Tonalite-trondhjemite fractionation of peraluminous magma and the formation of syntectonic porphyry copper mineralization, Gibraltar mine, central British Columbia

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ABSTRACT

The Gibraltar porphyry copper deposit is located in central British Columbia 362 km north of Vancouver, British Columbia. Production on the property began in March of 1972. As of December 1992, 241 000 000 tonnes of ore averaging 0.360% Cu have been milled: 147 500 000 tonnes averaging 0.301% Cu (0.008% Mo) have been defined as a mining reserve; and 546 600 000 tonnes averaging 0.287% Cu (0.007% Mo) have been classified as a mineral resource.

The Gibraltar deposit consists of six separate ore zones hosted by the Granite Mountain batholith, a zoned peraluminous subalkaline body which intrudes the Permian Cache Creek Group. The batholith and adjacent Cache Creek Group have undergone penetrative foliation and are metamorphosed to the upper greenschist facies. Magmatism, dynamothermal metamorphism and ore deposition occurred as a related chain of events over a period of tectonism extending from Upper Triassic to possibly earliest Jurassic. Fractional crystallization of the batholith involved a trend of increasing Na enrichment without an associated increase in K. The magmatic sequence was: tonalite (Mine Phase), to trondhjemite (Granite Mountain Phase), to leucotrondhjemite (Leucocratic Phase). Ore stage alteration and sulphide mineralization closely followed the emplacement of the leucotrondhjemite as a volatile-rich fraction of the tonalite-trondhjemite differentiation. The alteration process was dominated by K metasomatism, accompanied by the redistribution of Mg and Ca, and the net expulsion of Na.

Alteration assemblages consist of quartz, sericite, chlorite, epidote, and carbonate. Major sulphide minerals are pyrite and chalcopyrite. Molybdenite is a minor but economically significant component of the ore. Sulphide zoning is evident, consisting of chalcopyrite + molybdenite, to chalcopyrite, to chalcopyrite + sphalerite, to sphalerite. The orebodies were formed within an evolving environment of low angle, northeasterly directed compressional stress which resulted in the complex deformation of alteration and mineralization.

Introduction

The Gibraltar mine is located in central British Columbia (NTS 93B/9W), 362 km north of Vancouver (Fig. 1). Access is provided by 20 km of paved road from McLeese Lake, which lies 45 km north of Williams Lake on Highway 97. Latitude and longitude of the mine are 52°30′ N and 122°16′W, respectively.

The Gibraltar orebodies lie along the southern and western flanks of Granite Mountain at elevations ranging between 914 m and 1231 m. Granite Mountain forms the southern terminus of a north trending chain of rounded hills that extend as far as Dragon Mountain, some 50 km to the north. This upland sequence is bound on the west by a well-defined plateau which is underlain locally by flat-lying Miocene basalts. Within the Granite Mountain area, maximum relief from the plateau to mountain summit is 499 m. The Cuisson Creek drainage system lies at the base of the mountain and drains the mine area in a series of lakes, swamps, and streams which flow northward, along the plateau, to the Fraser River.

History

The earliest record of work is found in the 1917 British Columbia Minister of Mines Annual Report which describes the activities of Joseph Briand and partners exploring copper-bearing quartz veins on the Rainbow group of mineral claims. These original showings are believed to lie about 60 m west of the current Pollyanna pit. According to the annual reports, prospecting in the Granite Mountain area continued on through the 1920s and by 1928, the Sunset shear zone was discovered west of the Rainbow Group on ground held by H.F., H.B., and J.F. Hill. The discovery area is now known to have been the exposed southeast end of the Gibraltar West orebody. The Rainbow showings and the Sunset shear zone provided the focus for further prospecting up to at least the 1960s. In 1949, both showings were held by C.E. Johnson and R.R. Moffat who made a half ton shipment of ore from the Rainbow Group to the Tacoma smelter. By 1956, E. Kinder, T. Matier, and R.L. Clothier had acquired the properties, and in 1957, had completed a 36 m adit into the Sunset zone. Both properties were later allowed to lapse. In 1962, John Hilton restaked the general area of the Sunset zone, which was later to become the Gibraltar property, and in 1963, Robert Glen relocated the Pollyanna property, including the former Rainbow showings.

The early 1960s marked the entry of the major mining companies into the Granite Mountain area and the subsequent introduction of modern exploration techniques, which would ultimately lead to ore discovery. It should be stressed that of the six Gibraltar ore zones, only Gibraltar West offered any exposure of surface mineralization; Pollyanna and Gibraltar East had a few minor exposures of leached limonitic capping; Granite Lake, Gibraltar North, and the Sawmill zone were completely covered. In this environment the

FIGURE 1. Location of the Gibraltar mine area.

most effective exploration tools were soon found to be I.P. geophysics and diamond drilling. The first major company on the scene was Keevil Mines Ltd. who optioned the Pollyanna and Gibraltar properties in 1962, and proceeded to carry out an extensive geophysical and geochemical surveys before terminating the options in 1964. Duval Corporation optioned the Pollyanna property in 1965, and in 1967 formed a joint venture with Canex Placer Ltd. By 1969 a large part of the Pollyanna orebody had been outlined. In the Gibraltar area, John Hilton optioned his claims to Gibraltar Mines Ltd., then a minor company who, in turn, optioned the ground to Cominco Ltd. in 1966. Cominco, in partnership with Mitsubishi Mining Co., then delineated the Gibraltar West ore zone before terminating its option in 1967. Gibraltar Mines Ltd. began its own exploration and in 1969, drilled the discovery holes into the covered Gibraltar East orebody. The Gibraltar property was next optioned by the joint venture partners, Canex Placer and Duval Corporation. Canex later acquired the interest of Duval and then began an extensive diamond drill program which, by 1970, led to the discovery of the hidden Granite Lake orebody. A production decision was made in 1970 with Canex Placer Limited holding more than 70% of the Gibraltar Mines Ltd. issued shares. Production began in March 1972 with a 36 000 tonne per day concentrator. Mining reserves on December 31, 1971, at a 0.25% Cu cutoff were:

	Short tons	Cu (%)
Gibraltar East	150 000 000	.372
Granite Lake	120 000 000	.373
Pollyanna	81 000 000	.360
Gibraltar West	9 000 000	.400
Total	360 000 000 (326 500 000 tonnes)	.371 (.016% MoS_2)

The over-all strip ratio was 2.15:1. Not included in the total reserves was 12 700 000 tonnes of Granite Lake ore which was held by Cuisson Lake Mines Ltd.

Mining phase exploration began in 1977 with a special emphasis on geological mapping, I.P. geophysics and diamond drilling. The Sawmill zone was outlined in 1979 about 6 km south of the plant site. In 1980, a 27.2 million tonne extension to the Pollyanna zone was discovered beyond the eastwall of the Stage I pit. The Gibraltar North orebody was discovered in 1990, and as of 1993, is still being explored. The mining reserves as of December 31, 1992 were:

	Short dry tons	Cu (%)
Pollyanna	36 500 000	.322
Granite Lake	56 300 000	.324
Gibraltar East	69 800 000	.272
Total	162 600 000 (147 500 000 tonnes)	.301 (.008% Mo)

These are a combination of proven and probable reserves at cutoff grades of 0.18% Cu for Gibraltar East and 0.20% Cu for the other ore zones, and at a strip ratio of 1.20:1.

That part of the mineralized inventory deemed uneconomic under current conditions has been classified as a mineral resource. As of December 31, 1992, the Gibraltar mineral resources were:

	Short dry tons	Cu (%)
Gibraltar East	194 900 000	.256
Granite Lake	130 300 000	.305
Gibraltar North	102 200 000	.365
Pollyanna	67 100 000	.267
Sawmill Zone	75 500 000	.244
Gibraltar West	32 500 000	.300
Total	602 500 000 (546 600 000 tonnes)	.287 (.007% Mo)

A 0.20% Cu cutoff was used for Pollyanna and Granite Lake, and a 0.18% Cu cutoff was used for the other zones.

Milling commenced in March 1972. From that date to December 31, 1992, a total of 241 000 000 tonnes of ore averaging 0.360% Cu had been milled. Major ore production was from the Pollyanna, Granite Lake and Gibraltar East zones. A small tonnage was mined from Gibraltar West. Neither Gibraltar North nor the Sawmill have been mined.

Exploration Techniques

Geological modelling, I.P. geophysics and diamond drilling are the primary exploration tools used at the Gibraltar mine. The conceptual base for all exploration activity is provided by geological modelling which is becoming more vital as the exploration emphasis shifts from obvious, near surface targets to deep-level potential ore zones. For mineralization generally not exceeding 100 m in depth, the frequency domain I.P. method has been particularly useful. As a general practice, a percent frequency effect of 2.0 is taken as a threshold value and the anomalies are drilled off at a spacing of about 122 m. The use of I.P. geophysics in the original discovery of the Gibraltar deposits is covered by Cannon, Thornton and Rotherham (1972). Diamond drilling of NQ diameter is the only drilling method used for exploration and ore definition. For uniform ores, optimum drill spacing is about 60 m, preferably in a diamond pattern. For problematical ores, a reduction in drill spacing to 30 m has been employed. Most diamond drilling has been vertical.

Regional Geology

The Granite Mountain batholith, which is the host for the Gibraltar orebodies, is located within a wedge of Mesozoic and Paleozoic rocks bounded on the west by the Fraser Fault system and on the east by the Pinchi Fault system (Fig. 2).

A splay of the Fraser Fault is postulated to underlie the Cuisson Lake valley immediately west of the Gibraltar mine where it is manifested by a well-developed linear topographic low and a pronounced magnetic discontinuity. The Pinchi Fault system, which marks the boundary between the Cache Creek and the Quesnel terrane to the east, lies about 15 km to 20 km east of Granite Mountain where it is represented by an unknown number of fault splays, including the Quesnel Fault.

Rock units in the mine area include those specific to the Cache Creek terrane and also Late Jurassic and younger units that overlap the Cache Creek and Quesnel terranes. Mine area geology is illustrated in Figure 3.

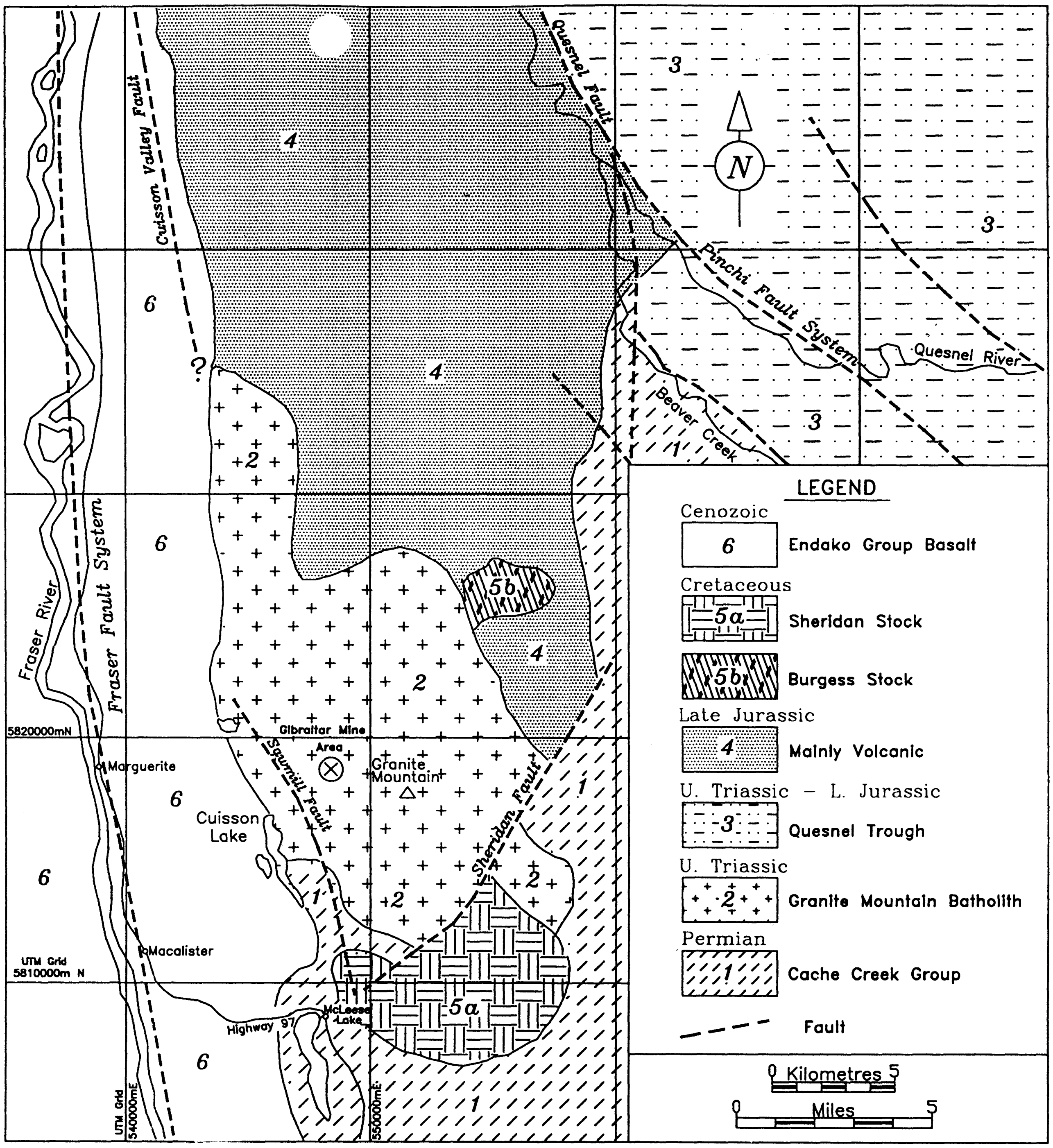

FIGURE 2. Generalized regional geology of the Granite Mountain area.

The oldest rocks of the local area are regionally metamorphosed sedimentary and volcanic rocks of the Permian Cache Creek Group (Tipper, 1959). The age of this dynamothermal metamorphism is considered to be latest Triassic to Early Jurassic (Mortimer et al., 1990). Locally, the Cache Creek Group consists mainly of andesitic to basaltic flows and associated volcanoclastic materials which have been transformed into a complex array of greenschists. Lenses of limestone, recrystallized to relatively pure marble, form a minor but widespread component of the predominantly volcanic assemblage. Some of the calcareous rocks have been metamorphosed to epidote-chlorite-garnet skarns by the Granite Mountain batholith. A graphitic phyllite unit can be traced more than 6 km along the southern edge of the belt of Cache Creek Group rocks south of the Granite Mountain batholith.

The Cache Creek Group is intruded by the latest Triassic to Early Jurassic Granite Mountain batholith and the Cretaceous Sheridan stock. The Granite Mountain batholith is a zoned, peraluminous, subalkaline body with a hybrid border, a tonalite central phase and trondhjemite northern phase (Fig. 3). The batholith and adjacent Cache Creek Group rocks have undergone penetrative foliation and are metamorphosed to the upper greenschist facies.

The Sheridan stock comprises tonalite and dioritic to granodioritic rocks. It lacks the deformation and alteration of the older rocks and postdates the regional metamorphism and ore stage mineralization.

Along the northern edge of the Granite Mountain batholith occurs a sequence of andesitic flows, breccia, greywacke, siltstone and conglomerate. These may be of Early Jurassic age (Panteleyev, 1977) and have been intruded by several small granitic plutons, the largest of which Panteleyev refers to as the Burgess stock, of pos-

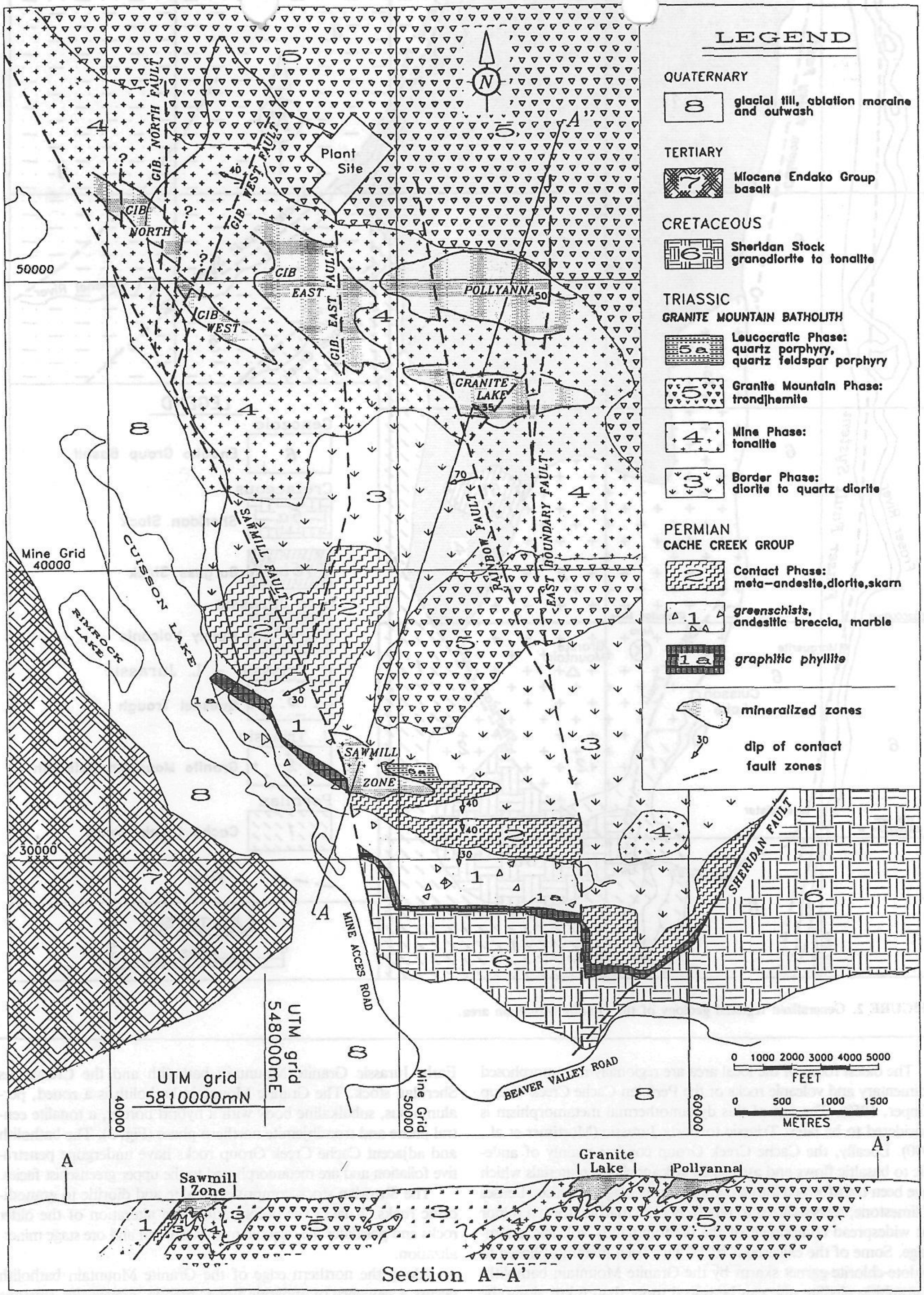

FIGURE 3. Gibraltar mine area geology.

sible Cretaceous age. Diamond drilling by Gibraltar Mines Ltd. has indicated the Jurassic sequence is underl[illegible]y a pyritiferous black argillite unit which locally is 90 m thick.

Flat-lying basaltic flows of the Miocene Endako Group cap the dissected plateau west of the batholith. Further to the west, in the Fraser River valley, these rocks overlie tilted volcanic and sedimentary rocks of possible Eocene age.

The area has been intensely glaciated and most of the bedrock is covered by tough impervious lodgement till, accompanied in places by ablation moraine and glaciofluvial deposits. In the Gibraltar East pit, the lodgement till overlies a thick deposit of brown, sandy till, which may be a remnant of an earlier glacial period.

Earlier descriptions of Granite Mountain and mine area geology are provided by Sutherland Brown (1958, 1967, and 1974), Eastwood (1970), Rotherham, Drummond and Tennant (1972), Drummond, Tennant and Young (1973), Drummond, Sutherland Brown, Young and Tennant (1976) and Panteleyev (1977).

Ore Deposit Geology

The Gibraltar mining property consists of six separate orebodies. Five of these — Pollyanna, Granite Lake, Gibraltar East, Gibraltar West, and Gibraltar North — occur within the batholith, in a broad zone of shearing and alteration. The sixth orebody, the Sawmill zone, lies about 6 km to the south, along the southern edge of the batholith, within a complex contact zone formed between the batholith and Cache Creek Group.

Petrology

The Granite Mountain batholith is a composite body consisting of three major phases — Border Phase diorite, Mine Phase tonalite, and Granite Mountain trondhjemite, and a minor late leucocratic phase of trondhjemitic composition. A photograph of the differentiated phases is shown in Figure 4. Table 1 summarizes the features of the principal intrusive rock units, classified after Streickeisen, 1973. Contacts between the major phases are gradational over widths ranging from 2 m to several hundred metres. Leucocratic phase contacts are both sharp and gradational, generally over widths less than a metre. Alterations and structures associated with ore mineralization affect all phases of the batholith.

Border Phase Diorite

A broad zone of assimilation and recrystallization has been formed between the mafic-rich Cache Creek Group and the intrusive batholith. This hybrid zone incorporates a baffling array of intermediate rock types and rapid textural variations which closely reflect the country rock composition at its outer edge and that of the parent magma at its inner edge. The outer, predominantly volcanic, portion of the hybrid zone has been categorized as Contact Phase - Cache Creek Group (Fig. 3). The inner, predominantly plutonic part of the hybrid zone, has been classified as Border Phase Diorite. These two rock units are the major hosts for the Sawmill zone orebody.

Typical Border Phase diorite consists of 45% to 50% saussuritized plagioclase, 35% chloritized hornblende and 15% fine-grained quartz. Textures are variable, with grain sizes of 1 mm to 5 mm. Mafic rich quartz diorites are also present and these are most prevalent near contacts with the Mine Phase tonalite.

Mine Phase Tonalite

Mine Phase tonalite is a minor host for the Sawmill orebody and the sole host rock for the other Gibraltar orebodies. It has a relatively uniform mineralogical composition (Table 1) of saussuritized andesine plagioclase, chlorite and quartz. The chlorite appears to be derived from biotite and minor hornblende. Accessory minerals may include magnetite and rutile. Plagioclase is variously altered to albite-epidote-zoisite and muscovite. The rock is generally equigranular with a grain size of 2 mm to 4 mm. Rock fabrics range from isotropic to intensely schistose. In most cases the unmineralized rock is only weakly foliated and the degree of penetrative deformation increases with increased alteration.

FIGURE 4. Differentiated phases of the Granite Mountain batholith, (1) Mine Phase Tonalite; (2) Granite Mountain Phase Trondhjemite; (3) Leucocratic Phase quartz feldspar porphyry.

A minor variation of the Mine Phase tonalite, which is exposed along the south rim of the Granite Lake pit, contains equant grains of biotite and hornblende, minerals which are normally rare throughout the batholith.

Granite Mountain Phase Trondhjemite

Geological mapping by Gibraltar Mines Ltd. geologists and British Columbia Ministry of Mines' geologists in 1977 (Panteleyev, 1977) indicated the north part of the batholith consists of an unusual coarse-grained leucocratic quartz diorite, now recognized to be trondhjemite. Deep diamond drilling later revealed this rock also underlies the Pollyanna, Granite Lake, Gibraltar East and Gibraltar North orebodies.

The trondhjemite consists of saussuritized plagioclase, quartz, and chloritized biotite (Table 1). Grain size is about 2 mm to 4 mm near contacts with the Mine Phase but reaches 8 mm to 10 mm a kilometre north of the contacts. The quartz commonly occurs as large grains or grain aggregates set in a finer grained, inequigranular matrix of quartz, plagioclase and minor chlorite. Foliation

TABLE 1. Descriptive summary of rock units

	erage mode (± 5%)		Normative Qtz-Or-An-	Normative An (%)
Border Phase Diorite	quartz plagioclase chlorite	-< 15% - 45% -< 45%	18-7-32-23	41
Mine Phase Tonalite	quartz plagioclase chlorite	- 30% - 50% - 20%	26-7-32-19	37
Granite Mountain Trondhjemite	quartz plagioclase chlorite	-≥ 45% - 45% - 10%	30-7-42-12	22
Leucocratic Phase (quartz plagioclase porphyry, trondhjemite)	phenocryst mode: quartz plagioclase groundmass: felsophyric felsite with 5%-10% sericite	 -25%-30% -70%-75%	31-6-46-11	20

TABLE 2. Chemical analyses

	Least altered and metamorphosed									Altered phases					
Wt. %	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	71.73	69.81	64.52	60.05	64.61	68.75	65.37	57.71	62.83	62.08	61.55	61.83	65.54	68.88	60.69
TiO_2	0.11	0.22	0.47	0.62	0.53	0.62	0.67	0.52	0.48	0.77	0.48	0.47	0.68	0.25	0.36
Al_2O_3	14.28	16.43	16.89	17.33	17.12	14.09	14.98	16.24	14.76	13.61	14.30	15.51	14.22	14.32	13.84
Fe_2O_3	1.34	1.22	2.22	2.84	1.59	2.47	3.28	6.62	4.33	9.19	2.03	8.71	6.48	4.64	4.73
FeO	0.07	0.87	2.16	2.60	1.96	0.08	2.90	0.15	4.40	0.22	3.25	0.16	0.24	0.07	0.28
MnO	0.03	0.09	0.12	0.12	0.06	0.18	0.23	0.35	0.41	0.06	0.74	0.01	0.03	0.04	0.12
MgO	0.46	0.84	2.06	2.72	1.87	0.82	2.18	2.08	2.73	0.77	2.10	0.50	0.75	0.57	1.92
CaO	2.87	2.39	3.98	5.48	4.27	3.31	1.78	8.82	0.93	0.13	3.89	0.24	0.39	0.49	5.65
Na_2O	5.41	4.94	3.82	3.67	4.32	4.01	2.91	2.43	0.27	0.35	1.95	0.49	0.31	0.44	2.85
K_2O	0.97	1.26	1.10	1.24	1.84	1.75	2.15	0.89	3.71	3.87	2.56	4.40	4.48	4.61	2.19
P_2O_5	0.10	0.04	0.04	0.21	0.40	0.06	0.14	0.13	0.16	0.17	0.16	0.14	0.12	0.07	0.11
LOI	1.52	1.31	2.14	2.41	1.67	2.46	2.83	2.90	4.17	6.05	6.55	6.40	4.35	4.05	6.24
S	0.34	0.00	0.003	< 0.003	n/a	0.13	0.17	0.03	n/a	5.85	n/a	5.60	3.31	2.70	1.38
TOTAL	98.56	99.43	99.53	99.30	100.24	98.61	99.53	98.80	99.38	97.23	99.73	98.85	97.63	98.40	98.97
ppm															
Ba	511	896	797	781	1075	n/a	775	275	848	900	644	661	848	975	720
Sr	333	281	344	432	620	n/a	174	700	71	50	195	74	42	50	250
No. of Samples	9	17	10	7	3	5	4	2	6	2	2	3	4	2	5

ROCK UNITS:
1: Quartz Feldspar Porphyry, Sawmill Zone
2: Granite Mountain Trondhjemite
3: Mine Phase Tonalite
4: Border Phase Diorite
5: Sheridan Tonalite
6: Granite Mountain Trondhjemite, Gibraltar North
7: Chlorite Darkened Mine Phase, Gibraltar North
8: Quartz Epidote, Gibraltar North
9: Dark Chlorite, Gibraltar North
10: Quartz Sericite Chlorite, Gibraltar North
11: Quartz Carbonate, Gibraltar North
12: Quartz Sericite, Gibraltar North
13: Quartz Porphyry, Gibraltar North
14: Quartz Porphyry, Granite Lake
15: Quartz Porphyry, Sawmill Zone

throughout the trondhjemite body tends to be weak or absent except along contacts with the Mine Phase or Leucocratic Phase. In extreme cases the development of foliation has been accompanied by metamorphic differentiation, manifested by pronounced mineralogical segregation; medium- to coarse-grained quartz-rich laminations separated by very fine-grained plagioclase-rich laminations with abundant epidote-sericite and chlorite. As the intensity of the penetrative deformation increases plagioclase is progressively destroyed and replaced by fine epidote and sericite.

Leucocratic Phase

Associated with all ore grade mineralization are minor zones of fine-grained rock classified as Leucocratic Phase due to a prevailing quartz plagioclase composition and general lack of mafic minerals. The term was first used by Drummond (Drummond et al., 1976) to describe leucocratic, porphyritic quartz diorite, but has since been expanded to include quartz porphyry and quartz plagioclase porphyry, representing a wide range of alteration and associated textural changes. Most of the leucocratic rocks occur as small zones less than 30 m thick. The Sawmill zone leucocratic body is, however, a small pluton with brecciated contacts against the Contact Phase of the Cache Creek Group.

Quartz plagioclase porphyry makes up a significant part of the Sawmill zone leucocratic body, where its mineralogy and texture is least altered. Its composition here is that of a leucotonalite or trondhjemite (Table 1). In thin section, the rock has a very fresh appearance with coarse quartz phenocrysts to 8 mm diameter and oligoclase (An 16 to 32, averaging An 20) phenocrysts to 5 mm diameter. Staining did not reveal any K-feldspar. The phenocrysts, which make up 50% to 60% of the rock, are set in a fine-grained, quartz-plagioclase-sericite groundmass with a felsophyric texture that shows little sign of recrystallization. At contacts and within schistose zones the quartz plagioclase porphyry is transformed to quartz porphyry. This is attended by significant mineralogical, textural and

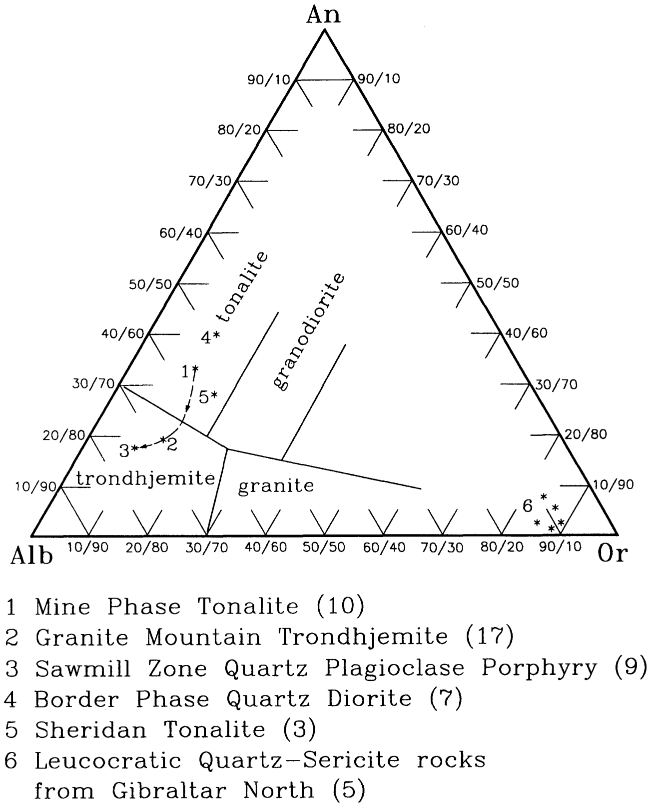

FIGURE 5. Plot of average normative Anorthite - Albite - Orthoclase of principal rock phases at Gibraltar. Number of analyses are indicated in the parentheses. Fields are after O'Connor (1965).

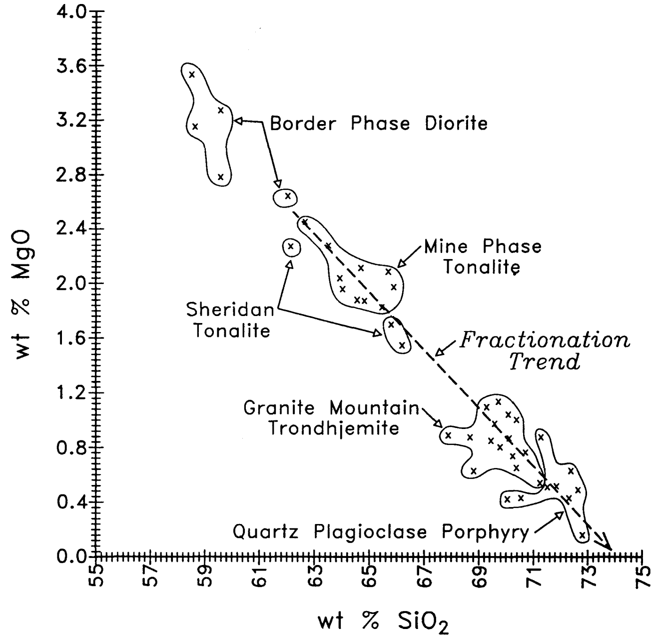

FIGURE 6. Fractionation trend of Mine Phase tonalite - Granite Mountain Phase trondhjemite Leucocratic Phase quartz feldspar porphyry shown by the weight % MgO against weight % SiO_2. Plots of Border Phase diorite and Sheridan tonalite are shown for comparative purposes.

chemical changes. The first of these is the progressive replacement of the plagioclase phenocrysts by saussurite, sericite and fine epidote. The second significant feature is the recrystallization of the original felsophyric groundmass to a fine mosaic of quartz and plagioclase. Quartz phenocrysts, originally single subhedral crystals, become highly sutured and some are in part made over to composite phenocrysts. These changes are accompanied by a marked decrease in Na_2O and increase in K_2O.

Contact relationships between the Leucocratic Phase and the other phases of the batholith have generally been obscured by late-stage deformation and alteration. In most cases, the leucocratic phase rocks appear concordant with the foliation. However, cross-cutting relations have been observed in the Pollyanna zone between leucocratic porphyritic quartz diorite and the tonalite host rock.

Geochemistry of Principal Intrusive Phases

The average whole-rock analyses of the main intrusive phases are shown in Table 2, as performed by the British Columbia Department of Mines in 1978 and 1979, and by Min-En Laboratories in 1993. The samples listed were selected from a larger group of analyses and were chosen to represent the least altered intrusive rocks.

Figure 5 is a ternary plot of normative Anorthite-Albite-Orthoclase of the various phases. Shown also are the Border Phase diorite and the altered and mineralized leucocratic quartz porphyry rocks of Gibraltar North for comparative purposes. The field boundaries are those of O'Connor (1965) for use with rocks with more than 10% quartz. This plot clearly expresses the tonalitic nature of the Mine Phase and the trondhjemitic nature of both the Granite Mountain trondhjemite and the leucocratic quartz plagioclase porphyries of the Sawmill zone.

The sequence of fractionation is considered to be from Mine Phase tonalite, to Granite Mountain trondhjemite to leucocratic quartz plagioclase porphyry. This is substantiated by plots of wt% MgO versus wt% SiO_2 (Fig. 6) and of conserved constituents MgO versus TiO_2 (Fig. 7).

The Mine Phase tonalite and Granite Mountain trondhjemite are peraluminous whereas the Sawmill zone leucocratic rocks range from weakly peraluminous to metaluminous. The lack of feldspathoids (both modal and normative) and pyroxene along with variation diagrams of the alkalis (Na_2O versus SiO_2, K_2O-CaO versus SiO_2 indicate a calcic series, whereas Peacock's alkali-lime index of 62 and MagmaChem's modified Peacock index [Keith (1987) for use with metaluminous rocks] of 61.5 indicates a calc-alkalic affinity. A total FeO/MgO versus wt% SiO_2 variation diagram indicates the principal intrusive phases; tonalite, trondhjemite and quartz plagioclase porphyry all plot in the moderately Fe-poor calc-alkaline field. Both the tonalite and trondhjemite are moderately oxidized whereas the leucocratic porphyries are strongly oxidized.

The few 1978 and 1979 whole-rock analyses of the Sheridan stock that are available indicate a tonalite composition, very similar to that of the Mine Phase (Figs. 5 and 7), but with a slightly greater differentiation index. Its composition clearly demonstrates that the same crustal magmatic source that generated the Granite Mountain batholith was active well into Cretaceous time.

Radiometric Ages

The age of the Granite Mountain batholith is considered by Drummond et al. (1976) to be 203 Ma to 204 Ma ± 6 Ma (latest Triassic), based on age-dating of hornblende. Biotite from one sample gave 82 Ma and 84 Ma ± 2.5 Ma in two analyses. In 1987 a Granite Mountain Phase trondhjemite sample (G77 DH-60) collected by A. Panteleyev, was analyzed by J. Harakal, R. Parrish and B. Ryan at The University of British Columbia Geochronometry Labratory. Zircon gave ages of 204 Ma to 217 Ma, whereas biotite gave ages of about 125 Ma to 128 Ma ± 4 Ma. Zircon from composited core samples of Granite Mountain Phase rocks in drill holes 82-26, 82-27, and 82-28 gave an age of about 217 Ma ± 12 Ma. From these dates it is concluded that the tonalitic and trondhjemitic magmatism was latest Triassic. Later thermal events are considered to have caused the younger ages obtained from biotite.

The University of British Columbia laboratory also determined an age of 137 Ma ± 5 Ma, Late Jurassic to Early Cretaceous, for

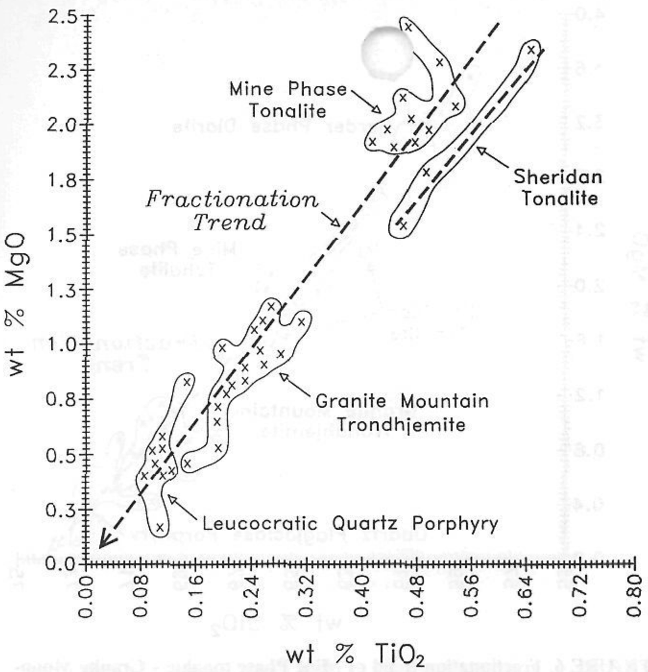

FIGURE 7. Conserved constituent scatter plot of principal intrusive phases. Note the well defined, but separate trend shown by the Sheridan tonalite.

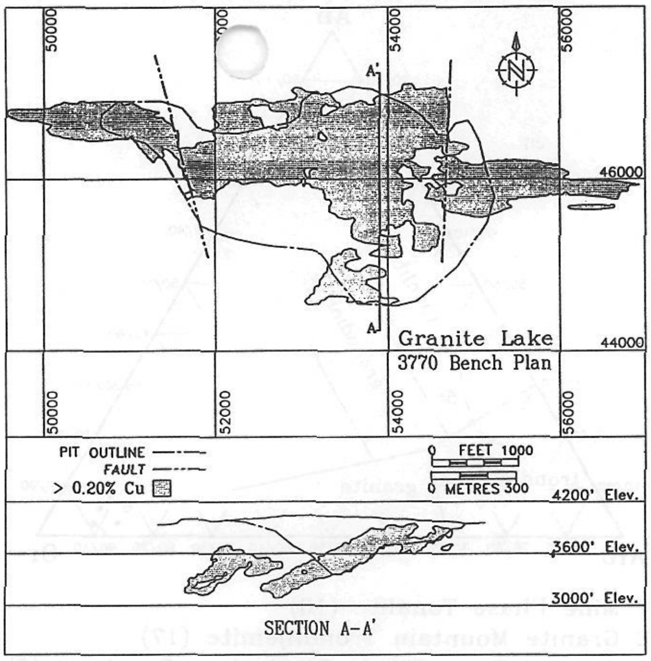

FIGURE 8. Section and plan of the Granite Lake orebody showing the over-all Granite Creek strike and low-angle southerly dip.

hornblende in a sample collected from the Sheridan stock, reported as an unfoliated, hornblende quartz diorite. The intrusion of the Sheridan stock clearly postdates the metamorphism, penetrative deformation and ore mineralization of the Granite Mountain batholith. However, its tonalitic nature indicates that the same magmatic processes that gave rise to the Granite Mountain batholith continued for some time after deformation ceased along this part of the Cache Creek terrane margin.

Structure

Penetrative deformation began during a period of regional stress and metamorphism which clearly affected the Granite Mountain batholith and Cache Creek Group rocks but left little imprint on either the Cretaceous Sheridan stock or the Jurassic rocks to the north. The present evidence suggests the same stress field was operative during the intrusion and differentiation of the Granite Mountain batholith and continued during the period of ore stage alteration and mineralization.

The deformation is made evident by the weakly foliated to schistose fabric of the batholith and Cache Creek Group rocks which has been imparted by the cataclastic grinding of plagioclase and quartz, and the planar alignment of chlorite and sericite. Associated metamorphic effects include the progressive replacement of plagioclase by fine-grained quartz, saussurite, sericite and epidote and the chloritization of mafic minerals. In the most extreme cases of metamorphism and deformation, mineral differentiation has occurred on the scale of centimetres, resulting in a rock with thin layers of quartz-rich and phyllosilicate-rich material. The prevailing strike of regional foliation is 310° to 330°, with subordinate strikes of 270° to 290°. Dip directions are southerly, generally at 30° to 50°. Stratified rocks of the Cache Creek Group and the major phases of the batholith have similar strike and southerly dip (Fig. 3). Diamond drilling along the southeast end of the Sawmill zone, indicate the Border Phase diorite overlies the Cache Creek Group in a manner suggestive of low angle northeasterly-directed thrusting, which concurs with the sense of movement indicated by the schistosity of the Granite Mountain batholith.

Regional deformation was accompanied by localized metasomatic alteration and associated sulphide deposition which led to the concentration of copper mineralization in specific areas of the batholith. Within the presently known Gibraltar orebodies, four major structural hosts for copper mineralization have been recognized:

(a) discrete lamellae of chlorite and/or sericite. (These microscopic and small-scale foliation structures are both penetrative and pervasive);

(b) complex sets of sheeted shear veins, collectively referred to as oriented stockworks;

(c) shear zones, consisting almost entirely of alteration and gangue; and

(d) dilation veins, composed mainly of quartz gangue.

Two major ore structure orientations have been recognized; the Sunset and Granite Creek systems. The Sunset system strikes 320° to 340° with one set dipping 35° to 45° southerly and a conjugate set, known as the Reverse Sunset, dipping 50° to 60° northerly. The Granite Creek system strikes 270° to 280° and dips 20° to 40° southerly with a subordinate set dipping steeply north. Ore host structures of the Sunset system are mainly shear zones, with minor development of stockworks and associated foliation lamellae. Ore host structures of the Granite Creek system are predominantly oriented stockworks with associated pervasive foliation lamellae.

The Gibraltar orebodies can be classified according to structural system. Granite Creek systems provide the major ore structures of Pollyanna, Granite Lake and the Sawmill zone. These bodies have the characteristic large diffuse nature of porphyry-type ore but retain the Granite Creek structural orientation along outside boundaries. The Gibraltar East deposit is essentially a system of interconnected Sunset zones which create a large body of fairly uniform grade yet maintain a strong degree of internal planar control. The Gibraltar West and Gibraltar North deposits are contained within a large complex shear zone which is predominantly Reverse Sunset. These orebodies are long and narrow, with sharp ore:waste cutoffs. Internally they are intricately folded. It has been the practice at the mine to refer to the Granite Lake, Pollyanna and Sawmill deposits as porphyry ores and the Gibraltar West and Gibraltar North as shear zone ores. Gibraltar East is considered to be transitional between porphyry and shear zone ore. The general configuration of the Granite Lake and Gibraltar North orebodies are shown in Figures 8 and 9, respectively.

The Gibraltar orebodies have been intersected and displaced by northerly trending, westerly dipping post ore faults (Fig. 3). The largest is the Sawmill Fault which is interpreted to be a normal fault with a net throw of at least 300 m. Other faults are smaller but also appear to have a large component of normal dip-slip movement. Along the Rainbow Fault, for example, the western tail of the Granite Lake orebody has been dropped a large distance, probably in excess of 350 m. Along the Gibraltar West Fault the northwest end of the Gibraltar West ore zone has been depressed approximately 61 m. Similar movements are considered for the East Boundary Fault. A different sense of movement is evident for the Gibraltar North Fault, across which the Gibraltar North orebody shows an apparent right lateral separation of about 122 m.

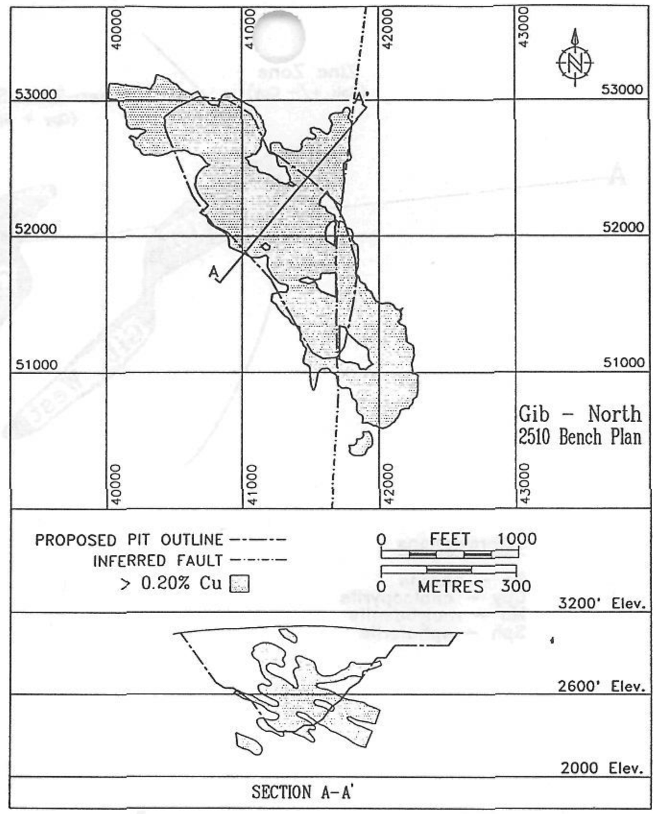

FIGURE 9. Section and plan of the Gibraltar North orebody showing the Sunset strike and reverse northeasterly dip.

Mineralization

There is a close spatial relationship between sulphide mineralization and alteration in the Gibraltar ore zones. Essentially, ore grade mineralization is developed where there has been extensive chloritization and sericitization. Pyrite and chalcopyrite are the principal primary sulphide minerals of the Gibraltar deposits. Fine-grained chalcopyrite, generally barely visible without magnification, forms up to 60% of the copper grade and constitutes the single most important form of copper mineralization. Most of this fine fraction is dispersed within the phyllosilicate foliation lamellae and forms the uniform, well distributed grades of the Gibraltar porphyry-type ores. The coarser grained chalcopyrite usually occurs in quartz veins and shear zones. Pyrite generally shows some degree of segregation from chalcopyrite. In the Pollyanna, Granite Lake and Sawmill deposits, pyrite segregation is of sufficient magnitude to form a halo, or blanket, of pyritic waste above and beyond the orebody. Large-scale pyrite zoning is also evident in the Gibraltar East deposit but without the formation of a separate pyrite waste halo. In Gibraltar West and Gibraltar North, pyrite is closely associated with the ore, often as massive zones 3 m to 7 m thick.

Small concentrations of other sulphides are present in the Gibraltar ores. Bornite, associated with magnetite and chalcopyrite, occurs along the low sulphur extremities of the Pollyanna and Sawmill deposits. Molybdenite is a minor but economically important associate of chalcopyrite in the Pollyanna, Granite Lake, and Sawmill deposits. Small zones of molybdenite mineralization also occur in Gibraltar East but are virtually absent in Gibraltar West and Gibraltar North. Sphalerite is present in the Gibraltar West zone and particularly abundant in parts of the Gibraltar North zone. Both of these deposits also have elevated silver concentrations associated with copper mineralization. The above relationships suggest a metal zonation from Pollyanna to Gibraltar North which involves a westerly decrease of molybdenum and a corresponding increase of zinc and silver (Fig. 10).

Alteration

Because metasomatic alteration was synchronous with dynamothermal metamorphism, a clear distinction cannot always be made between minerals formed by metamorphic recrystallization and those formed by metasomatic replacement. Alteration is, therefore, a general term used in this paper to classify non-metallic minerals formed in close conjunction with sulphide deposition, by both metamorphic and metasomatic processes. In all cases, alteration is closely associated with penetrative deformation, and in most cases, the strength of alteration increases with the intensity of deformation. A typical end product is a schistose rock consisting almost entirely of alteration minerals (Fig. 11).

The principal alteration minerals of the Gibraltar deposits are chlorite, sericite, epidote, carbonate and quartz. Ore grade mineralization is associated mainly with sericite and chlorite. Epidote and the carbonate minerals are not common associates of strong sulphide mineralization except in the Sawmill zone. Quartz is common throughout the alteration sequence as both a relict host rock mineral and an introduced mineral. It occurs in various combinations with the alteration minerals; for example, the most common ore grade alteration assemblage is quartz-sericite-chlorite. A common assemblage of barren rock is quartz-carbonate or quartz-epidote. Massive dark green chlorite is also a common ore host in all of the Gibraltar deposits, and is particularly abundant in the Gibraltar West and Gibraltar North zones where it is accompanied by euhedral disseminations of spessartine garnet. Gypsum is a common vein constituent of the low sulphide environments in the Sawmill zone ore and has been noted in similar environments of the Gibraltar East zone. It is noteworthy that neither K-feldspar nor biotite have been recognized as alteration minerals at the Gibraltar mine. Hydrothermal clay alteration of probable post-ore derivation has been noted along the boundaries of the Gibraltar North Fault, but elsewhere appears absent.

The classification of alteration mineralogy has not been possible in the Gibraltar porphyry-type ores due to the diffuse nature of the host rock structure and the overlapping distribution of alteration mineral assemblages. In the Gibraltar North environment however, mineral segregation in the large shear zones has been of sufficient magnitude to permit the recognition of six distinctive alteration assemblages which are outlined in Table 4. Three of the mineral assemblages, dark chlorite, quartz-sericite-chlorite and quartz-sericite, are major hosts for ore grade mineralization; while the other three, quartz-epidote, quartz-carbonate and the chlorite darkened phase, are generally hosts for weak sulphide mineralization.

The chemical analyses of Gibraltar North alteration assemblages are presented in Table 2, along with representative analyses of altered and least altered host rocks from other Gibraltar environments. The following discussion is based on these analyses and on the alteration phenomena observed in Gibraltar North, but is considered to be equally valid for the other Gibraltar deposits.

Fractionation of the Granite Mountain batholith produced

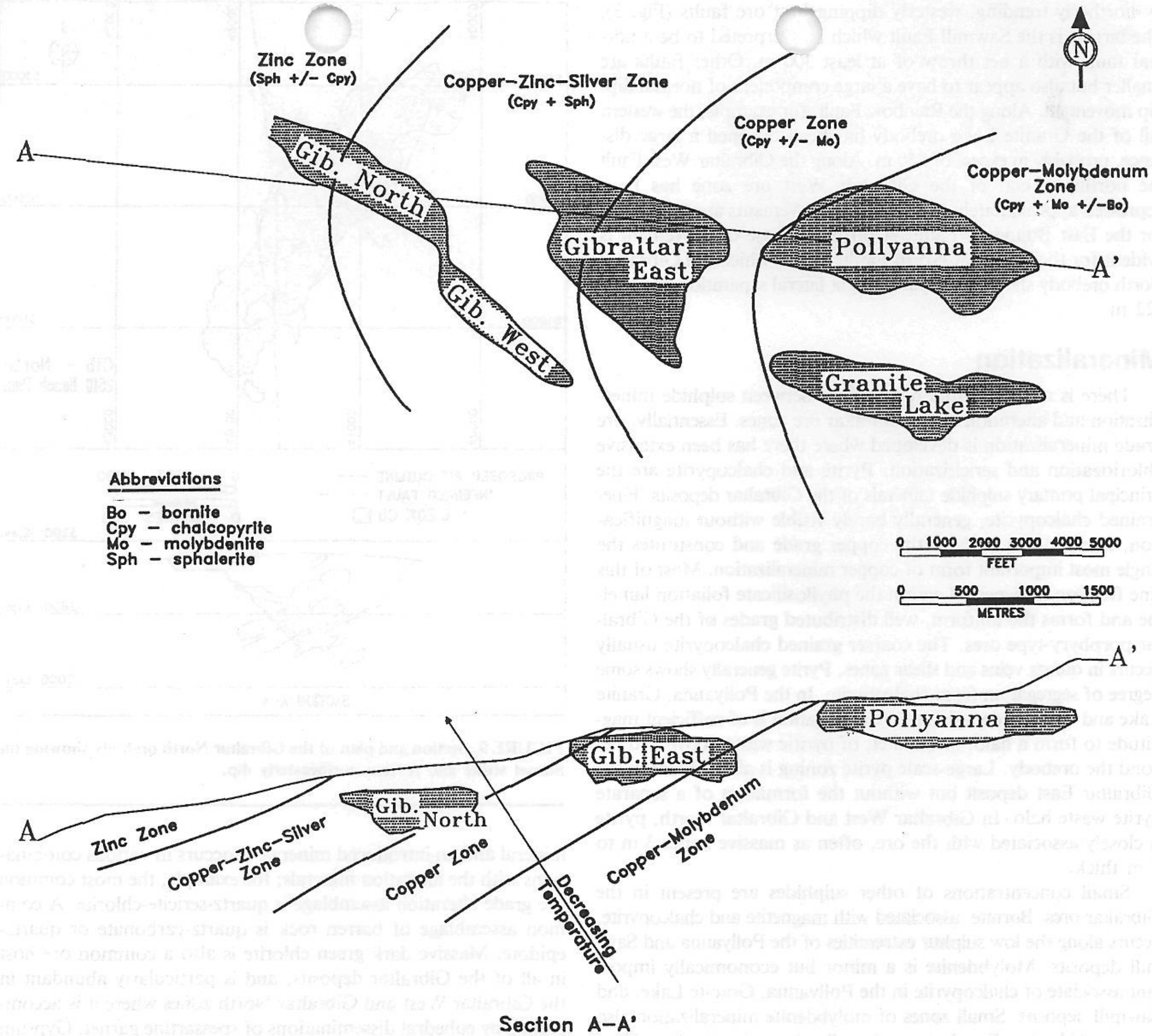

FIGURE 10. Section and plan of the Gibraltar mineralized system showing hydrothermal metal zonation and inferred orientation of temperature controls. Pyrite is widespread throughout all zones. Silver is hosted primarily by chalcopyrite.

rocks impoverished in K_2O and enriched in Na_2O, as exemplified by the chemical composition of the trondhjemitic quartz plagioclase porphyry and Granite Mountain trondhjemite. In contrast, the metasomatism that accompanied the mineralization process completely reversed this chemical trend and resulted in ore assemblages characterized by low Na_2O and high K_2O, in addition to high S, Cu and Fe^3/Fe^2. A major component of metasomatism was the sericitization of plagioclase feldspar, which involved the deposition of K as sericite, and the subsequent removal in solution of Ca and Na. Calcium was later deposited as epidote or carbonate, generally beyond the ore zone, but Na remained in solution to be totally removed from the system. The extent of sericitization can be expressed by the Na_2O/K_2O ratio which also shows an approximate inverse relationship with sulphide concentration. These relationships are summarized in Figure 12 which shows the distribution of K_2O and Na_2O in relation to sulphide mineralization, *alteration assemblage and Na_2O/K_2O ratio. The term distal refers* to barren, least altered host rock. Proximal denotes weak sulphide mineralization in the fringes of the ore zone, and ore zone refers to strong sulphide mineralization accompanied by intense sericitic or chloritic alteration. Figure 12 emphasizes the dominant role of K-metasomatism in the alteration process and implies further, the use of the Na_2O/K_2O ratio in outlining areas of potential ore grade mineralization. Metasomatism was also accompanied by the redistribution of Mg and Ca, with Mg being enriched in the ore zone and Ca-enriched in the proximal zone. Although Mg, in the form of chlorite, forms a major part of ore stage alteration and has been locally concentrated in shear zones, there is no evidence of large scale Mg introduction comparable with that of K.

Weathering and Supergene Effects

Most of the Tertiary weathering surface has been removed during the period of Pleistocene glaciation. The present zone of oxidation and leaching within the Gibraltar deposits is confined to the upper 1 m to 3 m of the bedrock surface. Corresponding supergene enrichment tends to be weak and pervasive (Pollyanna), or absent (Sawmill), or confined to small zones (Granite Lake, Gibraltar West, Gibraltar North). An exception is the Gibraltar *East deposit which is capped by an extensive blanket of super-*gene enrichment, interpreted to be a remnant of a pre-glacial, or interglacial, period of weathering. Gibraltar East is downfaulted relative to the Granite Lake and Pollyanna deposits which may have been a major factor in the preservation of the supergene blanket.

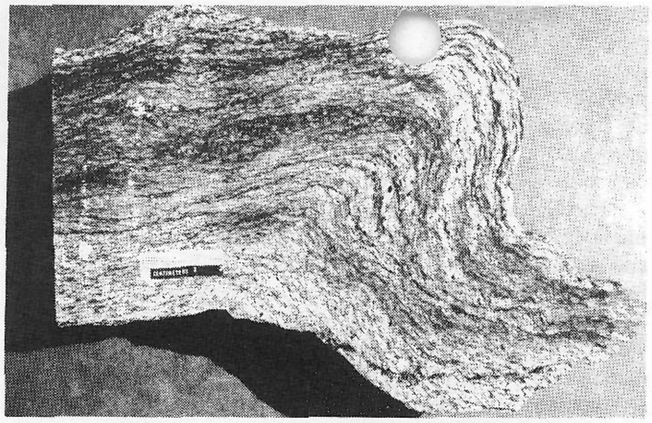

FIGURE 11. Sericitic altered tonalite from the supergene zone of Gibraltar East showing the foliated and folded nature of alteration and mineralization. The dark wisps are quartz-chlorite-pyrite-chalcocite lamellae.

TABLE 3. Average composition of Granite Mountain Trondhjemite compared to that of F. Barker's (1979)

Barker's Trondhjemite	Granite Mountain Phase
SiO_2 >68%, usually <75%	70.22%
Al_2O_3 >15%	16.53%
(FeO + MgO) <3.4%	2.94%
FeO:MgO = 2 to 3	2.5 %
CaO typically 1.5% to 3%	2.41%
Na_2O typically 4.0% to 5.5%	4.97%
K_2O typically <2%	1.27%

TABLE 4. Major alteration assemblages — Gibraltar North

Assemblage	Composition
1. Chlorite darkened phase	chlorite enriched halo
2. Dark chlorite	chlorite(>60%) ± carbonate ± epidote ± sericite ± chlorite ± garnet ± carbonate
3. Quartz sericite chlorite	sericite + chlorite (<20%) + quartz + carbonate
4. Quartz sericite	sericite + quartz
5. Quartz epidote	quartz + epidote ± chlorite
6. Quartz carbonate	quartz + carbonate ± chlorite ± sericite

In Gibraltar East the extent of supergene enrichment has been determined largely by the pyrite concentration in the oxidation zone. That is, the greatest degree of enrichment is associated with pyrite zone ore which during oxidation has apparently produced sufficient acid to fully mobilize and transport all copper to the underlying environment of secondary enrichment. The resulting oxide zone is a leached cap, consisting essentially of limonite and leached rock, usually completely devoid of copper carbonates or oxides. Supergene enrichment occurs directly beneath the leached cap, forming a blanket-like zone about 15 m to 30 m thick. Pyrite zone ore contains an average pyrite concentration well over 3%. In those areas of lesser pyrite concentration, the lower acidity of the oxidation process allows the fixation of copper within the oxide zone, thereby preventing the full development of the supergene enrichment zone. The oxide mineral assemblage in this case consists of limonite, manganese wad, malachite and azurite. Cuprite and native copper are also present but in erratic concentrations, generally occurring near the base of the oxide zone, or within the underlying supergene zone. The two minerals are closely associated; cuprite commonly occurs as replacement rims around native copper.

The supergene minerals recognized at Gibraltar are chalcocite, digenite and covellite. Chalcocite is assumed to be the predominant

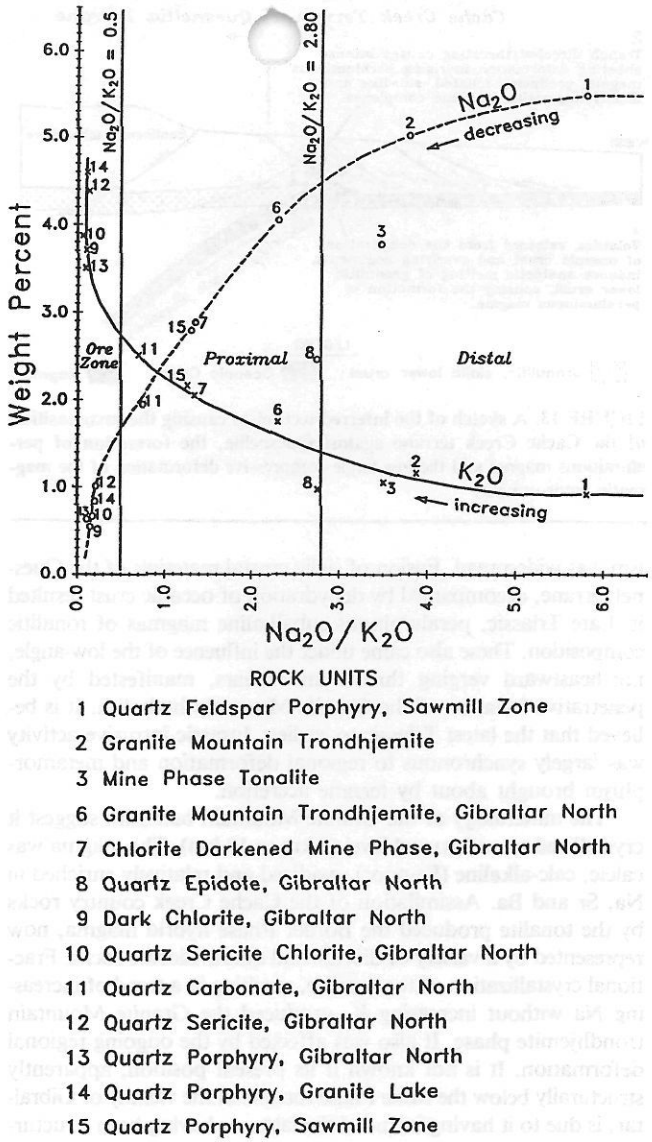

FIGURE 12. Distribution trend of Na and K from barren, least altered host rock (Distal), to weakly mineralized, altered marginal rock (Proximal), and to strongly mineralized intensely altered rock (Ore zone).

supergene mineral, and occurs principally as spongy aggregates coating chalcopyrite. As a general rule, pyrite shows a lesser degree of replacement which commonly consists only of thin chalcocite coatings, less than 20 μ thick. Digenite has been observed in polished sections closely intergrown with chalcocite as replacement rims around chalcopyrite grains. Covellite is a widespread but minor supergene mineral. In polished sections it appears as replacement rims on chalcopyrite, either alone, or in association with chalcocite and digenite. A copper sulphate mineral, tentatively identified as chalcanthite, occurs as a post-mining leaching product of the supergene ores.

Genesis of Deposit

Magmatism giving rise to the Granite Mountain batholith was initiated by the subduction of oceanic crust of the Cache Creek terrane eastward under the Quesnel terrane during the Triassic. The Pinchi Fault system, east of the Gibraltar mine, represents the suture between these two terranes. The volcanic and sedimentary cover of the oceanic crust, the Cache Creek Group, was detached from its basement as the relatively flat subduction proceeded and was caught up in trench-directed thrusting (Fig. 13). Little or no volcanism accompanied subduction west of the trench; whereas, east of the trench Triassic and Jurassic volcan-

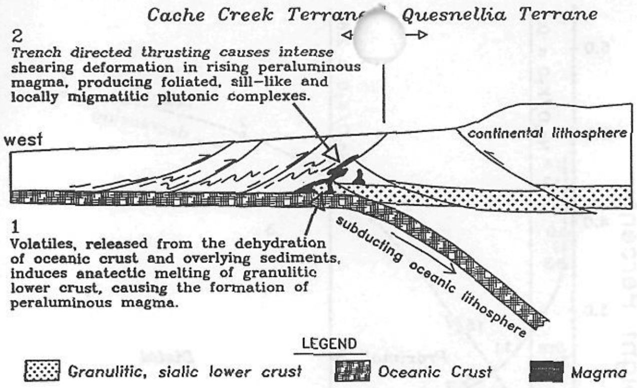

FIGURE 13. A sketch of the inferred tectonism causing the juxtaposition of the Cache Creek terrane against Quesnellia, the formation of peraluminous magma and the low-angle compressive deformation of the magmatic environment.

ism was widespread. Fusion of sialic crustal materials of the Quesnel terrane, accompanied by dehydration of oceanic crust resulted in Late Triassic, peraluminous subalkaline magmas of tonalitic composition. These also came under the influence of the low-angle, northeastward verging thrusts and shears, manifested by the penetrative foliation of the Granite Mountain batholith. It is believed that the latest Triassic to earliest Jurassic intrusive activity was largely synchronous to regional deformation and metamorphism brought about by terrane accretion.

The mineralogy of the Granite Mountain batholith suggest it crystallized at mid-crustal level (5 km to 18 km). The magma was calcic, calc-alkaline (Fe-poor), oxidized and relatively enriched in Na, Sr and Ba. Assimilation of the Cache Creek country rocks by the tonalite produced the Border Phase hybrid magma, now represented by a variety of dioritic and quartz dioritic rocks. Fractional crystallization of the tonalite, resulting in a trend of increasing Na without increasing K, produced the Granite Mountain trondhjemite phase. It also was affected by the ongoing regional deformation. It is not known if its present position, apparently structurally below the Mine Phase tonalite in the vicinity of Gibraltar, is due to it having intruded the latter or having been structurally juxtaposed.

Regional northeastward-directed tectonism continued throughout magmatic differentiation, and during the final consolidation stages of the batholith, resulted in localized zones of intense fracturing and dislocation. During this time, continuing fractional crystallization produced a late stage residual leucotrondhjemitic melt which, following rupture of the host rock was expelled into lower pressure regimes of adjacent wall rock to form bodies of Leucocratic Phase porphyry. The final product of magmatic differentiation was a volatile-rich residual fraction enriched in K_2O, CO_2 and metallic sulphides. The expulsion of these magmatic hydrothermal fluids into the zone of fracturing closely followed the emplacement of the Leucocratic Phase intrusions and for the most part was guided by the same structural controls. The ensuing metasomatic and mineralizing processes deposited sulphides; deposited K as sericite; redistributed Mg and Ca as chlorite, epidote and carbonate; and expulsed Na. Metals were deposited along a geothermal gradient in a sequence from higher to lower temperature of chalcopyrite + molybdenite, to chalcopyrite, to chalcopyrite + sphalerite, to sphalerite. Northeasterly-directed structural deformation continued throughout the period of metasomatism and mineralization to create the present foliated nature of ore, alteration and host rock.

Economics

Gibraltar is the lowest grade primary copper mine still operating in North America. As of 1993, projected mill heads will average approximately 0.30% Cu for a projected mine life of 12 years.

Ore reserves are calculated from diamond drill hole data, supplemented where appropriate, by blast hole assay data. Inverse distance squared, to the power 5, has been the most widely used method of grade estimation. Ordinary kriging and indicator kriging have been used on recent reserves where a higher degree of precision is required. In all cases, the method employed is rigidly controlled by the geological model.

The Gibraltar orebodies are mined by conventional open pit methods in sequential stages based on computerized pit designs and schedules. Mining is carried out on 13.7 m benches, with safety berms of 9.1 m minimum width installed every second bench. The design generally incorporates a working face of 63° which provides an over-all final pit slope of 38° to 52°. Ore and waste haulage is by a fleet of 240 ton and 170 ton diesel electric trucks. Ore haulage is supplemented by an in-pit crusher and overland conveyor system.

The Gibraltar mill uses conventional crushing, grinding, and froth flotation to process 27 000 to 40 000 tonnes of ore per day. Column flotation was added to the mill circuit in 1985. Copper recoveries average 78% to 80%; molybdenite recoveries are about 40%. The final copper concentrate, containing about 28% Cu, is trucked 29 km to the British Columbia Railroad rail line, then by rail to North Vancouver where it is loaded on boats for overseas shipment, primarily to Japan.

In 1986, a solvent extraction-electrowinning (SX-EW) plant was constructed to recover up to 4500 tonnes of copper metal per year from the acid leaching of Gibraltar's oxide ore and waste dumps.

The main environmental problem encountered at the mine has been localized acid generation from waste dumps. This has been caused principally by pockets of pyrite zone ore, containing 3% to 6% pyrite. To manage the problem, the mine operates under a zero discharge permit in which all process water and natural runoff is collected, treated, and recycled for use in the plant processing system.

Conclusions

1. Magmatism, dynamothermal metamorphism and ore deposition occurred as a related chain of events, over a period of tectonism extending from Upper Triassic to possibly earliest Jurassic.
2. The fractional crystallization of the Granite Mountain batholith followed a trend of progressive Na enrichment without an associated increase in K. The magmatic sequence was: Mine Phase tonalite, to Granite Mountain Phase trondhjemite, to Leucocratic Phase quartz feldspar porphyry or leucotrondhjemite.
3. Ore stage alteration and mineralization was accomplished by volatile-rich residual fractions of the crystallizing magma. The period of ore formation closely followed, and possibly overlapped, the intrusions of Leucocratic Phase rock.
4. Ore stage metasomatic alteration was dominated by a process of K enrichment and Na depletion. Ratios of Na_2O/K_2O provide a reliable index of alteration intensity which can be used as an exploration tool in the Gibraltar area.
5. The Gibraltar orebodies were formed within an evolving environment of low angle northeasterly-directed compressional stress, associated with the eastward subduction of the oceanic crust of the Cache Creek terrane beneath the continental margin of the Quesnel terrane. The resulting complex deformation of ore stage alteration and mineralization explains to a large degree the unique characteristics of the Gibraltar deposit.

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Metallurgy Special Volume 15, 1976. This work provided the foundation upon which the present geolog nodel has been formulated. The authors are also indebtea ꞷ 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.

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