GEOLOGY AND GEOCHEMISTRY OF THE HOTAILUH BATHOLITH AND SPATIALLY ASSOCIATED VOLCANIC ROCKS

by

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ABSTRACT

The Hotailuh batholith is within the Hinterland Belt of the Canadian Cordillera and is similar in geological setting to several other batholiths in British Columbia with which porphyry copper deposits are associated. It intrudes andesite, basalt, agglomerate and tuff of Late Triassic age which have been metamorphosed to amphibolite, chlorite schist and other metavolcanic rocks in a narrow contact aureole. Pebbles of batholithic material are found nearby in Lower Jurassic conglomerates. The batholith has a core of quartz monzonite which grades over several tens of meters into a periphery of granodiorite. Syenodiorite, quartz diorite and xenolithic granodiorite occur locally nearest the margins of the intrusion. Although concentrations of sulphide minerals occur in volcanic and metavolcanic rocks about the batholith, sulphide minerals are virtually absent within the batholith.

Average contents of Cu, Zn, Pb, Co, Mn and Fe are greatest in relatively fresh volcanic rocks, next greatest in metavoloanic rocks, and greater in granodiorite than quartz monzonite. Ni content is greatest in metavolcanic rocks, next greatest in volcanic rocks, and greater in granodiorite than quartz monzonite. In rocks of the batholith, results of R-mode factor analysis indicate two directly related metal associations,

a Zn-Mn-Pb and a Fe-Co-Cu-Ni association. However, in volcanic rocks a dominant Pb-Co-Ni-Fe association is inversely related to both a Zn-Mn and a Cu association. In metavolcanic rocks there are three associations, a Fe-Pb-Zn-Mn, a Cu-Mn, and a Ni-Co association. Metal associations in residual soils and silts reflect those in the rocks.

A comagmatic origin for the batholith and spatially associated volcanic rocks is suggested by their similar ages and comparable chemical compositions. Petrography, contact relationships, and distribution of rock types in the batholith indicate progressive inward fractional crystallization of an initially homogeneous granodioritic magma. Metal distribution in the batholith interpreted in the light of crystal field theory, indicates the metals were dispersed in lattice sites of ferromagnesian minerals and magnetite during crystallization. There was no concentration of metals in the residual silicate melt or a hydrothermal fluid capable of making a porphyry copper deposit within the batholith. However, in volcanic rooks, Cu and Zn were probably not dispersed in lattice sites of ferromagnesian minerals and magnetite and may have been susceptible to leaching and concentration within a hydrothermal regime generated near the margins of the batholith.

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CHAPTER 1

INTRODUCTION

1.1 Location and Access

The Hotailuh batholith (Figure 1) occupies 1000 square Km. between longitudes 129°15' and 130°00' W and latitudes 58°00' and 58°15' N in north-central British Columbia. Rugged mountains of the Three Sisters Range, a part of the extensive Stikine Ranges, dominate the physiography in the east half of the batholith. More subdued hills of the Hotailuh Range, a part of the Stikine Plateau, are typical of the west half (Holland, 1964).

Dease Lake (Figure 1), a growing frontier town, is the only community in the vicinity of the batholith and is easily accessible by road and air. It is on the Stewart-Cassiar highway 250 Km. south of Watson Lake, Yukon and 280 Km. north of Stewart. Regularly scheduled flights land at Dease Lake airport and charters are available for wheeled or float-equipped aircraft and helicopters. Despite easy access to the west margin of

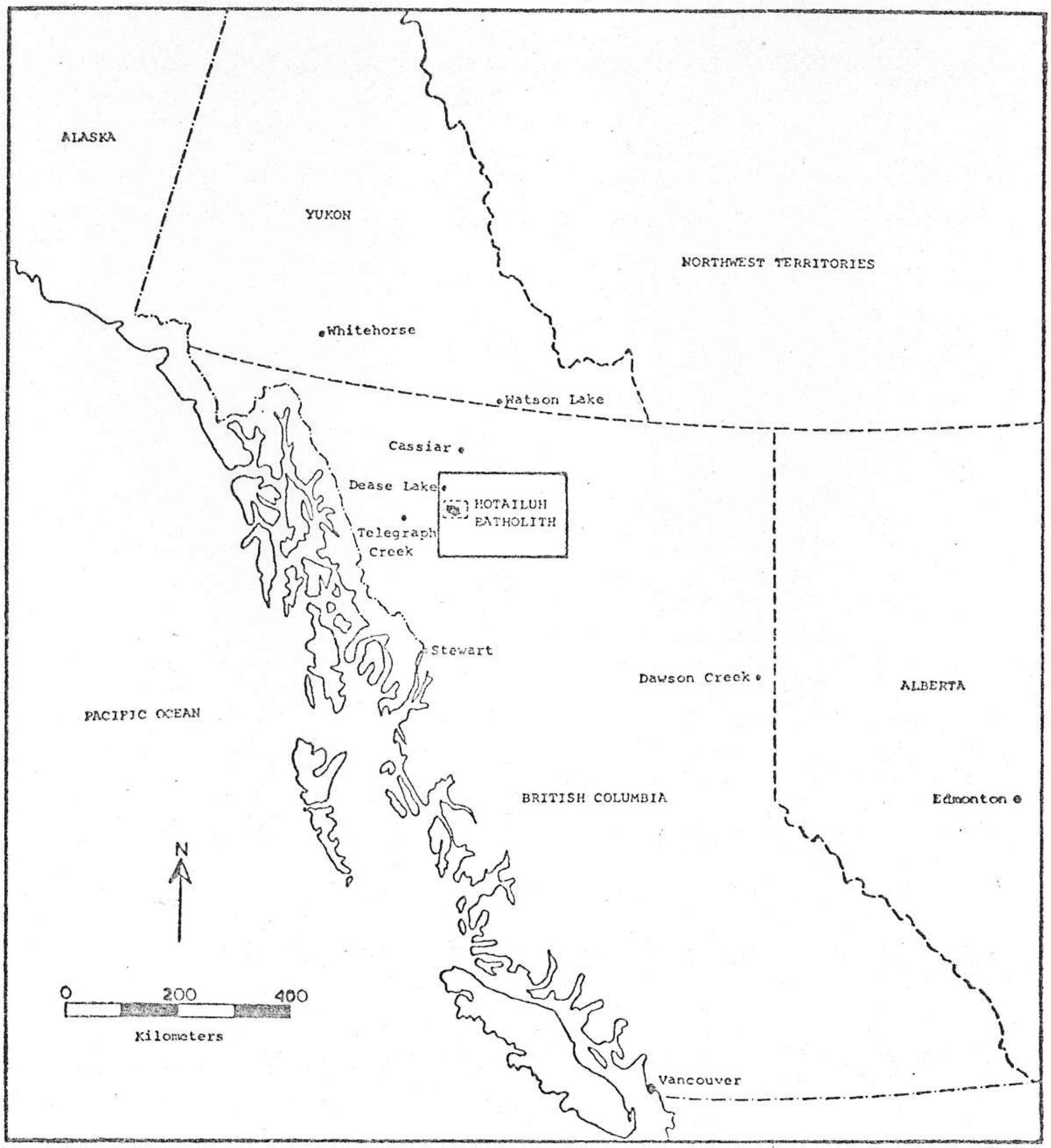


Figure 1: Location Map

the Hotailuh batholith via the Stewart-Cassiar highway and soon to be completed British Columbia Railroad, horses or helicopters are essential for efficient work in its interior.

1.2 Previous Work

Gold discoveries near Dease Lake in the early 1870's and the Klondike rush of 1897 brought many prospectors to rivers and creeks of northern British Columbia. Initial discovery of base metal was made in 1899 on what are now the Crown grant claims within volcanic rocks near the west edge of the Hotailuh batholith (Jeffrey, 1966). G. M. Dawson in 1887 was the first geologist of record through the district.
Kerr (1925) reported on the bedrock geology and placer deposits of the Dease Lake area, but Hanson and McNaughton (1936) were apparently the first to publish a map which included the Hotailuh batholith. In 1956 the Geological Survey of Canada undertook Operation Stikine, a comprehensive reconnaissance mapping of 66,000 square Km., including the Hotailuh region, at a scale of 1:250,000. Subsequently, geological maps of Cry Lake (Gabrielse, 1962) and Dease Lake (Gabrielse et al, 1962), of which the batholith is a small part, were published with more detail but at the same scale.

Ages of six rock samples from the batholith have been determined by the K-Ar method and interpreted as Late Triassic (Wanless et al, 1972). No detailed geological or geochemical work relating specifically to the nature of the batholith has been published although descriptions of the batholith and surrounding rocks have been incorporated in numerous papers on the tectonic framework and evolution of north-central British Columbia (Gabrielse and Wheeler, 1961; Gabrielse and Reesor, 1964; Souther and Armstrong, 1966; Roddick et al, 1967; Douglas, 1970; Monger et al, 1972; Wheeler and Gabrielse, 1972; Dercourt, 1972; Gabrielse and Reesor, 1974).

Prospecting within volcanic rocks near the west edge of the Hotailuh batholith located a copper occurrence of porphyry copper affinity in 1960 (Jeffrey, 1966). The property is presently called Dease Lake Mines with reserves estimated from drilling at 20 million tons of 0.44 percent copper (Canadian Mines Handbook, 1974-5). Exploration within the batholith itself has not been successful to date.

1.3 Statement of the Problem

The Hotailuh batholith has been recognized as a Late Triassic pluton intruding volcanic rocks of comparable age and composition. Other batholiths of similar age and nature and their attendant volcanic rocks host important porphyry copper deposits elsewhere in the Canadian Cordillera. Hence, this apparent potential for porphyry copper deposits in the Hotailuh region fostered reconnaissance exploration within and around the batholith before much was known of the geology or metal distribution.

The purpose of this thesis is three fold:

1. To document the geology and metal distribution of the Hotailuh batholith and spatially associated volcanic rocks.
2. To construct a genetic model for the batholith and volcanic rocks based upon the observed geological relationships and metal distribution.
3. To predict the potential for occurrence of porphyry copper deposits in rocks of the thesis area.

1.4 Approach to the Problem

Selected areas of the Hotailuh batholith and spatially associated volcanic rocks were mapped by the writer and other personnel of Amax Exploration Inc. during parts of the 1971 and 1972 field seasons. Silt, soil, water, and composite rock chip samples were collected along with hand specimens from outcrops. Method of field sampling is discussed in Appendix 1.

A geological map and idealized vertical section were constructed for the batholith and immediate vicinity. Major rock types noted during field mapping were further defined by thin section study at the University of Western Ontario which included modal analyses of nine thin sections representative of principal rock types in the batholith.

The silt, soil, water and composite rock chip samples were analysed for Cu, Zn, Pb, Ni, Co, Mn, Ag, Mo and total Fe by atomic absorption at Amax's Burnaby laboratory. Techniques of sample preparation and analytical procedure are included in Appendix 1. Metal contents of individual samples are tabulated in Appendix 2. Prior to an extensive statistical analysis of the analytical data, samples were divided into ten sample populations according to rock type and sample type.

Frequency distributions of both untransformed and logarithmically transformed data were evaluated for each metal in each sample population. This was done to test whether or not sample populations were of sufficient quality to ensure the validity of statistical results. Three standard test procedures, the method of moments, the chi-square test and the Kolmogorov-Smirnov test were used to compare the actual frequency distributions with those expected for normally and lognormally distributed data. Means, standard deviations and coefficients of variation were calculated and the most appropriate mean metal contents were determined.

Visual and statistical comparisons of metal distribution were made among rock types and sample types. Average metal contents were compared by multivariate analysis of variance and discriminant analysis supplemented by Student's t and Fisher's F tests. Metal associations were compared by R-mode factor analysis utilizing both a principal component and common factor approach. During factor analysis orthogonal Varimax, oblique Promax and factor score matrices were obtained. Comparisons among sample populations were also made in terms of coefficients of variation and with respect to relative concentrations of metals as indicated by metal ratios.

Regional trends for Cu, Zn, Pb, Ni, Co, Mn and Fe in rocks of the batholith were investigated by trend surface analysis. Third and fourth degree polynomial surfaces were calculated and plotted. The writer used computing facilities at the University of Western Ontario throughout all aspects of data analysis.

A genetic model for the Hotailuh batholith and spatially associated volcanic rocks was constructed to explain the observed geological relationships and metal distribution. Crystal field theory was used to interpret the behaviour of metals during those processes that contributed to metal distribution. Predictions expressing the potential for occurrence of porphyry copper deposits in rocks of the thesis area have been made from the model.

In an effort to check the validity of the proposed genetic model, further analytical work was done at the University of Western Ontario. Biotite, hornblende and magnetite separates from five intrusive rocks were analysed for Cu and Zn by atomic absorption. Pyroxene, hornblende, biotite and chlorite grains from three of the same five intrusive rocks were analysed for Mg, Si, Fe, Al, Ca, Na, K, Ti, Mn, Cu, Ni, Zn and Co by electron microprobe. Selected plagioclases from the three samples were analysed by electron microprobe for Na, Ca and K to determine their anorthite content.

Recommendations are included in Chapter 8 for further work to check the validity of the proposed model. Suggestions are made in Appendix 7 and in Appendix 8 pertaining to statistical approaches to data analysis, and to reconnaissance exploration for porphyry copper deposits within environments similar to that of the Hotailuh batholith.

CHAPTER 2

REGIONAL GEOLOGY

2.1 Geotectonic Framework of the Canadian Cordillera

The Hotailuh batholith is within the Cordilleran Orogen of western Canada, a complex structural province that is part of the circum-Pacific orogenic belt. The composite nature of the orogen has been recognized and it has been divided into five major northwest-trending belts, each with distinct stratigraphic and tectonic characteristics (Gabrielse and Wheeler, 1961; Gabrielse and Reesor, 1964; Souther and Armstrong, 1966; Roddick et al, 1967; Souther, 1971a; Monger et al, 1972; Dercourt, 1972). The belts have been named (Monger et al, 1972) from west to east, Insular Belt, Coast Plutonic Complex, Intermontane Belt, Omineca Crystalline Belt and Rocky Mountain Belt. Faults commonly mark the boundaries of these belts as shown by Figure 2.

The Insular Belt can be divided into a southern part characterized by a thick sequence of slightly deformed Triassic submarine basalts overlain successively by limestone and Jurassic pyroclastic rocks, and a northern part

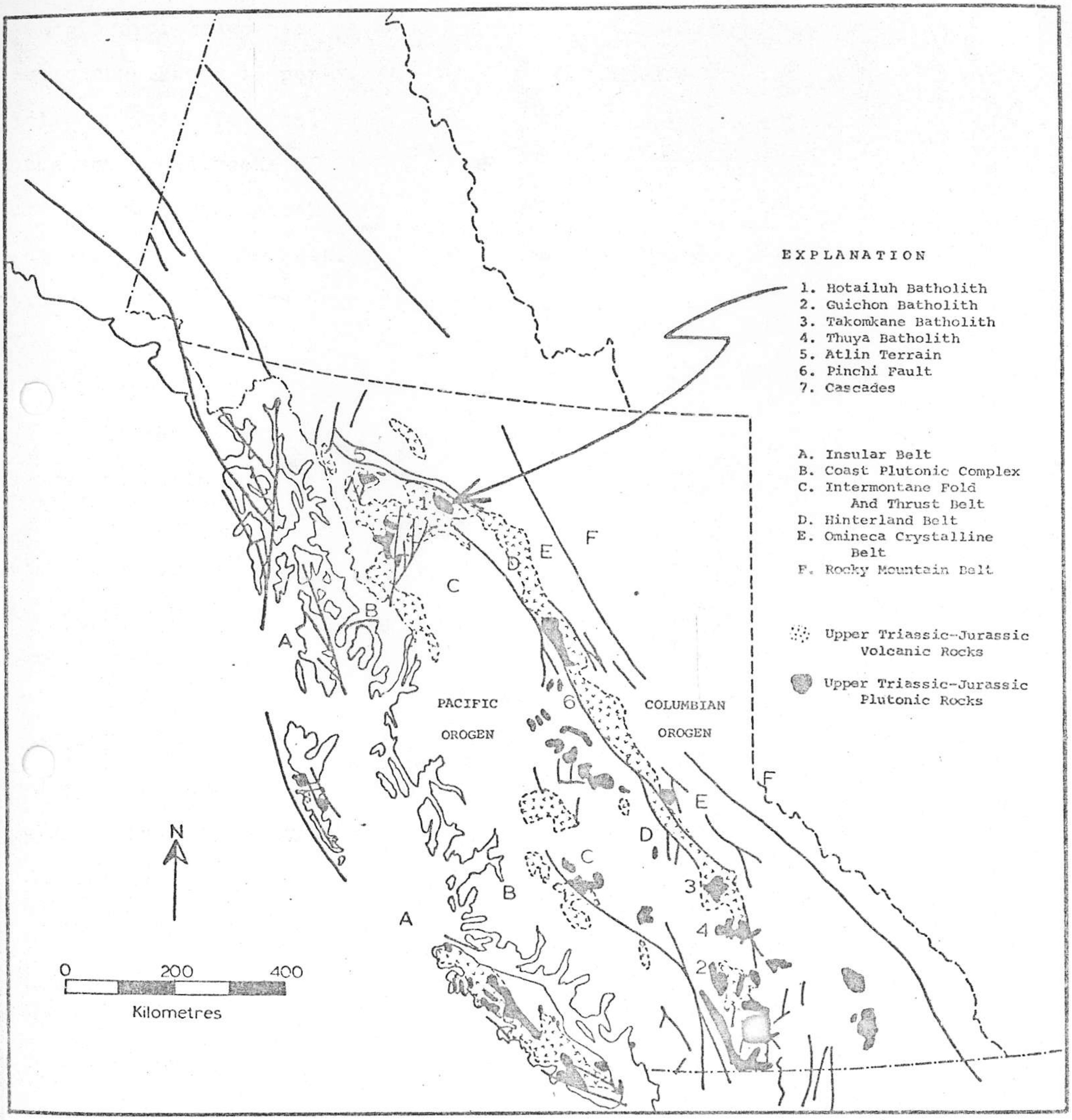
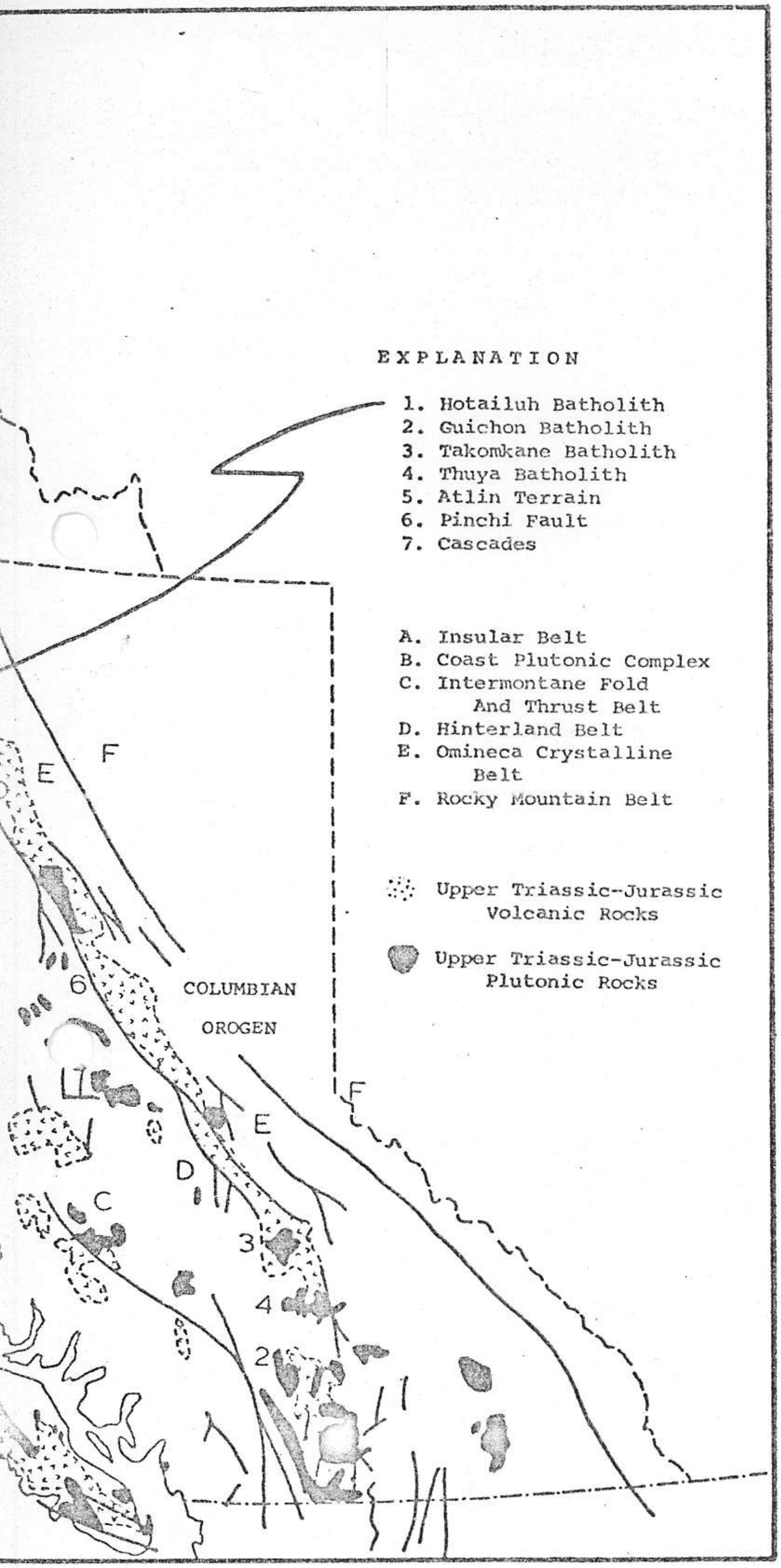


Figure 2: Geotectonic Map of the Canadian Cordillera



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that contains in addition a varied group of Paleozoic sedimentary rocks. Plutonic rocks occupy about 15 percent of the area and include mainly Jurassic diorites, quartz diorites and granites in the south and rocks of diverse age and composition in the north. Small stocks of Middle Tertiary age are present throughout this belt. Lower Tertiary and Quaternary volcanic rocks outcrop in the northern section.

The Coast Plutonic Complex principally consists of metavolcanic, gneissic and plutonic rocks. About half the area is composed of granitoid rocks, dominantly quartz diorite and granodiorite of Late Jurassic to Early Tertiary age. The younger plutons appear to outcrop within the eastern part of the belt. Tertiary volcanic centers are rare and Quaternary extrusive rocks occur most commonly in the south.

The Intermontane Belt is dominated by late Paleozoic, Triassic and Jurassic volcanic and clastic rocks covered in part by sedimentary rocks in successor basins. It is divided transversely by the Stikine Arch which passes through the thesis area and by the Skeena Arch farther to the south. Plutonic rocks intrude about 15 percent of the area and include calc-alkaline batholiths of Late Triassic to Jurassic age ranging in composition from quartz diorite to quartz monzonite, smaller alkalic diorite to syenite complexes of similar age, and many stock-sized

Tertiary plutons of variable composition. Lower Tertiary continental volcanic rocks and Upper Tertiary plateau basalts are widely distributed and many Quaternary volcanic centres occur in the north, particularly within the Stikine Arch.

The Omineca Crystalline Belt is characterized by highly deformed Proterozoic and early Paleozoic metasedimentary rocks and derived gneisses. Gneiss domes are a dominant feature in the south. Mesozoic volcanic rocks are insignificant but small batholiths and stocks of Cretaceous quartz monzonite make up about 10 percent of this belt. In further contrast to the more western belts Tertiary and Quarternary igneous rocks are virtually absent.

The Rocky Mountain Belt can best be described as a foreland fold and thrust belt with the Rocky Mountains in the west made up of Helikian to Paleozoic clastic and carbonate sediments, and the Foothills in the east made up of an imbricated coarse clastic wedge. Igneous rocks are limited to some basic sills and dykes of Helikian and Hadrynian age, a Devonian carbonatite, and a few Tertiary granitic stocks in southern British Columbia and Alberta.

Mesozoic metamorphic rocks of Barrovian greenschist and amphibolite facies occur within the Coast Plutonic Complex and Omineca Crystalline Belt. Sub-greenschist rocks of prehnite-pumpellyite and zeolite facies are characteristic of the Mesozoic volcanic rocks in the Insular and Intermontane Belts. Blueschist rocks have been found within the Atlin terrain to the north of the Hotailuh batholith, near the Pinchi Fault and in the Cascade Mountains of south-western British Columbia.

Recent work (Wheeler and Gabrielse, 1972) emphasizing structural evolution suggests that the Canadian Cordillera can also be described in terms of two orogens, the Pacific in the west and the Columbian to the east. In this revised approach each orogen is composed of a mobile core zone of granitic and medium to high-grade metamorphic rocks, flanked by belts in which tectonic transport has been directed away from the core zones. These core zones are coincident with the Coast Plutonic Complex and the Omineca Crystalline Belt. The two orogens coalesce in the Intermontane Belt which has been subdivided into the Hinterland Belt of the Columbian Orogen, and the Intermontane Fold and Thrust Belt of the Pacific Orogen. The Hotailuh batholith is within the Hinterland Belt as are several other Late Triassic plutons, notably the Takomkane, Thuya and Guichon batholiths (Figure 2).

The characteristic lithologies and structural styles of the five major belts can be discussed in terms of several distinct depositional environments. Figure 3 is a chart summarizing the distribution of the different

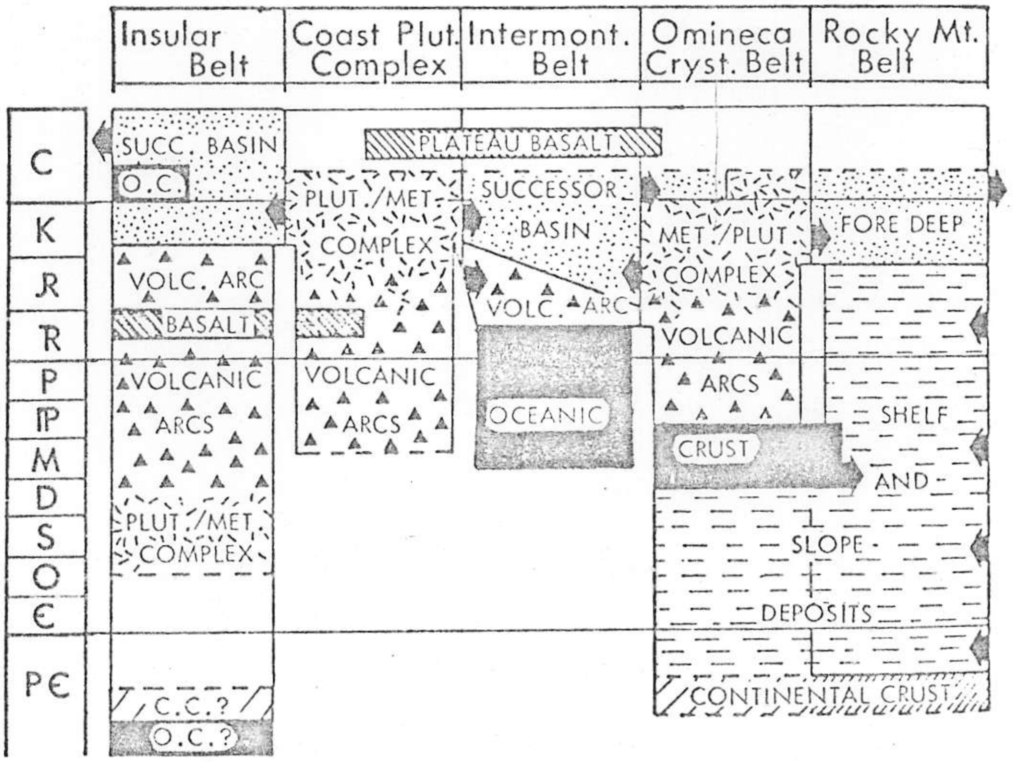

Figure 3: Tectonic Chart Summarizing the Evolution of the Canadian Cordillera (Monger et al, 1972)

environments throughout time. Numerous plate tectonic models have been proposed to account for the evolution of the Canadian Cordillera (Monger *et al*, 1972; Dercourt, 1972).

2.2 The Hotailuh Batholith and Environs

Souther and Armstrong (1966) discussed the geology and tectonic evolution of north-central British Columbia. Lithology of the area about the batholith includes strata representative of the tectonic environments of the Intermontane Belt. Figure 4 is a simplified geological map and stratigraphic column for this area.

Cache Creek Group rocks, the oldest in the area, outcrop within the fault-bounded Atlin Horst 24 Km. to the north of the batholith and also between the Stikine and Iskut Rivers farther to the southwest. These rocks of upper Paleozoic and lowermost Mesozoic age are metavolcanic flows, chert, limestone, slate and ultramafic rocks typical of oceanic crust. A detailed account of the stratigraphy and structure of the Cache Creek Group to the west of Dease Lake is given by Monger (1969).

A complex sequence of andesite and basalt flows, tuff, volcanic breccia and agglomerate with intercalated volcanogenic sandstone, conglomerate, greywacke, argillite and shale dominates the stratigraphic record of the thesis area. Fossils of Late Triassic age have been collected

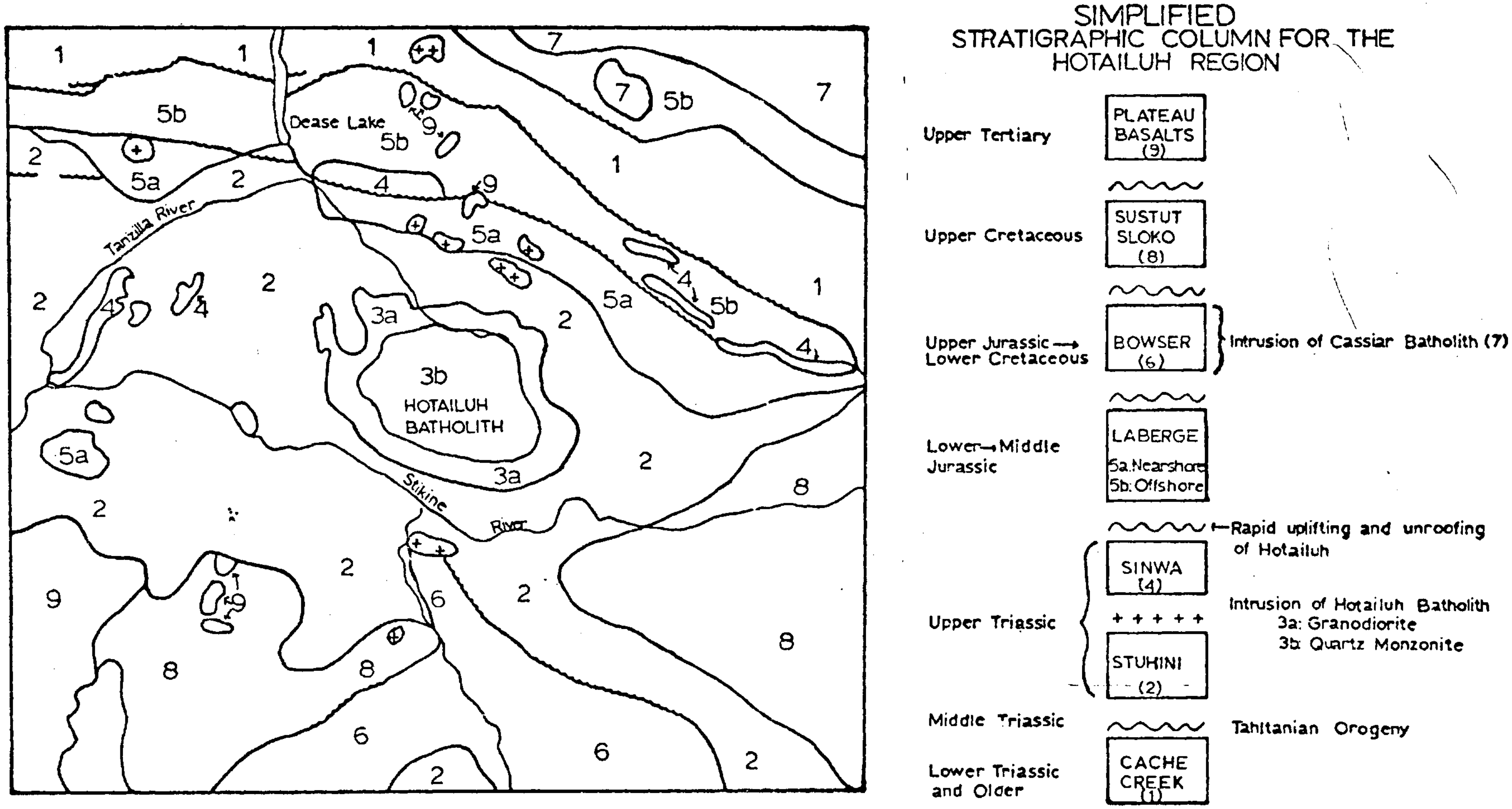

Figure 4: Simplified Geological Map and Stratigraphic Column for the Hotailuh Region

from this sequence in the Dease Lake map-area to the west of the Hotailuh batholith (Gabrielse <u>et al</u>, 1962). This is the MacLeod Series of Hanson and McNaughton (1936). and the Stuhini Group of Souther and Armstrong (1966). The latter name is used herein. It correlates with the Nazcha and Shonetaw Formations to the immediate northwest (Monger, 1969), the Lewis River Group of the Yukon Plateau (Wheeler, 1961), and with the Takla and Nicola Groups to the southwest (Tipper, 1959; Souther and Armstrong, 1966). Rocks of these groups are characteristic of island arcs.

Upper Triassic limestones are conformable upon Stuhini Group rocks west of the batholith and are overlain unconformably by, or are in fault contact with Lower Jurassic rocks of the Laberge Group to the north. The narrow width of the limestone outcrops and their areal distribution suggest that they may mark the boundary of an area emergent in the Late Triassic.

The Laberge Group is made up of well-bedded greywacke, conglomerate, sandstone, siltstone and shale and has been divided into a southern fossiliferous belt and a northern unfossiliferous belt (Gabrielse, 1962). The southern belt unconformably overlies Stuhini rocks and has features of near-shore, relatively shallow water deposition; the northern belt, in fault contact with the southern belt, has features of deep water deposition.

Conglomerates at the base of the Laberge Group to the southeast and southwest of Dease Lake contain pebbles and cobbles of granitoid rocks similar in lithology to those of the Hotailuh batholith (Gabrielse and Reesor, 1964) and hence suggest emplacement of the batholith to a shallow depth followed by rapid unroofing.

Successor basin strata of the Late Jurassic and Early Cretaceous Bowser Group are exposed over much of the area south of the batholith. Rocks within the Bowser Basin constitute a thick monotonous assemblage of marine greywacke, argillite, slate and pebble conglomerate. Coarse conglomeratic non-marine sediments of the Sustut Group outcrop within the Late Cretaceous and Early Tertiary Sustut basin that extends 300 Km. southeast from the headwaters of the Stikine River.

Felsic volcanic rocks of the Late Cretaceous and Early Tertiary Sloko Group occur within the Klastine Plateau south of the batholith. Upper Tertiary plateau basalts of uniform alkali-olivine composition outcrop in the Level Mountain Range 38 Km. to the west and within the Mount Edziza complex 50 Km. southwest of the batholith. Quaternary volcanic rocks of variable composition occur throughout the region and at Mount Edziza, a composite volcano that has erupted at least three times in the last 1800 years (Souther, 1966). Pleistocene and Recent fluviatile and glacial sedimentary material cover large parts of the area included in Figure 4.

CHAPTER 3

THE HOTAILUH BATHOLITH AND SPATIALLY ASSOCIATED VOLCANIC ROCKS

3.1 General Statement

Intrusive rocks of the Hotailuh batholith and volcanic rocks of the Stuhini Group dominate the lithology of the thesis area (Figure 5). The batholith is a zoned pluton in which a peripheral granodiorite grades into a more felsic core of quartz monzonite. Rocks of the Stuhini Group are principally andesites and basalts and are metamorphosed near the contact of the batholith.

3.2 The Hotailuh Batholith

Most outcrops of the batholith can be placed into one of two principal rock types, granodiorite or quartz monzonite. Less common rock types include quartz diorite, syenodiorite, granite and what can be referred to as hydrothermally altered equivalents of granodiorite and quartz monzonite. Felsic pegmatitic, aplitic or porphyritic phases are virtually absent, but mafic dykes occur

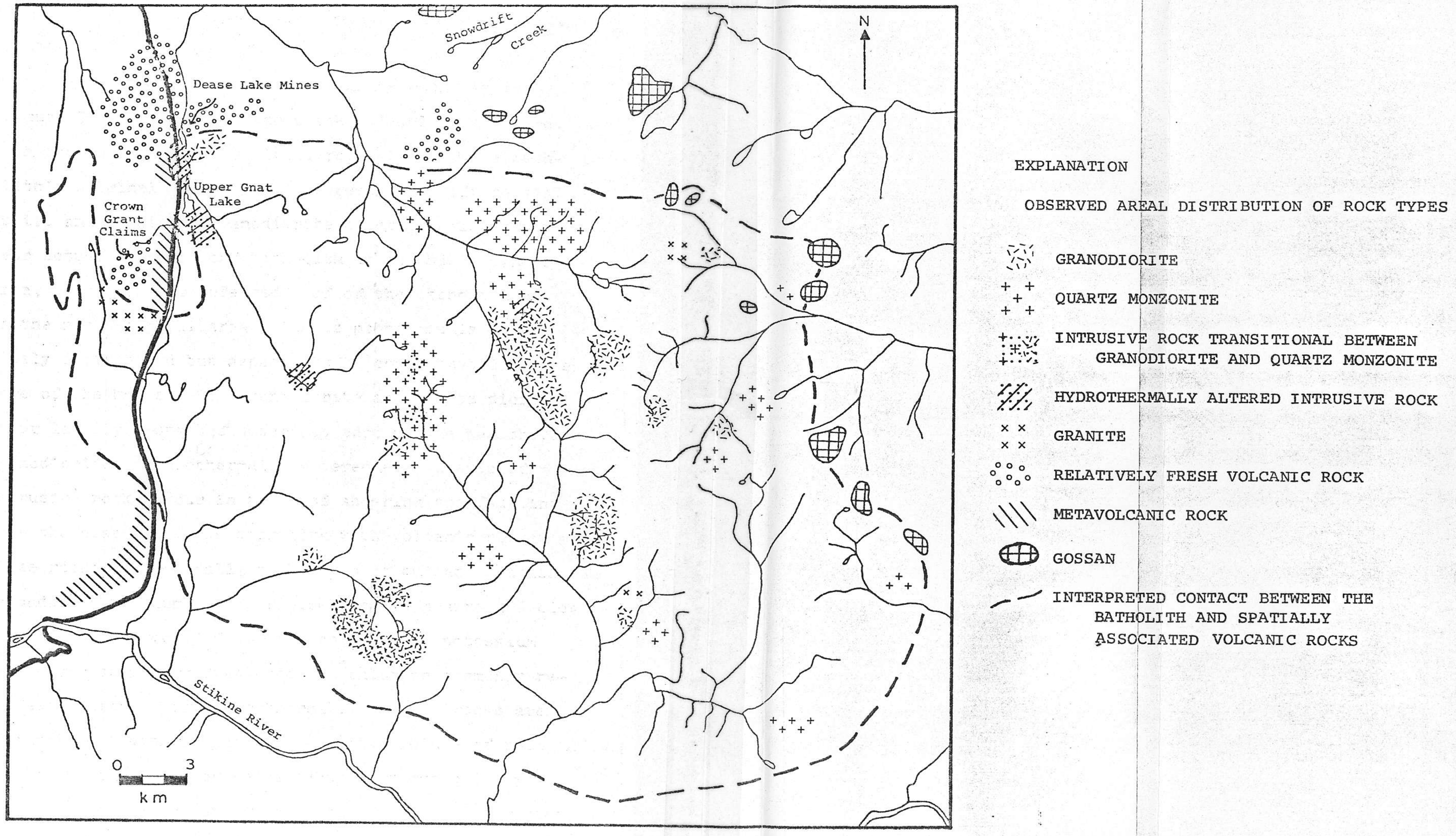

Figure 5: Geological Map of the Hotailuh Batholith and Spatially Associated Volcanic Rocks

locally as do veins with varying proportions of quartz, epidote and calcite.

Areal distribution of intrusive rock types (Figure 5) is complex at the present level of exposure. Such complexity may be a direct reflection of the batholith's original geometry or the result of differential uplift and erosion. Granodiorite outcrops principally near actual edges of the batholith as in the Gnat Lakes area, or within the inferred roof of the batholith as in the north-central area. Quartz monzonite is more widely distributed but appears to be concentrated in the core of the batholith. Syenodiorite and quartz diorite occur locally along the outermost edge of the peripheral granodiorite. Hydrothermally altered equivalents of intrusive rocks occur in areas of shearing and faulting near the contact of the batholith with volcanic rocks. These rocks are generally pinkish in colour and contain secondary potassium feldspar dispersed as grains and clots throughout the rock. Chlorite, epidote and potassium feldspar occur along fractures and chlorite commonly replaces biotite. Such hydrothermally altered rocks are insignificant with respect to the total volume of rock in the batholith. The few veins occur most commonly in quartz monzonite but are also found in altered intrusive rocks near the margins of the batholith.

Mafic inclusions or xenoliths of identifiable volcanic material make up from 5 to 80 percent of the batholith next to its contact with volcanic rocks in the Gnat Lakes area. Similar xenoliths occur in quartz diorite, syenodiorite and granodiorite of the north-central area but are of questionable affinity. However, a volcanic origin seems likely.

The contact between peripheral granodiorite and quartz monzonite of the core is typically gradational over distances that vary between several and hundreds of meters. In the few places where the contact is intrusive, quartz monzonite either cross-cuts granodiorite or contains inclusions of granodiorite. Transition between relatively mesocratic xenolithic granodiorite near the margins of the batholith and more leucocratic granodiorite nearer the core is also gradual and the width of this transition is quite variable. The quartz-epidote-calcite veins cross-cut all the intrusive rocks and appear to postdate any hydrothermal alteration that may have occurred.

Joints and faults are numerous throughout the batholith but there is no pronounced structural pattern. A vertical north-trending foliation defined by alignment of hornblende grains occurs in granodiorite near the margins of the batholith in the Gnat Lakes area.

The Hotailuh batholith is most probably Late Triassic in age. It intrudes volcanic rocks of the Stuhini Group which contain Late Triassic fauna. In addition, boulders of the batholith occur in conglomerates of the Laberge Group suggesting the batholith was unroofed before or during the Early Jurassic. K-Ar age determinations on two samples by the Geological Survey of Canada, Table 3 and Figure 6, are consistent with a Late Triassic age (Wanless et al, 1972). Indeed, these determinations support a Middle Triassic age of 215 m.y. Age determinations of four other samples cluster around 162 m.y., but the stratigraphic evidence is unquestionable and these younger ages are believed indicative of a thermal event in the Middle Jurassic perhaps related to the intrusion of quartz monzonite in the core of the Hotailuh Range to the west of the batholith (Wanless et al, 1972). A traverse in the Cake Hill area (Figure 6) where two of the samples that gave enigmatic ages were collected did not provide any evidence to support a separate intrusion of two magmas of diverse age.

The granodiorite and quartz monzonite are typically massive, medium-grained hypidiomorphic-granular rocks. There is a considerable variation in grain size locally and generally the quartz monzonite is more

Determination No.	Sample No.	Age (m.y.)	Mineral
GSC 70-27	GA 1390 (1)	147± 8	Hornblende
GXC 70-28	GA 1390	139± 6	Biotite
GSC 70-29	* GA 2/9/61/2A (2)	157± 11	Hornblende
	GA 2/9/61/2A	166± 11	Hornblende
GSC 70-30	GAD-132-3 (3)	155± 8	Hornblende
GSC 70-31	GAD-132-2 (4)	163± 9	Hornblende
GSC 70-32	GAD-132-2	163± 7	Biotite
GSC 70-33	GAD-132-1 (5)	215± 11	Hornblende
	GAD-132-1	213± 11	Hornblende
GSC 70-34	GA 67-98C (6)	217± 11	Hornblende
	GA 67-98C	217± 11	Hornblende

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*An earlier determination on biotite from this sample was reported as 193 m.y. (see GSC 62-71, GSC Paper 63-17). It should be noted, however, that this biotite had been 30% chloritized and contained inclusions of quartz.

Table 3: K-Ar Age Determinations

(Wanless et al, 1972)

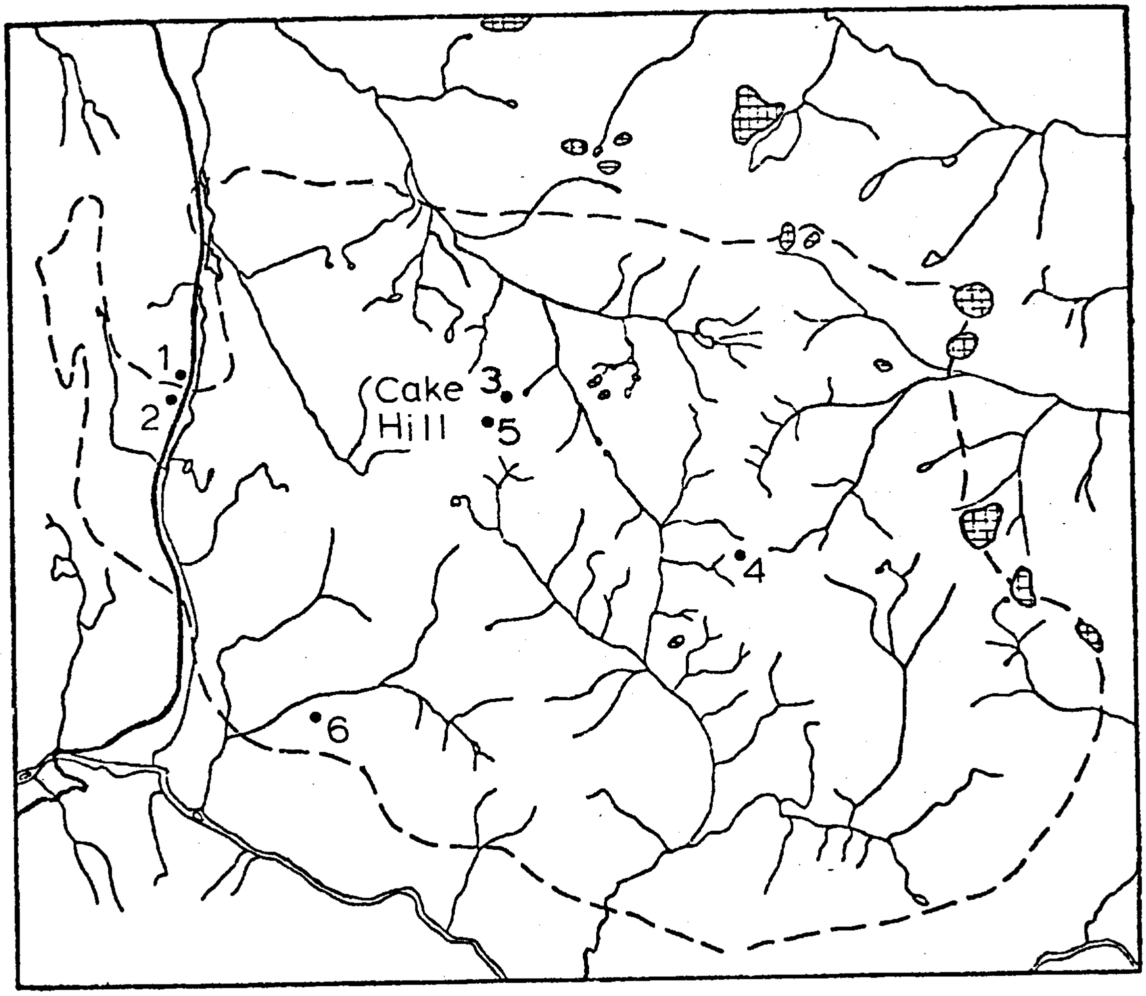


Figure 6: Location Map for Rock Samples that were used in K-Ar Age Determinations

coarse-grained and equigranular. Essential minerals in both rock types are plagioclase, potassium feldspar, quartz, hornblende and biotite. Accessory minerals include magnetite, sphene, zircon and apatite.

Table 4 lists the relative proportions of minerals in the two principal intrusive rock types as determined by modal analyses. Of particular note is the greater total content of ferromagnesian minerals and magnetite in granodiorite. Biotite is most abundant in granodiorite and is locally absent in quartz monzonite. Pyroxene makes up from one to five percent of granodiorite and up to one percent of quartz monzonite occurring near the margins of the batholith, but is absent in quartz monzonite from the core.

Modes of occurrence of the minerals are similar in both principal intrusive rock types. Plagioclase, the dominant mineral, usually occurs as euhedral to subhedral grains that are typically embayed by quartz and potassium feldspar. It is invariably twinned and commonly zoned. Cores and rims of 19 plagioclase grains from three samples, a granodiorite (2FKT844), a quartz monzonite from the core (1SKT1317), and a quartz monzonite from near the margin (2FKT848), were analysed for Ca, Na and K by electron microprobe. Table 5 is a summary of the analytical results in Appendix 3. Normal zoning is characteristic and occurs in all but

	Granodiorite				Quartz Monzonite						
	2FKT 839	2FKT 844	2FKT 847	2FKT 869	1SKT 1307	1SKT 1317	2FKT 806	2FKT 960	2FKT 848	Average Granodiorite	Average Qtz. Monz.
Quartz	5.2	10.7	8.6	8.7	15.8	11.2	27.0	14.4	22.0	8.3	18.1
K-feldspar	9.0	8.1	10.7	4.2	26.2	22.4	30.5	27.0	28.7	8.0	27.0
Plagioclase	59.6	53.8	52.4	55.2	47.5	52.3	36.9	50.3	38.1	55.3	45.0
Hornblende	10.1	13.3	18.1	12.9	8.2	12.8	3.7	7.2	6.8	13.6	7.7
Pyroxene	3.0	2.5	3.0	4.0	0.0	0.0	.1	.2	1.0	3.1	.3
Biotite	10.9	7.4	3.5	12.5	.2	-	.8	-	1.9	8.6	.6
Magnetite	1.9	2.2	2.3	2.4	1.0	1.2	1.1	.8	1.5	2.2	1.1
Chlorite	.1	1.9	1.0	-	-	-	-	-	-	.8	-
Sphene	-		.3	-	1.0	-	-	-	-	-	-
Qtz/K/Plag	7:12:81	15:11:74	12:15:73	13:6:81	18:29:53	13:26:61	29:32:39	16:29:55	25:32:43	12:11:77	20:30:50
Mafic/Felsic	32.6	34.6	35.8	43.1	9.4	15.0	4.9	8.1	10.9	36.5	9.7
K/Feldspar	13.1	13.1	16.9	7.0	35.5	30.0	45.2	34.9	42.9	12.5	37.7
Mafic (%)	24.1	25.1	25.6	29.4	8.4	12.8	4.6	7.4	9.9	26.1	8.6

Table 4: Modal Analyses of Intrusive Rock Samples

	CORES	RIMS
2FKT844		
Range	36.3-48.8	30.4-41.6
Average	40.4	36.9
2FKT848		
Range	26.5-46.9	18.7-24.0
Average	36.0	21.7
1SKT1317		
Range	19.9-25.6	20.2-25.7
Average	23.2	23.1

Table 5: Anorthite Contents of Plagioclase Grains from Granodiorite near the Margin of the Batholith(2FKT844),Quartz Monzonite near the Margin of the Batholith(2FKT848),and Quartz Monzonite near the Core of the Batholith(1SKT1317)

two of the grains. Oscillatory zoning was noted in one plagioclase from the granodiorite and one from quartz monzonite near the margin. In the granodiorite, cores and rims are andesine but the cores are consistently greater in anorthite content. In the quartz monzonite from the interior of the batholith, cores and rims are both oligoclase and very similar in composition. In the quartz monzonite from the margin, cores are andesine but rims are oligoclase.

Quartz is generally interstitial to plagioclase and forms individual anhedral grains or aggregates of anhedral grains. Undulose extinction is characteristic. Potassium feldspar is also anhedral and interstitial to plagioclase. Some of the larger potassium feldspar grains are perthitic and size and texture of the exsolved albite lamellae are quite variable.

Pyroxene, wherever it occurs, is rimmed and embayed by patchy hornblende. The pyroxene grains appear to have been interstitial to plagioclase and were euhedral to subhedral prisms. In addition to rims on pyroxene, hornblende occurs interstitially as dark green subhedral grains, as aggregates of subhedral to anhedral grains and as ragged spongy poikilitic clots or plates enclosing smaller plagioclase grains. Biotite occurs as rims around hornblende and as independent flakes with generally ragged edges. Where the percentage of biotite is less than average it predominantly rims hornblende, but where more abundant it appears both as rims and individual grains. Biotite tends to be more coarse-grained than all other minerals except plagioclase. Magnetite is found in all rocks of the batholith and typically occurs as inclusions of anhedral grains in hornblende. Sphene, zircon and apatite occur with felsic minerals in both granodiorite and quartz monzonite.

Chlorite, commonly accompanied by epidote, is an ubiquitous pseudomorph after biotite but rarely replaces hornblende. Sericite occurs as patches in plagioclase throughout the batholith and in some instances clouds the majority of grains, particularly cores of zoned crystals. There is no direct relationship between the intensity of sericite or chlorite development and rock type.

Electron microprobe analyses of Mg, Si, Fe, Al, Ca, Na, K, Ti and Mn in selected pyroxenes, hornblendes, biotites and chlorites from the three intrusive rock samples in which plagioclases were analysed, are tabulated in Appendix 3. Al and Ti contents are greater in pyroxenes from granodiorite than quartz monzonite (Table 6).

The nine modal analyses of Table 4, plotted on the triangular diagram of Figure 7, are mostly within

2FKT844			2FKT848		
OXWT	CPX1	CPX2	CPX1	CPX2	OXWT
MG	13.04	13.67	14.09	14.06	MG
SI	52.87	53.28	54.16	53.95	SI
FE	7.99	8.01	8.25	7.86	FE
AL	.55	.79	.24	.36	AL
CA	23.91	23.38	22.44	22.15	CA
NA	.26	.33	.33	.36	NA
K	.00	.00	.01	.01	K
TI	.08	.09	.05	.05	TI
MN	.27	.17	.38	.37	MN
CU	.00	.02	.00	.00	CU
NI	.00	.00	.01	.01	NI
ZN	.09	.08	.00	.00	ZN
CO	.00	.03	.00	.00	CO
TOTAL	99.05	99.84	99.96	99.18	TOTAL

Table 6: Summary of Electron Microprobe Analyses of Pyroxenes from Granodiorite(2FKT844) and Quartz Monzonite(2FKT848)

EXPLANATION

1. 2FKT839
2. 2FKT844
3. 2FKT847
4. 2FKT869
5. 1SKT1307
6. 1SKT1317
7. 2FKT806
8. 2FKT860
9. 2FKT848

● **Kerswill Analyses**
X **G.S.C. Analyses**

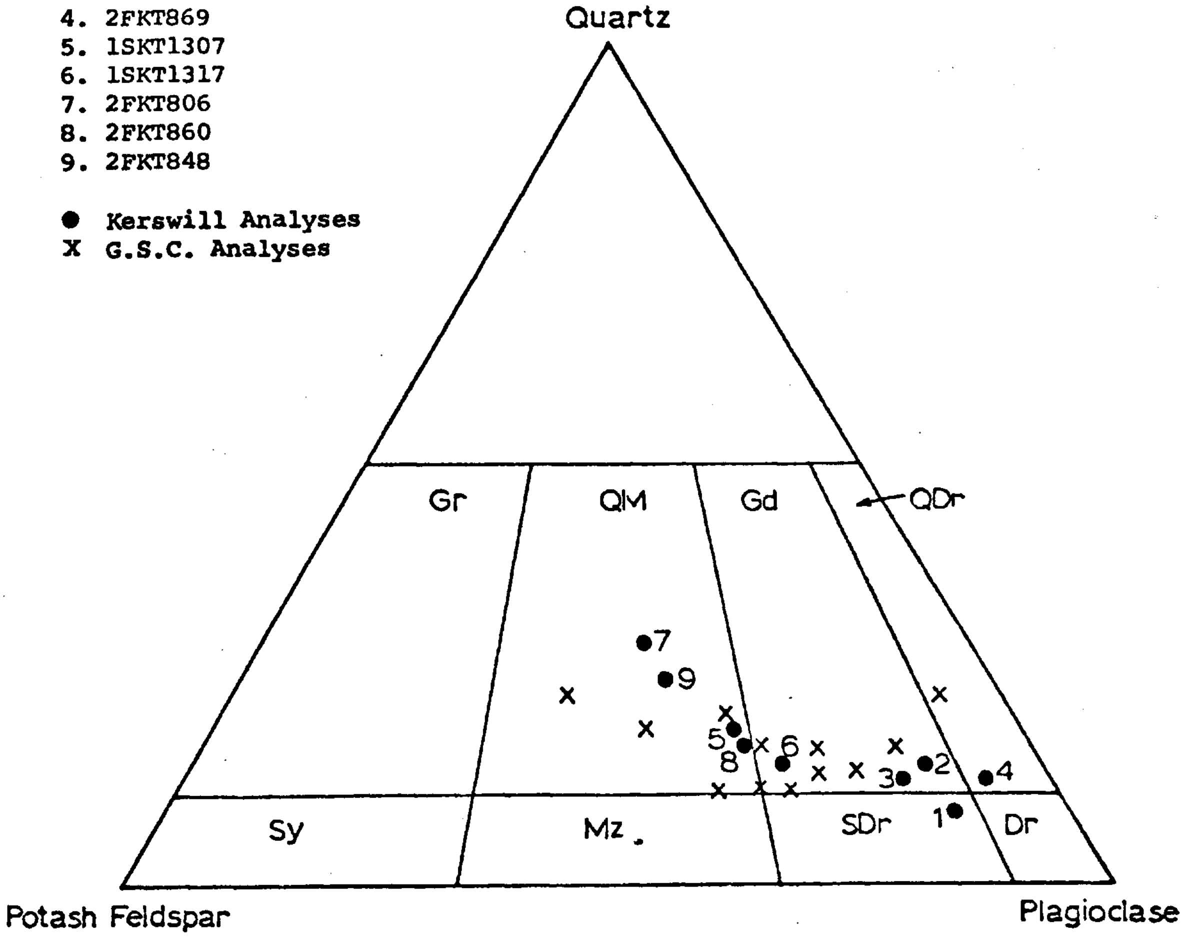


Figure 7: Classification of Intrusive Rock Samples

the areas of granodiorite and quartz monzonite and thus support the field classification of intrusive rock types. Sample #6, 1SKT1317, classified as quartz monzonite during field mapping plots as a granodiorite on Figure 7. However, this sample is closely similar to #5, 1SKT1307, which plots as a quartz monzonite. Eleven modal analyses done by the Geological Survey of Canada (Gabrielse and Reesor, 1974) occupy similar positions in Figure 7 and the correspondence between these analyses and those of the writer suggest the plotted variations in rock composition may indeed indicate the compositional range of the Hotailuh batholith. Although it is difficult to define trends on the basis of such diagrams there is a suggestion of a continuous gradation in composition from quartz diorite and syendiorite through granodiorite to quartz monzonite.

A comparison between Figure 7 and similar diagrams of modal composition for the Guichon, Thuya and Takomkane batholiths (Gabrielse and Reesor, 1974) indicates two things. The quartz content of the Hotailuh is less than that in the other batholiths, and the ratio of quartz to potassium feldspar is more constant in the Hotailuh batholith. Thus, the Hotailuh batholith is a relatively simple, less siliceous intrusion in comparison to three other batholiths of similar age and geological setting.

3.3 The Volcanic Rocks of the Stuhini Group

Volcanic rocks spatially associated with the Hotailuh batholith but unaffected by contact phenomena are typical of the Stuhini Group as described by Gabrielse (1962), Souther (1971b), and Wheeler and Gabrielse (1972). More specifically, the complex volcanic sequence is dominated by dark green to purple agglomerates and breccias containing bombs and fragments of porphyritic andesite or basalt with phenocrysts of either plagioclase or augite. The matrix of these rocks is similar in composition to the bombs and fragments which range in diameter from several mm. to a meter. Apparent flows of porphyritic andesite and basalt, also with either plagioclase or augite phenocrysts, are locally significant as are tuffaceous horizons. Pillow lavas were not noted in the vicinity of the batholith. Sedimentary rocks of volcanic detritus, principally greywacke of limited areal extent, are intercalated in the succession. Beds vary in thickness from several mm. to a meter and grain size ranges from very fine to coarse. Graded bedding commonly appears in those strata that contain a variety of grain sizes. The nature of the volcanic rocks suggests a depositional environment near the flanks of one or more volcanic centers where slumping and erosion were active processes.

Figure 8 is an idealized vertical section through the batholith and enveloping volcanic rocks. Amphibolite, chlorite schist and other metavolcanic rocks outcrop in a contact aureole along the west edge of the Hotailuh batholith adjacent quartz diorite, syenodiorite and xenolithic granodiorite. Width of this aureole is typically in the order of a few tens of meters. Amphibolite and chloritized volcanic rocks are widespread along the contact but chlorite schist occurs only in the Gnat Lakes area. The schistosity parallels the foliation in the granodiorite and suggests a nearly vertical north-trending contact between the batholith and volcanic rocks. Actual contact relationships between the schist, amphibolite and mafic intrusive rocks were not noted because of poor exposure.

A gradual decrease in intensity of contact metamorphism occurs as distance from the edge of the batholith increases. The transition from amphibolite to foliated and chloritized volcanic rock through to relatively fresh agglomerates, breccias and flows is locally gradual over several tens of meters but is also abrupt over a meter or so. A transitional relationship is generally apparent between rocks of the batholith and amphibolite. The most mafic intrusive rocks and the greatest number of xenoliths occur in contact with amphibolite.

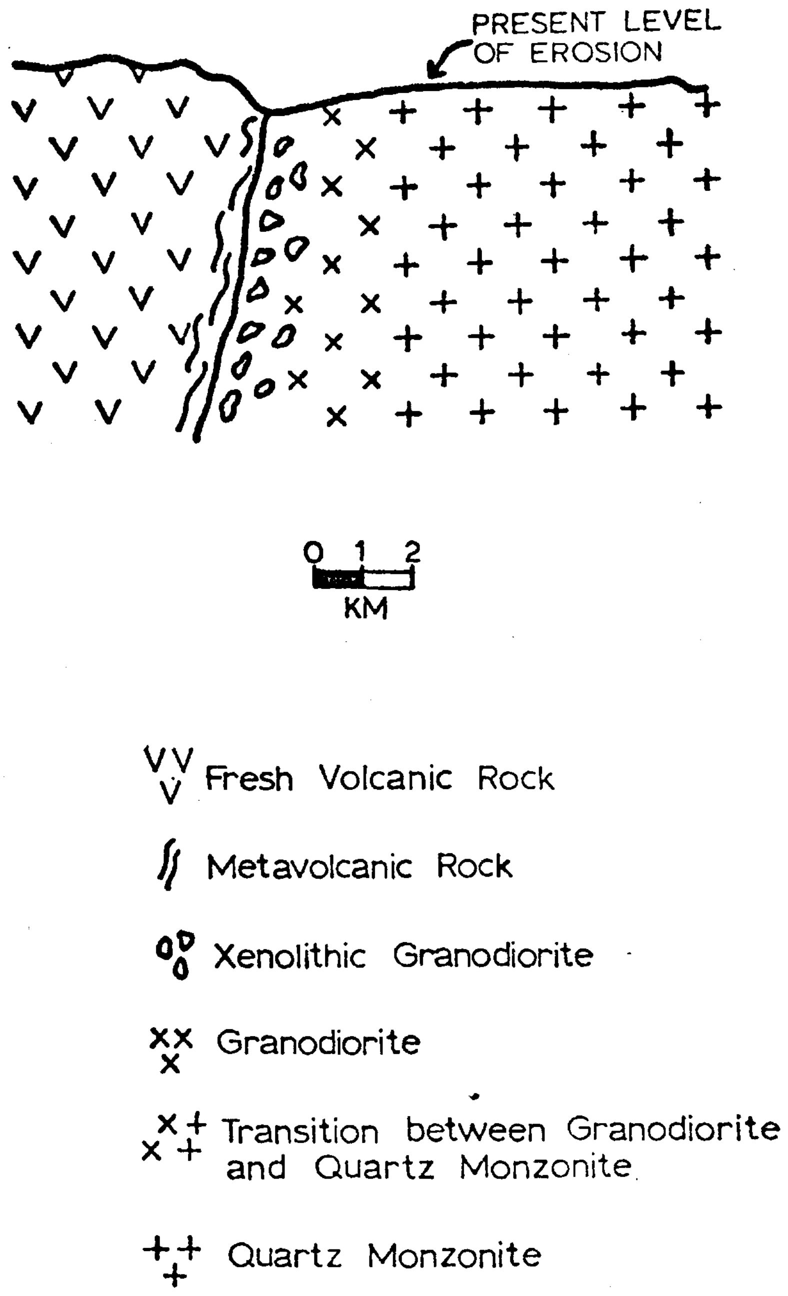


Figure 8: Idealized Vertical Section Through the Hotailuh Batholith and Spatially Associated Volcanic Rocks

3.4 Sulphide Mineral Occurrences

Within the Hotailuh batholith sulphide minerals are extremely rare and confined principally to a few fractures. Pyrite appears in several quartz-epidote calcite veins within quartz monzonite, and pyrite plus trace amounts of chalcopyrite occur in similar veins in granodiorite of the north central area. The latter are restricted to a family of near vertical joints trending N20°E. There are several small gossans, Figure 5, in the batholith which appear to be local concentrations of limonite after pyrite in shear zones. Along the western edge of the batholith in the Gnat Lakes area pyrite and trace amounts of chalcopyrite occur along fractures in small areas of intense hydrothermal alteration of the intrusive rocks.

Two sulphide mineral concentrations occur in volcanic rocks near the west edge of the Hotailuh batholith. The property of Dease Lake Mines with reported reserves of 20 million tons of 0.44 percent copper adjoins the Stewart-Cassiar highway and British Columbia Railroad in the Gnat Lakes area (Figure 5). Chalcopyrite and minor bornite occur along fractures, in breccia zones, and dispersed as grains throughout metavolcanic rocks in contact with an irregularly shaped porphyritic alaskite intrusion that is intensely fractured and essentially barren of sulphide minerals. Pyrite is minor but magnetite occurs in the metavolcanic rocks associated with fractures and in places there is a strong association of magnetite with chalcopyrite. Secondary minerals along fractures and as hydrothermal alteration products of wall rocks include sericite, calcite, hematite, chlorite and potassium feldspar. Tourmaline is an important constituent of the breccias and occurs along numerous fractures. Much of the rock exposed in drill core is cracked or brecciated, and cut by some strong fault zones (Jeffrey, 1966). This occurrence has been included in the Late Triassic porphyry deposits of the alkalic clan by Sutherland-Brown et al, 1971). A genetic relationship between the alaskite and the Hotailuh batholith has yet to be established but seems likely. Pyrite, chalcopyrite, arsenopyrite, bornite and magnetite, along with a gangue of altered rock, quartz, tourmaline and some barite occur on the Crown grant claims in volcanic rock adjacent an apophysis of the Hotailuh batholith (Figure 6). The sulphide minerals are confined to a north-trending shear zone that extends for about 800 meters with a width of up to 20 meters (Jeffrey, 1966).

Areas in the vicinity of Dease Lake Mines and the Crown grant showing have been prospected, staked, trenched and percussion drilled. To date such exploration has been unsuccessful. There are numerous gossans in volcanic rocks near the east edge of the batholith and also in the Snowdrift Creek area north of the batholith (Figure 6). The former are associated with tuffaceous horizons containing only pyrite, but local occurrences of molybdenite with pyrite have been found in the latter. Gossans after pyrite are also common in rocks of the Stuhini Group further to the west and south-east of the batholith.

In summary, sulphide mineral occurrences are significant in volcanic and metavolcanic rocks near the edges of the batholith. However, sulphide minerals are virtually absent in rocks of the Hotailuh batholith.

		UNTRANSFORMED			TRANSFORMED		
SAMPLE POPULATION	N	$\overline{X}$	σ	c.v.	$\overline{X}$	σ	c.v.
COMPOSITE GROUP	119	78.5	66.1	.84	53.7	.40	.23
INTRUSIVE ROCKS	84	50.2	38.9	.77	37.2	.34	.22
INTRUSIVE ROCKS	71	47.5	35.2	.74	35.5	.34	.22
VOLCANIC ROCKS	35	146.5	68.5	.47	128.8	.24	.11
METAVOLCANIC ROCKS	12	136.4	70.7	.52	120.2	.23	.11
VOLCANIC ROCKS	23	151.7	66.6	.44	134.9	.25	.12
GRANODIORITE	29	82.1	27.4	.33	77.6	.16	.08
QUARTZ MONZONITE	40	23.2	12.8	.55	20.4	.20	.16
RESIDUAL SOILS	54	52.4	43.6	.83	39.8	.32	.20
TOTAL SILTS	114	66.5	48.1	.74	55.0	.25	.15

N= SAMPLE SIZE

σ= STANDARD DEVIATION

$\overline{X}$= MEAN (ppm.)

c.v.= COEFFICIENT OF VARIATION

Table 8: Means, Standard Deviations, and Coefficients of Variation for Cu, Determined from Untransformed and Logarithmically Transformed Data

Sample Populations	No.	METALS							
		Cu	Zn	Pb	Ni	Co	Mn	Fe	Mo
Composite Group	119	53.7 L	43.7 L	10.5 L	20.4 L	20.0 L	467.7 L	3.72 L	–
Intrusive Rocks	84	37.2 L	31.6 L	7.9 L	15.3 N	14.1 L	331.1 L	3.09 L	–
Intrusive Rocks	71	35.5 L	29.5 L	7.4 L	14.7 N	13.5 L	309.0 L	3.02 L	–
Volcanic Rocks	35	146.5 N	91.2 L	20.4 L	52.5 L	44.7 L	1023.0 L	6.07 N	–
Metavolcanic Rocks	12	120.2 L	75.9 L	17.4 L	79.4 L	40.7 L	891.3 L	4.68 L	–
Volcanic Rocks	23	151.7 N	100.0 L	22.4 L	41.7 L	47.9 L	1122.0 L	6.76 L	–
Granodiorite	29	82.1 N	51.8 N	11.0 L	17.0 N	22.9 L	524.8 L	4.47 L	–
Quartz Monzonite	40	20.4 L	22.7 N	6.1 N	13.4 N	9.7 N	237.5 N	2.41 N	–
Residual Soils	54	39.8 L	89.1 L	19.7 N	41.9 N	20.6 L	602.6 L	4.17 L	1.32 L
Total Silts	114	55.0 L	77.6 L	15.1 N	31.4 N	20.9 L	588.8 L	3.98 L	1.91 L

N: Raw Data is Normally Distributed

L: Logarithms of Data are Normally Distributed

Table 16: Best Mean Estimates for Cu, Zn, Pb, Ni, Co, Mn, Fe, and Mo. All Estimates are Expressed in ppm. Except for Fe which is in percent. (No. Refers to the Size of the Sample Population.)

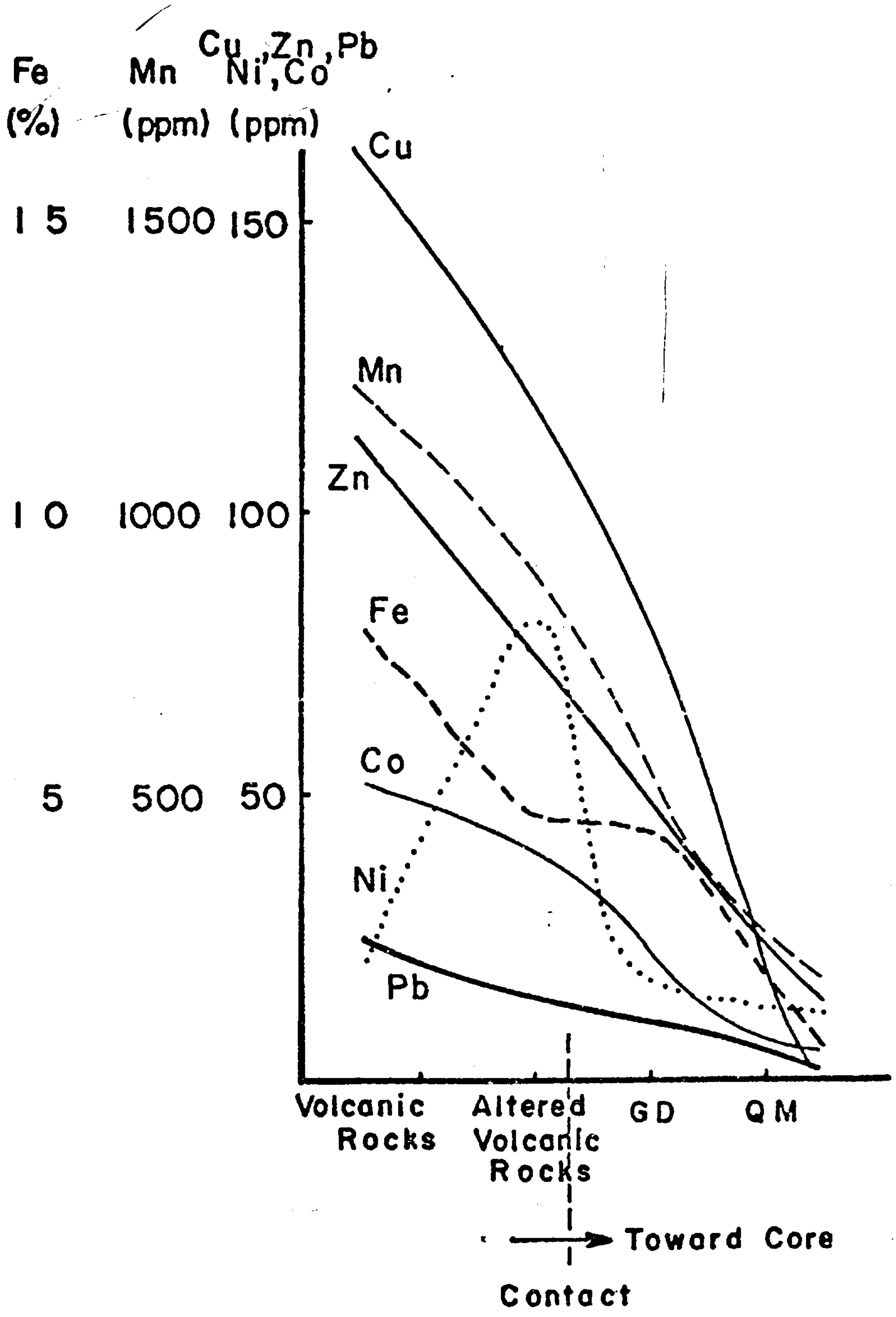


Figure 12: Average Metal Content in Major Rock Types Along an Idealized Traverse from Relatively Fresh Volcanic Rocks to Quartz Monzonite

near the contact of the Hotailuh batholith to quartz monzonite near the core of the intrusion. Cu, Zn, Pb, Co, Mn and Fe decrease in average abundance toward the core. In other words, the average abundances for these metals are greatest in fresh volcanic rock, next greatest in metavolcanic rocks of the contact aureole, and greater in granodiorite than quartz monzonite. Ni has the greatest average abundance in rocks of the contact aureole but like the other metals is more abundant in volcanic than intrusive rock and more abundant in granodiorite than quartz monzonite.

Figure 13 illustrates average metal contents for composite rock chip, residual soil and silt samples collected in comparable locations throughout the batholith. All metals have greater average abundances in residual soils and silts than in composite rock chips. Zn, Ni and Pb are more abundant in residual soils than silts but Cu is more abundant in silts than residual soils. Mn, Fe, and Co abundances are similar in residual soils and silts.

Multivariate analysis of variance, or MANOVA, was used to test the significance of differences in metal content suggested by Figures 12 and 13. The method simultaneously compared the relative locations of appropriate sample populations in a multidimensional space defined by the metals. More specifically, each sample population can be viewed as an ellipsoid in seven dimensional space and

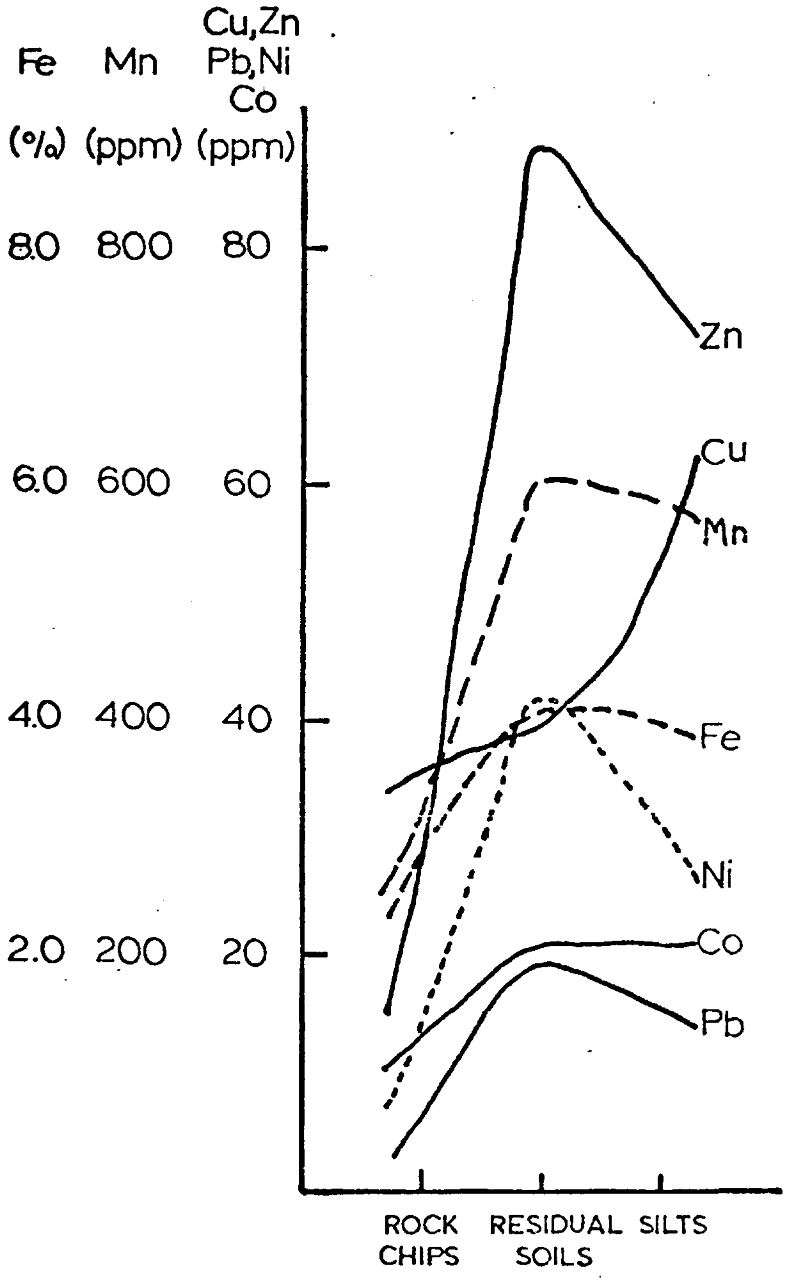


Figure 13: Average Metal Content in Composite Rock Chip Samples, Residual Soil Samples and Silt Samples

CHAPTER 5

A GENETIC MODEL

5.1 General Statement

A genetic model for the Hotailuh batholith must be consistent with the following observations:

1) The batholith is spatially associated with volcanic rocks of similar Late Triassic age and comparable chemical composition.

2) Lower Jurassic basal conglomerates to the north and west of the batholith contain boulders from the batholith.

3) In the batholith a peripheral granodiorite grades transitionally into a core of quartz monzonite. Abundant mafic xenoliths occur in granodiorite nearest the margins of the intrusion. Quartz diorite and syenodiorite occur locally adjacent a narrow contact aureole containing amphibolite, chlorite schist and other metavolcanic rocks.

4) The two principal rock types of the batholith, quartz monzonite and granodiorite, have similar medium to coarse-grained hypidiomorphic granular textures. Total

ferromagnesian mineral content in granodiorite is three times that in quartz monzonite and the relative abundance of biotite to hornblende is greater in granodiorite. Magnetite content is two percent in granodiorite and one percent in quartz monzonite.

5) Minor deuteric alteration including chlorite after biotite and sericite after plagioclase is uniform throughout the granodiorite and quartz monzonite. Hydrothermal alteration in the batholith is very local and restricted to secondary potassium feldspar and chlorite in areas of intensive fracturing.

6) Pegmatitic, aplitic and porphyritic rocks were not noted during field mapping within the batholith.

7) Sulphide minerals are virtually absent in the batholith but do occur in volcanic and metavolcanic rocks near the contact, particularly in the Gnat Lakes area.

8) Average contents of Cu, Zn, Pb, Co, Mn and Fe are greatest in volcanic rock unaffected by contact phenomena, next greatest in metavolcanic rocks of the contact aureole, and greater in granodiorite than quartz monzonite. Average Ni content is greatest in metavolcanic rocks, next greatest in volcanic rock, and greater in granodiorite than quartz monzonite.

9) In volcanic rock unaffected by contact phenomena, both a Zn-Mn association and a Cu association are

inversely related to a dominant Pb-Co-Ni-Fe association. Thus, Cu, Zn and Mn behaved quite differently than Pb, Co, Ni and Fe during the processes that contributed to metal distribution in the relatively fresh volcanic rocks. However, in metavolcanic rocks of the contact aureole a dominant Fe-Pb-Zn-Mn association is directly related to a Cu-Mn association but these associations are unrelated to a Ni-Co association.

10) In intrusive rocks of the Hotailuh batholith a Zn-Mn-Pb association is directly related to a Fe-Co-Cu-Ni association. More specifically, the seven metals behaved in a generally similar manner during whatever processes contributed to metal distribution in the batholith, but Zn, Mn and Pb behaved somewhat differently than Ni, Co, Fe and Cu. The pattern of metal association is more complex in quartz monzonite than granodiorite.

11) Relative dispersions of all metals are greater in quartz monzonite than granodiorite and greater in metavolcanic rocks than relatively fresh volcanic rocks.

12) Fifteen of a possible twenty-one metal ratios are equivalent in granodiorite and relatively fresh volcanic rock. Cu, Zn, Co and Mn are enriched relative to Ni, Fe, and Pb in granodiorite as compared to quartz monzonite.

5.2 The Model

A comagmatic origin for the batholith and spatially associated volcanic rocks is suggested by their similar ages and comparable chemical compositions. The batholith may be viewed as the plutonic equivalent of Late Triassic island arc volcanism that produced the rocks of the Stuhini Group. Such a genetic relationship between Upper Triassic igneous rocks of the Hinterland belt is generally accepted (Gabrielse and Wheeler, 1972).

Comparison between observed features of the batholith and Buddington's criteria (1959) for depth of emplacement suggest the pluton rose to a depth of five Km. in the region between epizone and mesozone. However, the suggestion from stratigraphic evidence that the batholith was unroofed shortly after its emplacement, the inferred occurrence of a subvolcanic setting in the central area of the batholith and the occurrence of a porphyry copper deposit in volcanic rocks near the margin of the intrusion imply a level of emplacement shallower than five Km.

Petrography, contact relationships, and areal distribution of rock types in the Hotailuh batholith can be adequately explained by progressive inward fractional crystallization of an initially homogeneous granodioritic magma. Throughout the cooling history an increasingly felsic residual melt migrated toward the interior of the intrusion to form a zoned pluton in which a core of quartz monzonite is surrounded by granodiorite. More specifically, the greater content of ferromagnesian minerals and lesser contents of potassium feldspar and quartz in granodiorite relative to quartz monzonite suggest the residual silicate melt became depleted in Ca, Mg and Fe but enriched in Na, K and silica as crystallization proceeded.

The general lack of aplitic, pegmatitic, or porphyritic textured rocks, sulphide-bearing veins and hydrothermal alteration indicates crystallization of the batholith took place in the absence of a magmatically-derived hydrothermal fluid. Such an absence was perhaps the combined result of a high confining pressure and the continued removal of water from the residual silicate melt through crystallization of hydrous minerals. Assimilation of volcanic rock near the margins of the intrusion may have contributed to the occurrence of abundant mafic xenoliths in granodiorite and to the local development of quartz diorite and syenodiorite adjacent the contact aureole.

The greater average metal content of granodiorite relative to quartz monzonite and the consistent pattern of metal association in the intrusive rocks indicate that fractional crystallization of the batholith was accompanied by dispersal of Cu, Zn, Pb, Ni, Co, Mn and Fe in the lattices of ferromagnesian minerals and magnetite. In other words, metal content in the Hotailuh batholith is directly related to the total content of pyroxene, hornblende, biotite, chlorite and magnetite in the intrusive rocks. Metals were not partitioned into the residual silicate melt or concentrated in a hydrothermal fluid. Statistical analysis further suggests metal distribution in the intrusive rocks was unaffected by hydrothermal alteration either during the final stages of crystallization or subsequent to complete solidification of the batholith. However, the greater complexity of metal associations and greater relative dispersions of metal contents in quartz monzonite than granodiorite suggest that volatiles became increasingly important as differentiation progressed even though a magmatically-derived hydrothermal fluid did not separate from the crystallizing magma. A greater volatile content would tend to complicate metal distribution by increasing the mobility of certain metals.

The pattern of metal association in volcanic rocks is different than the pattern in intrusive rocks of the batholith and suggests Cu, Zn and Mn were not dispersed in lattice sites of ferromagnesian or oxide minerals during crystallization of the volcanic rocks. These ions probably occur along cleavage planes, grain boundaries, or in sulphide minerals. Contrasting metal contents and different patterns of metal association in metavolcanic rocks of the contact aureole and relatively fresh volcanic rock suggest metal distribution in the contact aureole was affected by alteration related to intrusion of the Hotailuh batholith. It appears that all metals except Ni were leached from the metavolcanic rocks perhaps by circulating meteoric waters.

5.3 Discussion and Theoretical Considerations

The model of fractional crystallization proposed for the Hotailuh batholith is consistent with the principles of magmatic differentiation. Comparable models have been suggested for other similarly zoned plutons throughout the Cordillera (Compton, 1955; Putnam and Alfors, 1969; Carmichael et al, 1974). Indeed, the occurrence of intrusions in which relatively mafic margins surround more felsic cores is commonplace (Hamilton and Myers, 1967; Presnall and Bateman, 1973; Gabrielse and Reesor, 1974). Assimilation of mafic to intermediate volcanic rock is frequently called upon to explain apparently hybrid intrusive rocks occurring near the margins of batholiths (Turner and Verhoogen, 1960; Carmichael et al, 1974).

A greater anorthite content in plagioclase from granodiorite than from quartz monzonite (Table 5) and a lesser content of Al and Ti in pyroxene from quartz monzonite than from granodiorite (Table 6) provide additional support for the model. Kushiro (1960) and Le Bas (1962) have shown that aluminum increases systematically in calcium-rich pyroxenes in relation to decreasing silica concentration of the host magma (Carmichael et al, 1974).

The model for metal distribution in the Hotailuh batholith is consistent with an interpretation of metal behaviour based upon crystal field theory as discussed by Burns (1970). Metals of the Fe-Co-Cu-Ni association acquire crystal field stabilization energy in passing from tetrahedral sites in a magma to octahedral sites in crystallizing phases. However, metals of the Zn-Mn-Pb association acquire no such additional stability on entry into octahedral sites in minerals. The strong direct relationship between the associations, coupled with the decrease in metal content with progressive differentiation indicates the metals became gradually depleted in the residual silicate melt because of their incorporation in minerals such as pyroxene, hornblende, biotite, chlorite and magnetite. Metal associations further imply that the metals occurred principally as divalent ions during crystallization of the batholith.

Crystal field theory also predicts that divalent Ni will enter different octahedral sites in minerals than divalent Fe, Co and Cu. This is in part because the Ni ion attains the greatest amount of octahedral site preference energy but also because it prefers regular octahedral sites whereas the other ions prefer distorted octahedral sites. The large radius of divalent Pb relative to divalent Zn and Mn suggests this ion will remain in a silicate melt longer than Zn and Mn. These somewhat different behaviours of Ni and Pb relative to the other ions are clearly illustrated by the hierarchy of principal component metal associations in Figure 15.

Dispersion of metals in silicate and oxide lattices as the dominant mechanism for controlling metal distribution during magmatic crystallization has been suggested by a number of workers (Serykh, 1963; Tauson, 1967; Burnham, 1967; Putnam and Alfors, 1969; Graybeal, 1973). Thus from a practical viewpoint it is also quite reasonable to expect that metals will be distributed among available lattice sites in ferromagnesian minerals and magnetite, particularly in the absence of a hydrothermal fluid. As a test of this model for metal distribution in the Hotailuh batholith mineral separates of hornblende, biotite and magnetite were analysed for Cu and Zn by atomic absorption at the University of Western Ontario (Table 21). The ferromagnesian minerals and magnetite contain at least 100 ppm Cu and Zn and hence support the conclusion that metals are dispersed in such lattices. Of further note, biotite appears to be

	Granodiorite				Quartz Monzonite					
MINERAL SEPARATE	2FKT844		2FKT847		2FKT848		2FKT859		1SKT1317	
	Cu	Zn	Cu	Zn	Cu	Zn	Cu	Zn	Cu	Zn
HORNBLENDE	146	195	141	200	144	270	–	282	113	192
BIOTITE	250	330	235	295	213	322	–	–	–	–
MAGNETITE	123	203	110	254	135	238	230	328	109	218

Table 21: Cu and Zn Contents of Mineral Separates from Granodiorite and Quartz Monzonite

the most important host for these metals. The apparent lack of variation in Cu and Zn content of hornblende, biotite and magnetite in granodiorite and quartz monzonite suggests metal content in these minerals did not change appreciably during crystallization of the batholith, although total metal content did decrease. This suggestion is supported by the observation that both ferromagnesian mineral content, Table 4, and total metal content, Table 16, are greater in granodiorite than quartz monzonite by a similar factor.

The factor analysis results of Figure 23 can be interpreted with respect to the processes of dispersion of metals in lattice sites of biotite, hornblende and magnetite, and fractional crystallization and thus provide additional support for the proposed genetic model. The Plagioclase-Hornblende-Quartz-Potassium Feldspar association suggests the influence of differentiation and the other three associations suggest the metals are dispersed in ferromagnesian minerals and magnetite.

Curtis (1964) suggested that divalent Cu will tend to remain in a residual silicate melt because of its strong predicted preference for distorted octahedral sites. This idea has been adopted by recent researchers (Graybeal, 1973). However, results of this study do not support such an hypothesis and indicate that Cu, under appropriate conditions, can follow Fe, Co and Ni instead of Zn, Mn and Pb.

If concentration of metals in the residual silicate melt or a hydrothermal fluid had been important in controlling metal distribution in the batholith, Zn, Mn and Pb, and possibly Cu would have greater average contents in quartz monzonite than granodiorite. This interpretation based on crystal field theory is supported in experimental work by Burnham (1967), Kilinc and Burnham (1972), Holland (1972) and others who have shown that Zn, Mn and Pb partition strongly into a hydrothermal fluid phase, particularly in the presence of chloride species. In addition, a negative correlation should also exist between the two metal associations because Ni, Co, Fe and possibly Cu are predicted to enter crystallizing minerals.

If redistribution or migration of metals from quartz monzonite had occurred during later stages of differentiation to produce the greater metal content of granodiorite, the patterns of metal association in granodiorite and quartz monzonite would reflect this, and the coefficient of variation would be greater in granodiorite than quartz monzonite. The lack of such evidence in the statistical results for residual concentration or redistribution of metals in rocks of the batholith is consistent with the general paucity of features such as aplites, pegmatites, porphyries, sulphide-bearing veins and hydrothermal alteration.

Migration of metals upward or outward from the batholith into the enveloping volcanic rocks would have perhaps led to a greater metal content in metavolcanic rocks of the contact aureole than in the relatively fresh volcanic rock. Although no concentration of metals is observed in the aureole it is possible that metals leached from rocks of the aureole entered the hybrid intrusive rock types and contributed to the greater metal content in granodiorite relative to quartz monzonite.

A variable content of sulphide minerals in rocks of the batholith could conceivably account for the observed metal distribution, but sulphide minerals are virtually absent. The small total metal contents and the small coefficients of variation in the intrusive rocks also indicate that sulphide minerals were not important sites of metal concentration. The ubiquitous occurrence of magnetite further suggests that sulphur and oxygen fugacities and iron and trace metal activities were inappropriate for the crystallization of sulphide minerals. Conclusions from studies of immiscible sulphide melts indicate a low initial sulphur fugacity yields magnetite but not sulphide minerals (MacLean, 1969). If the sulphur fugacity had been great, the removal of FeO from the melt during magmatic crystallization would have decreased the solubility of sulfur in the melt and lead to appearance of sulphide minerals (MacLean, 1969).

The model for metal distribution in volcanic rocks is supported by the inverse correlation between the dominant Pb-Co-Ni-Fe association and the lesser Cu and Zn-Mn associations if the dominant factor is interpreted as representing dispersion of metals in lattice sites of ferromagnesian and oxide minerals. A lesser content of Cu, Zn, Pb, Co, Mn and Fe in metavolcanic rocks than volcanic rocks unaffected by contact phenomena, and the pattern of metal association in the volcanic and metavolcanic rocks, suggest that all metals, except Ni and Co, but particularly Cu, Zn and Mn, were susceptible to strong leaching. Such leaching could most readily occur if the latter metals were dispersed along grain boundaries, cleavage planes, or in sulphide minerals. Ni and to a lesser extent Co were more resistant than the other metals because of the high octahedral site preference energy they attain in appropriate lattice sites of silicate and oxide minerals.

The fairly common occurrence of pyrite in the unaltered volcanic rocks, supports the suggestion that sulphide minerals may be an important influence on metal distribution in these rocks. Indeed, the existence of the Dease Lake Mines deposit and several other sulphide mineral occurrences in volcanic rocks near the western contact of the Hotailuh batholith lends further support to the suggestion that Cu is not dispersed in silicate or oxide lattices. Volcanic rocks may have been the source of copper in the sulphide mineral occurrences.

5.4 Summary

Evolution of the Hotailuh batholith and spatially associated volcanic rocks included the following sequence of events.

1) A parent granodioritic magma was generated and collected in a Late Triassic subduction zone environment beneath an active island arc built upon Paleozoic oceanic crust.

2) The buoyant, initially water-undersaturated magma ascended toward the surface and was finally emplaced at a shallow depth within older comagmatic volcanic rocks. In the volcanic rocks, Cu, Zn and Mn were distributed along grain boundaries, along cleavage planes or in sulphide minerals.

3) The granodiorite magma crystallized through relatively simple progressive fractional crystallization in the absence of a magmatically-derived hydrothermal fluid. In the batholith, Cu, Zn, Pb, Ni, Co, Mn and Fe were dispersed in lattice sites of ferromagnesian minerals and magnetite.

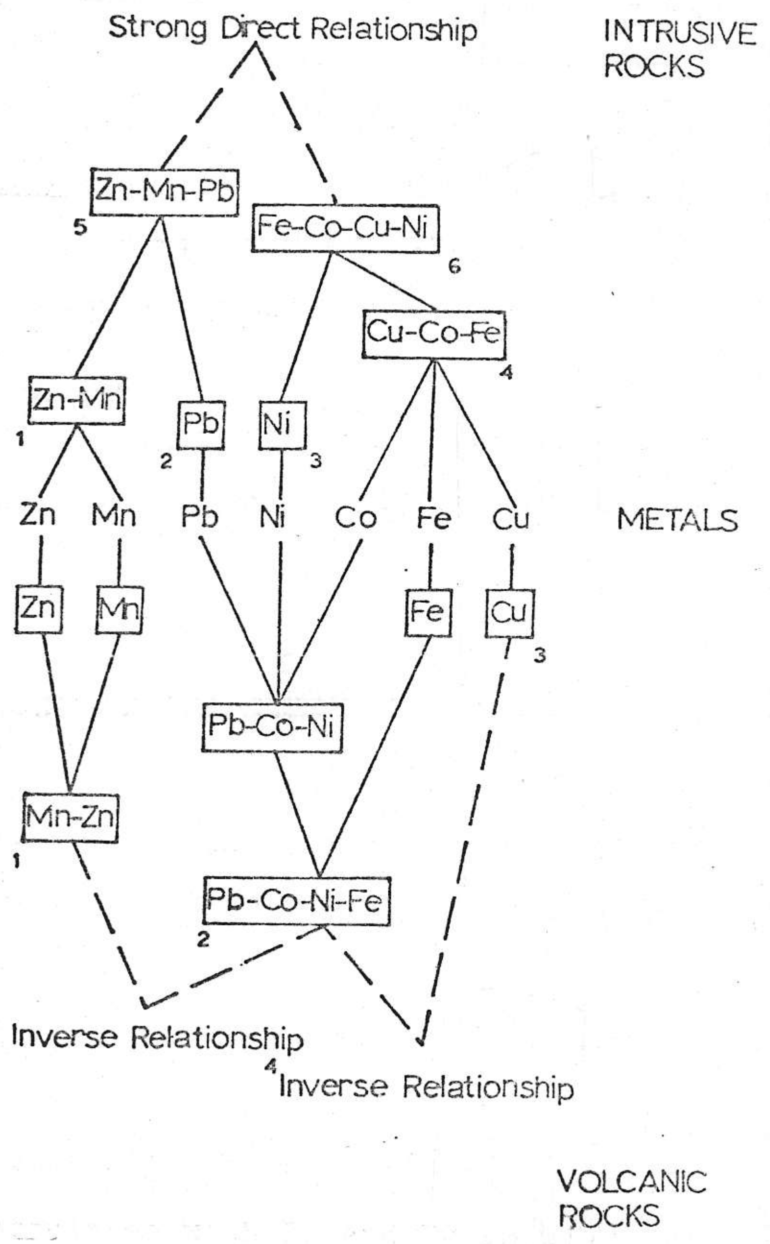
4) Volcanic rocks were assimilated in the crystallizing margins of the batholith and metamorphosed in a narrow contact aureole, perhaps in the presence of a

hydrothermal fluid derived from meteoric or connate waters circulating through heated permeable rocks near the contact. All metals except Ni were leached from rocks of the contact aureole.

5) The more felsic portions of the batholith crystallized from a residual silicate melt still undersaturated in water and other volatiles, but capable of weak deuteric alteration.

6) The batholith was rapidly uplifted and unroofed during the Early Jurassic and subsequently eroded to the present level of exposure.

Figure 30 is a summary of the theoretical aspects of metal distribution in the Hotailuh batholith and spatially associated volcanic rocks.



INTRUSIVE ROCKS

1. Zn^{++} and Mn^{++} ions do not gain crystal field stabilization energy (CFSE) in passing from tetrahedral sites in a magma to octahedral sites in minerals such as pyroxene, hornblende, biotite, chlorite and magnetite.

2. Pb^{++}, a relatively large ion, is not a transition metal and gains no CFSE.

3. Ni^{++} attains highest CFSE of metals in this study and favours undistorted octahedral sites in minerals; similar to Mg^{++} in radius.

4. Cu^{++}, Co^{++} and Fe^{++} gain CFSE upon entry into octahedral sites in crystals and favour distorted sites.

5. Zn^{++}, Mn^{++} and Pb^{++} are those ions that do not gain CFSE.

6. Ni^{++}, Cu^{++}, Co^{++} and Fe^{++} are those ions that gain CFSE.

7. Strong positive relationship between the two metal associations suggests that during fractional crystallization all the metals were dispersed in the lattices of ferromagnesian minerals and magnetite.

VOLCANIC ROCKS

1. Zn and Mn occur in same metal association as above for similar reason.

2. Ni, Co and Fe in this metal association suggest a control by silicate lattices, but the presence of Pb is unexplained.

3. Cu occurs in an unique association, unrelated with Ni, Co and Fe.

4. Inverse relationship between dominant Pb-Ni-Co-Fe association and other two associations suggests that Zn, Mn and Cu may not be dispersed throughout silicate and oxide lattices.

Figure 30: Summary of Interpretation of Metal Associations in Intrusive and Volcanic Rocks According to Crystal Field Theory

CHAPTER 6

POTENTIAL FOR PORPHYRY COPPER DEPOSITS

On the basis of the foregoing genetic model porphyry copper potential is minimal in the Hotailuh batholith. Hydrothermal activity was insignificant during magmatic crystallization and the possible ore metals were dispersed in crystallizing ferromagnesian minerals and magnetite and not concentrated in the residual silicate melt. The strong association of Cu with Ni, Co and Fe instead of with Zn, Mn and Pb virtually negates the possibility that porphyry copper deposits occur within the batholith at its present level of exposure.

Of particular note, metal behaviours in the Hotailuh batholith differ from those reported for the productive Guichon batholith. Brabec (1971) states that Zn but not Cu is correlated with Fe and Mg in whole rocks, and concludes that Cu is not solely dispersed in ferromagnesian minerals and magnetite.

In the volcanic rocks, ore potential is considerably greater principally because Cu and Zn do not appear to be dispersed in silicate or oxide lattices and may have been susceptible to leaching and concentration in a hydrothermal regime generated near the margins of the batholith. The relatively great background metal content in the volcanic rocks and the occurrence of the Dease Lake Mines deposit and several sulphide mineral showings near the west edge of the batholith support this conclusion.

CHAPTER 7

CONCLUSIONS

Conclusions consistent with the purpose of this thesis are:

1) The Hotailuh batholith is a simple zoned pluton in which a core of quartz monzonite is surrounded by a margin of granodiorite. It intrudes comagmatic volcanic rocks generated in a Late Triassic ensimatic island arc environment. Hybrid intrusive rocks occur adjacent a narrow contact aureole of amphibolite, chlorite schist and other metavolcanic rocks.

2) Individual rock types of the thesis area can be defined in terms of their average metal contents and by characteristic metal associations.

3) In the Hotailuh batholith Cu, Zn, Pb, Ni, Co, Mn and Fe were dispersed in lattices of ferromagnesian minerals and magnetite during progressive inward fractional crystallization of an initially granodioritic magma. The metals became increasingly depleted in the residual silicate melt as differentiation proceeded in the absence of a magmatically derived hydrothermal fluid.

Redistribution of metals did not occur during the late stages of magmatic crystallization or subsequent to complete solidification of the batholith. The potential for occurrence of porphyry copper deposits in the intrusion is minimal.

4) In volcanic rocks Cu and Zn probably occur in sulphide minerals or along cleavage planes and grain boundaries but are not dispersed solely in lattice sites of silicate and oxide minerals. Porphyry copper potential is significant in these rocks because Cu and Zn may have been susceptible to leaching and later concentration in a hydrothermal regime generated near the margins of the batholith. Indeed, volcanic rocks affected by contact phenomena may have been the source for the copper in the Dease Lake Mines deposit and the several sulphide showings that occur in volcanic rocks along the western contact of the intrusion.

5) Metal associations in the intrusive rocks are exactly those predicted from crystal field theory. This may indicate the theory is adequate for describing the behaviour of Cu, Zn, Pb, Ni, Co, Mn and Fe during magmatic crystallization.

APPENDIX 8

SUGGESTIONS FOR SUCCESSFUL PORPHYRY COPPER EXPLORATION

The following suggestions are considered appropriate for a porphyry copper exploration program:

1) Select an area for exploration based upon current metallogenic thinking and economic feasibility. A number of different models may have to be evaluated before such a decision can be made.

2) Map the field area to determine the number of different rock types, their areal distribution, contact relationships, structural features, the extent of alteration and sulphide occurrences. Country rocks should be mapped in the same detail as the intrusion. Carefully selected hand specimens of outcrops will facilitate subsequent petrographic study.

3) Collect a variety of sample types during field mapping and make detailed observations pertaining to location, rock type, occurrence of sulphide minerals and proximity to alteration or fractures at each sample site. Composite rock chip and residual soil samples

will best reflect metal distribution in the bedrock but silt samples often provide a more adequate coverage.

4) Attempt to collect a sufficient number of samples for each rock type in a random and unbiased manner. Inadequate sampling can lead to uninterpretable often incorrect results. Replicate samples at a number of locations provide the basis for estimates of both analytical precision and variability at different scales.

5) Analyse all sample types for a variety of metals and complete a thorough statistical analysis of the analytical data to provide a sound basis for understanding metal distribution in the area under study. Suggestions for such an analysis are outlined in Appendix 7. Whole rock analyses will provide significant information and may often be used instead of analyses of mineral separates. Patterns of metal association as well as differences in average metal contents should be considered in comparisons among rock types or sample types. Conclusions based solely upon average metal contents are prone to error. Because average metal contents and metal associations can be expected to vary with rock type, they should be determined for each rock type using appropriate sample populations. Background estimates based upon sample populations containing a variety of rock types may be quite inappropriate.

6) Construct a satisfactory genetic model for the area based on field observations and results of the statistical analysis. The degree of sophistication in any model depends upon the needs of the explorer. An appropriate model for metal distribution should be able to account for geochemical differences among sample types. For example, high Cu content in silts may be more dependent upon processes of weathering and transport than the Cu content of bedrock.

7) Predict potential for the occurrence of porphyry copper deposits on basis of the genetic model. Ore potential may be high if model suggests that metals became concentrated in a hydrothermal fluid or were redistributed during hydrothermal alteration. Greater than average metal contents do not necessarily reflect proximity to ore deposits and less than average contents need not imply a loss of metals from one area and their concentration elsewhere. It is to be expected that metal distribution will depend upon complex natural phenomena that interact differently in each area explored.

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