracture-filling is most intense.

The alteration zones and assemblages at Bell are similar to those of Granisle and are, therefore, not described in detail. The most significant difference is the presence, at Bell, of an irregularly-shaped zone of very intense quartz-sericite alteration (Figure 31) that incorporates much, but not all, of the orebody and extends well into the southern part of the pyrite halo. Much of the sericitized material is

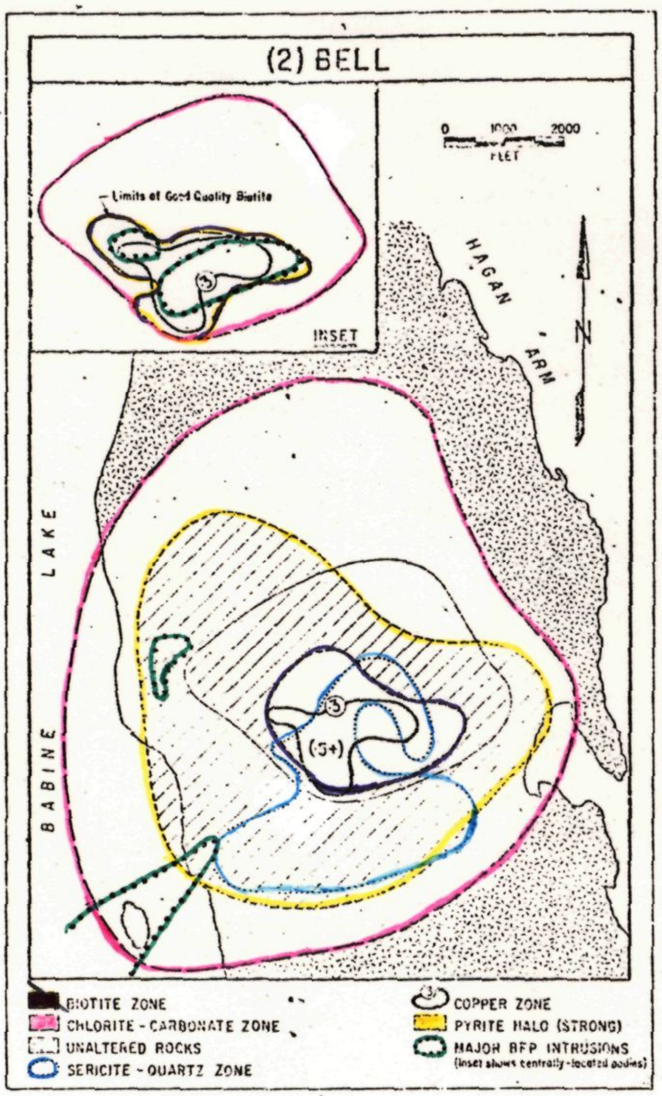

Figure 31 - Alteration zones at Bell Copper. The inset shows the centrally-located BFP intrusions, the total area in which hydrothermal biotite occurs, and the smaller area in which good-quality hydrotherm biotite is present.

intensely bleached and megascopically appears to have been altered largely to clay minerals. However, X-ray powder diffraction mounts made from numerous specimens, from specific areas in thin sections, consistently indicate that the alteration mineral is extremely fine-grained muscovite. X-ray diffractometer analyses by R.N. Delabio of the "clay" fraction of 4 intensely-altered samples (including the two shown in Figures 27 and 28) revealed the presence only of 2M "illite". Debye-Scherrer diffraction patterns of the same material indicate that it is $2M_1$ muscovite. Therefore, "illite" in this study has been equated with muscovite=sericite. These results suggest that most of the material that, in the field, seems to be altered to clay minerals properly belongs to a quartz-sericite (phyllic) assemblage rather than an argillic one. Although kaolinite occurs locally in the Bell deposit, no systematic pattern of distribution or abundance was found.

In most other respects, Bell is similar to Granisle and only a few additional comments need be made. Portions of the biotite halo have been partly masked by quartz-sericite alteration (Figure 31). The biotite halo as shown in the figure has been extended to include drill holes where biotitization is sporadic, and many occurrences are of moderate to poor quality (fine grained, green). The inset in Figure 31 shows a substantially smaller area in which nearly all secondary mafic mineral present is hydrothermal biotite of consistently "good quality". The 0.3% copper zone is contained within this area of good-quality biotite. Minor amounts of hydrothermal K-feldspar are also present.

A single drill hole in the northwest contains secondary biotite, but is well outside even the larger biotite zone. Data from this site are sufficient to establish that biotitization is localized, i.e., the site is an isolated "hot spot" surrounded by lower-grade chloritic alteration that clearly separates the area from the main biotite zone. Similar "hot spots" have been noted at other Babine deposits. They seem to be related to minor BFP dykes or sills that are peripheral to the main BFP intrusions and centers of copper mineralization.* It is possible, therefore, that the northern part of the larger of the biotite haloes may include several hot spots rather than being a single contiguous zone. Irrespective of which alternative is correct, the fact that nearly all of the extreme northern and eastern drill holes contain either sporadic, weak, fine-grained, or greenish secondary biotite typical of outer fringe material suggests that a copper zone, if present, should lie some distance inwards.

As at Granisle and all other Babine deposits, largely-unaltered biotite phenocrysts persist in all alteration zones. Alteration of plagioclase phenocrysts in BFP at Granisle shows a systematic pattern. Phenocrysts in the ore zone are fresh and unaltered and there is an increase in feldspar-destructive alteration outward to heavily clouded material in the pyrite halo. At Bell Copper, the intense alteration of plagioclase that occurs in much of the ore zone directly reflects the prominently-developed quartz-sericite alteration. The intensity of the alteration is variable from drill hole to drill hole, and at different footages within a hole. The replacement minerals are usually carbonates and/or sericite; kaolinization of plagioclase phenocryst cores is more prominent than at Granisle but nevertheless remains as a comparatively minor effect.

Tourmaline is very minor and sporadic, but is nevertheless more abundant at Bell than at Granisle. Of the 13 Bell drill holes in which the mineral was observed, 12 are either in the 0.3% copper zone or within a few feet of its margin. Epidote is present in minor amounts throughout all the alteration zones at Bell, but is most conspicuous in the outer parts

* Metamorphic biotite is present at some (barren) BFP contacts. Confusion could arise in separating "hot spot" biotite from metamorphic biotite, but the absence of secondary biotite in the BFP itself would indicate that the biotite is metamorphic and is not related to hydrothermal alteration associated with copper mineralization.

of the chlorite-carbonate zone, where it imparts an apple-green colour to many of the rocks.

MORRISON (3)

Introduction and general geology

The Morrison property, which is owned by Noranda Mines Limited, is about 14 miles north of Bell Copper (Figure 2). The geological setting (Figure 4) is similar to that of the porphyry copper deposits on and near Newman Peninsula; at Morrison a BFP plug and peripheral dykes and sills have intruded steeply-dipping clastic sediments that strike northwesterly. The copper zone, which dips steeply or vertically, contains about 70 million tons averaging 0.4-0.45% copper. All known outcrops and 86 diamond drill holes were examined and sampled for this study.

As is the case at Granisle and Bell, sulphide zoning at Morrison is readily apparent. Chalcopyrite is accompanied by very minor bornite in parts of the central (0.5% copper) portions of the irregularly-shaped copper zone (Figure 32). Outward, the chalcopyrite-bornite assemblage gives way to chalcopyrite-pyrite, and then to pyrite.

The peculiar dumbell shape of the Morrison ~~orebody~~ copper zone is the result of the original annular-shaped deposit having been faulted and displaced a horizontal distance estimated to be about 1000 feet. The fault is marked topographically by a small depression, most of which is occupied by a creek. In drill cores, the fault appears as a zone about 150 feet wide that contains abundant breccia and well-defined sections of gouge. Much of the breccia is cemented by carbonates that contain minor quantities of dark brown to black sphalerite. Associated with the zinc mineralization are pyrite and marcasite, and small amounts

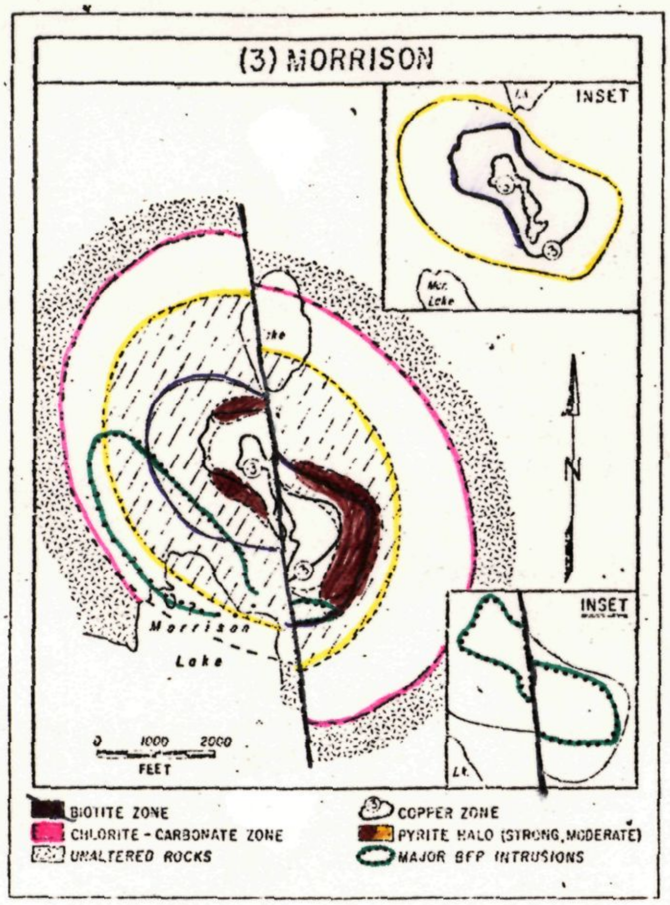

Figure 32 - Alteration zones at Morrison. The upper inset shows the biotite and copper zones restored to their pre-faulted positions. The lower inset shows the centrally-located BFP plug and biotite zone in their present (faulted) positions, and the main diagram shows the position of a large, northwest-trending BFP intrusion along the western side of the biotite zone. The outer limits of the chlorite-carbonate zone, especially near the fault, are partly interpretation, due to a scarcity of outcrops.

of arsenopyrite, galena, geocronite, and chalcopyrite. Although copper mineralization in the fault is erratic and may have been partly diluted or leached away, much of the fault zone coincides with the deposit's lower-grade (copper) core. The annular shape of the original deposit is particularly well-shown in the reconstruction of the pyrite halo and 0.3 copper zone (Figure 32-inset). In plan, Morrison corresponds well with the model proposed by Lowell and Guilbert (1970) for all porphyry copper deposits.

Biotite zone

The relationship of the present biotite halo and 0.3% copper zone is shown in Figure 32. The extension of the ore-grade copper to the edge of the biotite zone at the north and south ends of the deposit is anomalous in that biotitization usually extends appreciably beyond the ore zone. The effect is, however, the result of the previously-mentioned post-ore faulting; reconstruction of the deposit as it existed prior to faulting shows that the ore and alteration relationships are normal.

Sugary-textured brown hydrothermal biotite that has replaced hornblende phenocrysts and invaded the matrix of BFP, is common at Morrison. However, the Morrison biotite zone differs from that at Granisle as follows: (1) hydrothermal biotite is medium-grained, and coarse-grained biotite-sulphide lenses or pockets have not been seen; (2) hydrothermal and residual primary amphiboles are very common (Figures 22, 23, 24); (3) lenses of bleached BFP in which biotite, hornblende, and plagioclase phenocrysts are replaced by clay-carbonate alteration, are widespread.

A small area of hydrothermal biotite is present to the northwest of the main biotite zone. This area is interpreted as being a separate "hot spot" because it is surrounded by rocks containing chlorite-carbonate alteration.

Pyrite halo

The 0.3% copper zone is completely surrounded by a pyrite halo, containing > 2% pyrite, that encompasses most of the area shown in Figure 32. Within the larger pyrite halo are three areas that contain >5%-15% pyrite — quantities comparable to the pyrite haloes at Granisle and Bell. In places, these segments overlap the 0.3% copper zone. Unlike the central part of the Granisle orebody, which is largely free of pyrite, the Morrison 0.3% copper zone contains moderate amounts of pyrite. However, only very minor amounts of this mineral are present in the Morrison low-grade center.

Hydrothermal amphibole

At Bell and Granisle, the presence of residual amphibole phenocrysts in BFP and associated volcanics is a reliable indicator that copper-related hydrothermal alteration is absent or extremely weak. At Morrison, however, primary amphibole occurs within the copper zone and within thin sections containing well-developed secondary biotite. The primary amphibole is also accompanied, in many cases, by fine-grained, colorless to pale green, secondary amphibole in the tremolite-actinolite series (Figures 22, 23). Marked compositional differences between the primary and secondary amphiboles are evident from the electron microprobe analyses given in Table 2.

The significance of the secondary amphibole at Morrison was initially puzzling. The seemingly close association with the copper zone might at first suggest that secondary amphibole represents a "higher grade" of alteration than does biotitization (an analogous situation is the restriction of secondary K-feldspar to the central, ore-bearing part of the biotite zone). There are, however, a few occurrences of the secondary amphibole, such as in the northern biotite "hot spot" and at the northern extremity of the main biotite halo, that do not fit this picture. The results obtained from the Nakinilerak property (see further below) indicate that secondary amphibole is paragenetically later than hydrothermal biotite, and does not have the same intimate relationship to copper mineralization as biotitization.

Other minerals

The Morrison deposit does not show well-defined trends in its minor minerals. The carbonates occur throughout the copper zone and there is not a carbonate-free core as at Granisle. Of the total carbonate, the proportion that is calcite is considerably lower than at Granisle. Lenses of bleached BFP from <1' to 10'-20' wide are present at many localities within the biotitized BFP plug. These were originally mapped as "grey porphyry" but are due solely to the total replacement of BFP phenocrysts by clay and carbonate (Figure 16). The central fault zone contains 50'-100' widths of intense clay-carbonate alteration. As is the case in the other Babine area properties, kaolinite accounts for nearly all the clay alteration. X-ray diffractometer analyses of clay fractions separated from 11 drill cores showed only traces of montmorillonite in two, and none in the remainder. Sericitization and silicification are locally present, but are erratic even within single drill holes.

Among the minor minerals, Morrison differs from other Babine porphyry copper deposits in that apatite is more conspicuous and arsenopyrite has been found in several drill holes. In addition to the normally-present disseminated subhedral apatite, BFP in the copper zone commonly contains subhedral apatite in association with pockets and veinlets of quartz. Tourmaline at Morrison is very minor and has no discernible zonal pattern. Minor hydrothermal K-feldspar occurs in veinlets restricted to the higher-grade parts of the copper zone, but this mineral is as uncommon as at Granisle. Pyrrhotite was not seen in the copper zone, but small amounts are disseminated in fringe areas that commonly coincide with the outer limits of the biotite halo.

DOROTHY (4)

Introduction

The Dorothy property (Figure 2) is owned by Twin Peak Resources, Limited. A BFP plug has been emplaced at the contact between a dioritic stock and Hazelton volcanics and sediments. Disseminated chalcopyrite associated with the BFP was investigated by Ducanex Resources Limited, who bored approximately 30 diamond drill holes. The drilling outlined a large area in which copper grades are slightly greater than 0.2%, with no significantly higher-grade internal zones (Figure 33). Although molybdenite is more than three times as abundant at Dorothy than at the other Babine deposits, the grades nevertheless average only about 0.03% Mo. The copper zone is surrounded by an annular pyrite halo that contains some strong pyrite patches, but the halo is, on the whole, only of moderate intensity (3%-5% pyrite)

29 ddh 60 m. tons of 0.25% Cu + 0.02% MoS_2 to a vertical depth of 500 ft. [G.C.N.L Oct. 18/74]

Biotite zone

The biotite zone as shown in Figure 33 represents the total area of biotitization. It is surrounded by typical chlorite-carbonate alteration. Some outcrops and significant lengths of drill core within the

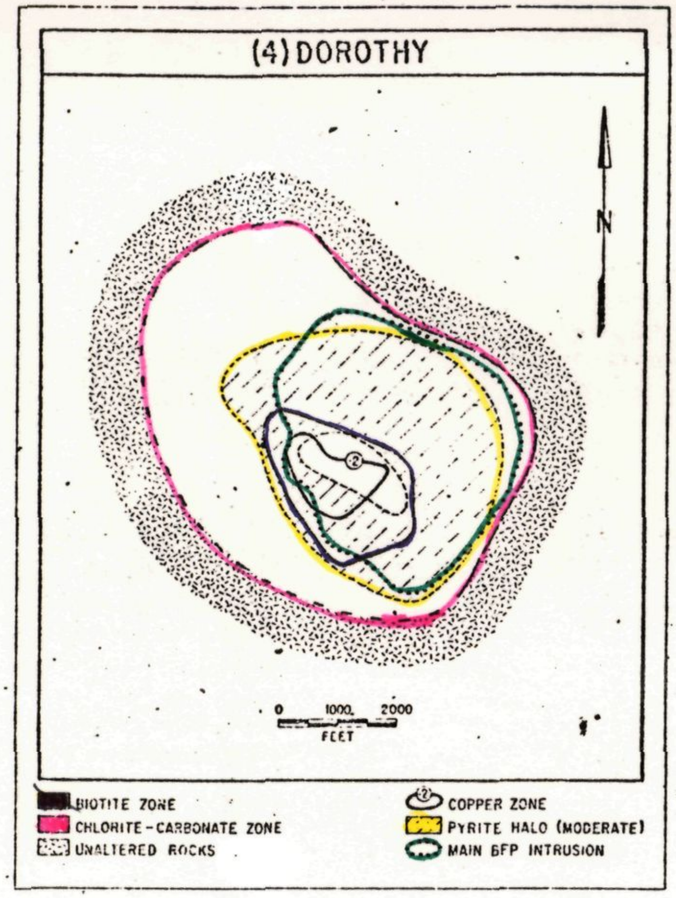

Figure 33 - Alteration zones at the Dorothy property. Extensions of the drift-covered, northwestern parts of the chlorite-carbonate zone and pyrite halo are interpretations.

biotite zone would be classified individually as being in the chlorite zone. Therefore, biotitization within the biotite zone is patchy rather than pervasive. Also, most of the hydrothermal biotite is fine-grained and greenish-brown to dark brown; medium to coarse-grained, sugary-textured biotite is not common. Biotitization, for the most part, is confined to pseudomorphs after hornblende, with very little disseminated in BFP matrices (Figure 18). Abundant chlorite is present in many of the biotitized rocks, and in some cases, chloritization of hydrothermal biotite has occurred. This is a "retrograde" effect that corresponds to a decrease in the intensity and quality of biotitization. This decrease coincides with patches of lower copper grades within the copper zone. Because they lack abundant coarse-grained, dark, hydrothermal biotite such as is common at Morrison and Granisle, rocks in the Dorothy biotite zone are typically greenish-grey rather than dark grey or black.

The characteristics of the hydrothermal biotite at Dorothy are similar to those found in the outer, lower grade (copper) areas of the Granisle, Bell, and Morrison biotite zones.

Other minerals

Chlorite generally occurs as simple pseudomorphs after hornblende and is common in both the biotite and chlorite-carbonate zones. Secondary carbonate, clay, and sericite are present, but not abundant, and do not occur in any discernible zonal configuration.

Minor amounts of only partly-replaced primary amphibole, and traces of hydrothermal amphibole, are present in the southern half of the biotite zone. Residual pyroxene is present in volcanics in the chlorite-carbonate zone at the western margin of the biotite zone. Tourmaline was not observed in any of the thin sections.

NORTH NEWMAN (5)

The economic potential of the North Newman property (Figure 2) was investigated by Noranda Exploration Company, Limited, who drilled the 16 diamond drill holes shown in Figure 34 (inset). Sample coverage for this study is given in Figure 3.

Hole 188 averages about 0.3% copper and 199 averages about 0.2% copper, but lower values ($\sim$0.1% Cu) are present in the closest surrounding holes, and grades fall off to $<$0.05% in the remaining holes. Thus there is a well-defined, but very small ($\sim$400' in diameter) and subeconomic porphyry copper deposit at North Newman.

Host rocks for the copper mineralization are arkoses, siltstones, and quartzites intruded by one or more narrow dykes or sills of BFP. Sulphide mineralization consists of fracture-filling and disseminated chalcopyrite and pyrite. Small amounts of sphalerite in carbonate veins were observed in holes 189 and 197. Surrounding the copper zone is a relatively large but notably weak pyrite halo that averages 1%-2% pyrite.

In spite of the small size and low grade of its centrally-located copper deposit, the North Newman alteration zone is more than a mile in diameter (Figure 34). Chlorite-carbonate is the most widespread alteration, but the copper zone is within an area of sericite-carbonate alteration. Hydrothermal biotite was observed in only three drill holes —191, 195 and 198. The biotite in hole 191 is part of a local "hot spot" because the remainder of the large mass of BFP in its vicinity contains chlorite-carbonate alteration. Biotitization within and near the copper zone is weak and has been further restricted because the host rocks are almost entirely mafic-deficient sediments which are not readily biotitized. Spotty alteration of hornblende to biotite has occurred only in the minor BFP present.

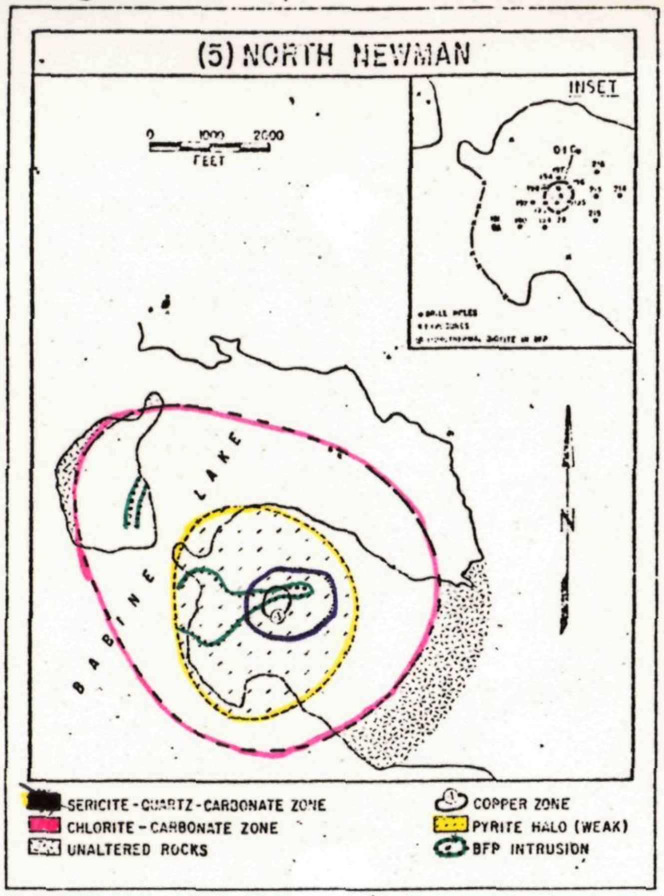

Figure 34 - Alteration zones at the North Newman property.

In summary, the North Newman prospect contains a copper zone about 400 feet in diameter, with <0.1-0.3% copper, that is accompanied by very weak biotitization and is enclosed in a zone of sericite-carbonate alteration. A very weak pyrite halo surrounds the copper zone. The outlying areas are characterized by chlorite-carbonate alteration.

NAKINILERAK (6)

Introduction

The Nakinilerak porphyry copper deposit is 8 miles northeast of Morrison (Figure 2). The geological setting (Carter, 1966) is similar to the other Babine deposits in that salic to intermediate volcanic rocks and associated sediments have been intruded by a stock and dykes of BFP. Twenty-seven diamond drill holes were bored by Noranda Exploration Company, Limited, to evaluate the deposit. Many of these were shallow x-ray holes.

A large but very low-grade (.05%-0.1% Cu) copper zone partly encircles a BFP stock (Figure 35). Disseminated and fracture-filling chalcopyrite, accompanied in a few places by very minor bornite, occurs within the stock and in the peripheral volcanics and sediments that are riddled with BFP dykes. In addition to being weak, the copper mineralization is extremely erratic — copper grades vary drastically, both from site-to-site and within individual drill holes. The grade contours shown in Figure 35 are thus very approximate. The data are, however, sufficient to reveal that the copper zone is annular, with a barren center.

Alteration

Encircling the copper zone is a very large pyrite halo in which the quantity of pyrite varies erratically. Areas with up to 10%

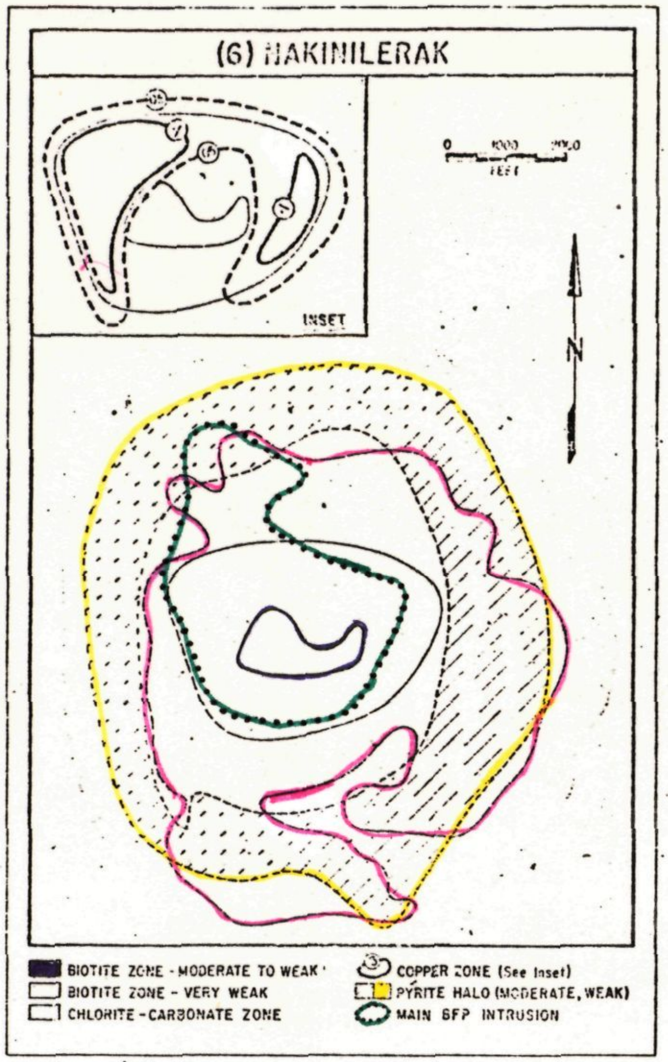

Figure 35 - Alteration zones at Nakinilerak. The main diagram shows the very large area in which biotitization has occurred, and the inset shows the close relationship between the copper mineralization and the area of better-quality hydrothermal biotite.

pyrite occurring along the eastern side are intermingled with weak (~1% pyrite) patches. On the south, the pyrite halo is very weak and similarly erratic. The halo's nature along the western side is unknown due to a lack of exposures, but its presence can be inferred on the basis of induced polarization surveys.

Although hydrothermal biotite is present in a very large area, the mineral shows features typically found in either the non-economic Babine deposits, or the weak, outer portions of the biotite zones of the economic deposits. Specifically, most secondary biotite at Nakinilerak is very fine grained, even where abundant, and much has a green to greenish-brown colour. However, medium-to coarse-grained, sugary-textured brown biotite is present in several drill holes in the copper-bearing parts of the BFP as shown in the inset of Figure 35. The precise boundaries of the total (green + brown) biotite zone and of the central better-quality area are difficult to define because the biotite occurrences are erratic— even within the central area, variations from moderately intense biotitization to chloritic (propylitic) alteration to virtually unaltered rock occur within a few feet. One such area of chloritic alteration coincides with the barren core of the copper zone. In higher-grade Babine deposits, it is not rare to have a few non-biotitized patches within the biotite zone; at Nakinilerak, however, the mixed alteration is the general rule. Another feature of Nakinilerak is the local presence of abundant residual unaltered hornblende and secondary amphibole within the biotite and chlorite-carbonate zones. Both types of amphibole are more common at Nakinilerak than at any other property studied.

From the foregoing, it is apparent that biotitization at Nakinilerak has a close spatial relationship to the copper mineralization (Figure 35, inset); both are weak and erratic.

The area containing biotitized rocks is succeeded outward by typical chlorite-carbonate alteration, but the carbonate component is very weak. Although the normal suite of calcite, dolomite, and siderite is present, calcite is by far the most abundant. At Granisle, only the outer part of the chlorite-carbonate zone contains a predominance of calcite. This suggests that the low total carbonate and prevalence of calcite at Nakinilerak are indicative of low-grade propylitic alteration, even though the area occupied by such alteration is large. The limits of the chlorite-carbonate zone are not exposed, but the diameter of the total Nakinilerak alteration area is obviously very large. Rather than a relatively smooth transition from chloritized to unaltered rocks as occurs at higher grade deposits, the outer portions of the Nakinilerak chlorite-carbonate zone in places is characterized by the appearance of increasingly large patches of unaltered rock.

Tourmaline is present in very minor quantities in most of the Babine deposits, but at Nakinilerak it is very common and widespread. Some outcrops, in both the biotite and chlorite-carbonate zones, contain veins of black tourmaline 1"-3" wide. Tourmalinization does not show a close spatial relationship with copper mineralization. Epidote and sphene are also more abundant at Nakinilerak than at the other properties, but neither appears to be associated with a specific alteration zone.

SOUTH NEWMAN (7)

A weakly altered area between Granisle and Bell is referred to as the South Newman prospect (Figure 2). Sporadic pyritization occurring in altered andesites and fine-grained sediments was investigated by a single inclined hole drilled by Phelps Dodge Corporation Limited on the western edge of Rum Island in Hagan Arm. Samples from this hole and from several outcrops were studied by the authors (see Figure 3).

Fig. 36

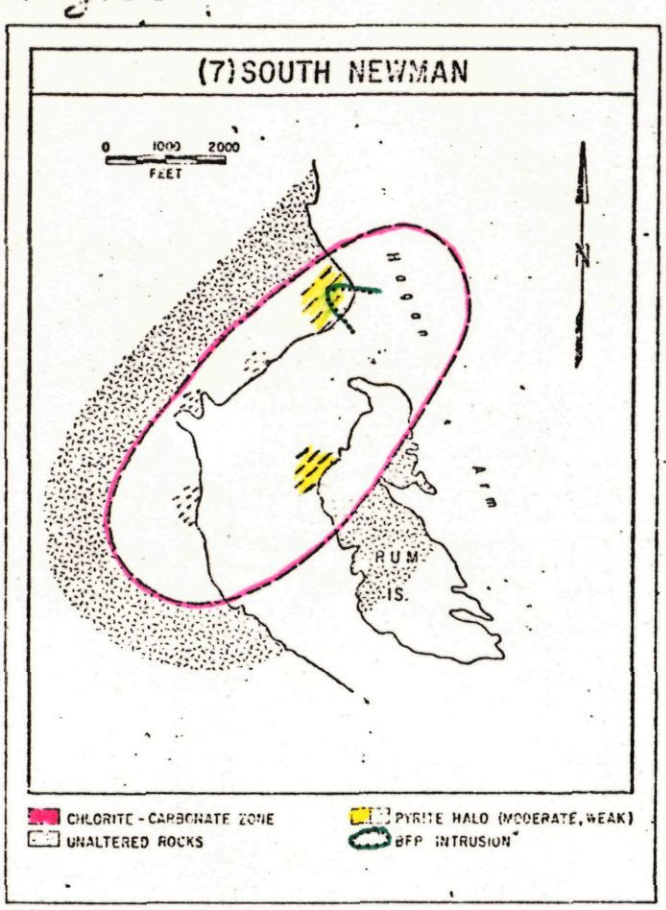

Figure 36 - Alteration at the South Newman property.

Alteration, occurring in an area about 6000 feet by 4000 feet (Figure 36), consists largely of chlorite and carbonates, with some epidote, and minor pyrite. Some BFP is present, but no hydrothermal biotite was found. The type of alteration at South Newman is typical of that occurring in the outer non-copper-bearing portions of the other Babine alteration haloes. This suggests that the South Newman halo is either too weak to harbour a porphyry copper deposit, or that a copper zone, if present, is at considerable depths.

SUMMARY AND INTERPRETATION

General

There is a regular zonal distribution of certain diagnostic hydrothermal alteration minerals that is common to all the Babine porphyry copper deposits (Figure 37). The copper-bearing zones, ranging from a few hundred to a few thousand feet in diameter, are contained within somewhat larger zones of hydrothermal biotite that are in turn surrounded by wide areas of chloritized rocks. Pyrite haloes encircle the copper zones. All deposits are closely associated with Eocene biotite plagioclase porphyry intrusions, but the alteration zones are centered on the copper deposits rather than the porphyries.

Hydrothermal biotite and copper mineralization

The most important finding of this study concerns the close relationship between copper mineralization and biotitization. In essence, <u>the size and grade of each copper zone corresponds with the areal extent</u>

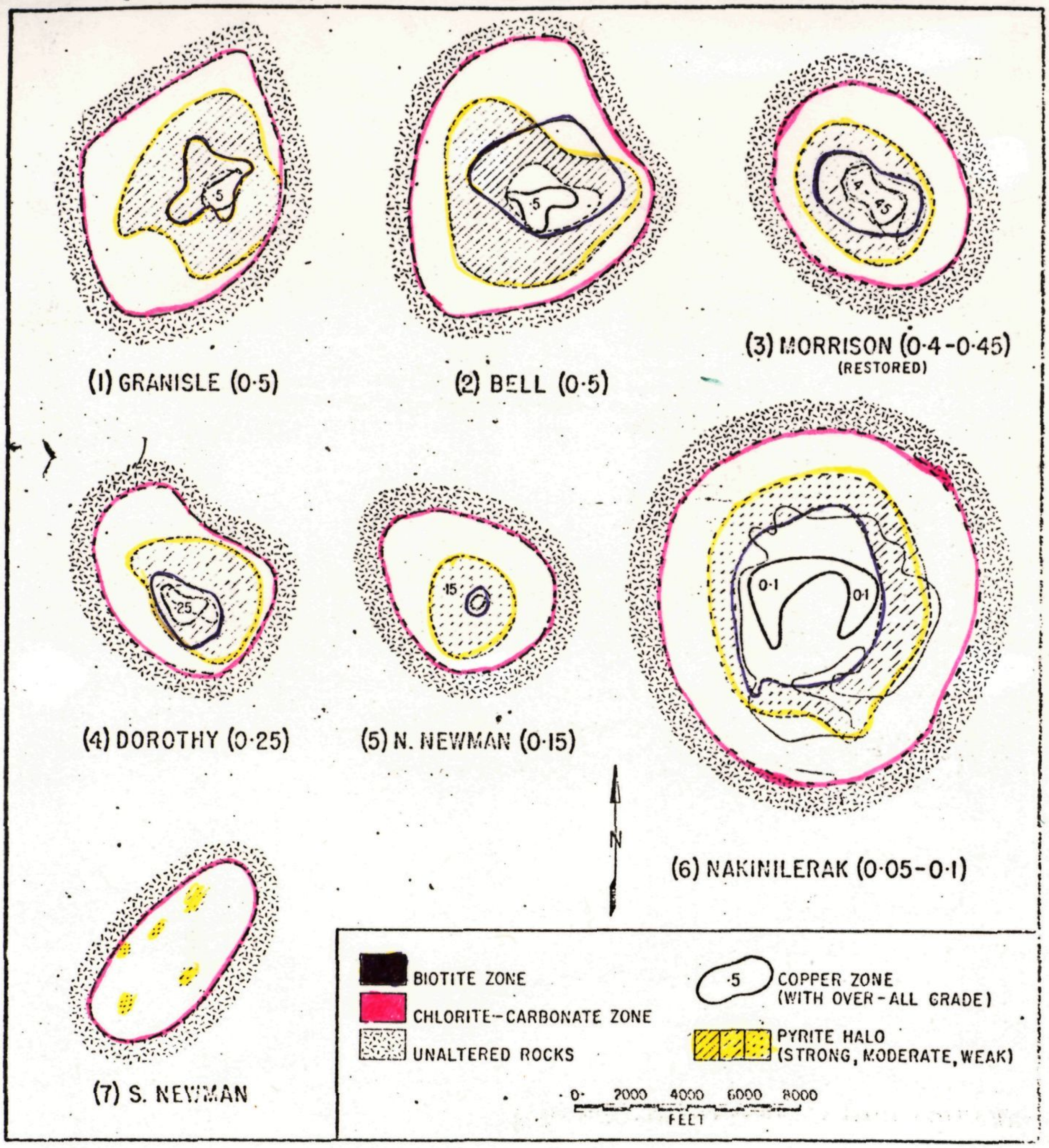

Figure 37 - Composite diagram of the Babine deposits showing the relative sizes and grades of the copper zones and associated alteration haloes. The deposits are numbered in the order of decreasing copper grades; note the corresponding decrease in the intensity of the pyrite haloes. The biotite zones contain both weak and well-developed hydrothermal biotites, and therefore do not include the quality factor. The North Newman biotite zone is schematic. The outer limits of the Nakinilerak zone are approximate.

and quality of hydrothermal biotite*. The interior portions of biotite haloes containing copper zones with average grades in excess of 0.4% copper (Granisle, Bell, Morrison) are characterized by consistently "good quality", brown, sugary-textured hydrothermal biotite. In the outer, less copper-rich portions of these haloes, the biotite is of poorer "quality" (finer-grained and greenish), and is accompanied by increasing quantities of chloritic alteration. This "poor-quality" biotite, accompanied by chlorite, is found intermingled with better-quality biotite throughout the entire biotite halo at a somewhat lower-grade deposit (Dorothy; 0.25% Cu). At the lowest grade deposit (Nakinilerak; 0.05%-0.1% Cu), the biotite zone, like the copper mineralization, is very weak and erratic. An alteration zone lacking hydrothermal biotite (South Newman) does not appear to contain significant copper mineralization.

In this paper, the biotite zones have been defined to include both good and poorer-quality biotites in order to facilitate comparisons among both economic and sub-economic deposits. Most published papers on porphyry copper alteration deal with economic deposits, and the "potassic" zones described correspond to the inner, better quality portions of the Babine biotite zones.

As is evident from Figure 37, there is a very rough correlation between the diameters of the Babine alteration haloes (to the limits of the chlorite-carbonate zones), and the sizes of the contained copper zones. Nakinilerak has the largest alteration and copper zones, and North Newman has the smallest copper zone and the smallest (though not proportionately so) copper-bearing alteration halo. In order to predict not only the size, but also the grade of the copper zones, it is necessary to determine the areal extent and quality of hydrothermal biotite. If an ore-grade deposit is

* The abundance of hydrothermal biotite correlates well with the intensity of coppe mineralization in all deposits except Bell, where much of the biotite has been obliterated by sericite-quartz alteration (figure 31 and section to follow). Although it is not abundant in parts of the Bell biotite zone, hydrothermal biotite is nevertheless present throughout the zone and is of consistently good quality within a large area that contains the orebody (figure 31).

present at or near the surface, it will be contained within a larger area of persistently good-quality hydrothermal biotite.

Sericitic alteration

Pervasive sericite-quartz alteration is extensive at Bell, where it surrounds part of the biotite zone and overlaps a large portion of the orebody. At Granisle, sericitic alteration occurs as an incomplete ring around the biotite zone and is not coincident with the orebody. Small patches of sericitic alteration are present at Morrison and Nakinilerak, but do not show any zonal arrangement. Sericite-carbonate alteration in mafic-poor sediments encloses the North Newman copper zone. At Dorothy, sericitic alteration is insignificant.

From the foregoing, it is apparent that sericitic alteration is not present at all Babine porphyry copper deposits, nor does it have the close relationship to copper mineralization exhibited by hydrothermal biotite. In the two deposits where sericitic alteration occurs in significant amounts, its position is roughly similar to that of the phyllic zone of Lowell and Guilbert (1970).

Sulphide zoning

The higher-grade Babine copper deposits exhibit well-defined sulphide zoning from a bornite-chalcopyrite core to chalcopyrite ± pyrite and outward to a pyrite halo. The zoning of sulphides is more pronounced in the "stronger" copper deposits as illustrated in Figure 38. At Granisle, the high-grade bornite-chalcopyrite core is separated from chalcopyrite-pyrite mineralization by a zone containing chalcopyrite with little or no pyrite. At the somewhat "weaker" Morrison deposit, bornite is only common in the few localities where grades are +0.6% copper, and there is no pyrite-

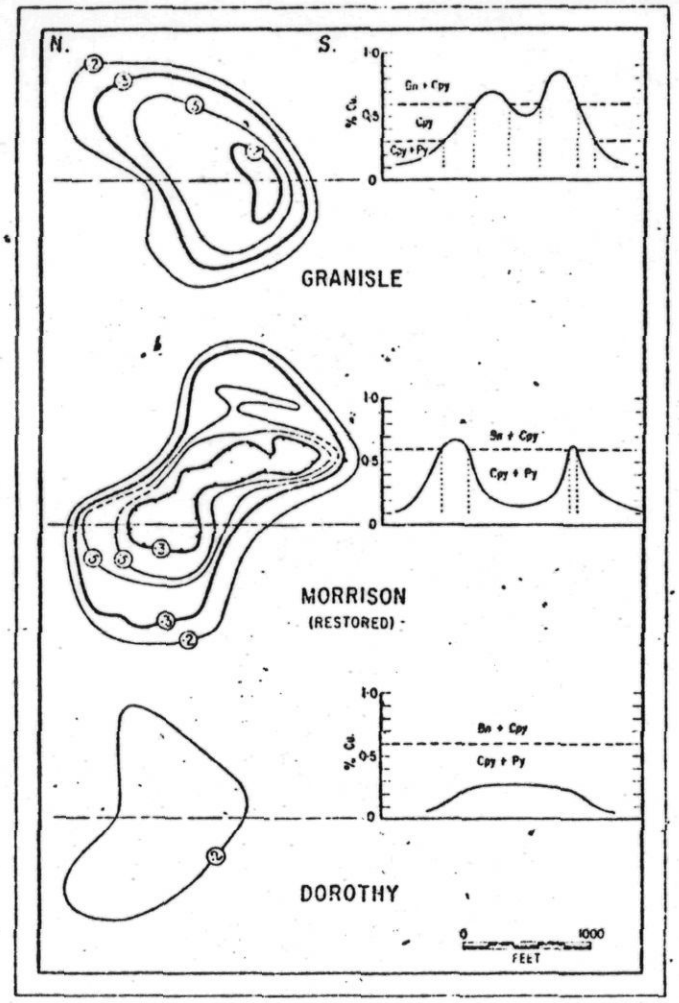

Figure 38 - Grade zones and grade profiles for copper at Granisle, Morrison, and Dorothy. The diagram illustrates the shapes, sulphide zoning, and copper abundances in these deposits. The horizontal dashed lines in the grade profiles show the relationship between % Cu and the sulphide mineralogy; the vertically-dashed lines indicate that the sulphide zones are steeply-dipping. The locations of the 0.5 and 0.7 grade lines at Granisle are based largely on field observations and are therefore approximate.

deficient chalcopyrite zone. Thus the sulphides at Morrison have not been segregated as strongly as at Granisle. The even weaker Dorothy copper zone has no bornite-bearing core and is entirely of the pyrite-chalcopyrite type.

According to Lowell and Guilbert (1970), the typical porphyry copper orebody has the form of a hollow cylinder. The Babine copper zones tend to assume vertically-dipping annular shapes, but there are all gradations from a complete ring (Morrison) through incomplete rings (Nakinilerak, Bell, Granisle?) to simple cylindrical shapes (Dorothy, North Newman). The pyrite haloes show less variation in form, but the most distinct annular shapes occur in higher-grade deposits because of their greater pyrite content and their stronger segregation of sulphides as given above. There is a definite relationship between the quantity of pyrite in the pyrite haloes and the quantity of copper in the copper zones. Thus the Granisle and Bell pyrite haloes are the most continuous and strongest, averaging about 10% pyrite. In the slightly lower-grade Morrison deposit, only the three segments shown in Figure 37 contain similar quantities of pyrite, and the quantities of pyrite at Dorothy, North Newman, and Nakinilerak are correspondingly lower. The pyrite haloes are most intense in the areas that overlap the outer parts of the biotite zones and inner portions of chlorite-carbonate zones. In some deposits these areas coincide with the maximum development of quartz-sericite (phyllic) alteration.

Theoretical considerations

Attention in this study has been focused on the potential practical applications of the mineralogical zoning. Less consideration has been given to the depositional sequence of individual minerals, and to mineral assemblages not readily applicable to exploration. Both aspects are, however, necessary to define the physico-chemical conditions in which the deposits have formed. Despite the above-stated restrictions, some general theoretical interpretations can be made.

The close association of secondary biotite with porphyry copper mineralization has been noted by Stringham (1953), Schwartz (1947), Lowell (1968), Nielsen (1968), Bryner (1969), Moore and Lanphere (1971), Macnamara (1968), and several others. Rose (1970) presented a brief summary of alteration in about a dozen porphyry deposits and convincingly made the point that the innermost zone of alteration is a biotite-K-feldspar one and that "the highest copper content normally occurs within the biotite-orthoclase zone or at its outer borders with quartz-sericite alteration" (Rose, 1970, p.920). It may be significant that in one of Helgeson's (1970) reactions of a hydrothermal solution with a hypothetical granodiorite, the appearance of biotite in the depositional scheme causes an abrupt shift in the direction of the reaction path, with the resultant trend being toward later saturation with chalcopyrite. If the solution had not reached saturation with biotite, magnetite instead of chalcopyrite would have appeared at a later stage of reaction progress (Helgeson, 1970, p.172). In the Babine deposits, the highest grades of copper mineralization are present in K-feldspar-biotite zones, but the character and areal extent of the biotite alone are considered to reflect the economic potential of a deposit.

With respect to the composition variations found for the Granisle secondary biotites, it has been shown by Heinrich (1946) and Nockolds (1947) that primary biotites in salic igneous rocks are generally more iron-and titanium-rich than the biotites in mafic igneous rocks. This correlation may reflect the original bulk compositions of the rocks and/or their different temperatures of crystallization. For the secondary biotites at

Granisle, however, the compositional variation seems to be largely independent of host rock compositions. The presence of centrally-located magnesium-rich biotites at Granisle thus may be largely a reflection of a thermal gradient, with the highest temperatures having been in the core of the deposit. This would fit with models by Sheppard et al.(1971) which show decreases in temperatures from the potassic core to the outer quartz-sericite zone. However, the fact that biotite compositions alone are being considered, rather than biotite-bearing equilibrium mineral assemblages, makes such interpretations tenuous. For example, Wones and Eugster (1965) have shown that, in biotite-sanidine-magnetite assemblages, the effect of temperature changes on biotite compositions is very dependent on the activities of oxygen and water. For a given isotherm, the biotite will become more magnesian with increasing $f(O_2)$. Although the stability of biotites in alteration processes is also dependent on other variables, such as sulphur fugacity (Hammarböck and Lindqvist, 1972) and K^+ and H^+ activities, the systematic nature of the variation in Granisle biotite compositions suggests that the system was open to oxygen and hence the effects of either $f(O_2)$ or temperature could have predominated.

The relative enrichment in Ti and Fe^{3+} as well as Mg in the central area biotites suggests that both temperature and oxygen activity were higher in this part of the deposit and decreased outwards. The chlorite-carbonate zone is a lower "grade" of alteration and was probably not completely open to oxygen; compositions of the original host rocks have therefore exerted a greater influence on chlorite compositions than on biotite compositions.

The alteration zoning from a biotite-rich zone to a quartz-sericite zone to a propylitic zone in porphyry copper deposits is commonly discussed in terms of the mineral stability relations given by Hemley and Jones (1964). The alteration zoning can be considered to be related to aK^+/aH^+, with the outward progression from K-feldspar to sericite to kaolinite signifying increased H^+ or decreased K^+ activities. The propylitic zone represents a low cation/aH^+ ratio. Rose (1970), however, has opted for cooling rather than chemical exchange as the principal control to explain the K-feldspar-biotite and quartz-sericite zoning. Thus cooling slightly beyond the K-feldspar-muscovite reaction boundary would normally consume H^+ as muscovite formed, and move the solution to higher K/H ratios. However, the initial K-feldspar could be stabilized and an outward quartz-sericite zone developed in a system of continuous cooling. This model would seem to be applicable to most of the Babine area deposits; the exception is Bell Copper, where the K/H ratio apparently overcame the cooling effects and an irregular quartz-sericite zone was superimposed on the existing biotite zone.

The replacement of amphibole by chlorite and carbonate is a useful criterion for establishing the outer limits of propylitic (chlorite-carbonate) alteration at Granisle. However, both primary and hydrothermal amphiboles occur within the biotite zones at Morrison, Nakinilerak, and Dorothy. At Bingham, Bray (1969) was able to map an actinolite zone that lay outside the biotite zone, and in the Rialto stock, New Mexico, Thompson (1968) reported the occurrence of actinolite-bearing magnetite veinlets in the propylitic zone. The explanation for these apparently divergent observations is that in each deposit different CO_2 activities prevailed. Where CO_2 activity was high (as at Granisle) the outer alteration assemblages contain abundant calcite, dolomite-ankerite, and siderite, but not amphibole. Where CO_2 activity was low, primary amphibole remained relatively stable and secondary actinolite was formed in minor amounts. The incompatibility of abundant carbonates with amphibole in the Babine deposits is especially evident at Nakinilerak, which has the most amphibole but only minor amounts of carbonate. It is also interesting that Bray (1969) noted that at Bingham, calcite decreases as secondary actinolite becomes prominent. Neither carbonate nor amphibole abundances reflect the intensity of copper mineralization. In the propylitic zone, however, a further correlation is that epidote, chlorite, and carbonate can coexist, but at high CO_2 activities epidote is excluded and chlorite plus carbonate, or chlorite + carbonate + clay can coexist. This fits with the general observations that epidote is most abundant at Nakinilerak and relatively unimportant at Granisle.

Application to other deposits

Only in recent years has the close zonal relationship between potassic alteration (biotite and/or K-feldspar) and copper-molybdenum mineralization at porphyry copper deposits been adequately appreciated (Lowell and Guilbert, 1970; Rose, 1970). This is partly due to the fact that many of the thoroughly-described deposits of the southwestern United States are secondary chalcocite blankets that, during the middle Tertiary, had their primary alteration zones largely or completely destroyed by supergene processes. The difficulty in distinguishing between primary (hypogene) and secondary (supergene) alterations has led to much confusion in the literature. Thus, pervasive clay alteration at the well-documented Morenci deposit (Lindgren, 1905; Moolick and Durek, 1966) was believed to be primary, but very recent studies have indicated that it is supergene and is underlain by the normal potassic-phyllic-propylitic primary zoning (Langton, 1971). An additional factor that may have obscured the relationship could be that, because many chalcocite orebodies, including that at Morenci, have formed by the enrichment of protore that is very low grade, the associated potassic alteration is probably also weak and has not therefore been mapped as potassic, even where exposed in deep pits or penetrated by deep drill holes. For example, potassic alteration has not been recognized as an important feature at Silver Bell (Kerr, 1951; Richard and Courtwright, 1966), yet hydrothermal biotite pseudomorphs after hornblende are present in the sub-economic "protore" exposed in the bottom of the pit (personal observation). Therefore, a potassic zone of "low grade" (as defined here) is probably present.

The seven Babine alteration zones studied in this paper illustrate not only the zonal relationship, but also *qualitative and quantitative relationships* between potassic (biotitic) alteration and copper mineralization. Further investigations, that in several cases have involved microscopic studies, have been made by one of the present authors (D.J.T.C.) on many additional porphyry copper-molybdenum deposits of both economic and sub-economic grades in various parts of the world, including British Columbia, the United States, South and Central America, Queensland, Papua, and Ireland. Supplemented by the extremely limited amount of published data that adequately set forth the *quality* of hydrothermal alteration as defined here (particularly for deposits of sub-economic grade), these investigations strongly suggest that a large majority of porphyry copper-molybdenum deposits adhere to the same rule as the Babine deposits, *i.e.* - *the size and grade of the copper-molybdenum zone varies directly with the areal extent and quality of the associated potassic alteration*.

Much detailed work would be required to definitely establish the validity, on a world-wide scale of the quantitative-qualitative relationship stated above. However, on the basis of present data, it appears to apply to most members of the main category of primary porphyry copper-molybdenum deposits —— those in which the fracture filling and disseminated copper-molybdenum mineralization occurs partly or largely within relatively small intrusions that possess prominent porphyritic phases. The relationship may also be applicable, in a modified form that allows, in some instances, for the partial to complete substituion of sericite for biotite and/or K-feldspar as the dominant potassium-bearing mineral, to deposits that occur in a batholithic environment (Highland Valley deposits, Brenda, Endako, Butte, Sierrita, etc.). A generalized scheme accommodating both categories of porphyry deposits is outlined below. This scheme does not appear to apply to some of the deposits of two other types that are often included as porphyry coppers —— deposits at which the copper-molybdenum mineralization occurs largely in contact metasomatic rocks (generally skarn) outside the main porphyry intrusions (Twin Buttes, Mission, etc.) and those at which the metalliferous mineralization is associated primarily with breccia pipes (Cananea).

Most higher grade (+0.6% Cu) primary prophyry copper-molybdenum deposits such as San Manuel (Lowell, 1968), Bingham (Bray, 1969) and Los Palambres (Sillitoe, 1973), have very strong potassic zones that include large volumes of pervasive, aplitic-textured potassic alteration*. At slightly lower grade deposits (0.5% Cu) such as Granisle and Bougainville (Fountain, 1972), the potassic alteration, though widespread and moderately strong, is not as pervasive. As the size and grade (strength) of the copper zones decrease, the intensity and quality of hydrothermal alterations also decrease, becoming increasingly dependent on the compositions and textures of the host rocks. The alteration zones also become more diffuse and there is a less distinct separation of higher "grade" from lower "grade" types (i.e.

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* In the few exceptions known to the authors, very intense sericite-quartz alteration or silicification apparently take the place of potassic alteration. These alterations may have largely obliterated biotite and/or K-feldspar, as appears to have occurred to a limited extent at Bell (previous sections).

potassic from propylitic). Within the potassic zones of deposits of marginal economic grade such as Sierrita (personal observation) and many of the British Columbia porphyries, including Morrison, Endako (Drummond and Kimura, 1969) and Brenda (Soregaroli, 1971), the lower "grade" propylitic or argillic alterations are commonly widespread and therefore intimately associated with the higher "grade" potassic alteration. Such mixed assemblages are considered here to reflect a decrease in the intensity ("grade") of alteration. Potassic minerals at marginal deposits are often of inferior quality (i.e. - prevalence of fine grained greenish biotite) and in most cases are patchy and/or almost entirely restricted to fractures and fracture selvedges, with the intervening rock largely unaltered or exhibiting lower grade alteration. In some instances, sericite partly (Highmont, Bergey et al., 1971), largely (Valley Copper, McMillan, 1971), or completely (Gibraltar, Drummond et al., 1973) substitutes for biotite and/or K-feldspar as the dominant potassium-bearing mineral associated with the marginal copper-molybdenum mineralization. Sub-economic porphyry copper deposits commonly have very spotty potassic alteration intermingled with stronger phyllic, propylitic, or argillic alterations. Potassic zones at the weakest porphyry copper deposits (±0.1% Cu --- Nakinilerak; Santa Rita, Nielson, 1968) may, in addition to the features found at marginal and sub-economic deposits described above, contain large patches of unaltered rock. Hydrothermal alteration zones of the porphyry type that lack potassic minerals, probably also lack significant copper-molybdenum mineralization.

Some sub-economic porphyry copper deposits could be at erosional levels that are either too shallow or too deep in alteration-mineralization columns similar to that proposed by Lowell and Guilbert (1970). However, where there are no indications of systematic changes in alteration and metal grades with depth, the entire deposit must merely be weakly developed.

Exploration applications

The results of this study can be usefully applied in the search for additional porphyry copper deposits in the Babine Lake area. The alteration zones are considerably larger, much better exposed, and therefore, more readily evaluated than their contained copper zones. Ore-grade porphyry copper deposits of the area that are at the surface and are therefore mineable by open-pit methods, are associated with all of the following features:

(1) altered intrusion(s) of biotite plagioclase porphyry (BFP). These are found at all the Babine porphyry copper deposits, and their presence provides assurance that a copper deposit, if present, will have alteration haloes conforming to the scheme presented here. Unaltered BFP intrusions are unrelated to copper mineralization. They are found throughout the Babine Lake area and can be eliminated from further exploration.

(2) a circular or elliptical area at least 7000' to 8000' in diameter in which all rocks are visibly altered and most contain abnormal quantities of pyrite.

(3) a large zone, several thousand feet in diameter, in which hydrothermal biotite is persistent. This large zone must contain an internal area, at least 2000' - 3000' in diameter, in which nearly all secondary mafic mineral is good-quality hydrothermal biotite. The ore zone is within this internal area.

(4) an annular pyrite halo, at least 1000' wide, that overlaps the outer edge of the biotite zone and contains in excess of 5% - 10% pyrite (average).

A certain minimum number of rock exposures are required in order to evaluate each of the above features. Outcrops in some parts of the Babine Lake area are sparse, but are generally sufficiently abundant to indicate whether or not a property has promise. Reliable observations made at 500'-1000' spacings should be adequate to establish the over-all zonal patterns. In some cases the biotite zone is largely covered, but if the total area of alteration appears to be of the required size, trenching and/or grid-drilling of short holes within the internal area, accompanied by microscopic studies, can be carried out to establish the presence, extent, and quality of the biotite zone. All additional exploration, including geological mapping, geophysics, geochemistry, and drilling can be concentrated within the biotite zone, thereby greatly reducing expenditures.

Diffuse alteration zones such as Nakinilerak may simply be weakly developed, or may represent the roots of richer deposits now largely removed by erosion. However, if there are indications that the "grade" of hydrothermal alteration (and copper) increases with depth, only the upper part of the deposit may be at the surface. In this case, deep drilling must be contemplated if it is considered feasible to mine porphyry copper deposits in the Babine area by underground methods.

ACKNOWLEDGMENTS

This study represents the combined effort of government and industry. It could not have been carried out without the extremely generous cooperation of several mining and exploration companies that have been active in the Babine Lake area. It is with much pleasure that we gratefully acknowledge the participation of Noranda Exploration Company, Limited, Bell Copper Limited, Granisle Copper Ltd., Twin Peak Resources Ltd., Texcal Resources Ltd., and Phelps-Dodge Corporation of Canada Ltd. Special thanks are due to A.M. Bell and G.E. Dirom of Noranda, R. Woolverton of Twin Peak Resources, R.P. Taylor and H. Kim of Granisle, G.B. Hardwick and S. Wilkinson, formerly with Granisle, R.V. Kirkham of the Geological Survey of Canada, and N.C. Carter of the B.C. Dept. of Mines and Petroleum Resources. We are grateful to D.F. Sangster and R.V. Kirkham for critical reading of the manuscript, and to many staff members of the Geological Survey of Canada and Noranda for analyses and services. In particular, we would like to express our appreciation to A.G. Plant and G.R. Lachance for microprobe analyses, M. Bonardi, G. Pringle, and R.N. Delabio for X-ray diffraction patterns, and J.J. Lynch, S. Courville, J.G. Gravelle, A. Whitehead, F.D. Cooke, G. Holland, W.I. Nelson Jr., A. Bentzen, and J. Staniszewski for various analyses or other assistance. Special thanks are given to Y. Khan of Noranda Exploration Co. Ltd., who drafted the figures and offered many helpful suggestions.

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Table 1. Chemical Analyses of Granisle BFP*.

Wt.%	G-19	G-20	G-17	G-55	69-24-482	69-43-362	70-5-120
SiO_2	60.8	58.8	58.0	63.1	61.6	62.2	63.3
Al_2O_3	17.6	16.8	16.3	17.1	17.6	18.8	17.8
Fe_2O_3	3.2	3.2	2.3	1.1	-	< 0.1	0.9
FeO	1.8	2.1	2.6	1.9	-	4.0	2.1
MnO	0.07	0.08	0.08	0.09	0.07	0.03	< 0.01
MgO	2.9	3.6	3.4	1.7	1.0	2.1	2.0
CaO	4.9	5.5	5.0	3.0	2.8	2.9	2.6
Na_2O	4.4	3.8	3.4	2.8	2.6	4.4	4.4
K_2O	2.4	2.3	2.3	3.5	2.9	1.5	2.6
TiO_2	0.77	0.78	0.75	0.50	0.61	0.61	0.65
H_2O	1.4	1.6	2.8	1.9	3.0	1.5	0.9
CO_2	0.6	0.6	2.7	2.6	2.7	1.2	0.5
P_2O_5	0.33	0.31	0.32	0.22	0.25	0.24	0.17
S	0.02	0.03	0.03	<0.02	2.49	0.60	0.09
O=S	0.01	0.01	0.01	0.0	0.93	0.23	0.03
Total	101.2	99.5	100.0	99.5		99.9	98.0

Analyses by Rapid Methods Group, Analytical Chemistry Section, G.S.C.

*G-19, G-20: unaltered BFP northwest of the Granisle alteration zone (Figure 5). G-17 from Newman Peninsula and G-55 from Sterret Island, both in the outer edge of the chlorite-carbonate zone. Drill core 69-24 in strong part of pyrite halo, near the orebody (carbonate-kaolinite-sericite alteration). Drill core 69-43 in weaker part of biotite zone, approximately 700 feet beyond 0.3% Cu boundary. Drill core 70-5 from biotite zone in the orebody.

Table 2. Electron Microprobe Analyses of Primary and Secondary Amphiboles in BFP.

Wt.%	Granisle G-19 phenocryst core	Granisle G-19 phenocryst rim	Granisle G-20 phenocryst core	Granisle G-20 phenocryst rim	Morrison M45-182 phenocryst core	Morrison M45-182 phenocryst rim	Morrison M48-68 pheno-cryst	Morrison M48-68 secondary aggregate	Morrison M57-105 pheno-cryst	Morrison M57-105 secondary veinlet	Morrison M28-599 pheno-cryst	Morrison M28-599 secondary aggregates		Morrison M28-599 second veinle
SiO_2	43.1	47.3	42.6	41.0	45.1	42.8	43.5	54.8	42.5	52.5	41.5	57.0	53.2	51.7
TiO_2	1.9	1.4	1.8	1.8	2.0	2.4	2.0	0.6	1.7	0.37	2.4	0.17	0.31	0.33
Al_2O_3	9.8	8.0	10.7	12.5	9.2	11.4	10.6	3.0	9.9	3.8	11.5	1.1	3.3	3.0
FeO*	15.2	14.4	10.6	12.6	13.7	12.0	13.7	9.5	14.1	9.2	13.5	8.2	8.9	9.8
MnO	n.d	n.d.	n.d.	n.d.	0.2	0.1	0.3	0.3	0.2	0.12	0.22	0.21	0.25	0.20
MgO	14.8	15.9	17.2	16.1	14.3	14.5	14.1	18.0	13.1	18.8	13.2	18.2	17.4	18.2
CaO	11.2	10.9	11.5	11.4	10.9	11.6	10.7	11.1	10.6	11.6	11.1	10.7	11.3	11.9
Na_2O	1.8	1.5	2.3	2.3	2.4	2.6	2.5	1.1	2.1	0.8	2.0	0.5	0.6	0.6
K_2O	0.8	0.9	0.6	0.7	0.9	0.7	0.7	0.25	0.68	0.17	0.81	0.04	0.22	0.17
Total	98.6	100.3	97.3	98.4	98.7	98.1	98.1	98.65	94.88	97.36	96.23	96.12	95.48	95.90

Analysts: G.R. Lachance and A.G. Plant

* Total Fe as FeO   n.d. = not determined

Table 3. Electron Microprobe Analyses of Feldspar in K-feldspar Veinlets in BFP, Granisle.

	1	2	3		4	
DDH*	69-5-451 K-feldspar	70-7-490 K-feldspar	70-26-283** K-feld.	Plagioclase	70-26-283** K-feld.	Plagiocla:
Wt.%						
SiO_2	65.5	65.2	66.0	65.9	66.7	65.0
Al_2O_3	18.3	18.3	18.4	21.6	18.7	22.4
CaO	0.04	0.03	0.2	2.0	0.2	2.2
K_2O	13.3	15.4	10.6	0.7	10.4	0.9
Na_2O	2.2	1.1	4.6	10.0	4.6	9.7
Total	99.34	100.03	99.8	100.2	100.6	100.2

Analyst: A.G. Plant

* Diamond drill hole, with the last 3 digits being the footage at which the sample was taken.

** Coexisting K-feldspar and plagioclase. Analyses in columns 3 and 4 are from different areas in one thin section.

Table 4. Electron Microprobe Analyses of Secondary Chlorites, Granisle

Sample No.	Type	SiO_2	Al_2O_3	Weight per cent FeO*	MnO	MgO
70-4-62	veinlet	27.7	22.0	18.5	0.0	23.2
	matrix	27.0	21.0	17.8	0.0	23.5
70-20-102	matrix	27.3	21.5	19.3	0.1	22.2
	matrix	26.7	21.4	19.5	0.1	21.0
69-19-257	veinlet	23.2	22.0	30.4	0.1	11.2
	matrix	23.6	23.1	27.1	0.0	14.3
69-17-179	veinlet	28.2	20.8	17.8	0.0	23.0
	veinlet	27.6	21.1	18.0	0.0	22.9
	matrix	26.5	23.2	17.6	0.0	22.5
69-38-104	matrix	27.1	24.1	14.3	0.0	23.5
	matrix	26.7	24.6	16.3	0.0	23.9
	matrix	26.0	22.6	13.6	0.0	24.7
69-39-384	veinlet	26.2	22.1	19.0	0.0	22.3
	matrix	26.4	20.9	17.6	0.0	23.4
69-35-411	matrix	26.7	21.8	14.0	0.0	24.5
	matrix	26.8	22.1	13.2	0.0	22.9
G-35**	hornbl. pseudo.	24	22	14	0.0	25
G-38	hornbl. pseudo.?	27.8	17.5	20.0	0.3	21.0
	hornbl. pseudo.?	28.0	19.1	19.9	0.3	21.4

Analyst: G.R. Lachance *Total Fe as FeO ** Very fine-grained