# Porphyry copper-gold-molybdenum deposits in the Island Copper Cluster, northern Vancouver Island, British Columbia

J.A. PERELLÓ
Minera BHP de Chile Inc., Santiago, Chile

J.A. FLEMING
BHP Minerals Canada Ltd., Port Hardy, British Columbia

K.P. O'KANE
Minera Escondida Ltda., Antofagasta, Chile

P.D. BURT
BHP Minerals Canada Ltd., Toronto, Ontario

G.A. CLARKE
BHP Iron Ore Pty. Ltd., Newan, Australia

M.D. HIMES
BHP Minerals Ltd., Kelowna, British Columbia

A.T. REEVES
BHP Minerals Canada Ltd., Port Hardy, British Columbia

## ABSTRACT

*The Island Copper Cluster (ICC), situated at the northern end of Vancouver Island, consists of five porphyry Cu-Au-Mo systems (Island Copper, Bay Lake, G zone, Red Island and Rupert Inlet) and a porphyry Cu-Mo system (Northwest zone) genetically associated with Jurassic stock and dike-like rhyodacitic porphyries (c.a. 175 Ma) that intruded comagmatic island arc, calc-alkaline basalts, andesites, pyroclastic and sedimentary marine rocks of the Bonanza Group. These share similarities in geometries of alteration and mineralization but exhibit a large range of size and grade. Copper-bearing garnet-pyroxene skarn (e.g., Northwest zone) and vein-type mineralization (A zone) also constitute integral parts of the porphyry systems.*

*The only orebody in the cluster supports the Island Copper mine, controlled and operated by BHP Minerals Canada Ltd. Between start of production in 1971 and the end of 1994 the mine produced 345 million tonnes of ore having average head grades of 0.41% Cu, 0.017% Mo, 0.19 g/t Au and 1.4 g/t Ag.*

*The Island Copper hydrothermal system evolved from an early, probably juvenile magmatic fluid-dominated stage, to one strongly influenced by meteoric waters, as the main heat source cooled and further intrusion and brecciation took place. Three main stages of alteration and mineralization have been differentiated. Most copper, gold and some molybdenum were deposited under K-silicate stable conditions during an Early stage related to the intrusion of a Main rhyodacite porphyry. This was followed by a copper-molybdenum-(gold?) Intermediate stage associated with quartz-sericite and quartz-sericite-clay (SCC) assemblages and by a copper-barren, pyrophyllite-rich Late stage under advanced argillic alteration conditions. These stages were assisted by Intra-mineral and Late-mineral rhyodacite intrusions.*

*Certain features of Island Copper such as the positive correlation between copper and gold, the association of gold with a potassic, biotite-rich alteration assemblage, and the high magnetite content (>8% by volume) in the system are characteristic of gold-rich porphyry copper deposits. The spatial arrangement of biotite-chalcopyrite ore zones around a copper-barren, quartz-magnetite-amphibole core is, however, considered to be a unique feature of the Island Copper orebody and other members of the cluster (Bay Lake, G zone, Red Island). Comparisons are also valid between the Fe-rich core of the systems of the ICC and iron ore mineralization of the Kiruna-type.*

## Introduction

The Island Copper orebody is near the north end of Vancouver Island on the north shore of Rupert Inlet (Fig. 1), at latitude 50°36′N, longitude 127°28′W (NTS 92L/11E, 12W), about 16 km by paved road south of the town of Port Hardy, British Columbia (Fig. 2). Port Hardy is served by daily, direct flights from Vancouver 335 km southeast and is 500 km by highway from Victoria. The other five mineral deposits in the cluster lie on a trend 10 km long and are reached by logging roads. Copper concentrates are shipped from a dock at the mine to markets in south-east Asia, principally Japan.

The area north of Rupert Inlet (Fig. 3) is characterized by rounded hills up to 150 m high. Outcrops are sparse, as glacial till, colluvium, peat and moss from 1 m to 30 m, but locally greater than 75 m thick, cover much of the area. Episodic glaciation during late Wisconsinan, and gradual evolution of landscapes during Holocene time comprise the late Quaternary geological history of northern Vancouver Island (Bobrowsky and Meldrum, 1994). The last glaciation occurred 20 000 to 14 000 years ago, with ice flow regionally to the northwest. Timber cover consists of dense primary and secondary growth of principally coniferous forest including

Metallurgy Special Volume 15, 1976. This work provided the foundation upon which the present geological model has been formulated. The authors are also indebted to the British Columbia Ministry of Energy, Mines and Petroleum Resources, and particularly to A. Panteleyev, for Granite Mountain area age dates and whole rock chemical analyses which have formed a vital part of this paper.

## REFERENCES

ARMSTRONG, R.L., 1988. Mesozoic and Early Cenozoic magmatic evolution of the Canadian Cordillera. Geological Society of America, Special Paper 218, p. 55-91.

BARKER, F., 1979. Trondhjemite: definition, environment and hypotheses of origin. *In* Trondhjemites, dacites, and related rocks, developments in petrology 6. *Edited by* F. Barker. Elsevier Scientific Publishing, Amsterdam, p. 1-12.

CANNON, R.W., THORNTON, J.M. and ROTHERHAM, D.C., 1972. Induced polarization and resistivity in the Gibraltar area, British Columbia. AIME Transactions, 252, No. 4, p. 392-397.

DRUMMOND, A.D., TENNANT, S.J. and YOUNG, R.J., 1973. The interrelationship of regional metamorphism, hydrothermal alteration and mineralization at the Gibraltar mines copper deposit in B.C. The Canadian Institute of Mining and Metallurgy, CIM Bulletin, 66, No. 730, p. 48-55.

DRUMMOND, A.D., SUTHERLAND BROWN, A., YOUNG, R.J. and TENNANT, S.J., 1976. Gibraltar — regional metamorphism, mineralization, hydrothermal alteration and structural development. *In* Porphyry Deposits of the Canadian Cordillera. *Edited by* A. Sutherland Brown, The Canadian Institute of Mining and Metallurgy, Special Volume 15, p. 195-205.

EASTWOOD, G.E.P., 1970. Geology of the Granite Mountain Stock. *In* Geology, Exploration and Mining in British Columbia 1969, British Columbia Department of Mines and Petroleum Resources, p. 162-172.

MORTIMER, N., VAN DER HEYDEN, P., ARMSTRONG, R.L., and HARAKAL, J., 1990. U-Pb and K-Ar dates related to the Timing of magmatism and deformation in the Cache Creek Terrane and Quesnellia, Southern British Columbia. Canadian Journal of Earth Sciences, 27, p. 117-123.

O'CONNOR, J.T., 1965. A classification for quartz-rich igneous rocks based on feldspar ratios. U.S. Geological Survey, Professional Paper, 525-B, p. 79-84.

PANTELEYEV, A., 1977. Granite mountain project. *In* Geological Fieldwork, 1976. British Columbia Ministry of Mines and Petroleum Resources, p. 39-42.

ROTHERHAM, D.C., DRUMMOND A.D. and TENNANT, S.J., 1972. Exploration of Gibraltar. Western Miner, 45, No. 2, p. 25-28.

STRECKEISEN, A., 1973. IUGS subcommission on the systematics of igneous rocks, plutonic rocks, classification and nomenclature. Geotimes, October, p. 26-30.

STRUIK, L.C., 1988. Crustal evolution of the eastern Canadian Cordillera. Tectonics, 7, No. 4, p. 727-747.

SUTHERLAND BROWN, A., 1958. McLeese - Cuisson Lake area. *In* Annual Report. British Columbia Department of Mines and Petroleum Resources, p. 14-18.

SUTHERLAND BROWN, A., 1967. Geology of the Granite Mountain - Cuisson Lake area. *In* Annual Report. British Columbia Department of Mines and Petroleum Resources, p. 121-124.

SUTHERLAND BROWN, A., 1974. Gibraltar Mine. *In* Geology, Exploration and Mining in British Columbia, 1973. British Columbia Department of Mines and Petroleum Resources, p. 299-318.

TIPPER, H.W., 1959. Quesnel, British Columbia. Geological Survey of Canada, Map 12-1959.

**FIGURE 1. Aerial view (1993) of the Island Copper mine looking from above Rupert Inlet northwest across the open pit and plant site. In the foreground is Red Island surrounded by the marine waste dump. Bay Lake lies on the far side of the pit and Quatse Lake is in the distance. Holberg Inlet and the (unincorporated) municipality of Coal Harbour are visible to the upper left. In the pit, the End Creek Fault occurs as a dark trace down the south wall. *The Pyrophyllite breccia zone lies at the west end of the pit between the fault and the talus slope in the middle of the far wall.* The pit bottom is 340 m below sea level. The ultimate pit bottom will be 402 m below sea level, deeper than the surface of the Dead Sea (398 m below sea level), the deepest site on earth with direct sunlight.**

western hemlock, western red cedar, Pacific silver fir, sitka spruce and Douglas fir. Mean annual precipitation varies from 1.7 m to 2.2 m (Howes, 1981), and temperatures range annually from ~7°C to 27°C, with an annual mean of 8°C.

## History

### Discovery

In 1963, the British Columbia Department of Mines and the Geological Survey of Canada released results of an aeromagnetic survey flown in 1962 over the northern part of Vancouver Island. These results attracted considerable exploration interest, mainly for skarn-type iron deposits, but the mining companies that investigated the area did not find significant mineralization. Gordon Milbourne, a local prospector involved in follow-up work, staked about 150 claims around a magnetic anomaly near Bay Lake, north of Rupert Inlet (Fig. 4). In 1965, he located a small piece of massive chalcopyrite in float south of the west end of Bay Lake, and exposed massive chalcopyrite in volcanic bedrock in two shallow pits (A zone). Utah Construction and Mining Co. geologist, G.A. Noel, examined the showing in October 1965 and recommended that an option be taken on the claims. A formal agreement with Mr. Milbourne was signed in January 1966.

Drilling commenced immediately in the A zone using an X-ray drill and a program of geological mapping, soil sampling and magnetic and limited induced polarization surveying was undertaken. In May and June of 1966, a 500 m by 250 m, 200 ppm, B horizon copper anomaly located 2.3 km southeast of the A zone (Fig. 4) was tested by four EX holes 20 m to 30 m deep. They intersected disseminated chalcopyrite grading from 0.05% Cu to 0.46% Cu over intervals of 1 m to 4 m in a dark, chlorite-magnetite altered, andesite tuff and a light coloured rock called "felsite". The Island Copper discovery hole, drilled in February 1967, intersected disseminated chalcopyrite grading 0.45% Cu over an interval of 88 m. It was the eighty-second drill hole of the program and the first deep, follow-up hole on the anomaly. By May 1969, 128 diamond drillholes totalling 35 595 m had been completed to define the Island Copper deposit (Young and Rugg, 1971).

The remaining systems of the porphyry copper cluster: Bay Lake, G zone, Northwest zone, Red Island and Rupert Inlet (Figs. 4 and 5) have been explored intermittently since 1971.

### Ownership

The Island Copper mine is controlled and operated by BHP Minerals Canada Ltd., the Canadian subsidiary of BHP Minerals, a business group of The Broken Hill Proprietary Company Limited

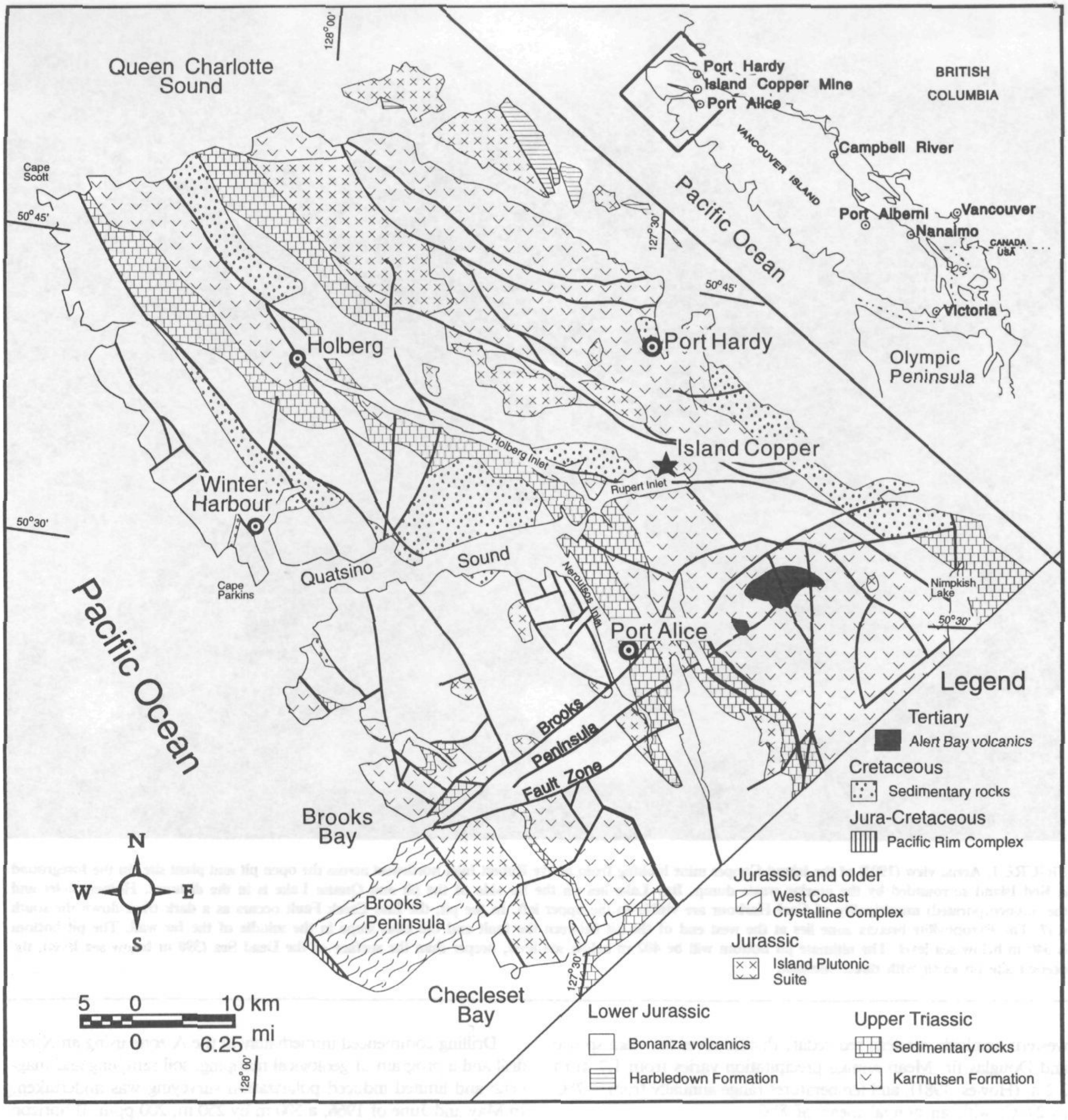



**FIGURE 2. Location of Island Copper mine and regional geology (after Nixon et al., 1994).**

of Australia. BHP acquired the Island Copper operation of Utah Mines Limited in 1984 with the purchase of Utah International Inc. from the General Electric Company.

## Production

Production commenced in 1971, and to the end of 1994 approximately 1000 million tonnes of ore and waste were mined. About 345 million tonnes of mill feed with average head grades of 0.41% Cu, 0.017% Mo, 0.19 g/t Au and 1.4 g/t Ag have yielded approximately 5 million tonnes of copper concentrates containing about 1200 million kg of copper, 33 000 kg of gold and 336 000 kg of silver. In addition, approximately 68 000 tonnes of molybdenum concentrate were produced containing about 30 million kg of molybdenum and 27 000 kg of rhenium. Accordingly, mill recoveries averaged approximately 84% copper, 50% molybdenum and about 50% gold. Gold production, which averaged 1200 kg to 1500 kg annually, makes Island Copper the seventh-overall largest lode gold producer in British Columbia. Monthly mean gold head-grades from 1988 through 1994 ranged from 0.07 g/t to 0.27 g/t and averaged 0.15 g/t, a significant decrease with depth compared to an average of 0.21 g/t for the period 1975 to 1987 inclusive.

## Applied Exploration Techniques

The exploration methods used in the discovery of the Island Copper deposit described by Young and Rugg (1971), Cargill et al. (1976) and Witherly (1979) are only summarized here. Initial testing of geochemical and geophysical anomalies using X-ray size drill holes established that soil geochemistry was the most effective method of detecting copper mineralization. By comparison, mag-

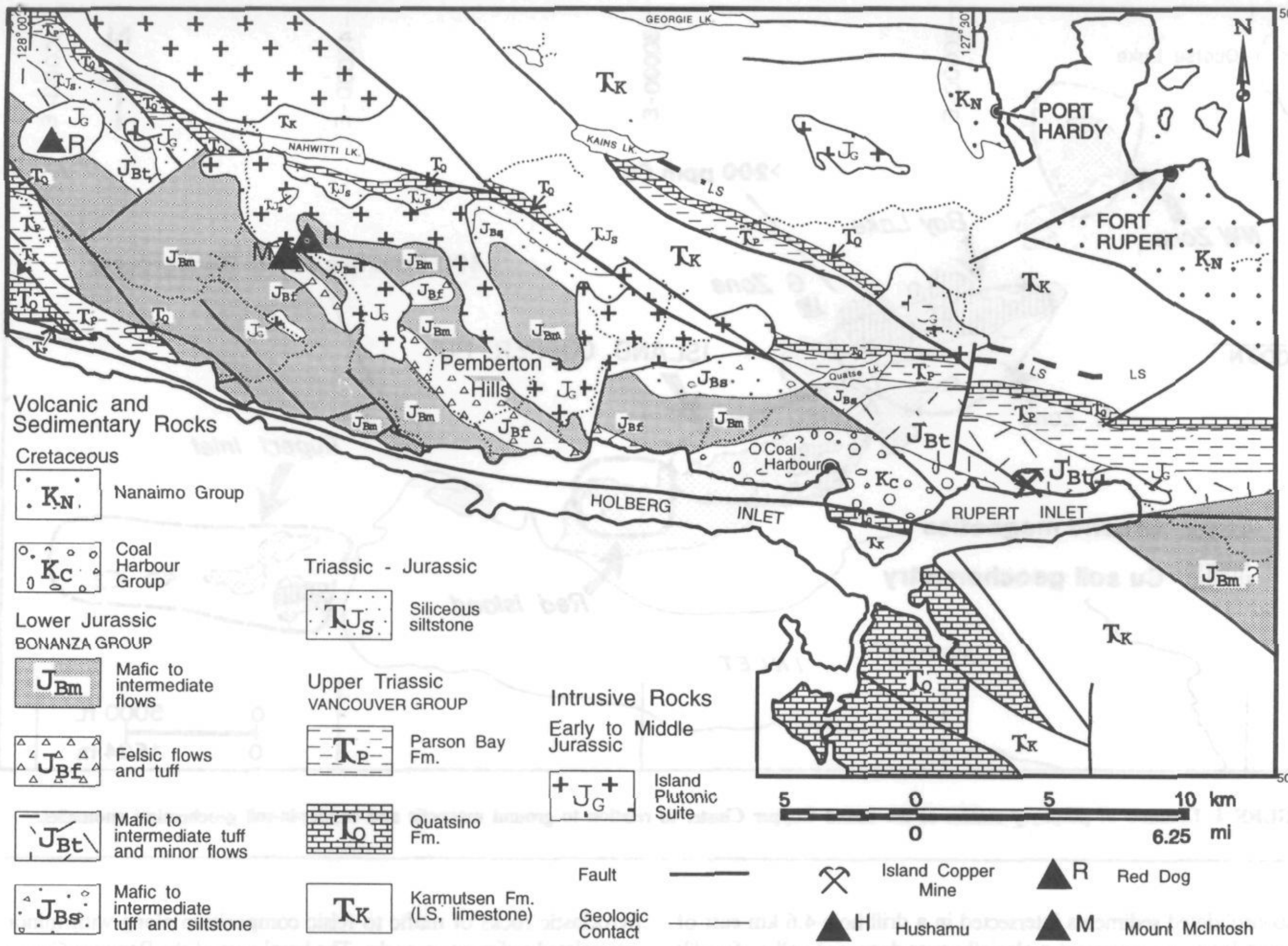



**FIGURE 3. Generalized geology of the area north of Holberg and Rupert inlets (after Nixon et al., 1994). The Rupert Stock is at the east end of Rupert Inlet.**

netic and induced polarization anomalies generally delineated either magnetite with minor chalcopyrite, or abundant pyrite, respectively. Consequently, priority for further drilling was given to copper-in-soil geochemical anomalies.

The B horizon copper anomaly delineated over the Island Copper deposit was subsequently shown to be controlled mainly by overburden thickness and type; the anomaly was detected where the overburden was less than 9 m thick. A re-evaluation (Smee, 1991) of a geochemical orientation study conducted in 1969 prior to mining shows that humus produced broader anomalies directly over the orebody and more accurately traced copper mineralization further up-ice to the east and beneath thicker overburden than did the B horizon.

Induced polarization surveying was restricted in extent prior to discovery of the deposit because of high survey cost, equipment malfunctions caused by wet weather and poor delineation of chalcopyrite. More extensive induced polarization surveys conducted later showed chargeability highs straddling a central magnetic anomaly to be a characteristic signature of the Island Copper, Bay Lake and Northwest zone porphyry centres (Fig. 4).

## Regional Geology

Northern Vancouver Island (Fig. 2) forms the southern part of Wrangellia tectono-stratigraphic terrane, which lies west of the Coast Plutonic Belt and is underplated on the west by the Pacific Rim and Crescent accretionary complexes (Wheeler and McFeely, 1991). The region is underlain by a thick sequence of Upper Triassic and Lower to Middle Jurassic sedimentary and volcanic assemblages of the Vancouver and Bonanza groups, respectively (Muller et al., 1974; 1981). Many of these rocks have undergone regional metamorphism grading from prehnite-pumpellyite to zeolite facies (Muller et al., 1974; Kuniyoshi and Liou, 1976).

In the area north of Rupert and Holberg inlets (Fig. 3), the Triassic Vancouver Group (about 6000 m thick according to Muller et al., 1974) comprises the progressively younger Karmutsen, Quatsino and Parson Bay formations. The overlying Bonanza Group comprises an assemblage of mafic to intermediate, with subordinate felsic, flows and tuffs that may be as thick as 3500 m. The Vancouver and Bonanza group rocks are intruded by Jurassic rocks of the Island Plutonic Suite, which range in composition from quartz diorite to monzogranite. All known porphyry-type deposits of northern Vancouver Island, such as the Red Dog and Hushamu porphyry Cu-Mo-Au deposits (Fig. 3), and most of the mineral occurrences classified as skarns, are genetically related to these intrusions.

About 1000 m of Lower to Upper Cretaceous, marine and nonmarine, coarse-grained clastic strata unconformably overlie these older units. Coal seams have long been known to occur in these rocks (Dawson, 1887), and coal was mined from the Suquash basin, situated southeast of Port Hardy, from 1849 to 1852. Neogene volcanic rocks of the Twin Peaks volcanic complex, part of the Alert Bay volcanic belt, occur southeast of the Island Copper mine (Fig. 2), and mafic to felsic dikes of similar age up to 3 m thick are found throughout the area.

Regional structures are predominantly northwest to west-northwest-striking, steeply-dipping faults, many exhibiting south-side-up and strike-slip motions (Nixon et al., 1994). The major Holberg Fault, along Holberg Inlet, is well exposed in shoreline outcrops south of Coal Harbour, where it juxtaposes Upper Triassic and Cretaceous strata. The fault appears to continue east through Rupert Inlet just south of the Island Copper mine. Thick (215 m)

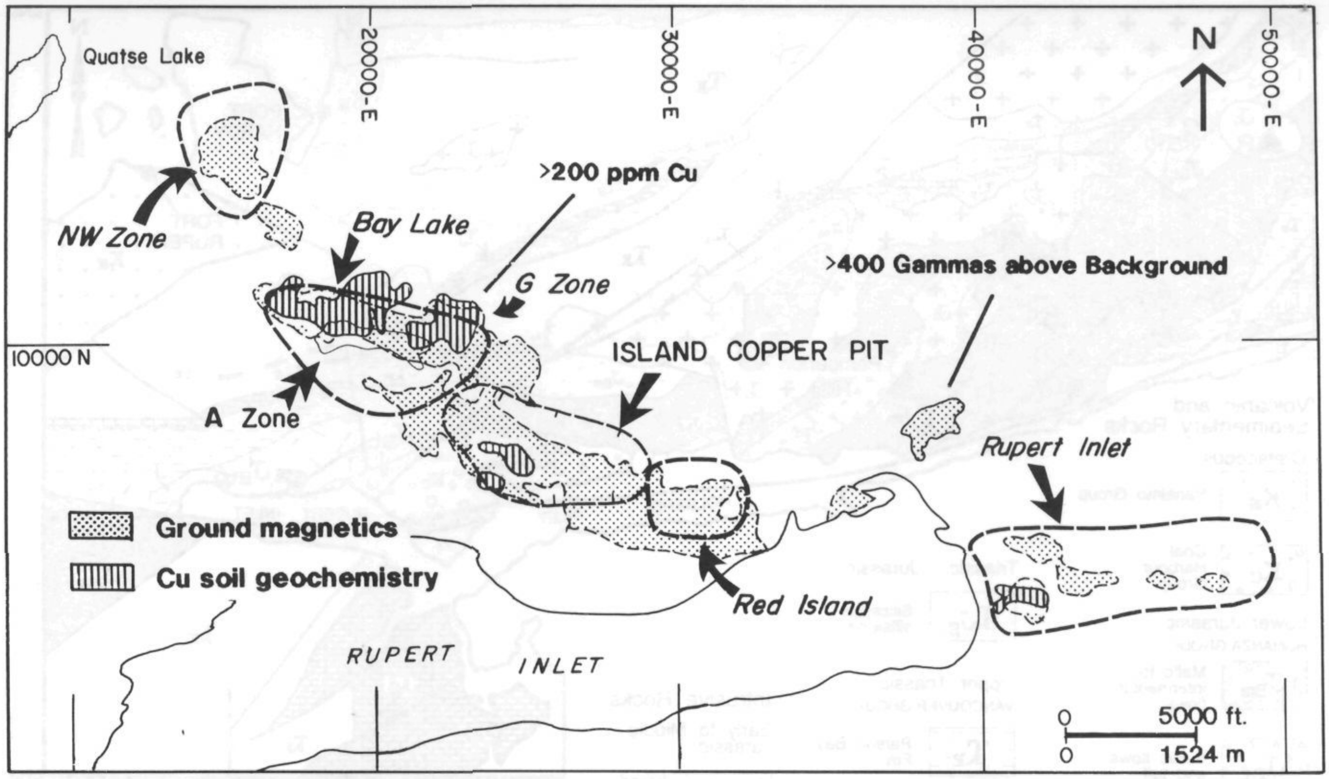



**FIGURE 4. Location of porphyry centres of the Island Copper Cluster in relation to ground magnetic and copper-in-soil geochemical anomalies.**

unconsolidated sediments intersected in a drill hole 4.6 km east of Rupert Inlet may represent a glacially over-deepened valley (fjord?) associated with the fault (Bobrowsky and Meldrum, 1994). Motion on most major faults in the area appears to postdate the deposition of Lower to Middle Cretaceous strata, although some may have been synchronous with Upper Cretaceous Nanaimo Group sedimentation (Nixon et al., 1994).

## Local Geology

Local stratigraphy (Fig. 3) is dominated by rocks of the Vancouver and Bonanza groups, which form a moderately-dipping, south to southwest-facing, homoclinal succession. Only the uppermost part of the Karmutsen Formation appears to be exposed within Figure 3, where it consists of aphanitic to coarsely plagioclase-phyric lavas, locally intercalated with beds 100 m thick of micritic limestone and minor packstone and wackestone. The Karmutsen Formation is conformably overlain by the Quatsino Formation, a medium to dark-grey, thick-bedded to massive, locally fossiliferous micritic limestone 30 m to 300 m thick (Jeletzky, 1976; Nixon et al., 1993). The Quatsino Formation grades upward into the Parson Bay Formation, a sequence (300 m to 400 m thick) of dark-grey to black, medium to thin-bedded or laminated limy mudstone, calcareous siltstone and fissile, carbonaceous black shale. Near the Island Copper mine, the "Parson Bay Formation" may be subdivided into a lower calcareous and an upper non-calcareous, fine-grained siliciclastic sequence. The latter contains medium-bedded, andesitic crystal tuff and Early Jurassic (early Middle Sinemurian) bivalves (Haggart and Tipper, 1994). It appears to represent either the basal part of the Bonanza Group or a separate stratigraphic entity (Harbledown Formation; Haggart and Tipper, 1994). A siliceous siltstone unit north of Holberg Inlet appears to occupy the Triassic-Jurassic boundary (Hammack et al., 1994).

The Lower Jurassic Bonanza Group comprises a predominantly pyroclastic-epiclastic, subaqueous succession locally over 500 m thick overlain by a sequence about 3000 m thick of subaerial lavas and pyroclastic rocks of mafic to felsic composition along with minor intercalated sedimentary rocks. The basal part of the Bonanza Group is composed of mafic to intermediate tuff, tuffaceous sandstone and siltstone overlain by and grading laterally into lithic tuff and tuff-breccia that are succeeded upward by intercalated tuffs and flows. Near the Island Copper mine (Fig. 5), basal pyroclastic-epiclastic sequences of the Bonanza succession are >1000 m thick and contain interbedded tuffaceous and fossiliferous cherty sediments, dacitic tuffs and andesitic and basaltic flows (Fahey, 1979). Recent geological mapping by Nixon et al. (1994) places host rocks on the Island Copper intrusion about 1000 m above the base of the Bonanza Group, close to the transition between the subaqueous and subaerial volcanic assemblages. A bivalve fossil from the open pit was identified as Middle Jurassic (Aalenian) in age (Poulton, 1980; Poulton and Tipper, 1991).

Lower Cretaceous strata, equivalent to the Longarm Formation and Coal Harbour Group (Nixon et al., 1994), exposed north of Rupert and Holberg inlets (Fig. 3), consist of sandstone, pebble conglomerate and siltstone with coal seams up to 10 cm in thickness. Strata equivalent to the Upper Cretaceous Nanaimo Group and comprising similar rock types occur near Port Hardy (Fig. 3).

The most important structure in the mine area (Fig. 5), the End Creek Fault (ECF), trends about 300° for more than 3 km. In the Island Copper pit the ECF parallels the trend of the rhyodacite porphyries and consists of a tabular, steeply northeasterly-dipping zone of fault breccia and clayey gouge about 60 m thick. Toward Bay Lake, it separates into several splays, in a horsetail array. One of these, the West Bay Splay (WBS; Burt and Fleming, 1988; Burt, 1989), is a fault zone nearly 40 m thick. The ECF crosscuts mineralization at Island Copper and the A zone, and the WBS disrupts the Bay Lake system. Displacement style along these structures is unknown due to lack of kinematic indicators, but strike-slip and normal movements are favoured (Perelló, 1987; Sillitoe, 1989b). Northeast-striking faults are also prominent in the area, and a southward plunging, asymmetrical antiform occurs on the north side of the pit.

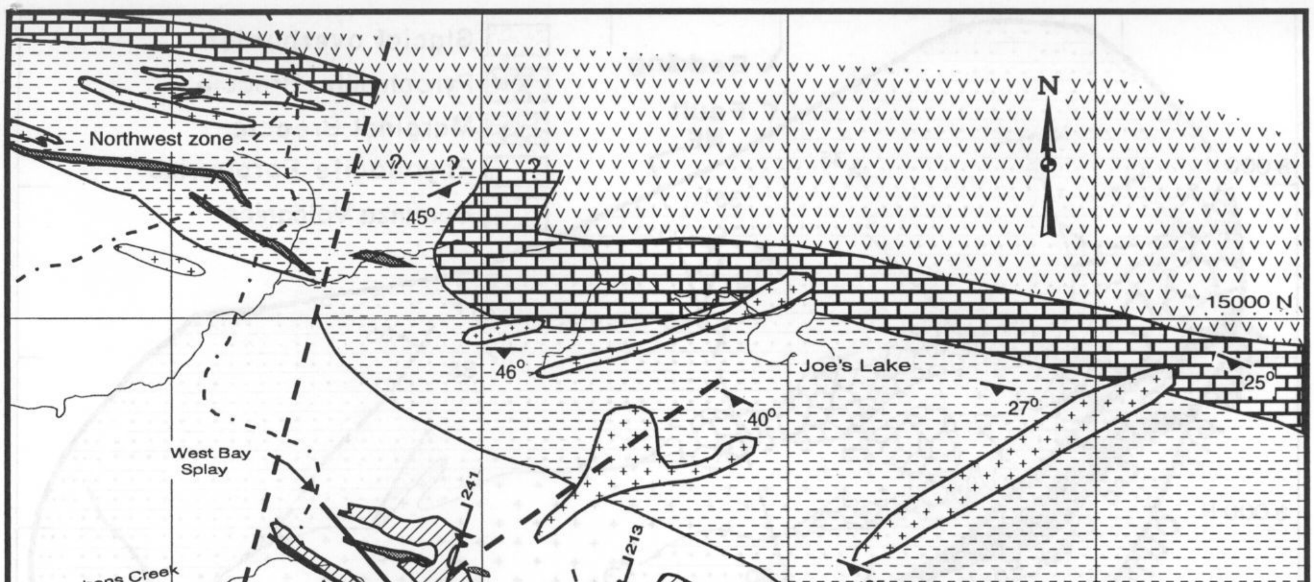



**FIGURE 5. Geology of the Island Copper mine area. Rhyodacite porphyry contacts and 0.2% Cu boundaries are projected to the 920 elevation (sea level = 1000 feet) for the Red Island, Island Copper and P zone centres and to the 1140 elevation for the Bay Lake and G zone centres.**

## Isotopic Ages

Whole-rock K-Ar ages, for andesites and rhyodacites from the Bonanza Group on northern Vancouver Island, range from 161 Ma to 103 Ma. These ages are considered as mimima (Northcote and Robinson, 1973; Muller et al., 1974). Muller (1977) reported a Rb-Sr isochron age of 184 ± 5 Ma for Bonanza Group rocks, and more recently, Panteleyev et al. (1995) provide maximum $^{40}Ar/^{39}Ar$ ages of 167 Ma to 160 Ma for alunites, considered to represent hydrothermal alunite formed during acid sulphate alteration, from the Pemberton Hills rhyolite unit.

Biotite from the Rupert Stock, about 3.5 km east of the mine (Fig. 3), was dated using the K-Ar method at 154 ± 6 Ma (Northcote and Robinson, 1973) and using the $^{40}Ar/^{39}Ar$ method at a maximum age of 174 ± 2 Ma (Archibald and Nixon, 1995). A Rb-Sr whole-rock (five point) isochron age of 174 ± 17 Ma was obtained by Armstrong (1983) for a suite of rhyodacite porphyry samples from the Island Copper deposit. These ages are coincident with the Early-to-Late Jurassic range determined for Island Plutonic Suite rocks on northern Vancouver Island (148 ± 8 Ma to 181 ± 8 Ma, K-Ar, Muller et al., 1974) and elsewhere on Vancouver Island (174 ± 10 Ma, Rb-Sr isochron, Muller, 1977).

Based on isotopic age data and field evidence, Northcote and Muller (1972), Northcote and Robinson (1973) and Muller (1977) proposed a comagmatic relationship between the Island Plutonic Suite and Bonanza volcanic rocks. It was also proposed that porphyry intrusions, such as the Island Copper rhyodacitic complex and other intrusions, were feeders for the felsic members of the Bonanza Group (Northcote and Robinson, 1973; Muller et al., 1974). This relationship is supported by stratigraphic, paleontological and geochronological data currently available (Archibald and Nixon, 1995).

## The Island Copper Cluster

At least five porphyry copper-gold-molybdenum centres (Island Copper, Bay Lake, G zone, Red Island and Rupert Inlet) and one porphyry copper-molybdenum centre (Northwest zone) comprise the Island Copper Cluster (ICC). The centres (Fig. 4) coincide with magnetic highs aligned in a northwesterly direction for >10 km

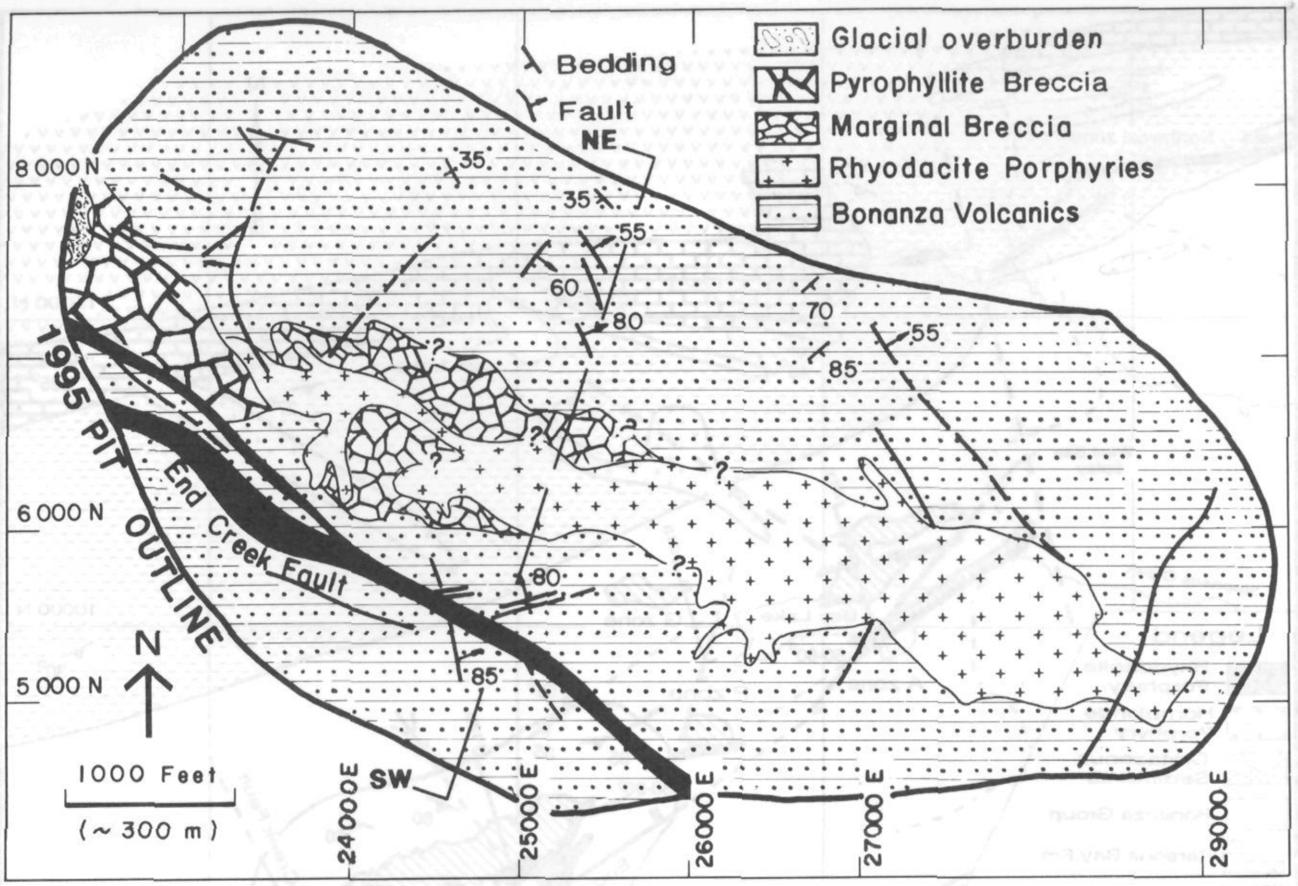



**FIGURE 6. Composite plan: Geology of the Island Copper deposit.**

between Quatse Lake and Rupert Inlet. These highs are, in turn, associated with several stocks and dike-like bodies of rhyodacite porphyry that intruded all Vancouver Group and Bonanza Group rocks recognized in this area. Current understanding of the systems within the cluster suggests that they share many similarities in alteration and mineralization geometry but exhibit a large range of size and grade. Other components of the ICC include porphyry-related, copper skarn mineralization of Quatsino Formation limestone and to a lesser extent of limy, Parson Bay Formation strata underlying the Island Copper, Bay Lake, G zone and Northwest zone centres (Red Island and Rupert Inlet centres are not drill-tested at depth), and vein-type, massive sulphide occurrences in the A zone at Bay Lake (Fig. 5).

The Rupert Inlet centre is the least altered and mineralized of the cluster and has received the least exploration work. It is, therefore, included as a member of the cluster, but not described in this paper. In addition, a small Cu-Mo-Au deposit (P zone) west of the pit (Fig. 5), considered to be part of the Island Copper centre, is not described separately.

In this paper, mine grid co-ordinates shown on plan maps (except Figs. 2 and 3) are in feet. Elevations on sections are also in feet with sea level equal to 1000.

## Geology of Island Copper

### Rock Types

Three main rock units are recognized in the Island Copper pit (Fig. 6): Bonanza Group volcanic rocks; rhyodacite porphyries; and hydrothermal breccias. The last includes the Marginal and Pyrophyllite breccias of the mine nomenclature (Cargill et al., 1976).

### Bonanza Group Volcanics

Bonanza rocks in the pit consist typically of lithic tuff, breccia, and interbedded andesitic and basaltic flows. The flows are commonly massive and have aphanitic to medium-grained, porphyritic and brecciated textures. Typical mineralogy includes plagioclase of labradorite-bytownite composition, augite, hypersthene and amphibole. Some of these flows are calc-alkaline, high-alumina basalts (Arancibia, in prep.).

Fragmental rocks comprise lithic, crystal, and lapilli tuff, lesser ash tuff and volcanic breccia, and minor cherty tuff. The tuffs are fine to coarse-grained, massive to thinly-bedded, and composed of angular to subrounded volcanic and lithic fragments as well as plagioclase and quartz crystals. Graded bedding is a common feature. The volcanic breccias are typically massive and contain poorly-sorted crystal tuff and porphyritic basalt fragments in a lithic tuff matrix. Other features of these rocks include beds of accretionary lapilli and rhyodacitic lapilli tuff and bivalve fossils in fine- to medium-grained lithic sandstone interbeds (e.g., the trigonoiid Myophorella taylori; Poulton, 1980).

### Rhyodacite Porphyries

The dike-like rhyodacite porphyry body exposed in the pit (Figs. 6 and 7) has been considered either a single intrusion (Cargill, 1975; *Cargill et al., 1976) or multi-phase (Arancibia, in prep.*; Fleming, 1983; Perelló, 1987; Perelló et al., 1989). Three phases (Main, Intra-mineral and Late-mineral) are distinguished here based on alteration and veining intensities, cross-cutting relations and xenolith compositions.

All these porphyry bodies are similar in texture and composition. Where less altered, the porphyry (Cargill, 1975; Arancibia, *in prep.; Leitch, 1988)* typically develops a coarse-grained, porphyritic texture characterized by 10% to 30% subrounded, bipyramidal quartz phenocrysts 0.5 cm to 1 cm diameter, 15% to 35% white, subhedral, medium-grained (0.2 cm to 0.5 cm) plagioclase phenocrysts of oligoclase-andesine composition ($An_{30-40}$) and 10%

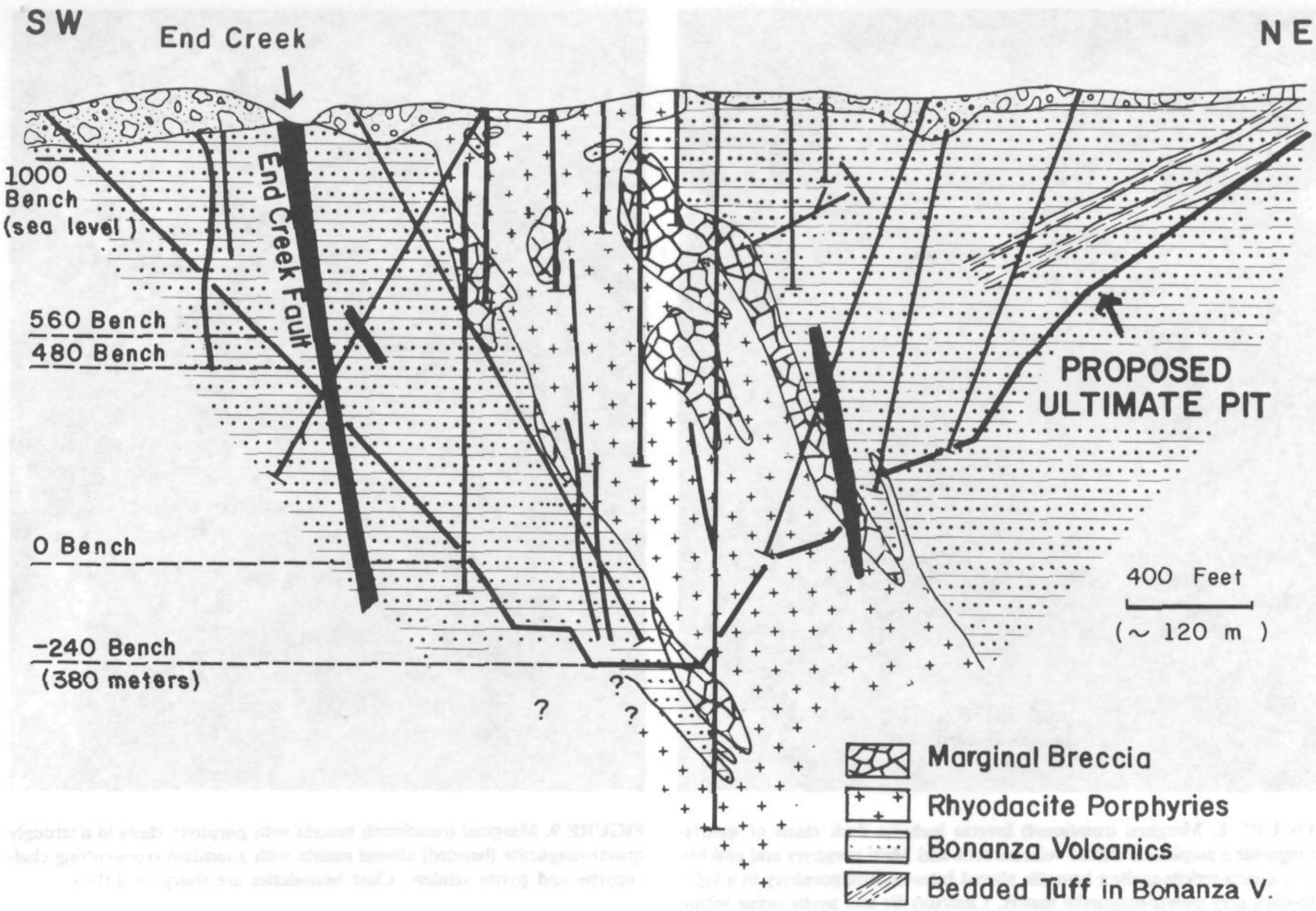



**FIGURE 7. Vertical section 173: Geology of the Island Copper deposit.**

or less of chloritized biotite phenocrysts up to 0.2 cm across in a groundmass of fine-grained quartz (10% to 25%) and K-spar (15% to 25%) or albite. Normative calculations indicate that the Main porphyry is rhyodacitic in composition (Arancibia, in prep.).

The Main porphyry is a dike-like intrusion >1200 m long and 100 m to 300 m thick. It strikes 320°, dips about 60° north, and is arcuate in longitudinal section, plunging both gently eastward and steeply westward. It has been intersected in drill holes to depths of at least 400 m below sea level (Fig. 7). This porphyry contains the most intense alteration and mineralization of the porphyry phases and is considered genetically related to the main Cu-Au-Mo event at Island Copper. It is characterized by intense magnetite-quartz stockwork, banded quartz-magnetite veins and/or flooding by disseminated magnetite that partly or totally destroys the porphyry texture, and lesser quartz-pyrite ± chalcopyrite-molybdenite-magnetite veins (Leitch et al., 1995).

Younger porphyry phases (Intra-mineral and Late-mineral) are sometimes distinguished from the Main porphyry by their coarser-grain sizes and the presence of more angular quartz phenocrysts. Intra-mineral porphyry contains minor quartz-magnetite veins, abundant quartz-pyrite ± chalcopyrite ± molybdenite veinlets and rare clasts of Main porphyry, and truncates quartz-magnetite veins (Leitch et al., 1995). Late-mineral porphyry lacks the quartz-magnetite stockwork, intense hydrothermal alteration and sulphide mineralization that characterize the Main and/or Intra-mineral porphyry bodies. Typically, Late-mineral porphyries intruded the core of the system to produce the "fresh core" of the Island Copper system (Perelló et al., 1989; Sillitoe, 1989b) (Figs. 12 and 23 a-c).

## Hydrothermal Breccias

Breccias are volumetrically significant at Island Copper. Two main types, Marginal and Pyrophyllite breccias, are generally recognized (Cargill, 1975; Cargill et al., 1976; Perelló, 1987), and are identifiable readily from textural, mineralogical and alteration features. In addition, scattered, steeply-dipping, northerly-striking pebble dikes cut Bonanza volcanic rocks beyond the limits of the Marginal breccias. They are generally <3 m thick, contain rounded clasts of rhyodacite porphyry, volcanic rocks and quartz, and are strongly chlorite-sericite-pyrite altered.

Marginal breccias include breccia bodies along the contact between the Main porphyry and Bonanza volcanics, as well as those within apophyses of the porphyry itself. Most of these breccias are distributed along the northern and western contacts (Fig. 6), and their volume decreases with depth (Fig. 7). Although typically magnetite-rich, Marginal breccias display a large range of composition depending on their location with respect to the rhyodacite porphyry. Three main types of Marginal breccia are differentiated (crackle, rotational and milled).

Crackle breccia, with little or no clast rotation, comprises stockworks of closely-spaced, quartz-amphibole-magnetite veinlets, and is developed mainly along the porphyry-wallrock contact. Rotational breccia occurs primarily at the west end of the deposit as a body, roughly oval-shaped in plan (Fig. 6) and semicircular in vertical section, overlying the steeply westward plunging Main porphyry dike (Padilla, 1993). It reached the pre-mined, subcrop surface, extends to a depth of at least 450 m below sea level and had a maximum size in plan of about 250 m by 350 m at a depth of 50 m to 120 m below sea level. The breccia (Fig. 8) is clast-supported (60% to 90% clasts), possesses varied proportions of subangular to subrounded clasts of mineralized andesitic volcanics and rhyodacite porphyry, mostly 1 cm to 20 cm and occasionally >1 m in diameter, and contains, locally, chalcopyrite and molybdenite veins cross-cutting both clasts and matrix. Local spheroidal clasts are interpreted as the products of hypogene exfoliation (Sillitoe, 1989b). The

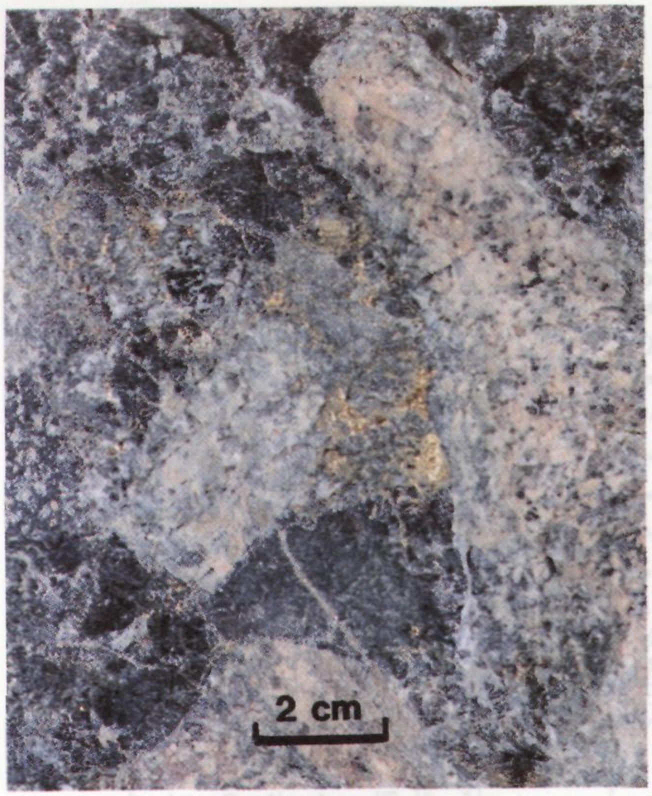



FIGURE 8. Marginal (rotational) breccia includes dark clasts of quartz-magnetite ± amphibole altered volcanic rock and Main porphyry and pinkish-tan, quartz-sericite-pyrite ± hematite altered Intra-mineral porphyry in a light-to-dark grey quartz-magnetite matrix. Chalcopyrite and pyrite occur within fragments and matrix.

FIGURE 9. Marginal (rotational) breccia with porphyry clasts in a strongly quartz-magnetite (banded) altered matrix with abundant cross-cutting chalcopyrite and pyrite veinlets. Clast boundaries are sharp to diffuse.

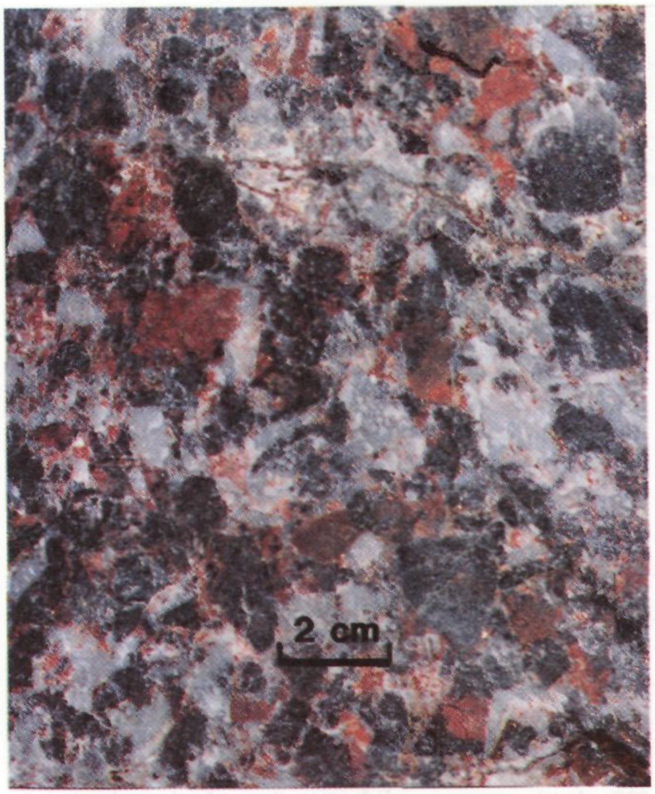



FIGURE 10. Marginal (milled) breccia with subangular to rounded dark clasts of quartz-magnetite-pyrite altered fine-grained volcanic(?) rock and white to grey, irregular clasts of clay-sericite-pyrite altered rhyodacite porphyry in a light grey, quartz-rich matrix.

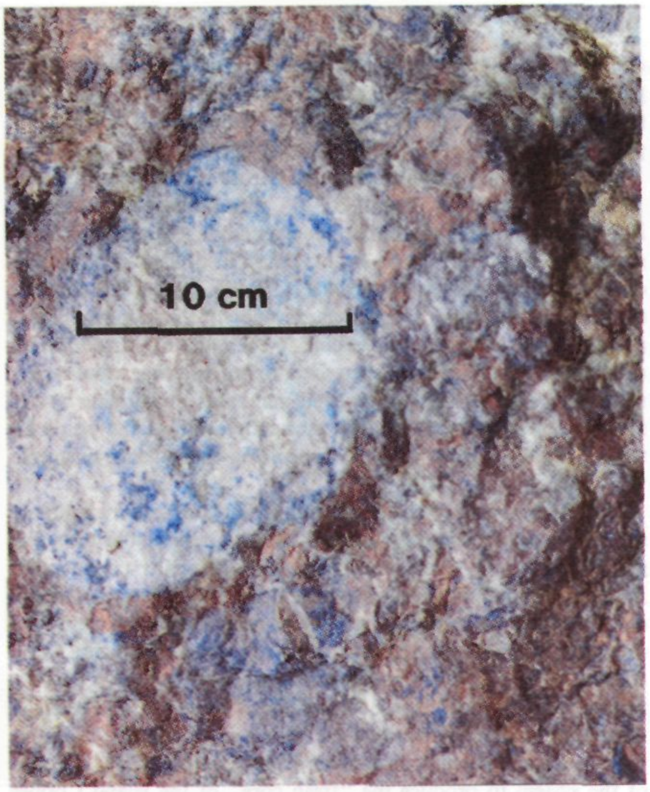



FIGURE 11. Pyrophyllite breccia with rounded, pyrophyllite (tan-grey) and dumortierite (blue) altered rhyodacite porphyry and volcanic rock fragments in a pyrophyllite rich matrix.

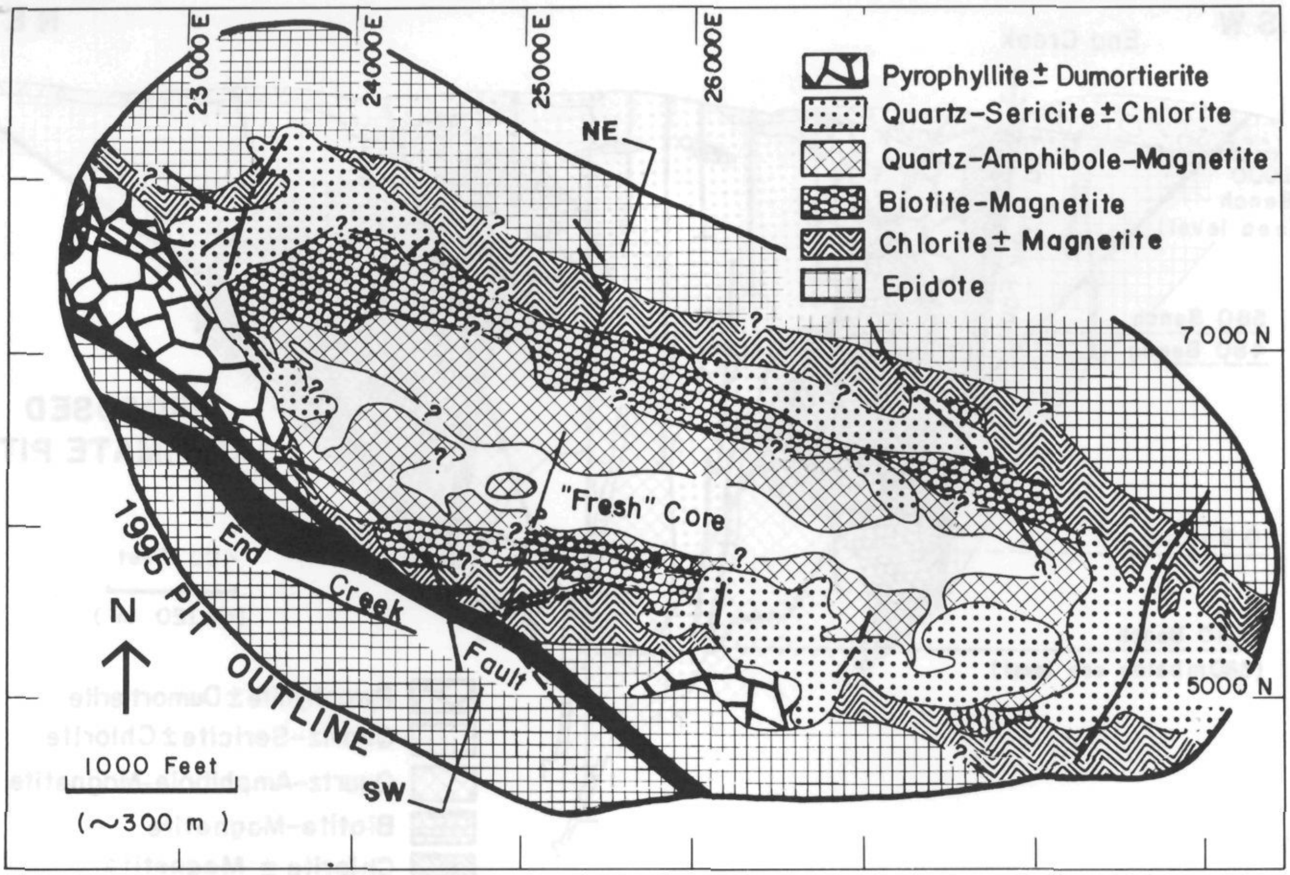



**FIGURE 12. Composite plan: Alteration types of the Island Copper deposit.**

matrix is commonly dark, quartz-magnetite altered (Fig. 9) and tourmaline-bearing (Arancibia and Clark, in prep.) or igneous (rhyodacitic) and, locally, intensely flooded with quartz. Milled breccia (Fig. 10) occurs within the rotational breccia. It comprises 60% to 80%, well sorted, subrounded to rounded, mineralized and unmineralized, black, quartz-magnetite-pyrite altered volcanic clasts and ragged, light-coloured, sericite-clay-pyrite altered rhyodacite porphyry clasts, 1 cm to 3 cm in diameter, in a grey quartz ± magnetite altered matrix.

Pyrophyllite breccia (Fig. 6) forms a funnel-like body of poorly-sorted, angular to subrounded clasts of Bonanza rocks, Late-mineral (unmineralized and unstockworked) rhyodacite porphyries and vein quartz which range from a few cm to more than 1 m in diameter (Fig. 11). Clasts of earlier breccias have not been recognized. The pre-alteration matrix is interpreted as rock flour, now transformed to pyrophyllite, kaolinite, sericite, dumortierite and irregularly distributed pyrite. Tourmaline has been identified in the lower reaches of the breccia (Arancibia and Clark, in prep.). The Pyrophyllite breccia cuts chlorite-altered Bonanza rocks, is truncated by the End Creek Fault (Fig. 6) and is intruded locally by a Late-mineral rhyodacite porphyry dike.

## Hydrothermal Alteration

Three main stages of alteration are identified at Island Copper (Perelló et al., 1989) (Figs. 12 and 13):

1. Early stage alteration, formed during intrusion of the Main porphyry, involved development of four roughly concentric alteration zones: stockworked quartz-amphibole-magnetite core, biotite-magnetite, chlorite ± magnetite and epidote.

The quartz-amphibole-magnetite stockwork occurs along the contact between the Main porphyry and Bonanza Group volcanic rocks (Figs. 12 and 13). Textures are partly preserved in quartz-magnetite-amphibole altered porphyry but almost totally obliterated in volcanic rocks. Vein stockworks are developed intensely and characterized by several generations of veins and veinlets containing quartz, actinolite, hornblende and albitic plagioclase. Minor apatite and scapolite also are observed. Chalcopyrite, pyrite and molybdenite are present locally, but neither copper nor molybdenum grades are significant. Mass balance calculations for this assemblage suggest gains of up to 450% Fe and 42% Na (Arancibia and Clark, 1990).

The biotite-magnetite zone is well developed in Bonanza rocks surrounding the quartz-amphibole-magnetite core, and grades outward to chlorite-dominated assemblages (Figs. 12 and 13). Biotite accompanied by albitic plagioclase, magnetite and minor amphiboles and K-feldspar occurs along hairline partings and veinlets, and as replacements of original ferromagnesian components. Most of the ore ($\geq 0.2\%$ Cu) at Island Copper is in this K-silicate alteration zone. In decreasing abundance main sulphides are chalcopyrite, pyrite and molybdenite.

Peripheral chlorite ± magnetite and epidote zones correspond to typical propylitic assemblages that surround porphyry-type deposits elsewhere. Both zones are developed in Bonanza rocks (Figs. 12 and 13) and are characterized by various combinations of chlorite, epidote, calcite and pyrite along with minor amounts of sodic plagioclase, amphiboles, magnetite and chalcopyrite. Primary textures of the rocks are partly obliterated, but plagioclase phenocrysts are recognizable. Ferromagnesian minerals are altered to chlorite, epidote and calcite. Copper grades in the chlorite and epidote zones average $<0.3\%$ Cu and $<0.1\%$ Cu, respectively.

2. Intermediate stage alteration and mineralization at Island Copper is characterized by various combinations and generations of quartz, sericite, kaolinite, illitic clays and chlorite accompanied by pyrite, molybdenite and minor chalcopyrite. This stage is recognized in two main forms: pervasive and structurally controlled quartz-

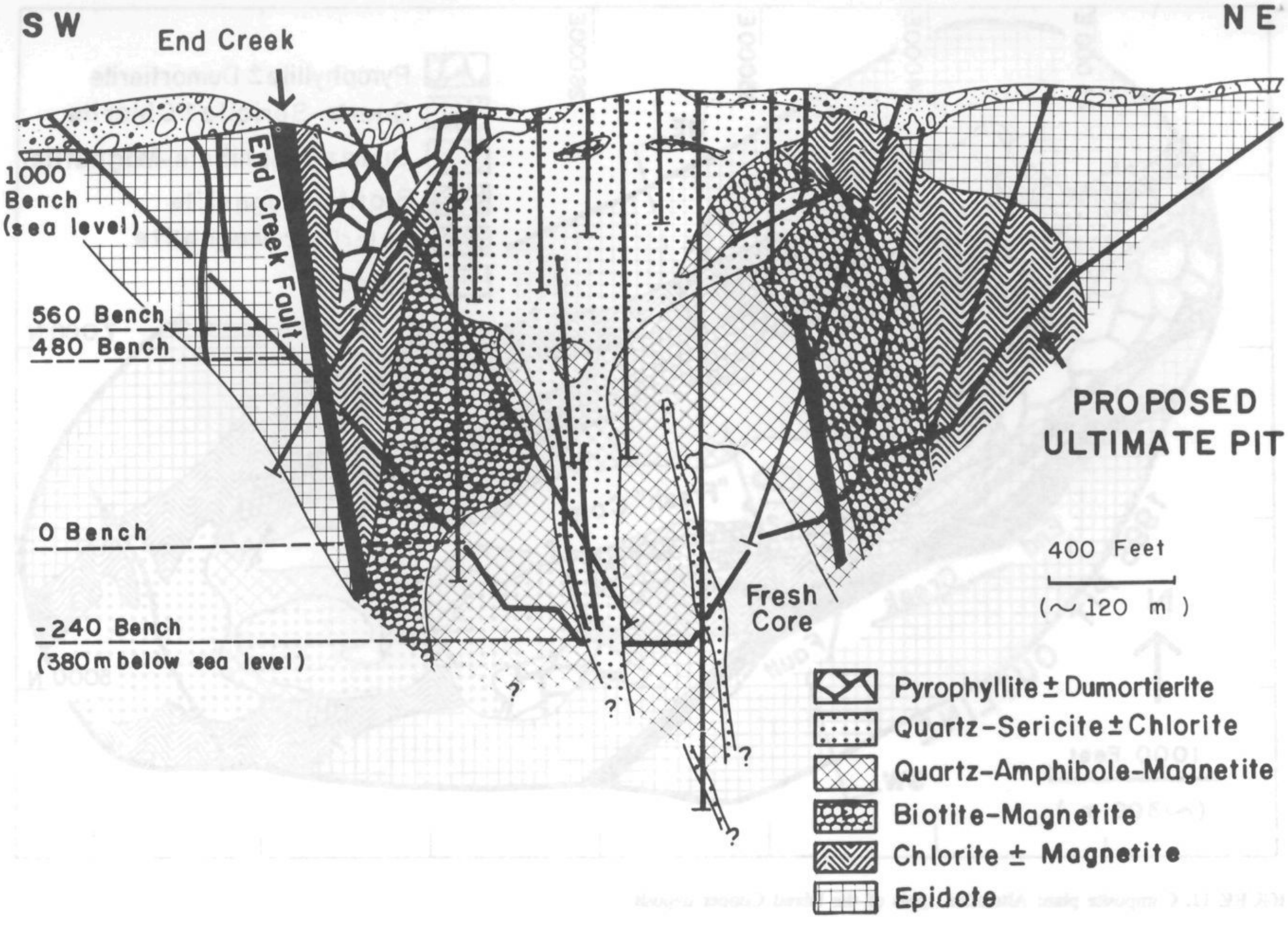



**FIGURE 13. Vertical section 173: Alteration types of the Island Copper deposit.**

sericite-pyrite, and pervasive sericite-clay (illite)-chlorite-pyrite (SCC; Sillitoe and Gappe, 1984). Both forms are observed as overprints on all pre-existing alteration and mineralization zones. The two types were recognized but were not routinely mapped separately before 1988 (Sillitoe, 1989b) and are therefore shown as one assemblage in Figures 12 and 13.

The quartz-sericite-pyrite assemblage typically destroyed textures and affected relatively small volumes of rock in the pit (Fig. 12). The assemblage is structurally controlled by faults, stockworks and hydrothermal breccias. Sericite imparts a white colour to the rock which contrasts with the greenish, soapy nature of sericite (and/or illite) characteristic of SCC alteration.

The SCC assemblage affected much larger rock volumes in the upper parts of the Island Copper system (Fig. 13). The assemblage overprinted Early-stage, feldspar-stable alteration, including the ore zone, and partly or totally destroyed biotite, amphiboles and feldspars, although rock texture was retained. Other effects include hematization (martitization) of magnetite, introduction of pyrite, and possibly some removal of copper and gold (cf., Sillitoe and Gappe, 1984).

3. Late stage alteration is restricted mainly to the Pyrophyllite breccia in the western part of the system (Figs. 12 and 13). The alteration is advanced argillic and is dominated by a texture-destructive assemblage of pyrophyllite, quartz, sericite, kaolinite and dumortierite. Lowermost levels of this alteration type are dumortierite-free but contain trace tourmaline (Arancibia, in prep.).

Later, lower-temperature alteration stages recognized in the pit include ankerite-calcite in fracture-related veins (the "Yellow Dog breccia" of Cargill et al., 1976), zeolites, and precipitation of remobilized (possibly from the fossiliferous Parson Bay Formation), carbon-bearing organic compounds of gilsonite type (Fleming, 1983).

## Copper and Molybdenum Mineralization

Several generations of copper- and molybdenum-bearing veinlets have been distinguished at Island Copper (Cargill, 1975), although only one important stage of copper introduction is currently recognized. This stage deposited quartz-chalcopyrite-magnetite-pyrite, quartz-chalcopyrite-pyrite-biotite ± K-feldspar and chalcopyrite-pyrite ± magnetite ± molybdenite veinlets lacking alteration selvages (Arancibia, in prep.). This copper stage was followed by molybdenum introduction in quartz-molybdenite-pyrite-chalcopyrite veinlets with distinct quartz-sericite haloes and, later and more importantly, in molybdenite-pyrite-chalcopyrite veinlets. Molybdenite is present mainly along veinlet margins, as in the B-type veins described by Gustafson and Hunt (1975) at El Salvador, Chile, and on slip surfaces. Copper and molybdenum zones overlap (Figs. 14a, 14b) because of the close spatial relationship between chalcopyrite and molybdenite.

Most of the ore at Island Copper is contained within the biotite zone and, in general, the more intense the brown colour of the rock, the more strongly developed the biotitization and copper mineralization. Ore occurs as an annulus around a low-grade to barren core, which splits into two separate ore limbs at depth (Fig. 15). Copper grades within the ore shell define inner, higher grade zones giving way outward to lower grade mineralization. Most of the copper ore occurs as chalcopyrite (see above), typically as fine, disseminated grains and hairline fracture fillings in the groundmass of the volcanic rocks or in primary ferromagnesian sites. Bornite occurs in the deposit, usually in the Marginal breccias, but only in minor amounts. Because of the close association of copper with biotite alteration, including the presence of chalcopyrite-biotite veins, it is believed that most copper mineralization and K-silicate alteration are temporally coincident.

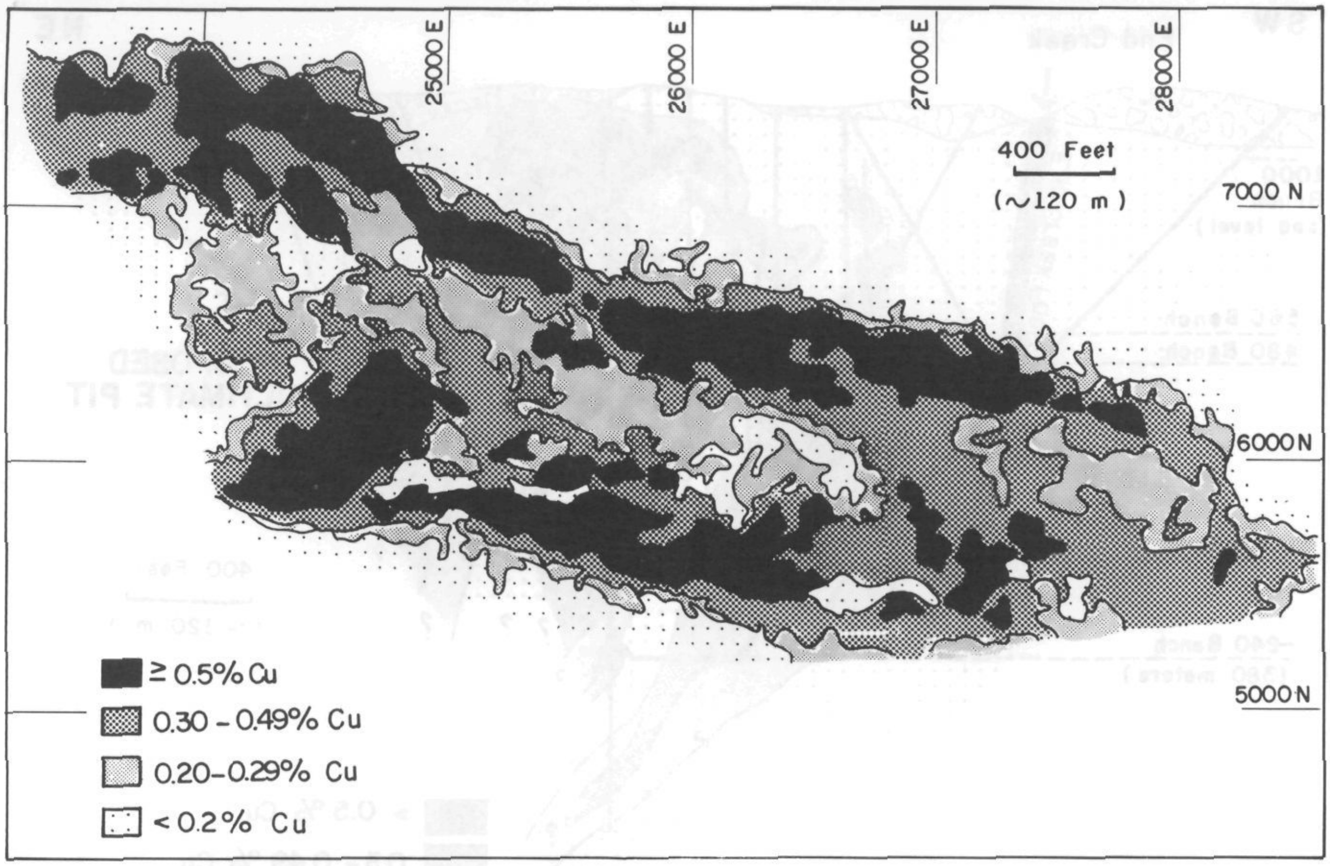



**FIGURE 14a. 560 bench plan: Copper distribution in the Island Copper deposit.**

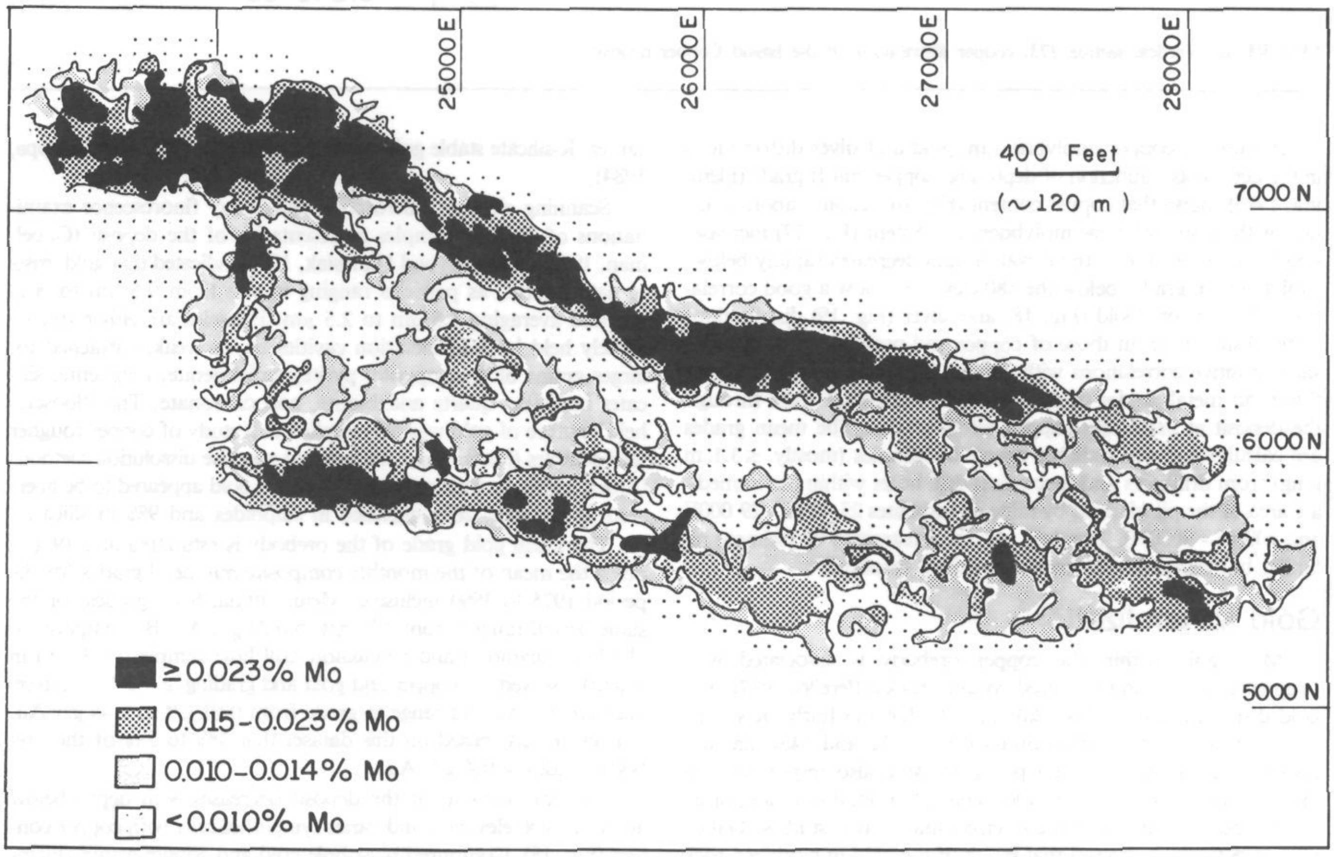



**FIGURE 14b. 560 bench plan: molybdenum distribution in the Island Copper deposit.**

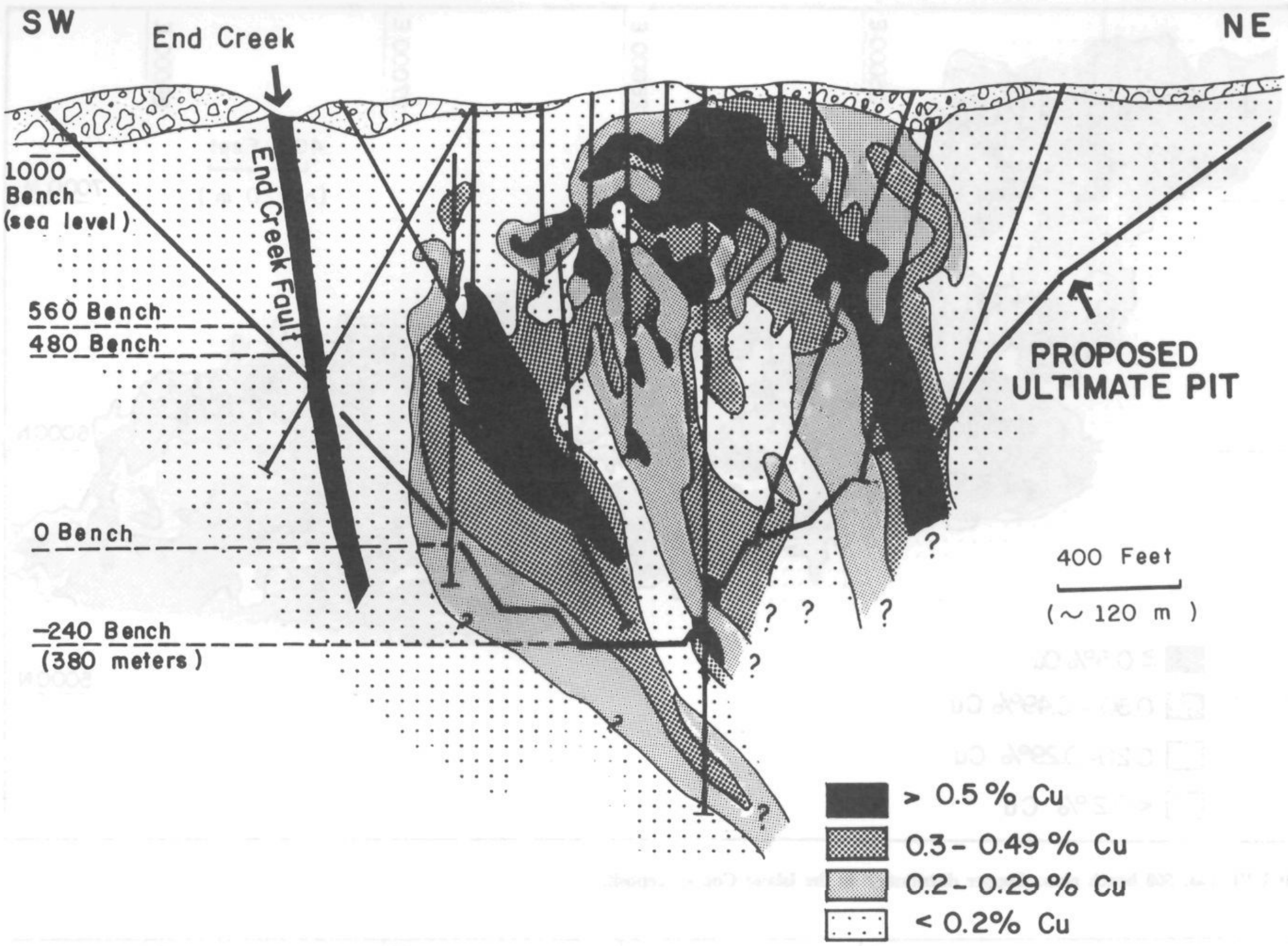



**FIGURE 15. Vertical section 173: copper distribution in the Island Copper deposit.**

A study of copper, molybdenum, gold and silver distributions in the deposit as a function of depth and copper cutoff grade (Fleming, 1995) shows that copper content (Fig. 16) remains about constant with depth, whereas molybdenum content (Fig. 17) increases steadily to about the −160 elevation and decreases rapidly below. Molybdenum grades below the 880 elevation show a good correlation with copper. Gold (Fig. 18) and silver (Fig. 19) distributions differ distinctly from those of copper and molybdenum, but also show positive correlations with copper. The data points represent the mean metal grades of 60.1 m-thick, horizontal slices through the deposit at increasing copper cutoff grades. The mean grades are calculated from available assays of samples (mostly ≤3.1 m long) from drillholes and percussion drill holes within the immediate area of the pit (defined by mine co-ordinates 23 400E - 29 000E and 4000N - 9000N). The data are not constrained by ultimate pit limits, but represent the entire, as-drilled resource.

## Gold Mineralization

Most gold within the copper orebody is associated with magnetite-bearing and biotitized volcanic rocks (Perelló, 1987). The gold distribution (e.g., Fig. 20) suggests that the Early, K-silicate alteration and copper mineralization (Figs. 12 and 14a) that followed intrusion of the Main porphyry were also responsible for introduction of most of the gold. This interpretation is supported by microscopic and scanning electron microscope studies (Gabelman, 1982) which showed that much of the gold in biotitized rock is intimately associated with biotite. Higher gold grades (≥0.4 g/t) are associated locally with quartz-sericite stockworks in porphyry and adjacent volcanic rocks. It is unknown whether this gold was introduced into the system or hydrothermally remobilized from the earlier, K-silicate stable gold mineralization (cf., Sillitoe and Gappe, 1984).

Scanning electron microscope and X-ray fluorescence examinations of 26 rock samples representative of the deposit (Gabelman, 1982; Gabelman and Hanusiak, 1986) indicated that gold exists in native form, as particles ranging in size from 0.5 μm to 20.8 μm and averaging 1.5 μm to 2.5 μm. Particles are either free or loosely held in fluid inclusion cavities in, or weakly attached to, larger grains of chalcopyrite, pyrite, molybdenite, magnetite, silicates including quartz and biotite, and carbonate. The "loosely-held" nature of gold was also implied in a study of copper rougher feed samples (Ratte et al., 1982), using selective dissolution methods (Bruce, 1976), in which about 65% of the gold appeared to be liberated or exposed, 26% enclosed in sulphides and 9% in silicates.

The mean gold grade of the orebody is estimated at 0.19 g/t, being the mean of the monthly composite mill head grades for the period 1975 to 1994 inclusive. Mean annual head grades for the same period ranged from 0.10 g/t to 0.28 g/t Au. By comparison, all (3345) diamond and percussion drill hole samples (≤3.1 m in length), assayed for copper and gold and grading ≥0.2% Cu, average 0.16 g/t Au and range in grade from 0.01 g/t to 1.44 g/t Au. It is estimated, based on this dataset that 3% to 5% of the orebody grades ≥0.4 g/t Au.

The gold content of the deposit decreases with depth below about the 440 elevation and varies sympathetically with copper content (Fig. 18). Contoured blast-hole gold and copper assays (Fleming, 1983; Perelló, 1987) show, in general, a spatial correlation (e.g., Fig. 20). The correlation coefficient between gold and copper, calculated from 5031 diamond and percussion drill hole sample assays from throughout the deposit, is 0.50. The above factors

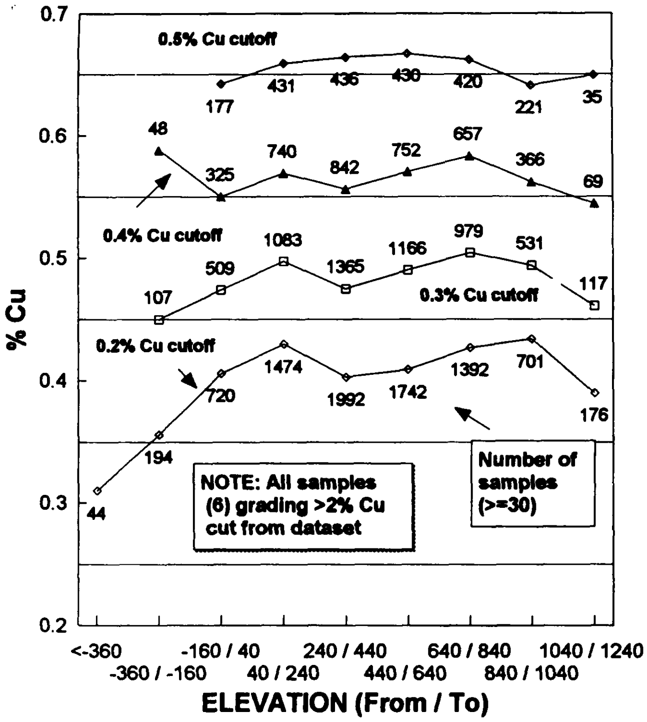



FIGURE 16. Copper distribution in the Island Copper deposit as a function of depth and copper cutoff grade.

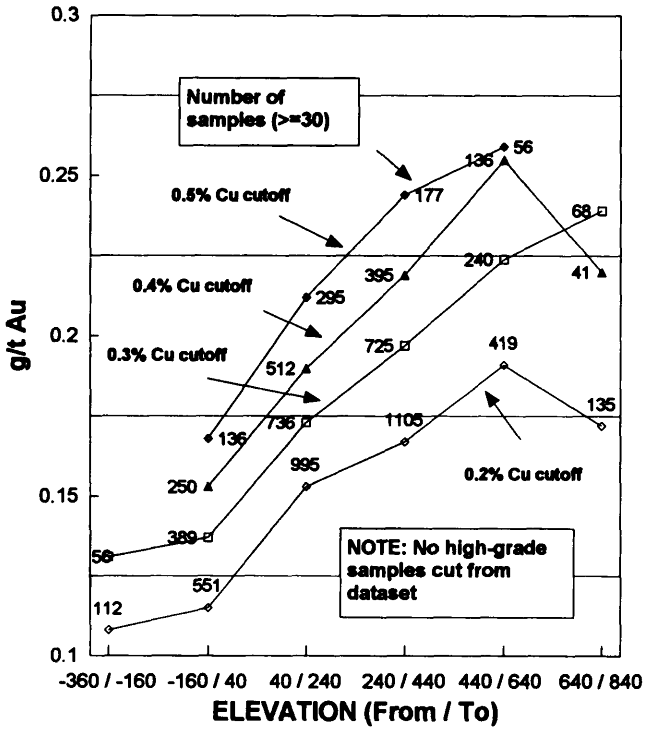



FIGURE 18. Gold distribution in the Island Copper deposit as a function of depth and copper cutoff grade.

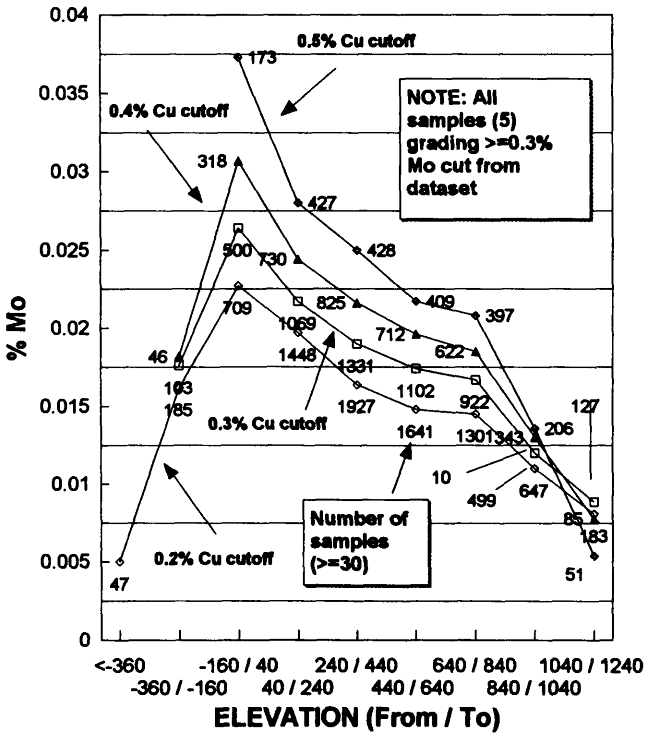



FIGURE 17. Molybdenum distribution in the Island Copper deposit as a function of depth and copper cutoff grade.

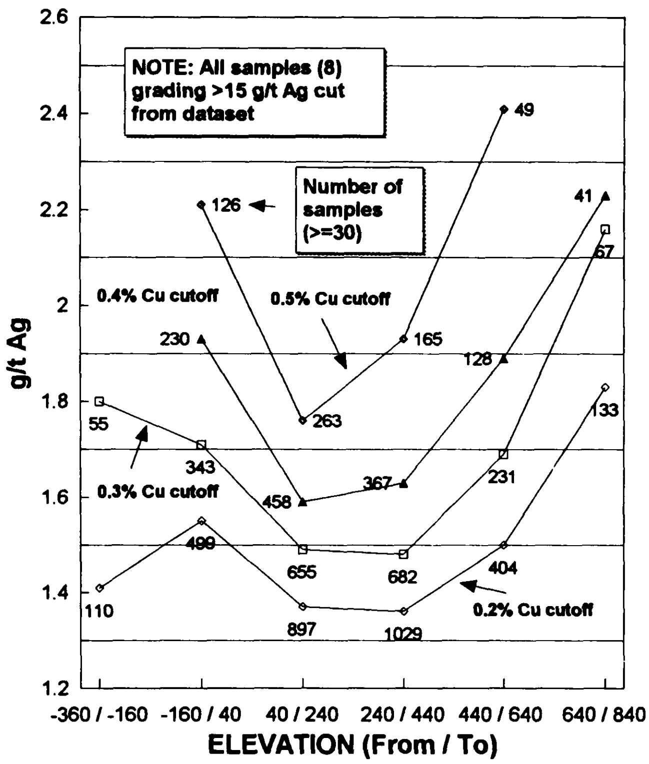



FIGURE 19. Silver distribution in the Island Copper deposit as a function of depth and copper cutoff grade.

corroborate the substantial decrease in gold head grade (see Production) experienced as a result of mining deeper in the deposit and reducing the copper cutoff grade from 0.3% to 0.2% Cu.

## Geology of G Zone and Bay Lake

The G zone and Bay Lake (Fig. 5) make up two separate porphyry centres partly exposed in the Bay Lake area, between 300 m and 1200 m, respectively, from the Island Copper pit (Perelló, 1989). These two systems extend for about 2000 m in a northwest direction, and coincide with the two magnetic highs along the north shore of Bay Lake (Fig. 4).

### Rock Types

Both porphyry centres are similar geologically to Island Copper. They are associated with quartz-bearing rhyodacite porphyries

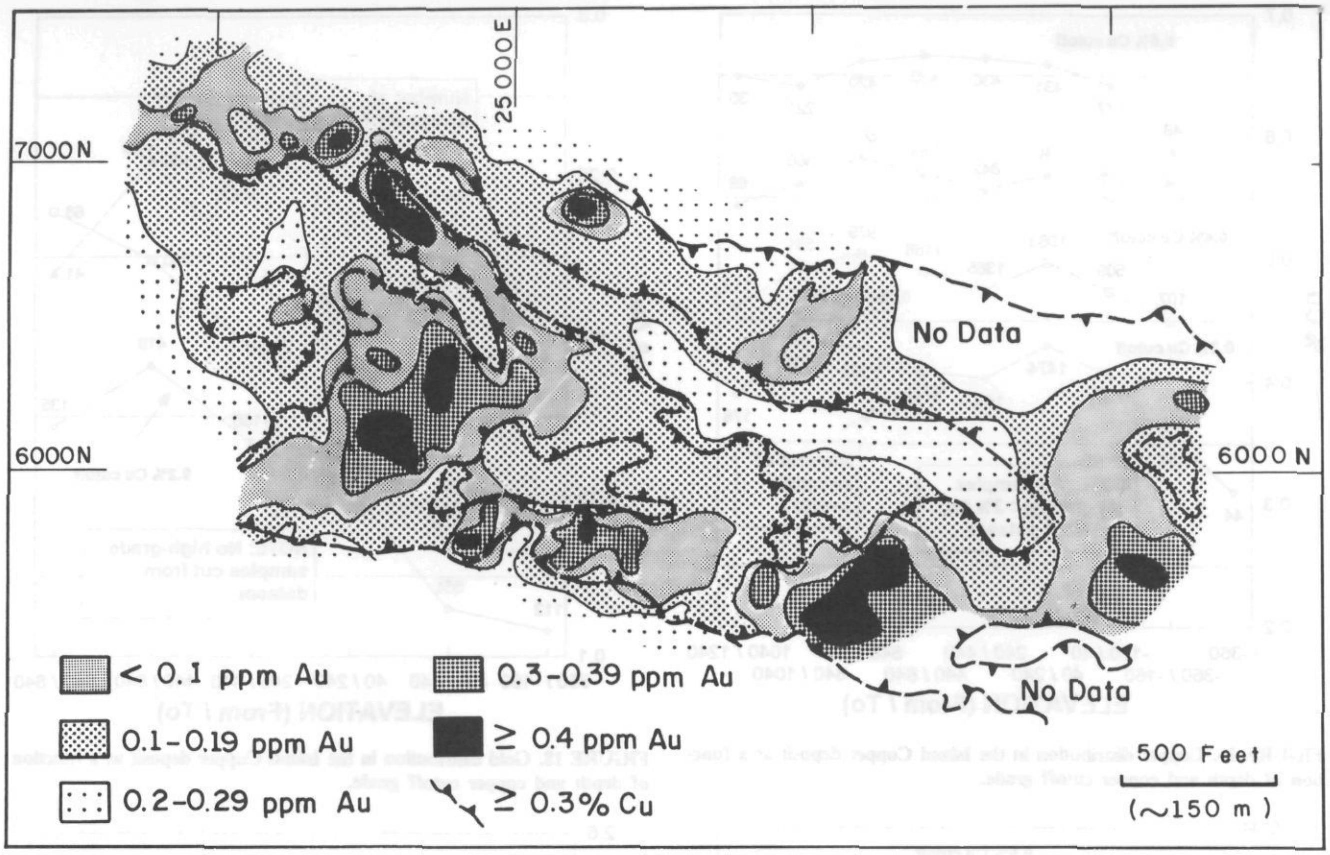



**FIGURE 20. 560 bench plan: gold distribution in the Island Copper deposit.**

that cross-cut basaltic flows and volcaniclastics of the Bonanza Group. Late-mineral rhyodacite intrusions have also been detected in the cores of the systems (Perelló, 1989), as at Island Copper. Much of the porphyry is not exposed at surface, but has been intersected by drill holes (Figs. 21a and 22a).

## Hydrothermal Alteration

The two porphyry systems are characterized by the alteration pattern shown in Figures 21b and 22b (Perelló, 1988; 1989):

1. A "fresh"-looking core bordered by moderately to intensely stockworked zones of quartz-amphibole-pyroxene-magnetite alteration developed in both Main porphyry and volcanic wallrocks. The core coincides with a Late-mineral dike. Vein-controlled, hydrothermal diopside, hornblende and actinolite are common constituents of the stockworked zone together with appreciable dispersed albitic feldspar and apatite. In places, the amphibole textures may be interpreted as evidence for a pyroxene precursor (C.H.B. Leitch; pers. comm., 1989).
2. This pyroxene and amphibole-bearing zone grades outward to a biotite-magnetite-dominated assemblage developed mainly in volcanic wallrocks. Fine-grained brownish biotite occurs as pervasive replacements of the rock matrix and as millimetric to centimetric veinlets. Magnetite is either disseminated or vein-controlled. Minor quartz-amphibole-magnetite veining persists because the contact with the inner alteration zone is transitional.
3. The biotite zone grades outward to chloritic volcanic rocks, characteristically containing moderate amounts of disseminated and veinlet magnetite. Carbonates, zeolites and epidote increase outward as the outermost epidote zone is approached.

Rock types in the G zone exert a control on alteration minerals. Thus, biotite is best developed in the volcanic units whereas hedenbergitic pyroxene and minor garnet occur locally within limy volcaniclastic interbeds.

Intermediate stage alteration in both systems consists of both structurally controlled and pervasive quartz-sericite-pyrite and SCC assemblages, which overprint earlier alteration and are associated with major fault zones (e.g., ECF and WBS; Fig. 2). Late-stage alteration is characterized by structurally-controlled zeolite and carbonate veining.

## Copper, Molybdenum and Gold Mineralization

Copper (Figs. 21c and 22c) follows the alteration geometry described above. Most copper is confined to the biotite zone and the inner part of the chlorite zone. The quartz-magnetite-dominated core of the system and the outermost epidote zone generally grade less than 0.1% Cu. Similarly, late-stage sericitic and intermediate argillic assemblages contain no copper and are interpreted to have been copper-destructive, but these assemblages contain pyrite.

Nearly all copper discovered is present as fine-grained disseminations, veinlets and veins of chalcopyrite, commonly with pyrite and magnetite. Veins and veinlets containing biotite, amphibole, chalcopyrite, magnetite and minor pyrite and bordered by albite are common. Replacement of ferromagnesian phenocrysts by chalcopyrite, magnetite and pyrite is also widespread. The average grades of drill core from the G zone and the hangingwall portion of the Bay Lake system above the 500 m elevation are 0.26% Cu and 0.25% Cu, respectively, at a 0.2% Cu cutoff. The footwall limb (Fig. 21c) of the Bay Lake system, however, averages 0.35% Cu and looks very similar to Island Copper biotite-zone ore.

Most molybdenite is present within quartz ± pyrite veins, with only minor amounts as disseminated grains or coatings on fractures. A comparison of copper and molybdenum assays from Bay Lake and G zone drill core grading ≥ 0.2% Cu shows that molybdenum correlates well with copper, as at Island Copper, although the average molybdenum grades of 0.008% to 0.013% Mo are lower than the Island Copper average of 0.017% Mo.

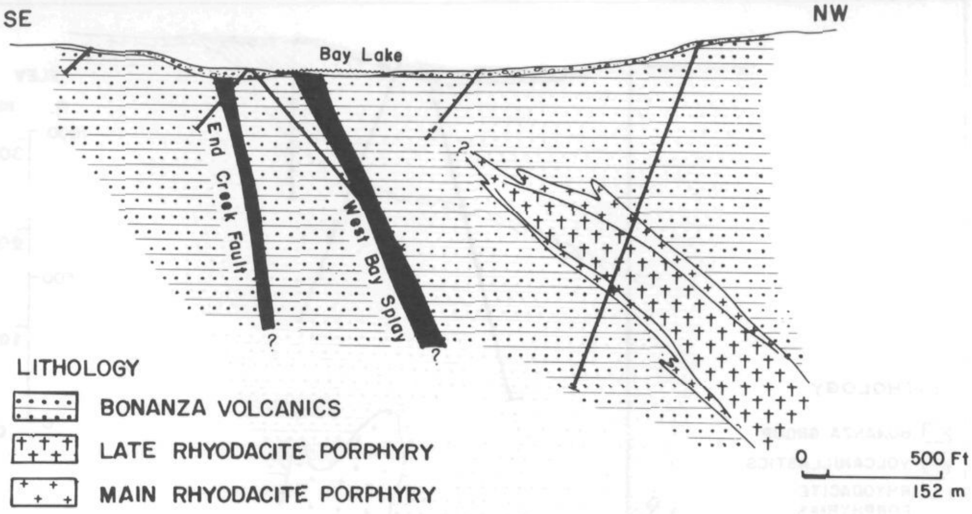



**FIGURE 21a. Vertical section 241: Geology of the Bay Lake porphyry centre.**

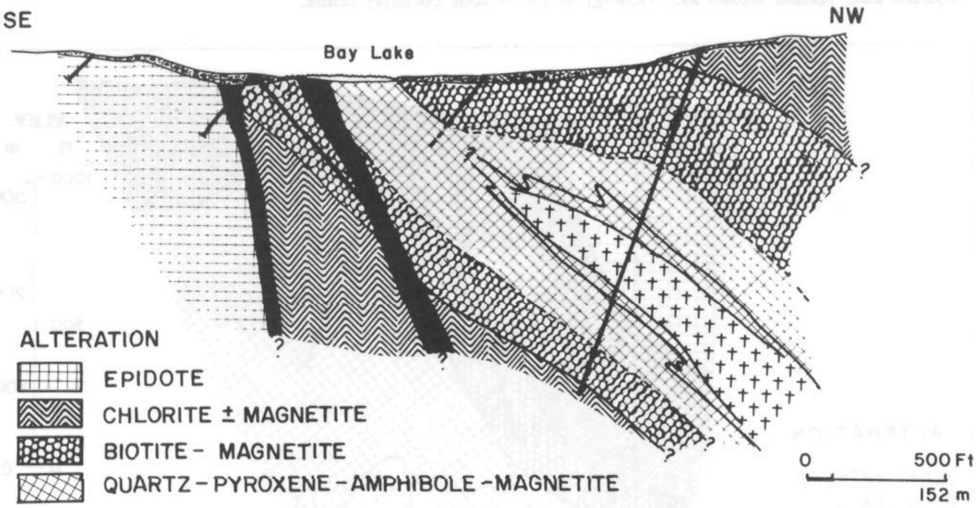



**FIGURE 21b. Vertical section 241: Alteration types of the Bay Lake porphyry centre.**

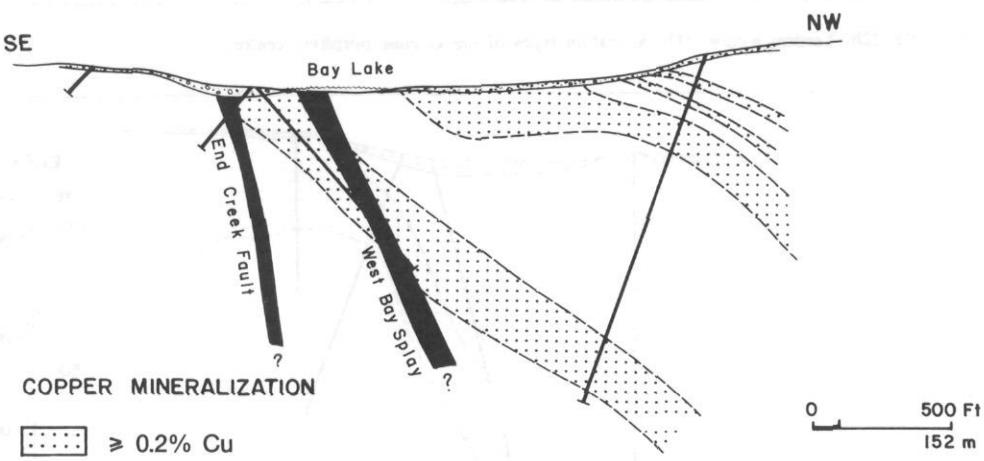



**FIGURE 21c. Vertical section 241: Copper distribution in the Bay Lake porphyry centre.**

Gold grades at Bay Lake and G zone are considerably lower than those at Island Copper, averaging <0.12 g/t. Nevertheless, as at Island Copper, gold and copper grades have an overall sympathetic relationship, and most of the gold probably is present as particles associated with chalcopyrite in K-silicate alteration.

## Geology of Red Island

The Red Island porphyry centre lies immediately southeast of the Island Copper pit (Fig. 1) and makes up a porphyry system that is projected, based on drill hole data, to extend from the Is-

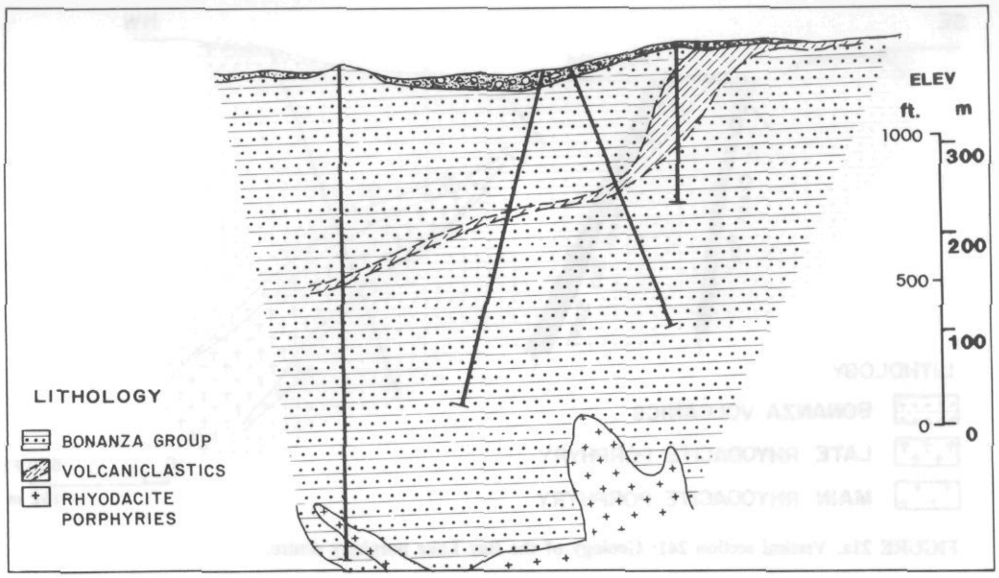



**FIGURE 22a. Vertical section 213: Geology of the G zone porphyry centre.**

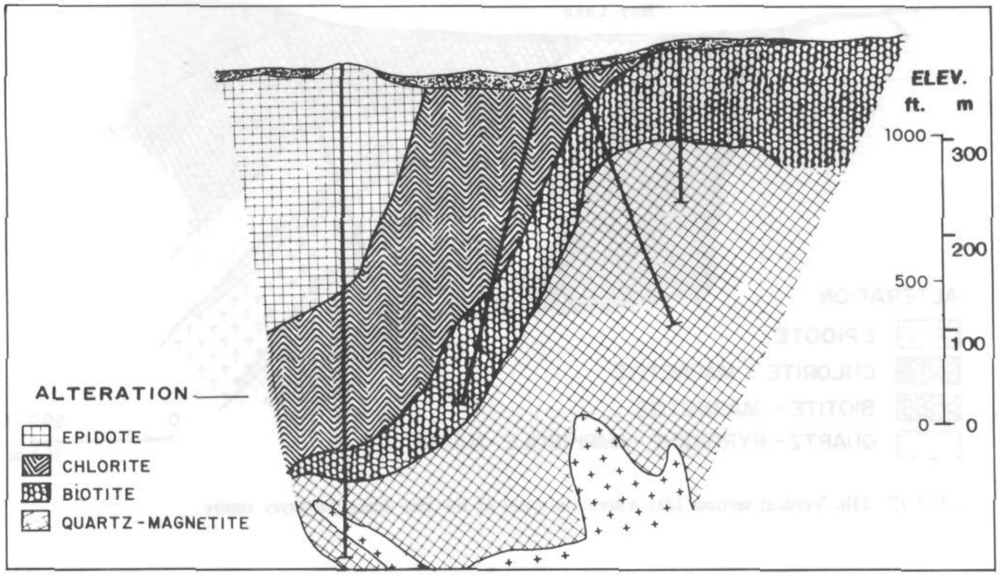



**FIGURE 22b. Vertical section 213: Alteration types of the G zone porphyry centre.**

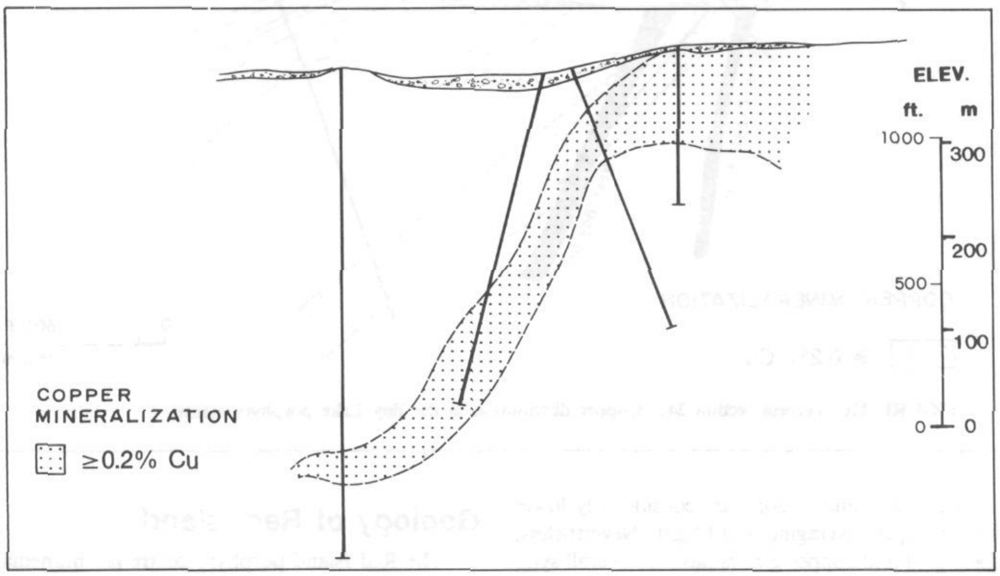



**FIGURE 22c. Vertical section 213: Copper distribution in the G zone porphyry centre.**

land Copper pit to east of Red Island (Fig. 5). The centre underlies both Rupert Inlet and the foreshore, and is marked by a strong aeromagnetic anomaly (Fig. 4) caused by chalcopyrite-bearing, quartz-magnetite breccia at the eastern end of this system in Red Island. Alteration assemblages similar to those developed in the Island Copper centre are zoned around the porphyries, and Cu-Mo-Au mineralization occurs mainly in altered Bonanza Group volcanics and Marginal breccia.

### Rock Types

The Red Island porphyry centre consists of at least two, subparallel, dike-like, west-striking and north-dipping rhyodacite porphyry bodies intruded into Bonanza Group basaltic tuffs and massive feldspar-phyric basalt flows. One porphyry body underlies Red Island and extends westward to the pit, its upper contact plunging to the west, and a smaller porphyry body lies about 450 m north of the Island. Marginal breccia exposed in Red Island is intensely quartz-magnetite altered and consists mainly of rotated volcanic clasts.

The rhyodacite porphyries are interpreted, based on differences in the intensity of alteration and mineralization, to comprise phases corresponding to the Main and Intra-mineral porphyries of the Island Copper centre. Only minor volumes of Late-mineral porphyry are identified. The Main porphyry at Red Island is silicified and cut by quartz-magnetite ± chalcopyrite veinlets and stockworks, and intruded by Intra-mineral porphyry. The latter lacks quartz-magnetite veining and is less intensely altered and mineralized than the Main porphyry. Granodiorite occurring at depth in the centre is probably part of the weakly mineralized Rupert Stock, which is a possible end-stage intrusion that truncated the Red Island system at depth (Sillitoe, 1989b).

### Hydrothermal Alteration

Hydrothermal alteration is considered to represent the Early and Intermediate stages of the Island Copper system. The Late stage alterations are not present in this system, although later stage zeolite and calcite veins crosscut Early and Intermediate stage assemblages.

Early stage alteration produced four concentric zones that are similar to, but not as clearly defined as, the zones at Island Copper. The inner, quartz-magnetite-amphibole stockwork zone is only observed at the east end of the Red Island system, mainly in Marginal breccia, and amphibole is not everywhere present. Alongside is an extensive zone, characterized by magnetite-amphibole ± biotite ± albite ± quartz ± chlorite, in which early biotite appears cut by quartz-magnetite ± apatite veinlets with albite-amphibole envelopes (Leitch, 1990). This zone is bordered by a narrow biotite-magnetite zone that, in turn, gives way outward to chlorite ± magnetite and epidote zones.

Intermediate stage alteration, both structurally controlled and pervasive, is a superimposed sericite-chlorite-pyrite ± clay (SCC) assemblage affecting volcanic rocks in the western part of the system and the Main porphyry underlying Red Island. It is characterized by dark green altered tuff clasts and light green altered matrix in the volcanic rocks and dark to light green altered ferromagnesian and feldspar phenocrysts in the porphyry. Tuff and porphyry textures along with sulphides are generally preserved, although magnetite is martitized.

### Copper, Molybdenum and Gold Mineralization

Copper occurs entirely in chalcopyrite, mainly as veinlets and fracture fillings, with or without magnetite, in amphibole-magnetite-albite-chlorite ± biotite altered volcanic rocks. Lesser amounts occur as disseminated grains accompanying chlorite after amphibole and in quartz-pyrite ± molybdenite veinlets. Chalcopyrite also appears associated with late-stage fracturing and the introduction of pyrite, chlorite, epidote, sericite, calcite and dolomite (Leitch, 1990). The average copper and molybdenum grades of all diamond drill core assaying ≥0.20% Cu are 0.35% and 0.009%, respectively, both significantly lower than the Island Copper averages. Small volumes of Marginal breccia are cut by quartz-magnetite-chalcopyrite-molybdenite veinlets and stockworks with copper grades exceeding 1%. Molybdenite occurs mainly in quartz ± pyrite ± chalcopyrite veinlets and as coatings, with or without chalcopyrite, on fractures. Quartz-molybdenite veinlets cross-cut magnetite-amphibole veinlets. Gold grades are generally in the 0.10 g/t to 0.30 g/t range, but locally attain 2 g/t. Statistical correlation of the gold and copper grades of drill core samples is poor.

## Geology of the A Zone

The A zone comprises a fault-controlled, near-surface, high-grade copper-(silver) vein occurrence within an area 300 m by 250 m in size on the periphery of the Bay Lake porphyry system (Fig. 5). Mineralization is predominantly massive to semi-massive chalcopyrite veins with lesser pyrite, martitized magnetite, and minor sphalerite and gold hosted by Bonanza Group andesitic tuffs and flows. The position of the veins on the south side of the postmineral End Creek Fault makes it difficult to relate them to a specific porphyry system.

### Hydrothermal Alteration

The host rock is weakly to moderately altered to chlorite-epidote, but contains intense epidote-calcite ± zeolite alteration along a fracture zone on the west side of the system. Chlorite, sericite and clay occur in or adjacent to sulphide veinlets, and correlate with Intermediate stage sericite-pyrite and SCC types at Island Copper. The chlorite and sericite in the veins suggest that vein formation took place in a SCC-stable environment.

### Mineralization

The mineralization occurs mainly as chalcopyrite and pyrite veins up to 30 cm thick in three, north-striking, steeply-dipping faults up to 300 m long, 15 m wide and extending discontinuously to a depth of at least 90 m. The highest grade trench sample was 3.6% Cu over an interval of 30 m (includes 16% Cu and 120 g/t Ag over 6 m) and the highest grade drill hole intercept was 11.1% Cu over 7 m. Silver content varies almost linearly with copper. Subsidiary structures are also mineralized but are thinner and less continuous. Other forms and types of sulphide mineralization in the A zone include chalcopyrite-pyrite-calcite ± sphalerite stringers with chlorite or ankerite envelopes, chalcopyrite-pyrite as fracture coatings, chalcopyrite disseminations and late-stage(?) pyrite ± chalcopyrite veins in narrow (< 1 cm) structures with intense sericite-clay-pyrite envelopes.

## Geology of the Northwest Zone

The Northwest zone (Fig. 5) is a large, mineralized, porphyry Cu-Mo system. In contrast to the other centres in the ICC, this centre is mainly within Vancouver Group rocks. Branching, west-northwest-striking, north-dipping rhyodacite porphyry dikes, similar in composition to Late-mineral phases of the Island Copper porphyry, have been intersected by drill holes over a strike length of more than 1800 m. A strong, central, magnetic anomaly (Fig. 4) rimmed by a horseshoe-shaped chargeability high coincides with the zone and is explained by the moderate to high magnetite and pyrite contents zoned around the porphyry dikes. Copper skarn and porphyry Cu-Mo mineralization are also zonally distributed about the porphyry intrusions. The centre contains abundant molybdenite in quartz-pyrite veins.

### Rock Types

The zone is underlain by a gently south-dipping sequence of Quatsino Formation limestones and interbedded volcanic rocks over-

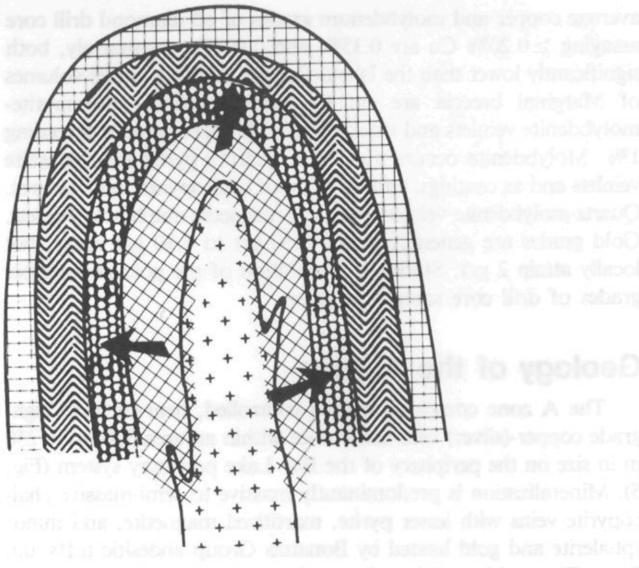


**FIGURE 23a. Schematic section: Evolution of the Island Copper deposit — Early Stage.**

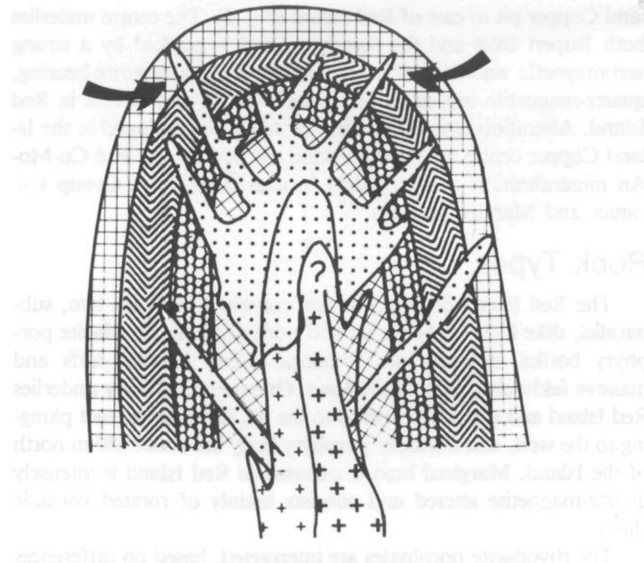


**FIGURE 23b. Schematic section: Evolution of the Island Copper deposit — Intermediate Stage.**

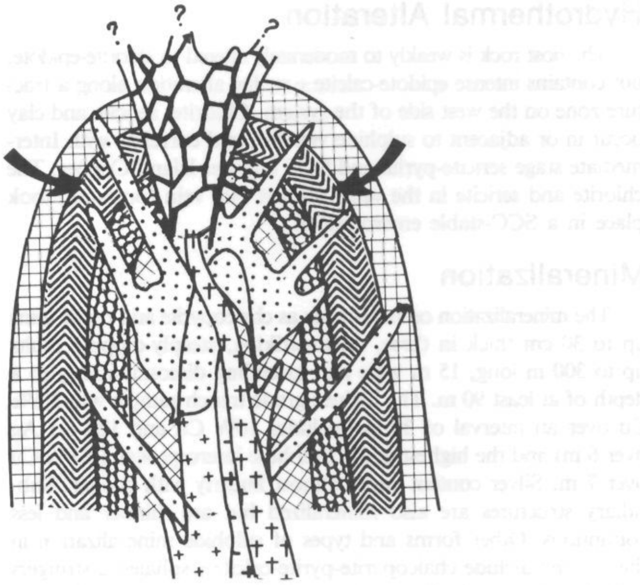
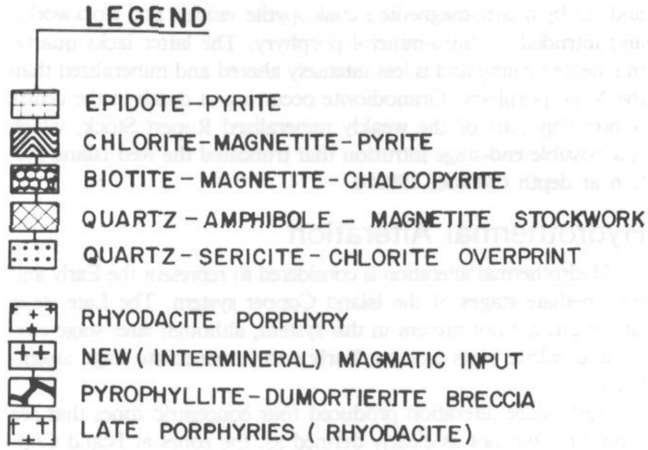


**FIGURE 23c. Schematic section: Evolution of the Island Copper deposit — Late Stage.**




lain by Parson Bay calcareous and carbonaceous shales, siltstones and interbedded volcanic rocks. Hornblende porphyry dikes and sills that predate the rhyodacite porphyry-related hydrothermal alteration are common in these units.

More than one phase of altered and/or mineralized porphyry is present, equivalent to the Main or Intra-mineral porphyries in the other centres. A weakly altered and copper-deficient phase equivalent to Late-mineral porphyry is the most abundant type seen in outcrop and drill core. Although no cross-cutting intrusive relationships are recognized, mineral zonation around late-mineral porphyries suggests that these porphyries intruded and consumed the earlier phases responsible for the alteration, as in the Island Copper and Bay Lake systems.

## Hydrothermal Alteration

The extensive, varied and zoned alteration and mineralization in the Northwest zone reflects mainly the composition of protoliths, distance from intrusions, and stage of mineral formation with respect to porphyry intrusion (Fleming and Clarke, 1989). Alteration assemblages typical of copper skarns (e.g. Einaudi et al., 1981) are dominant and include andradite garnet ± diopsidic pyroxene skarn developed in Quatsino limestones, and pyroxene ± garnet hornfels and skarn in the calcareous shales of the Parson Bay Formation. Changes in skarn mineralogy with increasing distance from intrusions include decreasing garnet/pyroxene, chalcopyrite/pyrite, magnetite/hematite and Cu:Zn ratios, and a gradation in andradite garnet colour from dark reddish-brown next to intrusions through brown to greenish-yellow near the marble front (Meinert, 1986). These changes occur over distances of up to about 800 m away from and perpendicular to the intrusive contacts. Changes in garnet colour also occur over shorter distances across strata away from contacts with volcanic units. Porphyry-style alteration zonation, similar to that at Island Copper, is developed to varying degrees in interbedded volcanic rocks, hornblende porphyry dikes and sills, overlying Bonanza Group volcanics and underlying Karmutsen basalts.

Three main stages of alteration and mineralization are interpreted for the Northwest zone. These equate to the metamorphic-metasomatic-retrograde evolutionary stages characteristic of skarn deposits (Meinert, 1983):

1. Metamorphic stage generated marble in Quatsino limestone, bleached (decarbonized) and developed calc-silicate hornfels in Parson Bay calcareous and carbonaceous shales, hornfelsic(?) biotite in volcanic strata, and recrystallized siltstone to quartzite. Carbon removed from sedimentary rocks at this stage is probably the source of pyrobitumen found in Bonanza volcanic rocks. No sulphide mineralization is identified with this alteration stage.
2. Metasomatic-stage alteration and mineralization is represented mainly by garnet ± pyroxene ± magnetite skarn in limestone, pyroxene ± garnet ± magnetite skarn in calacareous shale, and quartz-magnetite ± amphibole (stockwork) and biotite-magnetite alteration in volcanic rocks. These alteration types correspond to the Early stage at Island Copper. Copper, silver and zinc minerals accompanied this phase.
3. Retrograde-stage alteration includes actinolite or hornblende after pyroxene and epidote-pyrite-quartz after garnet in altered sedimentary rocks, and chlorite-epidote after quartz-biotite-magnetite-amphibole in volcanic rocks. Sericite-chlorite (SCC) alteration is intense locally, particularly in faulted, sheared and brecciated rhyodacite porphyry. This alteration correlates with the Intermediate stage at Island Copper. Both chalcopyrite and molybdenite appear to have been deposited in this stage.

## Copper and Molybdenum Mineralization

The Northwest zone carries anomalous amounts of copper, molybdenum, zinc and silver, but not gold. Copper occurs as chalcopyrite veins, mainly in proximal, brown-garnet ± pyroxene skarn, and zinc as sphalerite in distal, pyroxene ± yellow-green garnet skarn. Assays as high as 2.9% Cu over 3 m (Fleming and Clarke, 1987) and 4% Zn over 2 m (Fleming, 1986) are recorded from these units. Biotite-magnetite alteration in volcanic units host patchy, disseminated copper mineralization. In contrast to the other centres, the biotite-chalcopyrite-molybdenite association is developed only weakly and most biotitized volcanic rock lacks appreciable copper mineralization. Low-grade copper mineralization also occurs in quartz-pyrite ± molybdenite ± magnetite veinlets which appear to postdate the disseminated copper mineralization. Molybdenum, as molybdenite in quartz-pyrite veins cutting all but the Late-mineral porphyry, gives rise to grades up to 0.055% Mo over 175 m. Molybdenite does not generally occur in the same vein sets as chalcopyrite. Molybdenum grades are higher compared with (non-skarn) copper grades in this zone than any of the other ICC centres.

## Summary Model

The dynamic evolution of the Island Copper and other deposits in the ICC involved several episodes of intrusion, alteration and mineralization (Figs. 23 a-c):

1. An Early stage (Fig. 23 a), wherein the Main rhyodacite porphyry intruded comagmatic Bonanza volcanics, possibly in a subvolcanic environment, and produced four alteration zones: a core of quartz-amphibole-magnetite surrounded successively outward by zones dominated by biotite, chlorite and epidote.
2. An Intermediate stage (Fig. 23 b) was superimposed on earlier assemblages following various stages of development of the Marginal breccias. It was structurally controlled, and possibly associated with intrusion of Intra-mineral rhyodacitic magma during waning of the hydrothermal system. The common alteration products include quartz-sericite and sericite-clay-chlorite (SCC) assemblages.
3. A Late stage (Fig. 23 c), associated with development, mainly in the Pyrophyllite breccia, of high-temperature advanced argillic alteration containing pyrophyllite, kaolinite, sericite and abundant dumortierite. The Pyrophyllite breccia may also have been emplaced at this stage.

Most copper-gold mineralization occurred during the Early stage under K-silicate-stable conditions. It was followed by the main episode of molybdenum mineralization during Intermediate stage, under feldspar-destructive conditions. Most recoverable copper occurs in biotitized volcanic rocks, although appreciable amounts are also associated with quartz-sericite and SCC alteration that overprinted earlier K-silicate zones.

Similar evolutionary histories apply to the other porphyry systems in the ICC. The Bay Lake, G zone and Red Island centres, in particular, are similar to Island Copper in terms of alteration and mineralization (Early and Intermediate stages) and geometry of zones with 0.20% Cu. They are, however, smaller and of much lower grade. Porphyry-related copper skarn developed in the Quatsino limestone at the Island Copper, Bay Lake, G zone and Northwest zone centres (Red Island zone not drill-tested at depth). Only the Northwest zone, however, has extensive skarn development and significant copper mineralization. No anomalous gold concentrations were detected in any of the porphyry-related skarn.

## Ore Reserves

Initial ore reserves of the Island Copper deposit were 257 million tonnes averaging 0.52% Cu and 0.017% Mo using a cutoff grade of 0.30% Cu (Young and Rugg, 1971). Final total production is now expected to be 355 million tonnes averaging 0.41% Cu and 0.017% Mo. The reserves are encompassed by a single, oval-shaped pit designed to be 2450 m long, 1130 m wide, and 475 m deep extending to a depth of 402 m below sea level. The overall stripping ratio will be 1.84 to 1.

Significant increases in reserves resulted from lowering the cutoff grade to 0.2% Cu, as a result of production improvements, and from expanding the pit into Rupert Inlet to add about 75 million tonnes grading 0.35% Cu at a 0.20% Cu cutoff grade. The pit expansion required construction of a 1.2 km long, concrete seepage barrier wall in the marine waste dump (Findlay et al., 1990).

Ore reserves were originally based on 12.2 m thick polygons generated from diamond drill holes using a maximum horizontal projection of 86.3 m from any drill hole, the diagonal of a 61 m by 61 m drill pattern. Modifications made to the grade assignment method in the late 1970s, based on predicted-versus-actual ore comparisons, reduced polygons >0.75% Cu to 0.75% Cu. Since 1991, an inverse-distance-squared (IDS) block modelling method incorporating semi-variogram modelled search parameters and constrained by geologically determined lithological and 0.2% Cu grade boundaries has been used to generate block grades.

## Mining

Production commenced in 1971 at 30 000 tonnes per day using the largest proven mining equipment at the time. By 1989, mining equipment upgrades and additions, including installation of an in-pit, semi-mobile crushing station (Fig. 1) and associated conveyors late in 1984 (Robertson and Dowall, 1986), and optimization of the grind circuit increased ore production to 48 500 tonnes per day. The maximum daily mine production of 160 000 tonnes of ore-plus-waste per day was achieved in 1982. Mine production is currently (January 1995) 66 800 tonnes per day and is achieved with three 11.5 $m^3$ shovels, ten R170 trucks, two R190s, and three 60R drills. Bench heights are 12.5 m, and single and double-bench heights are used to achieve final-wall pit configuration. In-pit dumps have been used for part of the waste rock mined since 1990 and for all waste rock since January 1994.

The low-grade nature of the Island Copper orebody has required use of very aggressive slope designs. Traditional design methods using rock structure as the failure mechanism, with an allowable 20% probability of failure, were used until the mid 1980s. Large slope failures caused by rock fabric failure prompted development of an Island Copper rock mass rating system to aid in design of pit walls (Robertson et al., 1987). Slope angles vary from 53° in fresh north wall volcanic rocks to as low as 28° in strongly sericite and pyrophyllite altered south-wall andesites.

## Metallurgy

The Island Copper concentrator employs standard techniques for ore comminution (Brown, 1975). The grinding circuit currently uses six, computer-controlled semi-autogenous mills and five ball-mills to achieve the target grind of approximately 18% plus 100 mesh. The flotation circuit employs 140 8.5 $m^3$ rougher cells followed by three stages of cleaning and a cleaner-scavenger to produce a copper-molybdenum concentrate that grades about 24% Cu with historical, overall recoveries of 82% to 84% achieved on feed grades of 0.3% to 0.45% Cu. The copper concentrate contains 5 g/t to 9 g/t Au and 65 g/t to 80 g/t Ag. Concentrate from the final cleaners is fed to the molybdenum circuit where copper is depressed and molybdenum concentrate upgraded to approximately 45% Mo. Recoveries in the order of 50% to 65% are achieved for non-carbon-bearing ore. Rhenium, in amounts up to 1400 g/t, is found in the molybdenum concentrate. Island Copper is Canada's only producer of this element, and a significant world producer.

A few deleterious substances have been encountered in Island Copper ore, the most serious of which has been gilsonite, a hydrocarbon found within the central portion of the north limb of the orebody. This carbon floats naturally in the molybdenum circuit, contaminating the concentrate and reducing its grade to <30%. Other contaminants, reporting to the copper concentrate, are occasional low but troublesome levels of mercury and arsenic.

## Environmental Program

The Island Copper mine is located on the shore of Rupert Inlet, a marine fjord. Tailings are currently deposited into the inlet at the rate of 47 000 tonnes per day. Deposition rates of waste rock and tailings have been as high as 160 000 tonnes per day. To the end of 1994, the mine has disposed of about 89 million tonnes of waste rock on land dumps and 540 million tonnes in Rupert Inlet. In addition, about 350 million tonnes of tailings from the concentrator will have been deposited on the inlet floor through a sub-aqueous disposal system at closure.

Approval of these waste and tailings disposal methods resulted in the need for a comprehensive, oceanographic and terrestial environmental monitoring program that covers Rupert Inlet and the surrounding fjord system (Pelletier, 1982; Ellis, 1989). The program is audited and critiqued by an independent environmental review panel. It has allowed the mine to develop a closure plan that will have no long-term impact on the marine and surface water environments.

Land dumps contain quantities of acid generating rock that are currently oxidizing, causing localized acidic conditions in rainfall-generated runoff waters. The result has been elevated levels of copper and zinc in the water, especially during autumn rainfall events when oxidation products generated during the summer are flushed from the dumps. Present mitigation methods involve collecting all runoff water and pit dewatering system discharges into a central collection pond for use as plant water, thereby reducing fresh water requirements. Water in compliance with allowable discharge criteria is released into the marine waste dump for ex-filtration into the environment.

The marine waste rock dump's main impact on the environment has been to occupy space that previously was used by marine organisms. A positive aspect of this dump has been to submerge most of the mine's waste rock, much of which would otherwise have been acid generating. Oxidation of the mined sulphides is reduced or eliminated. Use of sub-aqueous deposition of the mill tailings, also potentially acid generating, is similarly a positive mitigation technique.

Reclamation of completed land dumps and portions of the marine dump has been ongoing during mine operation. Slopes are contoured, previously mined topsoil and glacial tills are placed on new slopes, and the area is seeded with a variety of grasses. Tree planting is also done. The success rate is extremely high. Normally one reapplication of fertilizer is required a year after reclamation to ensure stable long term growth. A total of 170 ha of land dumps have already been reclaimed, and a remaining 23 ha, along with 200 ha of marine dump, will be reclaimed within 18 months of mine closure. The pit will ultimately be filled with sea water following completion of mining in mid- to late 1995.

## Discussion and Conclusions

Island Copper is a subvolcanic, gold-rich porphyry copper-molybdenum deposit that resulted from intrusion of an approximately 175 Ma, multiple-stage rhyodacite porphyry complex into comagmatic Bonanza Group volcanic rocks. It forms part of a regional cluster that contains at least five porphyry systems (Island Copper, Bay Lake, G zone, Red Island and Rupert Inlet) and additional massive sulphide vein (A zone) and copper skarn (e.g., Northwest zone) mineralization peripheral to the porphyry centres. It is proposed that all the systems in the cluster were emplaced essentially simultaneously along a regional, deep-seated structure. Such a structure, schematically depicted in Figure 24, would have accommodated intrusion of subvolcanic rhyodacitic magma in tensional openings or dilational jogs (cf., Sibson, 1987) associated with intermittent, dextral, strike-slip movements.

Each porphyry system appears to have evolved separately and formed early, high-temperature, quartz-amphibole-magnetite stockwork cores surrounded by biotite-, chlorite- and epidote-dominated zones. Albitic feldspar is a frequent accompaniment to the Fe-rich core and the biotite zone. Substantial structurally-controlled and pervasive, Intermediate-stage alteration accomplished at lower temperatures takes the form of quartz-sericite and sericite-clay-chlorite (SCC) assemblages, which affected all the systems with variable intensity. Where structurally controlled, these assemblages occur with district-wide structures. Local stockworks and hydrothermal breccias are interpreted to be associated with the waning of the hydrothermal systems.

Similar alteration geometries are recorded at other productive Cu-Au porphyry deposits. Central zones of quartz-magnetite-amphibole alteration occur at Panguna, Papua New Guinea (Ford, 1978), Tanamá, Puerto Rico (Cox, 1985), Mamut, Malaysia (Kosaka and Wakita, 1978), Santo Tomas II and Dizon, Philippines (Sillitoe and Gappe, 1984), and in the Tombulilato cluster, North Sulawesi, Indonesia (Carlile and Kirkegaard, 1985). Actinolite, hornblende and magnetite replaced primary pyroxene and form veinlets and fracture coatings that predate biotite-bearing, K-silicate alteration at Panguna, whereas actinolitic hornblende accompanies veins of magnetite, with or without quartz, at Tanamá (Cox, 1985) and Santo Tomas II (Sillitoe and Gappe, 1984), and albite is a dominant constituent in Tombulilato (Carlile and Kirkegaard, 1985).

Pre-amphibole hydrothermal pyroxene together with quartz, amphibole and magnetite forms the stockwork core at the Bay Lake centre. This type of assemblage and geometry is less common in porphyry systems, although some parallels can be drawn with the associations described at Koloula, Guadalcanal Island (Chivas, 1978), where hydrothermal pyroxene appears to both coexist with and be replaced by hydrothermal amphibole of actinolitic composition. This assemblage, with quartz and magnetite, is in turn bordered by low-grade copper mineralization in K-silicate alteration facies. At Mount Polley and Galore Creek, British Columbia, pre-amphibole pyroxene seems to accompany K-silicate alteration (Sillitoe, 1990).

Conclusions derived from studies of these deposits and elsewhere (Eastoe, 1978; Chivas, 1978; Takenouchi, 1981; Cox, 1985) suggest that the quartz-amphibole-magnetite core zones of the systems and surrounding feldspar-stable, K-silicate alteration assemblages formed at temperatures ranging from 350°C to 700°C or higher, as at Panguna, with copper, gold, iron sulphides and oxides, quartz and associated silicates deposited by dense, strongly saline (>45 equiv. wt. % NaCl), boiling fluids of magmatic derivation. By analogy with these deposits and based on very preliminary fluid inclusion data from Bay Lake and Island Copper (J. Reynolds, pers.

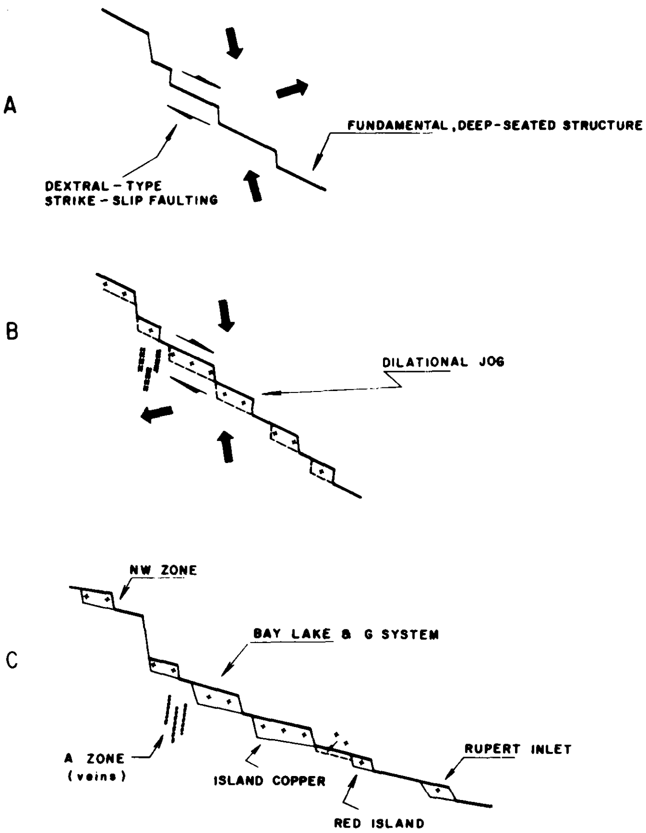



**FIGURE 24. Hypothesized structures controlling emplacement of the porphyry systems of the Island Copper Cluster.**

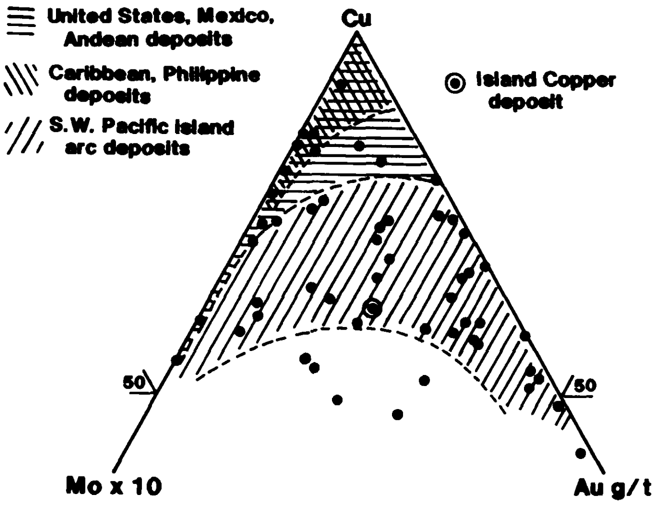



**FIGURE 25. Fifty-four porphyry copper deposits (after Cox and Singer, 1988 and Sillitoe, 1991, in McMillan, 1991) including Island Copper plotted that show variation in amounts of Cu (%), Mo (% x 10) and Au (g/t) in relation to principal porphyry deposit regions (after Titley and Beane, 1981).**

comm., 1989), similar fluid characteristics and temperatures can be theorized for the Island Copper cluster. It is further suggested that the non-precipitation of copper and gold in the quartz-amphibole-magnetite zones in these systems was due to the unduly high temperatures and/or salinities of the magmatic-hydrothermal fluids, perhaps too high to destabilize chloride complexes of copper and gold (Sillitoe, 1989b).

As the systems cooled, magmatic fluid activity waned allowing meteoric water to become progressively more abundant in central parts of systems and able to produce local sericitic and widespread SCC alteration. At Island Copper and Red Island, SCC-type alteration is known to contain appreciable Cu-Au mineralization, although it remains obscure whether this mineralization was effectively introduced by the fluids that caused the alteration or was inherited from pre-existing K-silicate alteration (cf., Sillitoe and Gappe, 1984). Heat to sustain meteoric-hydrothermal circulation was provided by Intra-mineral dikes. Similarly, inflow of cool groundwater as the hydrothermal system decayed would have induced multiple phreatic explosions in the upper parts of the system at Island Copper and elsewhere in northern Vancouver Island (see below) under advanced argillic alteration conditions.

The Cu-Au-Mo metal association of the Island Copper ore and some satellite deposits, and of other deposits (e.g., Hushamu; Dasler et al., 1992; Dasler et al., this volume) in northern Vancouver Island (Fig. 3), together with the rhyodacitic nature of the causative intrusions and the island-arc setting of the mineralization, are factors that mitigate against Kesler's (1973) preliminary conclusion that porphyry copper deposits can be grouped into two main categories: copper-molybdenum and copper-gold. According to Kesler (op cit), the copper-molybdenum class is, with some prominent exceptions to the generalization, characteristic of continental margins constructed above subduction zones whereas copper-gold members are rather associated with dioritic intrusions in island-arc settings. It is suggested here, however, that Island Copper (Fig. 25), its satellites and other examples in the region confirm that porphyry deposits cannot be subdivided only into copper-gold and copper-molybdenum categories but are rather part of a broader spectrum containing Cu-Au-Mo examples with copper, gold and molybdenum-only porphyry deposits as end members of this spectrum (Perelló and Cabello, 1989; Cox and Singer, 1992; Vila and Sillitoe, 1991).

The Cu-Au-Mo orebody at Island Copper displays typical features of gold-rich porphyry copper deposits (Sillitoe, 1979; 1990; Perelló and Cabello, 1989), including a positive correlation between copper and gold, abundant (8 vol. % to 10 vol. %) hydrothermal magnetite, mineralization hosted by feldspar-stable, K-silicate alteration and a significant volume of the deposit averaging >0.4 g/t Au.

Most of the Cu-Au mineralization in the ICC is an integral part of the quartz-deficient, biotite-magnetite assemblage, rather than the barren inner zone of quartz-amphibole-magnetite stockworks. This spatial arrangement is considered unique among magnetite-bearing porphyry deposits (Sillitoe, 1989b) because copper-gold ore normally accompanies the quartz-magnetite stockwork veinlets (Santo Tomas II, Dizon; Sillitoe and Gappe, 1984). Nevertheless, the central quartz-amphibole-magnetite-albite zone with appreciable apatite and scapolite at Island Copper, and additional pyroxene at Bay Lake, shows strong similarities with the mineralogy of the contact-metasomatic deposits in the Cretaceous Iron Belt of Chile (Bookstrom, 1977; Oyarzún, 1987; Arancibia and Clark, 1990) and Perú (Vidal et al., 1990), which have been considered examples of the Kiruna type of iron ore (Geijer, 1931). Superimposed, sulphide-poor (pyrite, chalcopyrite), K-silicate alteration in the Chilean deposits is extremely weak (Bookstrom, 1977; Oyarzún, 1982) and apparently absent in the Peruvian examples. Similarities are also found between the mineralogy of the central zone and that of Kiruna-type occurrences associated with rocks of Early Proterozoic age at Great Bear Lake, Northwest Territories, Canada (Hildebrand, 1986; Reardon, 1990) and the Olympic Dam-type mineralization of South Australia (Hitzman et al., 1992).

Extensive zones of argillic and more restricted advanced argillic alteration occur in northern Vancouver Island at Mount McIntosh-Husahmu Creek, Red Dog Hill and the Pemberton Hills (Fig. 3). These zones are characterized by assemblages containing kaolinite, pyrophyllite, alunite, zunyite and diaspore, which indicate acid-sulphate-style leaching and epithermal alteration (Panteleyev and Koyanagi, 1993; 1994). These high-level systems may be expressions of porphyry Cu-Au-Mo systems at depth as at Island Copper, McIntosh-Hushamu, and Red Dog (Perelló, 1992). At McIntosh-Hushamu, advanced argillic alteration is copper-bearing and associated with a high-sulphur assemblage of enargite, chalcocite, covellite and bornite (Perelló, 1992), whereas at Island Copper it is barren of copper and dominated by pyrite. The advanced argillic alteration suite in Pemberton Hills contains alunite, pyrite, marcasite and native sulphur, and is interpreted to be associated with a flow-dome complex (Perelló, 1992). Geological mapping by Nixon et al. (1994) suggests that the advanced argillic alteration at Mount McIntosh and Pemberton Hills is hosted by rhyolitic flow-dome complexes and non-welded to welded ash-flow tuffs that reflect small-scale caldera complexes and flow-dome aprons.

All styles of mineralization described in this paper, including the massive sulphide veins of the A zone, the skarn-type mineralization peripheral to Island Copper, the high-sulphur advanced argillic alteration zone at McIntosh-Hushamu and the dome-related advanced argillic alteration zones at Pemberton Hills are interpreted to form integral parts of the island-arc porphyry Cu-Au-Mo systems of northern Vancouver Island. Similar island arc-type geotectonic settings are found in the Tertiary arcs of the Philippines, Indonesia and elsewhere in the Southwest Pacific region where they constitute one of the world's best mineralized provinces (cf., Sillitoe, 1989a).

## Acknowledgments

The authors would like to thank BHP Minerals Canada Ltd. for permission to publish this paper. The support of BHP personnel J.D. Excell, R.B. Findlay, T.W. Janes, D.N. leNobel and E.A. Pettigrew is gratefully acknowledged. Discussions with O.N. Arancibia, P.T. Brobrowski, A.H. Clark, K.M. Dawson, F.R. Gatchalian, J.L. Hammack, L.D. Meinert, C.H.B. Leitch, R.H. McMillan, W.J. McMillan, G.T. Nixon, A. Panteleyev, T.J. Reynolds, K.V. Ross, and R.H. Sillitoe have been most useful and are also gratefully acknowledged. Special thanks are extended to G.T. Nixon and J.L. Hammack of the British Columbia Geological Survey Branch for their substantial contributions to the Regional Geology, Local Geology and Isotopic Ages sections and for providing Figures 2 and 3. Credit is due to the late John Lamb, D.G. Cargill, BHP Minerals geologists H. Lubis, R.A. Padilla and F.R.L. Quiroz and other geologists previously at or associated with Island Copper for their contributions to the understanding of the Island Copper geology. Island Copper personnel who kindly reviewed sections of the paper or provided information include J.W.T. Bell, R.B. Findlay, H. Glasswick, N.J. Hopland, I.H. Horne and M.J. Di Marco. The reviewers, J.M. Hamilton, R.H. McMillan and R.H. Sillitoe, are commended for the care and skill they applied to their task, and in addition, editor Tom Schroeter is thanked for his patience and encouragement.

### REFERENCES

ARANCIBIA, O.N., in preparation. Geological evolution of the Island Copper porphyry copper (-molybdenum, gold) deposit, VancouverIsland, British Columbia. Unpublished Ph.D. thesis, Queen's University, Kingston, Ontario.

ARANCIBIA, O.N. and CLARK, A.H., in preparation. Magnetite-amphibole-plagioclase alteration-mineralization at Island Copper, British Columbia: Early hydrothermal processes in a porphyry copper-molybdenum-gold deposit. Queen's Unviersity, Kingston, Ontario.

ARANCIBIA, O.N. and CLARK, A.H., 1990. Early Magnetite-rich alteration/mineralization in the Island Copper porphyry copper-molybdenum-gold deposit, British Columbia. *In* Geological Association of Canada/Mineralogical Association of Canada, Program with Abstracts, 15, p. A4.

ARCHIBALD, D.A. and NIXON, G.T., 1995. $^{40}Ar/^{39}Ar$ geochronometry of igneous rocks in the Quatsino-Port McNeill map area, northern Vancouver Island (NTS 92L/12, 11). *In* Geological Fieldwork 1994, British Columbia Ministry of Energy, Mines and Petroleum Resources. *Edited by* J.M. Newell and B. Grant. Paper 1995-1, p. 49-60.

ARMSTRONG, R.L., 1983. Rb-Sr isochron results from suite of whole rocks from the Island Copper deposit. Unpublished letter to Utah Mines Ltd., 3 p.

BOBROWSKY, P.T. and MELDRUM, D., 1994. Preliminary drift exploration studies, northern Vancouver Island (92L/6 and 11). *In* Geological Fieldwork 1993, British Columbia Ministry of Energy, Mines and Petroleum Resources. *Edited by* B. Grant and J.M. Newell. Paper 1994-1, p. 87-99.

BOOKSTROM, A.A., 1977. The magnetite deposits of El Romeral, Chile. Economic Geology, 72, p. 1101-1130.

BROWN, C.M., 1975. Island Copper mine — milling for copper and molybdenum. *In* Proceedings, Seventh Annual Meeting of the Canadian Mineral Processors, p. 313-322.

BRUCE, R.W., 1976. Determining the nature and association of gold in a mill tailing. *In* Proceedings, Eighth Annual Meeting of the Canadian Mineral Processors, p. 311-324.

BURT, P.D., 1989. Preliminary report on Bay Lake surface geology from 1987 and 1988 field data. Unpublished company report, BHP-Utah Mines Ltd., Vancouver, British Columbia, 1989, 23 p.

BURT, P.D. and FLEMING, J.A., 1988. 1987/1988 FAME drilling report, Island Copper mine. British Columbia Ministry of Energy, Mines and Petroleum Resources, FAME Report ID#10963-M14, 25 p.

CARGILL, D.G., 1975. Geology of the "Island Copper" mine, Port Hardy, British Columbia. Unpublished Ph.D. thesis, The University of British Columbia, Vancouver, British Columbia, 133 p.

CARGILL, D.G., LAMB, J., YOUNG, M.J. and RUGG, E.S., 1976. Island Copper. *In* Porphyry Deposits of the Canadian Cordillera. *Edited by* A. Sutherland Brown. Canadian Institute of Mining and Metallurgy, Special Volume 15, p. 206-208.

CARLILE, J. and KIRKEGAARD, G., 1985. Porphyry copper-gold deposits of the Tombulilato District, North Sulawesi, Indonesia: An extension of the Philippines porphyry copper-gold province. Asia Mining '85, London, The Institution of Mining Metallurgy, p. 351-363.

CHIVAS, A.R., 1978. Porphyry copper mineralization at the Koloula igneous complex, Guadalcanal, Solomon Islands. Economic Geology, 73, p. 645-677.

COX, D.P., 1985. Geology of the Tanamá and Helecho porphyry copper deposits and vicinity, Puerto Rico. United States Geological Survey Prof. Paper 1327, 57 p.

COX, D.P. and SINGER, D.A., 1992. Distribution of gold in porphyry copper deposits, United States Geological Survey Bulletin 1877, p. C1-C14.

DASLER, P.G., PERELLÓ, J.A. and YOUNG, M.J., 1992. Expo porphyry copper property. Abstract, Canadian Institute of Mining and Metallurgy, CIM Bulletin, July/August 1992, p. 51.

DASLER, P.G., YOUNG, M.J., PERELLÓ, J. and GIROUX, G., 1995. The Hushamu porphyry copper-gold deposit, northern Vancouver Island, British Columbia. *In* Porphyry Deposits of the Northwestern Cordillera of North America. *Edited by* T.G. Schroeter, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46.

DAWSON, G.M., 1887. Report on a geological examination of the northern part of Vancouver Island and adjacent coasts. Geological Survey of Canada, Annual Report 1886, v. 2, Pt B, p. 1-107.

EASTOE, C.J., 1978. A fluid inclusion study of the Panguna porphyry copper deposit, Bougainville, Papua New Guinea. Economic Geology, 73, p. 721-748.

EINAUDI, M.T., MEINERT, L.D. and NEWBERRY, R.J., 1981. Skarn deposits. *In* Economic Geology 75th Anniversary Volume. *Edited by* B.J. Skinner, p. 312-391.

ELLIS, D., 1989. Mining — Island Copper (Canada). *In* Environments at Risk (Case Histories of Impact Assessment). Springer-Verlag, Berlin, p. 70-107.

FAHEY, P.L., 1979. The geology of Island Copper mine, Vancouver Island, British Columbia. Unpublished M.Sc. thesis, University of Washington, Seattle, Washington, 52 p.

FINDLAY, R.B., ROBERTSON, R.B. and O'KANE, K.P., 1990. The Island Copper south wall pushback project. *In* Mine Planning and Equipment Selection. *Edited by* Singhal and Vavra. Balkema, Rotterdam, p. 257-268.

FLEMING, J.A., 1983. Island Copper. *In* Geological Association of Canada/Mineralogical Association of Canada/Canadian Geophysical Union, Joint Annual Meeting, Victoria, British Columbia, Field Trip 9, Guidebook to Mineral Deposits of Vancouver Island, p. 21-35.

FLEMING, J.A., 1986. Diamond drilling, Central-86 Group. Assessment Report, Utah Mines Ltd., Port Hardy, British Columbia, No. 281-14 777, 9 p.

FLEMING, J.A., 1995. Metal distributions in the Island Copper deposit. Unpublished company report, BHP Minerals Canada Ltd., Port Hardy, B.C., 3 p.

FLEMING, J.A. and CLARKE, G.A., 1987. Diamond drilling and down hole pulse EM survey, Apple-88 Group. Assessment Report, Utah Mines Ltd., Port Hardy, British Columbia, No. 411-16 152, 9 p.

FLEMING, J.A. and CLARKE, G.A., 1989. Diamond drilling, Kol 90, East 90 and Central 90 Groups. Assessment Report, BHP-Utah Mines Ltd., Port Hardy, British Columbia, No. 18 805, 27 p.

FORD, J.H., 1978. A chemical study of alteration at the Panguna porphyry copper deposit, Bougainville, Papua New Guinea. Economic Geology, 73, p. 703-720.

GABELMAN, J.W., 1982. The geological occurrence of gold, Island Copper mine, Vancouver Island, British Columbia, a summary of Phase I investigations. Unpublished company report, Utah International Inc., San Francisco, California, 1982, 27 p.

GABELMAN, J.W. and HANUSIAK, W., 1986. Gold occurrence at Island Copper mine, British Columbia. Abstract, Journal of Geochemical Exploration, 25, p. 252.

GEIJER, P., 1931. The iron ores of the Kiruna-type. Geographical distribution, geological characters, and origin. Sveriges Geol. Undersokning, Ser. C, 367, 39 p.

GUSTAFSON, L.B. and HUNT, J.P., 1975. The porphyry copper deposit at El Salvador, Chile. Economic Geology, 10, p. 857-912.

HAGGART, J.W. and TIPPER, H.W., 1994. New results in Jura-Cretaceous stratigraphy, northern Vancouver Island, British Columbia. Geological Survey of Canada, Paper 94-1E, p. 59-66.

HAMMACK, J.L., NIXON, G.T., KOYANAGI, V., PAYIE, G.J., PANTELEYEV, A., MASSEY, N.W.D., HAMILTON, J.V. and HAGGART, J.W., 1994. Preliminary geology of the Quatsino-Port McNeill area, northern Vancouver Island, (92L/12, 11W). British Columbia Ministry of Energy, Mines and Petroleum Resources, Open File 1994-15.

HITZMAN, M.W., ORESKES, N. and EINAUDI, M.T., 1992. Geological characteristics and tectonic setting of proterozoic iron oxide (Cu-U-Au-REE) deposits. Precambrian Research, 58, p. 241-287.

HILDEBRAND, R.S., 1986. Kiruna-type deposits: Their origin and relationship to intermediate subvolcanic plutons in the Great Bear magmatic zone, northwest Canada. Economic Geology, 81, p. 640-659.

HOWES, D.E., 1981. Terrain inventory and geological hazards: Northern Vancouver Island. British Columbia Ministry of Environment, Lands and Parks, APD Bulletin 5, 105 p.

JELETZKY, J.A., 1976. Mesozoic and ?Tertiary rocks of Quatsino Sound, Vancouver Island, British Columbia. Geological Survey of Canada, Bulletin 242, 243 p.

KESLER, S.E., 1973. Copper, molybdenum and gold abundances in porphyry copper deposits. Economic Geology, 80, p. 591-613.

KOSAKA, H. and WAKITA, K., 1978. Some geologic features of the Mamut porphyry copper deposit, Sabah, Malaysia. Economic Geology, 73, p. 618-627.

KUNIYOSHI, S. and LIOU, J.G., 1976. Burial metamorphism of the Karmutsen volcanic rocks, northeastern Vancouver Island, British Columbia. American Journal of Science, 276, p. 1096-1119.

LEITCH, C.H.B., 1988. Brief summary of mafic-potassic style alteration as applied to the Island Copper porphyry deposit, British Columbia. Unpublished company report, Utah Mines Ltd., Vancouver, British Columbia, 5 p.

LEITCH, C.H.B., 1990. Petrographic examination of 8 core specimens from Red Island near the Island Copper mine. Unpublished company report, BHP-Utah Mines Ltd, Vancouver, British Columbia, 9 p.

LEITCH, C.H.B., ROSS, K.V., FLEMING, J.A. and DAWSON, K.M., 1995. Hydrothermal alteration events at the Island Copper deposit, northern Vancouver Island, British Columbia: Preliminary studies. *In* Current Research, Part A. Geological Survey of Canada, Paper 95-1A, p. 51-59.

McMILLAN, W.J., 1991. Porphyry deposits in the Canadian Cordillera. *In* Ore Deposits, Tectonics and Metallogeny in the Canadian Cordillera. *Edited by* B. Grant and J.M. Newell. British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1991-4, p. 253-276.

MEINERT, L.D., 1983. Variability of skarn deposits: guides to exploration. *In* Revolution in the Earth Sciences — Advances in the Past Half-Century. *Edited by* S.J. Boardman. Kendall/Hunt Publishing Company, Iowa, p. 301-316.

MEINERT, L.D., 1986. Island Copper skarn mineralogy. Unpublished company report, BHP-Utah Mines Ltd., Port Hardy, British Columbia, 5 p.

MULLER, J.E., 1977. Evolution of the Pacific Margin, Vancouver Island and adjacent regions. Canadian Journal of Earth Sciences, 14, p. 2062-2085.

MULLER, J.E., NORTHCOTE, K.E. and CARLISLE, D., 1974. Geology and mineral deposits of Alert Bay-Cape Scott map area, Vancouver Island, British Columbia. Geological Survey of Canada, Paper 74-8, 77 p.

MULLER, J.E., CAMERON, B.E.B. and NORTHCOTE, K.E., 1981. Geology and mineral deposits of Nootka Sound map area (92E), Vancouver Island, British Columbia. Geological Survey of Canada, Paper 80-16, 53 p.

NIXON, G.T., HAMMACK, J.L., HAMILTON, J.V. and JENNINGS, H., 1993. Preliminary geology of the Mahatta Creek area, northern Vancouver Island (92L/5). *In* Geological Fieldwork 1992. British Columbia Ministry of Energy, Mines and Petroleum Resources. *Edited by* J.M. Newell and B. Grant. Paper 1993-1, p. 17-35.

NIXON, G.T., HAMMACK, J.L., KOYANAGI, V.M., PAYIE, G.J, PANTELEYEV, A., MASSEY, N.W.D., HAMILTON, J.V. and HAGGARD, J.W., 1994. Preliminary geology of the Quatsino-Port McNeill map areas, northern Vancouver Island (92L/12,11). *In* Geological Fieldwork 1993. British Columbia Ministry of Energy, Mines and Petroleum Resources. *Edited by* B. Grant and J.M. Newell. Paper 1994-1, p. 63-85.

NORTHCOTE, K.E. and MULLER, J.E., 1972. Volcanism, plutonism and mineralization: Vancouver Island. The Canadian Institute of Mining and Metallurgy, CIM Bulletin, 65, p. 49-57.

NORTHCOTE, K.E. and ROBINSON, W.C., 1973. Island Copper mine. *In* Geology, Exploration and Mining in British Columbia-1972. British Columbia Department of Mines and Petroleum Resources, p. 293-303.

OYARZÚN, J., 1982. El potencial ferrífero y cuprífero de los magmas, en función de su hidratación inicial, evolución y condiciones de emplazamiento. Congreso Geológico de Chile, Concepción, Chile. 3rd. Actas, 2, p. E349-E363.

OYARZÚN, J., 1987. The geological frame of some Andean metallic belts related to volcanogenetic processes. UNESCO-SERNAGEOMIN Workshop, Santiago, Chile, 1987, Abstracts, 4 p.

PADILLA, R.A., 1993. Breccias in the Island Copper deposit, Vancouver Island, Canada. Unpublished company report, Minera BHP-Utah, Hermosillo, Mexico, 7 p.

PANTELEYEV, A. and KOYANAGI, V.M., 1993. Advanced argillic alteration in Bonanza volcanic rocks, northern Vancouver Island — transitions between porphyry copper and epithermal environments (92L/12). *In* Geological Fieldwork 1992. British Columbia Ministry of Energy, Mines and Petroleum Resources. *Edited by* B. Grant and J.M. Newell. Paper 1993-1, p. 287-293.

PANTELEYEV, A. and KOYANAGI, V.M., 1994. Advanced argillic alteration in Bonanza volcanic rocks, northern Vancouver Island — lithologic and permeability controls (92L/12). *In* Geological Fieldwork 1993. British Columbia Ministry of Energy, Mines and Petroleum Resources. *Edited by* B. Grant and J.M. Newell. Paper 1994-1, p. 101-110.

PANTELEYEV, A., REYNOLDS, P.H. and KOYANAGI, V.M., 1995. $^{40}Ar/^{39}Ar$ ages of hydrothermal minerals in acid sulphate altered Bonanza volcanics, northern Vancouver Island (NTS 92L/12). *In* Geological Fieldwork 1994. British Columbia Ministry of Energy, Mines and Petroleum Resources. *Edited by* B. Grant and J.M. Newell. Paper 1995-1, p. 61-66.

PELLETIER, C.A., 1982. Environmental data handling and long-term trend monitoring at Island Copper mine. *In* Marine Tailings Disposal. *Edited by* D.V. Ellis. Ann Arbor Science, Ann Arbor, 6, p. 197-237.

PERELLÓ, J.A., 1987. The occurrence of gold at Island Copper mine, Vancouver Island, British Columbia. Unpublished M.Sc. thesis (Mineral Exploration), Queen's University, Kingston, Ontario, 85 p.

PERELLÓ, J.A., 1988. 1988 drilling program: Bay Lake Project, Island Copper mine, Vancouver Island, British Columbia. Unpublished company report, BHP-Utah International Inc., Salt Lake City, Utah, 18 p.

PERELLÓ, J.A., 1989. Final report on the geology and mineral inventory of the porphyry copper mineralization at Bay Lake, Vancouver Island, B.C., Canada. Unpublished company report, BHP-Utah International Inc., Salt Lake City, Utah, 8 p.

PERELLÓ, J.A., 1992. Comments on the exploration potential for epithermal Au and Cu at McIntosh, South McIntosh, and West Pemberton, Expo claims, Vancouver Island, British Columbia. Unpublished company report, BHP Minerals Canada Ltd., Vancouver, British Columbia, 1992, 13 p.

PERELLÓ, J.A., ARANCIBIA, O.N., BURT, P.D., CLARK, A.H., CLARKE, G.A., FLEMING, J.A., HIMES, M.D., LEITCH, C.H.B. and REEVES, A.T., 1989. Porphyry Cu-Mo-Au mineralization at Island Copper, Vancouver Island, B.C. Geological Association of Canada Cordilleran Section, Porphyry Copper-Gold Workshop, Vancouver, British Columbia, 1989, Abstracts, 2 p.

PERELLÓ, J.A. and CABELLO, J., 1989. Pórfidos cupríferos ricos en oro: una revisión. Revista Geológica de Chile, 16, No. 1, p. 73-92.

POULTON, T.P., 1980. Trigoniid bivalves from the Bajocian (Middle Jurassic) rocks of central Oregon. Geological Survey of Canada, Current Research, Part A, Paper 80-1A, p. 187-196.

POULTON, T.P. and TIPPER, H.W., 1991. Aalenian ammonites and strata of western Canada. Geological Survey of Canada, Bulletin 411, 71 p.

RATTE, A.K., TAKENAKA, T. and BUCKINGHAM, L., 1982. Characterization of Island Copper gold. Unpublished company report, Utah Mines Ltd., Port Hardy, British Columbia, 8 p.

REARDON, N.C., 1990. Altered and mineralized rocks at Echo Bay, N.W.T. and their relationship to the Mastery Island intrusive suite. Geological Survey of Canada, Current Research, Part C, Paper 90-K, p. 143-150.

ROBERTSON, A.M., OLSEN, R.S. and PIERCE, G.L., 1987. Assessment of the weak altered rock masses at the Island Copper mine. *In* Proceedings of SME Annual Meeting, Denver, 6 p.

ROBERTSON, R.B. and DOWALL, W.M., 1986. Movable in-pit crushing and conveying system at Island Copper mine, British Columbia. *In* Transactions of The Institution of Mining and Metallurgy (Sect. A: Mining Industry), 95, p. A165-170.

SIBSON, R.H., 1987. Earthquake rupturing as a mineralizing agent in hydrothermal systems. Geology, 15, p. 701-704.

SILLITOE, R.H., 1979. Some thoughts on gold-rich porphyry copper deposits. Mineralium Deposita, 14, p. 161-174.

SILLITOE, R.H., 1989a. Gold deposits of the western Pacific Island arcs: the magmatic connection. Economic Geology Monograph 6, p. 274-192.

SILLITOE, R.H., 1989b. Comments on the Island Copper and associated porphyry copper-gold systems, Vancouver Island, British Columbia, Canada. Unpublished company report, BHP-Utah Mines Ltd., Vancouver, British Columbia, 7 p.

SILLITOE, R.H., 1990. Gold-rich porphyry copper deposits of the Circum-Pacific region — An updated overview. Pacific Rim Congress 90, Gold Coast, Queensland, Proceedings, Australasian Institute of Mining and Metallurgy, 2, p. 119-126.

SILLITOE, R.H., 1991. Gold-rich porphyry copper deposits: Occurrence, model and exploration implications. *In* Mineral Deposit Modelling Session. International Association for the Genesis of Ore Deposits (IAGOD), 8th Symposium, 1990, Ottawa, Ontario.

SILLITOE, R.H. and GAPPE, I.M., 1984. Philippine porphyry copper deposits: Geologic setting and characteristics. United Nations ESCAP, CCOP Technical Publication, No. 14, 89 p.

SMEE, B.W., 1991. An assessment of the soil geochemistry over the Island Copper property, Holberg Inlet, Vancouver Island, British Columbia. Unpublished company report, BHP-Utah Mines Ld., Vancouver, British Columbia, 28 p.

TAKENOUCHI, S., 1981. Preliminary studies on fluid inclusions of the Santo Tomas II (Philex) and Tapian (Marcopper) porphyry copper deposits in the Philippines. *In* Granitic Magmatism and Related Mineralization. *Edited by* S. Ishihara and S. Takenouchi. Mining Geology Special Issue No. 8, p. 141-150.

TITLEY, S.R. and BEANE, R.E., 1981. Porphyry copper deposits, Part I, geological settings, petrology, and tectogensis. *In* Economic Geology 75th Anniversary Volume. *Edited by* B.J. Skinner, p. 214-235.

VIDAL C.E., INJOQUE-ESPINOZA, J., SIDDER, G.B. and MUKASA, S.B., 1990. Amphibolitic Cu-Fe skarn deposits in the central coast of Peru. Economic Geology, 85, p. 1447-1461.

VILA, T. and SILLITOE, R.H., 1991. Gold-rich porphyry systems in the Maricunga belt, northern Chile. Economic Geology, 86, p. 1238-1260.

WHEELER, J.O. and McFEELY, P. (Compilers), 1991. Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America. Geological Survey of Canada, Map 1712A, scale 1:2 000 000.

WITHERLY, K.E., 1979. Geophysical and geochemical methods used in the discovery of the Island Copper deposit, Vancouver Island, British Columbia. *In* Geophysics and Geochemistry in the Search for Metallic Ores. *Edited by* P. Hood. Geological Survey of Canada, Economic Geology Report 31, p. 685-696.

YOUNG, M.J. and RUGG, E.S., 1971. Geology and mineralization of the Island Copper deposit. Western Miner, 44, No. 2, p. 31-40.