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Geology of the Kitsault Molybdenum Deposit, British Columbia

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Abstract

The Kitsault molybdenum deposit is related to the 54-m.y.-old Lime Creek Intrusive Complex which is hosted by sedimentary rocks along the eastern margin of the Coast Plutonic Complex. The Alice Arm intrusive rocks, of which the Lime Creek Complex is a member, are probably related to the latest intrusive phase of the Coast Plutonic Complex.

The Lime Creek Complex is a series of nested stocks that intrude the Bowser Lake Group graywackes and argillites of Jurassic age. A broad zone of biotite hornfels developed in the sedimentary rocks as a result of the intrusive activity. The oldest member of the Complex is the East Lobe. It in turn is followed by the Border, Southern, and Central stocks, and the Intramineral dikes and the related Northeast Porphyry. These intrusions vary from diorite of the East Lobe to quartz monzonite of the Northeast Porphyry, suggesting a differentiation trend. Postmineral lamprophyre and basalt dikes are common.

Mineralization is related to the Central stock and Northeast Porphyry. The molybdenite shell generally occupies the contract zone of the Central stock. Quartz-pyrite, with or without, scheelite veins occurs on the hanging wall of the molybdenite zone, while barren quartz veins occupy the footwall. A series of postmolybdenite polymetallic sulfide quartz veins have a northeast trend and a greater lateral extent than any other vein type. Four ages of mineralization have been identified. The first three are molybdenite bearing, whereas the last consists of polymetallic sulfides.

Hydrothermal alteration is directly related to the mineralization. A central silicified zone occurs on the footwall side of the molybdenite zone. There is a close correlation between molybdenite and potassium silicate alteration. Peripheral to the molybdenite zone and associated with the quartz-pyrite veins, phyllic alteration is common. All alteration is vein related as envelopes with the intervening areas being altered to propylitic to argillic assemblages.

There appear to be several significant similarities and differences between the Kitsault-type deposits and those of the Climax type (White et al., 1981). The similarities appear to be in the style and nature of the intrusive activity and associated hydrothermal events. Both types of deposits are characterized by multiple igneous and hydrothermal events. Another common feature is the presence of intramineral dikes and related stocks. The significant differences appear to be the smaller size and lower grade of the Kitsault deposit, which may have had a smaller and less concentrated hydrothermal system. The other significant difference is in the composition of the source intrusions. The Kitsault deposits are characterized by siliceous quartz monzonites and granodiorites whereas the Climax-type deposits are characterized by rhyolites and granites. Alteration and trace element assemblages are similar in both types of deposits except that alteration is not as pervasive and trace elements are not as abundant in the Kitsault deposits.

Introduction

THE Kitsault molybdenum deposit is approximately 135 km northeast of Prince Rupert, British Columbia, and 6 km southeast of the Kitsault townsite (Fig. 1). The mine site is approximately 600 m above sea level, in an area of extreme topographic relief that is modified by numerous swamp-covered benches.

During 1956 the Kitsault molybdenite showings were brought to the attention of Kennco Exploration (Western), a subsidiary of Kennecott Copper Corporation. Kennco acquired the property in 1957, and formed British Columbia Molybdenum, Ltd., in 1963 to begin development of the ore deposit. Mining operations began in 1967 but were suspended in August 1972 due to a weak molybdenum market. Total production for the five years of operation was approximately 10,400 tons of molybdenum. In 1973, Climax Molybdenum Corporation of British Columbia purchased the property from Kennecott Copper Corporation and renamed it the Kitsault Project. Additional exploration and feasibility studies were undertaken by Climax, leading to a decision to return the property to production.

Regional Geology

The Kitsault deposit is within the Intermountain tectonic belt, more specifically the western margins of the Bowser basin, approximately 2 km east of the

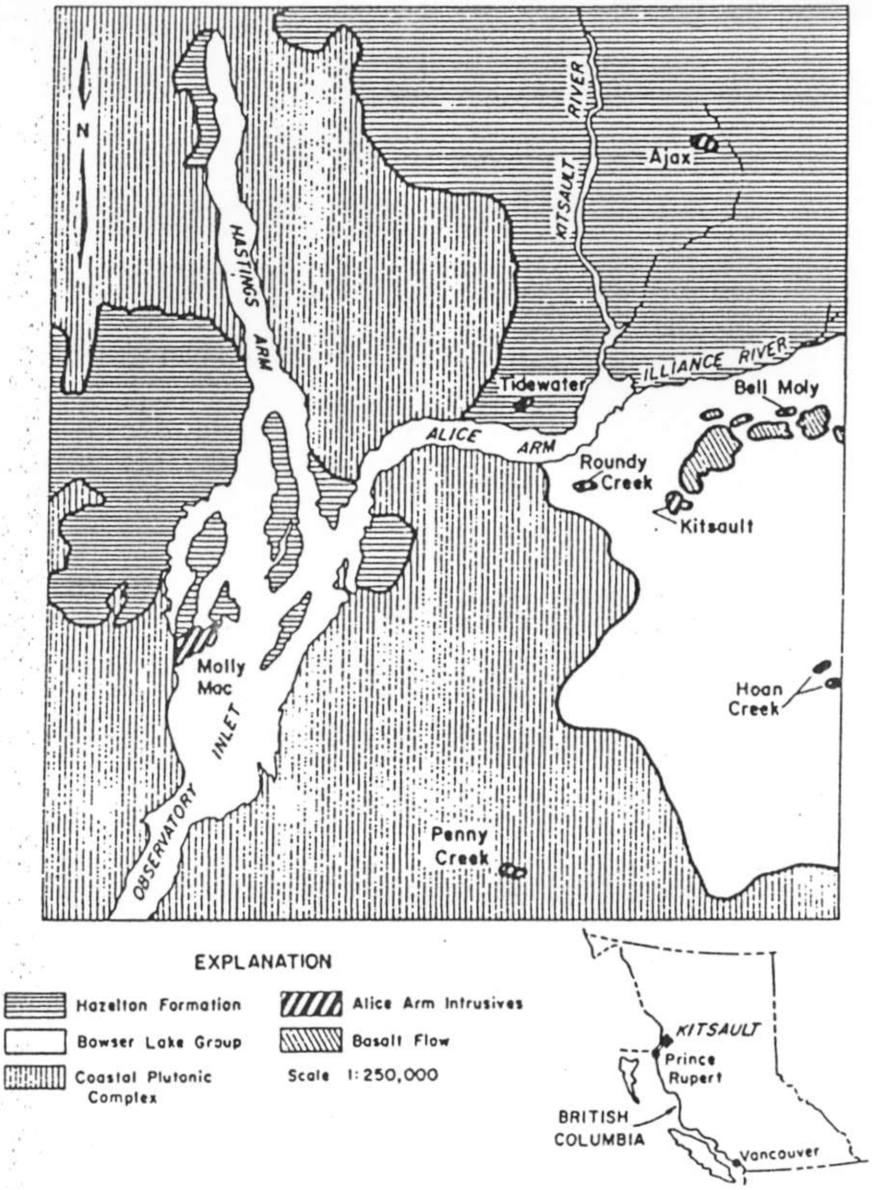

FIG. 1. Geology of the Alice Arm area and location of the Kitsault deposit.

Coast Plutonic Complex. The region is one of intense igneous activity much of which is related to the Coast Plutonic Complex and numerous younger events up to and including Recent plateau-type lava flows.

The oldest exposed rocks in the region are members of the Lower to Middle Jurassic Hazelton Formation which crops out north of Alice Arm and the Illiance River (Fig. 1). Here the Hazelton Formation consists of volcanic breccia, tuff, conglomerate, and andesitic flows, all of which are regionally metamorphosed to greenschist facies.

The Hazelton Formation is unconformably overlain by the Upper Jurassic to Lower Cretaceous Bowser Lake Group (Richards, 1983), which consists of interbedded graywacke and argillite (locally referred to as micrograywacke), and minor conglomerate and limestone. Individual beds vary in thickness from a few centimeters to 15 m, with graywacke comprising approximately 80 percent of the formation, argillite approximately 19 percent, and conglomerate and limestone approximately 1 percent. The Bowser Lake Group lithologies have been regionally metamorphosed to greenschist facies. A typical graywacke consists of about 35 percent crystal and rock fragments in a fine-grained matrix. Fragments range from 0.1 up to 10 mm, with an average of about 0.6 mm, and occur in a matrix that has a grain size of approximately 0.02 mm. Argillite has a composition similar to graywacke except that the grain size is much finer.

The Coast Plutonic Complex is a northwest-trending belt of metamorphic and intrusive rocks, the eastern margin of which consists predominantly of granodiorite to quartz monzonite plutons. In the Alice Arm area, quartz diorite, granodiorite, and lesser amounts of quartz monzonite are common. Wanless et al. (1966) reported a 47 ± 1.2-m.y. date for a quartz monzonite along Observatory Inlet, whereas dates from 79 to 40 m.y. from intrusive bodies along the eastern margin of the complex have been reported (Wheeler and Gabrielse, 1972). Intrusions along the eastern margin of the Coast Plutonic Complex have produced a hornfels aureole in the Bowser Lake and Hazelton Formations as much as 1.5 km outward from the contact.

Adjacent on the east to the Coast Plutonic Complex are a group of 50 to 55-m.y.-old intrusions, principally stocks with associated molybdenite, that have been referred to as the Alice Arm Intrusives (Carter, 1981). A common feature of these intrusions is that the oldest phase is the most mafic and the later phases are more siliceous, principally quartz monzonite. Molybdenite related to the Lime Creek Intrusive Complex is the best known and highest grade of this group. Other significant mineralized systems include Roundy Creek, Bell Moly, Tidewater, and Ajax (Dak River). The other members of the Alice Arm Intrusive contain visible molybdenite but in amounts that cannot be considered mineral resources at the present time.

West-central British Columbia and southeast Alaska are characterized by numerous 35-m.y.-old lamprophyre dike swarms. Smith (1973) suggests that these dikes are chemically similar to vogesite and spessartite but are petrographically classified as odinite or spessartite. Most of the lamprophyres occur in northeast-trending dike swarms a few kilometers wide and several kilometers long. Within a swarm, there may be ten to hundreds of dikes per kilometer, but between swarms, lamprophyres are rare if not absent. Individual dikes vary in thickness from a few centimeters to 30 m, with the majority being 1 to 3 m thick. Strikes of N 35° E to N 80° E and dips within 10° of vertical are common. These swarms seem to center on the earlier intrusive events in the region, and particularly on the Alice Arm Intrusives.

Numerous Recent plateau-type olivine basalt flows, cinder cones, and feeder dikes occur throughout the area. Age dates indicate that this igneous activity is approximately one million years old.

Kitsault Geology

The Upper Jurassic to Lower Cretaceous Bowser Lake Group (Richards, 1983) hosts the Early Tertiary Lime Creek Intrusive Complex. The oldest recognized member of the Complex is the East Lobe (Fig. 2), which is succeeded by the Border stock, Southern stock, Central stock, and Northeast Porphyry and Intramineral dikes. Mineralization is related to the last two phases of the Lime Creek Intrusive Complex. Postmineralization lamprophyre dikes and basalt flows are common in and near the deposit.

At Kitsault the Bowser Lake Group consists of interbedded argillite and graywacke with minor conglomerate and limestone. Individual beds vary in thickness from a few centimeters to several meters. Regionally, the Bowser Lake Group has a northwest strike and a steep northeast dip, although this trend is interrupted by small-scale folds. Typical graywacke at Kitsault consists of 40 percent angular chert and

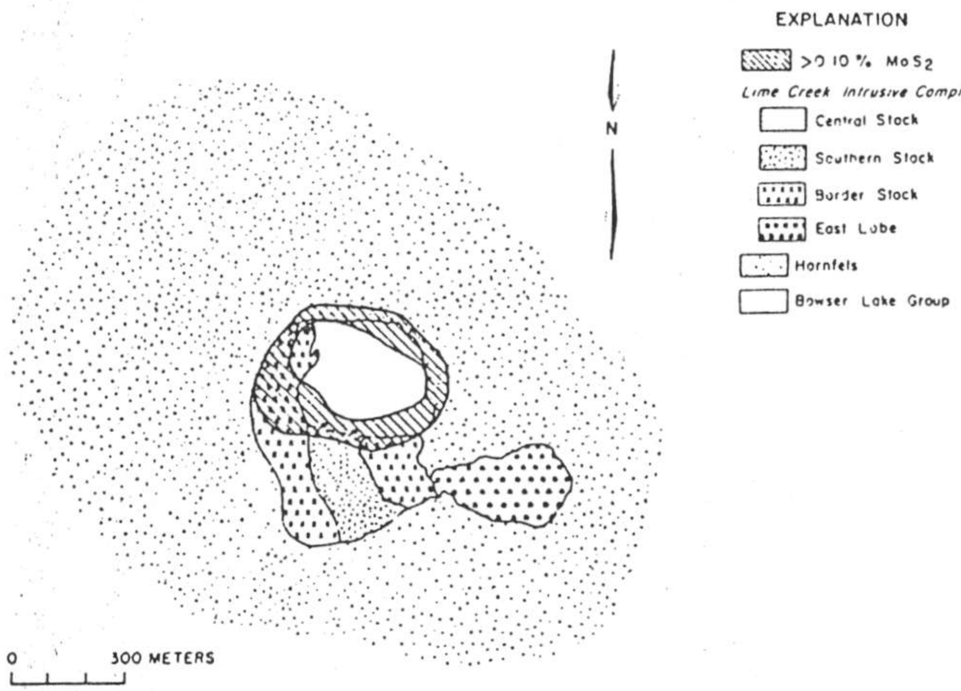

FIG. 2. Generalized geology of the Kitsault mine area.

rock fragments in a fine-grained matrix. Argillite is dark gray to black and mineralogically similar to the graywacke. The only significant difference between these two rock types appears to be grain size and a lack of visible chert in the argillite. The mineralogy of both lithologies is detailed in Table 1.

Lime Creek Intrusive Complex

East Lobe: The East Lobe intrusion forms an eastern extension of the Lime Creek Intrusive Complex (Fig. 2). Not only is the Lobe the oldest recognized member of the Lime Creek Complex, it is the most mafic. Poor exposure and limited drill intersections make this member of the complex the least understood.

The petrography and chemistry of the intrusion are summarized in Tables 2 and 3. The East Lobe is characterized by a higher amphibole (hornblende?) content than the other members of the complex. This phase is an equigranular quartz diorite composed of subhedral to anhedral mineral grains.

Border stock: Rocks of the Border stock are common along the west and southeast margins of the complex (Figs. 2 and 3). Along the northern margin of the complex and for several hundred feet below the surface, drilling has intersected an intrusive member that looks similar to the Border stock. Also, in the central part of the complex, in an area where the contact between the Central and Southern stocks is postulated, a septa of Border stock (?) has also been intersected by drilling. If all of these occurrences are indeed Border stock, it suggests that this member of the complex extended over much of the area now occupied by younger intrusive rocks.

Carter (1981) reported a 51.4 ± 1.5 m.y. potassium argon age date from this unit. This date is suspect since it is taken from within the mineralized area and probably reflects the age of mineralization rather than the igneous event.

The petrography and chemistry of the Border stock are summarized in Tables 2 and 3. Although this stock is more mafic than younger intrusions, it is not as mafic as the East Lobe. The Border stock contains only minor amounts of hornblende, with biotite being the dominant ferrnmagnesium mineral. Mineralogically, the stock is an equigranular granodiorite to quartz diorite.

Southern stock: The Southern stock occurs in the south-central portion of the complex. The recognition of a separate igneous event in this area is a departure from past studies. A contract between this stock and the younger Central stock has not been observed but is postulated because of the difference between the chemistry and mineralogy of rocks from the respective areas. Also, the shape of the molybdenite zone and its adherence to the contact of the Central stock suggest a change in rock type in this general area. The presence of a septa of Border stock (?) is yet another line of evidence suggesting two separate intrusive units.

Woodcock (1964) reports a potassium-argon age date of 53.5 m.y. for a sample collected in the area of the Southern stock. The sample location is only generally known, but no sample description has been found.

The petrography and chemistry of the Southern stock is summarized in Tables 2 and 3. This stock is more siliceous than the East Lobe, but more iron rich than the Central stock. The Southern stock contains a higher plagioclase and mafic mineral content and a lower alkali feldspar and quartz content than the Central stock. Mafic minerals are primarily biotite with minor hornblende. Mineralogically, the intrusion is an equigranular to weakly porphyritic granodiorite with phenocrysts of subhedral plagioclase and biotite in a groundmass of anhedral quartz, hornblende, alkali feldspar, and minor apatite, zircon, and opaques.

Central stock: The Central stock is the earliest of the molybdenum-related intrusive units and occupies the northern half of the Lime Creek Intrusive Complex (Figs. 2, 3, and 4). Along a portion of the western contact a septa of hornfels separates the Central and Border stocks indicating that there is a time and space division between these two units.

Carter (1981) reported one potassium-argon age date for the Central stock at 53.0 ± 3 m.y. The sample is from the orebody, and based on Carter's description, appears to be partly altered. Wray (1972) reported a potassium-argon date of 63.2 ± 2.1 m.y. for a sample of Central stock collected approximately 2,000 ft below the surface. Descriptions of this rock suggest that it is only slightly altered. An explanation of the two ages might be

TABLE 1. Typical Mineralogy of Bowser Lake Group Graywacke and Argillite

Mineralogy	Graywacke (%)	Argillite (%)
Plagioclase (An_{5-15})	15 to 60 Avg. 31.3	5 to 50 Avg. 30
Quartz and chert	20 to 55 Avg. 37.4	20 to 53 Avg. 36.8
Sericite	1 to 15 Avg. 8.2	2 to 20 AVG. 12.4
Chlorite	6 to 20 Avg. 12.6	2 to 20 Avg. 112.5

Both rock types contain trace amounts of epidote, sphene, carbon, pyrite, pyrrhotite, and magnetite

TABLE 2. Modal Analyses of the Lime Creek Intrusive Complex

Intrusive minerals	East Lobe	Border stock	Southern stock	Central stock	Intramineral dikes	Northeast porphyry	Lamporphrye
				(%)			
Plagioclase	55	51	55	42	45	41	38
An	An_{39}	An_{38}	An_{36}	An_{38}	An_{38}	An_{34}	An_{55}
Alkali feldspar	2	11	12	23	21	22	
Quartz	9	17	14	21	23	30	
Biotite	10	16	14	10	6	6	36
Amphibole	19	1	2		3		26
Sphene	1	1	1	1	1	tr	
Apatite	1	1	tr	1	tr	tr	
Zircon	tr	tr	tr	tr	tr	tr	
Monazite	tr	tr		tr	tr	tr	
Opaques	3	2	2	2	1	1	

An average of at least five samples per rock type

that the 53-m.y. date reflects the age of mineralization, whereas the older dates represent the period of intrusive activity.

Aplite: Numerous aplite dikes are common throughout the Lime Creek Intrusive Complex and in particular in the northern and western portions (Figs. 3 and 4). These dikes were previously called alaskites because of their lack of mafics. However, because the aplitic texture is most common, aplite is a more suitable term, although a complete range of textures from felsite to pegmatite can be found. Labeling these units "dikes" is also a misnomer, since their form varies from irregular pods to true through-going dikelike bodies. The aplite phase cuts

TABLE 3. Chemistry of the Lime Creek Intrusive Complex

	East Lobe	Border stock	Southern stock	Central stock	Aplite	Intramineral	Northeast porphyry	Lamprophyre
				%				
SiO_2	56.75	67.60	64.6	68.45	74.9	66.4	68.45	65.8
Al_2O_3	16.70	14.75	15.5	13.85	10.0	15.0	13.95	14.7
Fe_2O_3	3.45	1.40	0.76	1.13	0.2	1.7	1.80	2.7
FeO	2.85	1.80	2.7	1.40	0.15	1.8	0.62	4.1
MgO	2.75	1.35	1.3	1.15	0.15	1.6	0.71	3.3
CaO	5.55	2.75	3.4	2.80	1.2	3.1	2.25	2.0
Na_2O	3.85	3.30	4.2	3.35	1.2	6.9	3.65	1.8
K_2O	2.85	4.85	4.8	5.00	7.1	4.1	4.65	4.3
F	0.21	0.15	0.074	0.11	0.048	0.15	0.11	0.10
				ppm				
Rb	195	210	170	230	300	200	240	230
Ba	1,250	1,000	1,000	1,000	500	1,100	1,000	5,000
Co	5	5	<5	<5	<5	<5	<5	15
Cu	65	45	<10	<10	3	12	19	30
La	20	20	30	25	20	25	20	<0
Mn	600	225	700	300	30	350	350	1,000
Nb	20	10	20	<20	<20	<20	<20	20
Sr	2,850	250	700	400	200	600	500	100
Ti	2,000	2,250	2,000	1,500	200	1,500	1,000	3,000
V	100	40	50	25	<10	45	20	70
Zn	20	100	30	60	<20	50	65	50
Rb/K_2O	68	43	35	46	42	54	52	53
$\frac{Na_2O + R_2O}{CaO}$	1.20	2.69	2.65	2.98	4.42	3.55	3.69	3.05

Chemical analyses by Skyline Labs, Inc., Denver, Colorado, using ICP and AA techniques; reported analyses are an average of at least two determinations per rock type

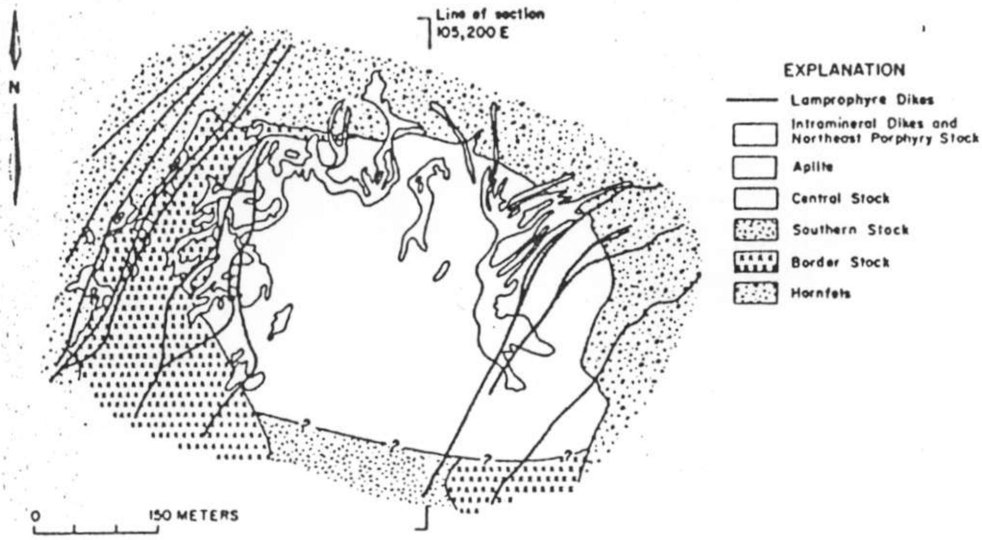

FIG. 3. Generalized geology of the northern part of the Lime Creek Intrusive Complex.

the Central and Border stocks and is cut by the Intramineral dikes, thus placing its apparent age between the Central stock and the Northeast Porphyry, although it may be a late differentiated phase of the Central stock.

The chemistry of the aplite is summarized in Table 3. One of its distinctive characteristics is disseminated molybdenite that appears to be a primary rock-forming mineral. Also present are incipient quartz veins that appear to have crystallized as part of the magma. The presence of these two features suggests that the aplite is a transition phase between a true igneous stage and the first hydrothermal event. Mineralogically, the aplite has an equigranular texture, composed of plagioclase, quartz, alkali feldspar, and minor biotite.

Northeast Porphyry and Intramineral dikes: The Northeast Porphyry and related Intramineral dikes are the youngest recognized members of the Lime Creek Intrusive Complex. The Northeast Porphyry forms a stocklike body at depth in the northeast portion of the complex and has been intersected by only a few drill holes. Its true distribution is imperfectly known. The Intramineral dikes occur as a series of dikes that appear to be related to the Northeast Porphyry for the following reasons: (1) their mineralogical and chemical similarity (Tables 2 and 3), (2) similarity of relative age relationships with respect to molybdenum mineralization, (3) the abundance of Intramineral dikes near the Northeast Porphyry and their decrease in abundance away from the stock, and (4) the lack of crosscutting relationships between the two units.

Carter (1981) reports a date of 53.7 ± 1.7 m.y. for the Intramineral dikes and 48.3 ± 1.6 m.y. for the Northeast Porphyry. Since his description suggests that both rocks are altered, it is possible that both dates were reset by hydrothermal events.

Petrographic and mineralogic summaries for both units are presented in Tables 2 and 3. The distinctive characteristic of the Intramineral dikes and Northeast Porphyry is their texture. These rocks are the only

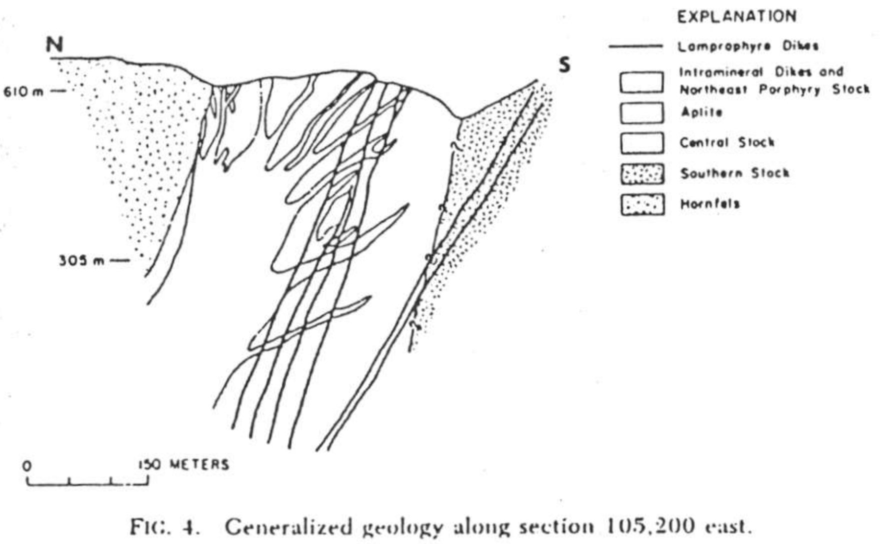

FIG. 4. Generalized geology along section 105,200 east.

well-developed porphyries known at the property. Many of the Intramineral dikes also contain wall-rock fragments.

Mineralogically, the Intramineral dikes are granodiorites composed of subhedral phenocrysts of plagioclase, quartz, and alkali feldspar in a groundmass of subhedral to anhedral plagioclase, quartz, alkali feldspar, biotite, amphibole, and accessory minerals. Northeast Porphyry is a granodiorite to quartz monzonite composed of the same group of phenocrysts and groundmass minerals as the Intramineral dikes. The exception is the lack of amphibole in the Northeast Porphyry.

Breccia dikes: In the extreme western part of the orebody, at least one intrusive breccia dike has been identified in drill core and float at the surface. This dike is up to 15 cm wide and consists of fragments of the hornfels and Lime Creek Intrusive in a siliceous matrix. Molybdenite in the matrix and quartz molybdenite veins in the fragments suggest that it is intramineral in age and may be the distal end of an Intramineral dike.

Petrochemical evolution of the Lime Creek Intrusive Complex: Samples of the freshest available rocks of the various members of the intrusive complex were analyzed for major and minor elements (Table 3). There is a general increase in SiO_2 and K_2O with a younger age (Fig. 5), whereas Al_2O_3, CaO, and MgO decrease. Na_2O remains approximately constant throughout the development of the intrusive complex. As shown on these diagrams, there are some trend reversals that may represent analytical error rather than real differences. Several trace elements also show changes with time (Fig. 6). Titanium decreases, whereas rubidium increases slightly. The other elements are too erratic to identify definite trends.

The chemical data (Table 3) suggest that the ore-producing intrusions, namely the Central stock and Northeast Porphyry, are slightly more siliceous and alkalic than the premolybdenite members of the complex, suggesting a slight differentiation of the complex with geologic time.

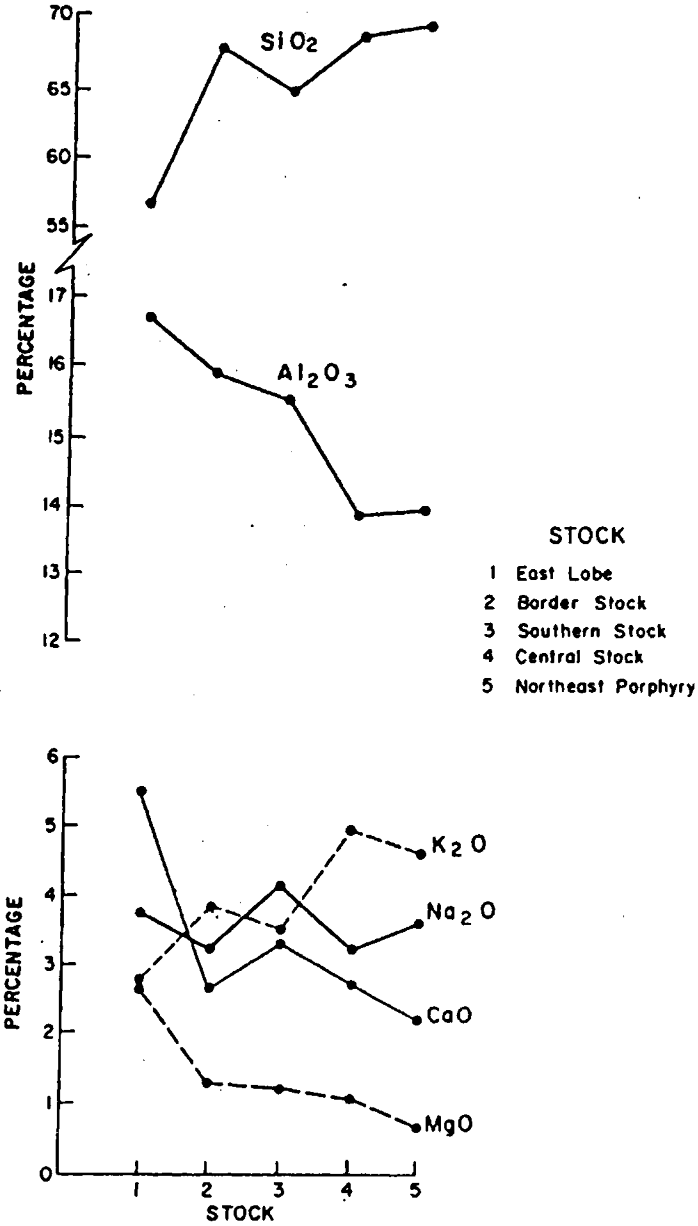

FIG. 5. Major element trends within the Lime Creek Intrusive Complex.

Lamprophyre dikes

Lamprophyre dikes are common throughout the Kitsault area and intrude both the Lime Creek Intrusive Complex and the Bowser Lake Group. These dikes vary in width from a few centimeters to several meters and are traceable for several hundred meters along strike and downdip. The dikes generally strike northeast, dip steeply northwest, and are commonly sinuous. Lamprophyres are post-molybdenite mineralization but are cut by a few calcite veins. Carter (1981) reported a potassium-argon date of 36.5 ± 1.2 m.y. for a dike from the Kitsault deposit.

Modal analyses and chemical data for these dikes are shown in Tables 2 and 3. The distinctive characteristics of the lamprophyre dikes are that they are hornblende-biotite porphyries with plagioclase in the groundmass. Hornblende phenocrysts as much as 4 mm in length are common.

Extrusive rocks

Olivine basalt flows and related feeder dikes are common throughout the Kitsault area. One basalt flow occurs just north of the Kitsault deposit. These flows consist of a number of separate units that display well-developed columnar jointing. Carter (1981) reports two potassium-argon age dates from the Alice Arm flows of 1.1 ± 0.8 and 1.6 ± 0.8 m.y.

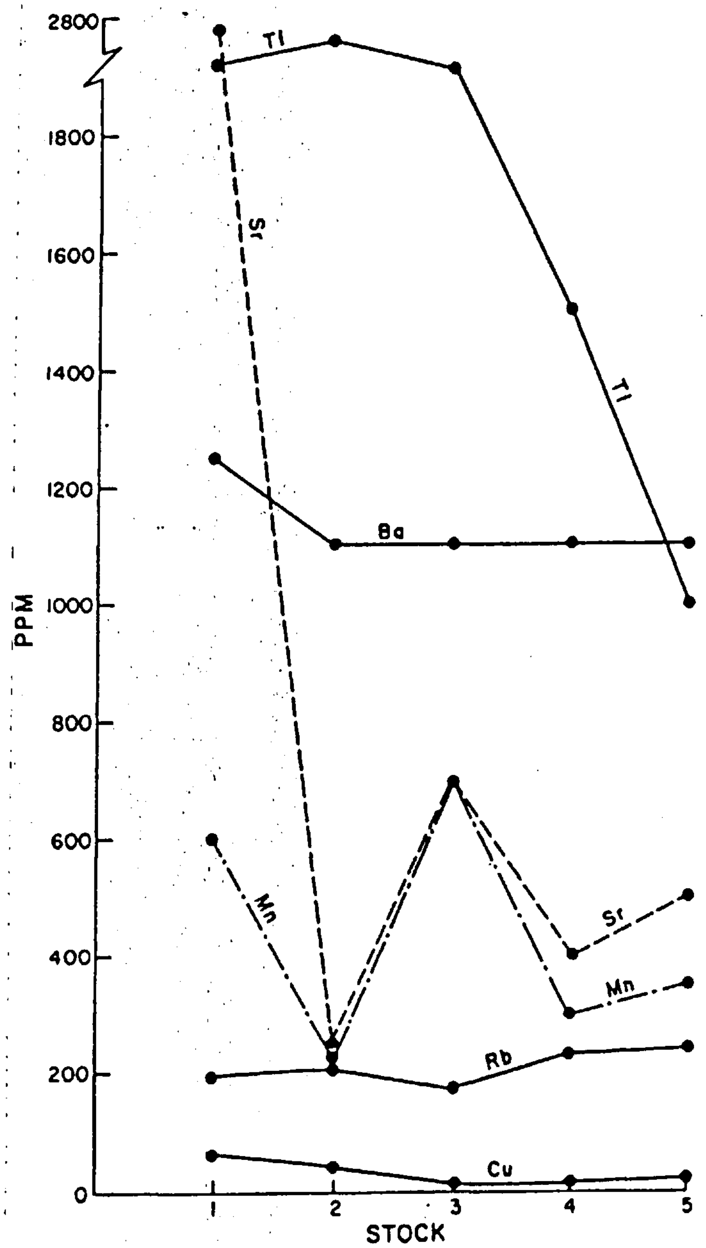

FIG. 6. Minor element trends within the Lime Creek Intrusive Complex. Stock numbers same as Figure 5.

Structure

Geologic sections, as illustrated in Figure 4, suggest that the entire Lime Creek Complex is tilted to the southwest. Since the youngest intrusions are in the northern part of the complex, they have caused a doming and tilting that produced the present geometry. The Northeast Porphyry, which is the youngest known intrusion, also appears to be tilted, suggesting either a later intrusion or a regional deformation.

Generally, all known faults consist of gouge and broken rock zones up to a few meters wide with minor normal displacement. Even though most of the faults are postmineral, little deformation of the orebody is known. Most faults strike northeast and dip northwest, a trend that was also followed by late veins and lamprophyre dikes.

Hydrothermal and Thermal Alteration

Associated with the intrusion of the early members of the Lime Creek Complex is a contact metamorphic zone of hornfels in the argillite and graywacke. Hydrothermal alteration associated with the mineralization can be subdivided into a central silicified zone that is surrounded by a zone of potassium silicate (potassic) alteration. Outward from the potassic zone is a weakly developed phyllic zone. Argillic and propylitic alterations exist peripheral to the phyllic zone but are weakly developed because they are superimposed upon the hornfels. Generally, the higher temperature assemblages (i.e., silicic, potassic, and phyllic) occur as vein envelopes. Except in areas where a stockwork of veins has developed and the alteration envelopes overlap, argillic and propylitic alteration are common peripheral to the higher temperature alteration envelopes.

Thermal metamorphism

Thermal metamorphism is expressed as a hornfels aureole that extends up to 750 m away from the intrusive contact (Fig. 7). This aureole is developed in argillites and graywackes that are regionally metamorphosed to a chlorite-sericite-epidote-albite greenschist facies assemblage (Woodcock, 1964). Superimposed upon the inner part of the hornfels aureole is a later hydrothermal overprint. The hornfels itself can be subdivided into an outer weak albite-epidote hornfels facies (with incipient sericite-chlorite), a central pale-brown biotite zone, and an inner brown biotite zone (Kamilli, 1977).

Several mineralogic changes can be documented proceeding from the outer limit of hornfels inward to the stock contact (Fig. 7). Biotite in the outer zone first appears as pale-brown, fine-grained mica replacing sericite. Toward the stock, biotite increases in abundance and size and darkens to brown or green brown before being bleached by the hydrothermal overprint. Sedimentary carbon and chert grain boundaries disappear toward the intrusive contact. Feldspar and quartz appear to be more resistant to contact metamorphic effects, remaining as sharply defined grains much closer to the igneous contact, but eventually they, too, lose their grain edge boundaries and become irregular shapes. Feldspar becomes increasingly clouded by fine-grained allophane but eventually is completely destroyed leaving only cloudy relics.

The hydrothermal overprint is characterized by several mineralogical changes. Sericite is coarser, segregated in patches with chlorite and calcite, and appears to be replacing metamorphic biotite. Bleached zones occur adjacent to veins and consist of pale-green chlorite, sericite, and calcite. Epidote in veins and as matrix replacements is most abundant toward the inner part of the hornfels aureole. The assemblage chlorite, calcite, epidote, and sericite

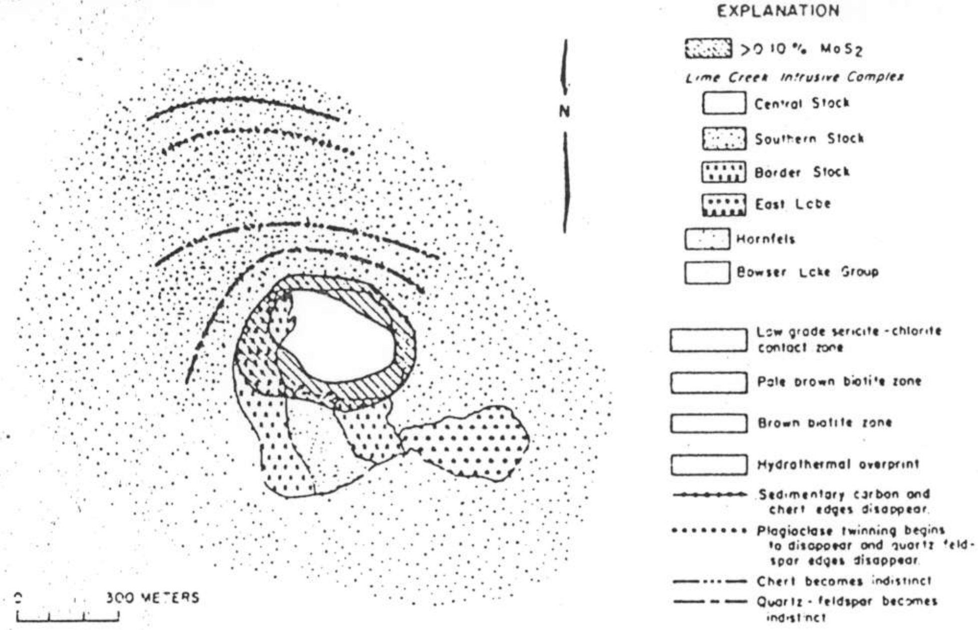

FIG. 7. Generalization map showing the distribution of hornfels subzones.

probably represents the propylitic zone associated with hydrothermal alteration. Since the hydrothermal fluids were attacking a refractory metamorphic rock, the development of low-temperature hydrothermal alteration was inhibited, therefore producing only a poorly developed propylitic zone.

Hydrothermal alteration

Propylitic: Propylitic alteration is common peripheral to higher temperature vein alteration envelopes within the orebody and superimposed on the hornfels aureole. Propylitic alteration of hornfels is described in the preceding section. Within the intrusive rocks, the most abundant propylitic alteration minerals are sericite and carbonate and minor chlorite and epidote. Generally, plagioclase is replaced by sericite and carbonate. The sericite is actually a fine-grained white mica that may be paragonite. Biotite is commonly replaced by a mixture of chlorite, sericite, opaques, and epidote. The other primary igneous minerals, quartz and alkali feldspar, appear to be unaffected by this type of alteration.

Argillic: Argillic alteration is common throughout the orebody, generally as isolated patches between higher temperature alteration types, although there is a slight increase in intensity of this type of alteration toward the outer margin of the ore zone and in one strong zone in the west part of the orebody. This latter area appears to be fault related and is characterized by green clay which is a mixture of montmorillonite and sericite. Fault-related argillization is superimposed upon the earlier hydrothermal alteration and may represent the alteration related to the waning hydrothermal fluids.

Typical argillic alteration associated with the molybdenum-bearing hydrothermal stages is characterized by white clay, which is generally a combination of sericite and kaolin group minerals. Both of these layered silicates replace plagioclase and mafics but have little or no effect on quartz and alkali feldspar.

Phyllic: Phyllic alteration occurs as envelopes associated with quartz-pyrite-scheelite veins in a zone that is peripheral to, and partly superimposed upon, the hanging wall of the orebody (Figs. 8 and 9). These envelopes are dark siliceous zones that are seldom more than a few millimeters wide. Pyrite and scheelite are so erratically distributed in the veins that in places they appear to be barren quartz veins.

Within the phyllic envelopes, the rock is completely replaced by a fine-grained mixture of quartz, sericite, and/or pyrite. This alteration affects all igneous minerals except primary quartz, although quartz overgrowths have been observed.

Potassic: Potassic alteration (K-feldspathization), i.e., alkali feldspar replacement with minor secondary biotite, occurs as envelopes along the margins of barren quartz veins. With increasing alteration intensity the color changes from a vivid pink, to a light pinkish tint, to white in the pervasive zones. Plagioclase is the first mineral replaced, followed by biotite. The last stage of this alteration was the development of secondary rims on primary alkali feldspar grains. Although plagioclase is replaced first, most patches of potassic alteration contain at least a few remnants of unaltered or sericitized plagioclase. Secondary biotite occurs as small unaltered anhedral grains scattered throughout the more intensely feldspathized rock. Where primary and secondary biotite are in close proximity, the former is propylitically altered whereas the later is unaltered, suggesting that propylitic alteration preceded potassic alteration.

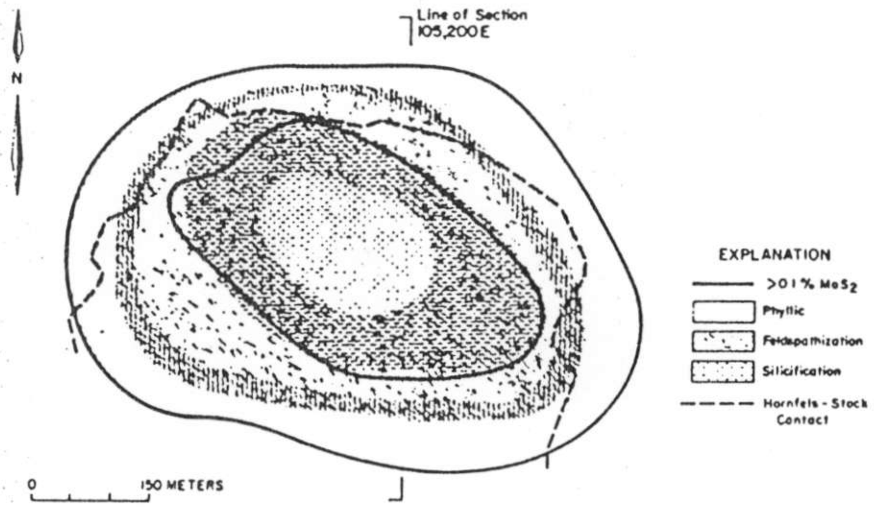

FIG. 8. Generalized plan of hydrothermal alteration.

Potassic alteration occupies the same general areas as the higher grade molybdenite zones. Rather than a zone of complete replacement this is an area where potassic alteration may occur. All variations exist from minor to total replacement of the host rock. This alteration zone occupies, and partly overlaps, the peripheral phyllic and the interior silicified zones.

Silicification: Silicification is characterized by quartz veins with minor amounts of replacement out from the vein margin and by local pervasive zones. Silicification is most intense along and below the footwall of the molybdenite zone.

All primary mineral phases can be replaced by secondary quartz. Primary quartz grains commonly have overgrowths in silicified areas. In places where more intense silicification is present, small 0.05- to 0.02-mm rounded quartz grains form a mozaic throughout the groundmass.

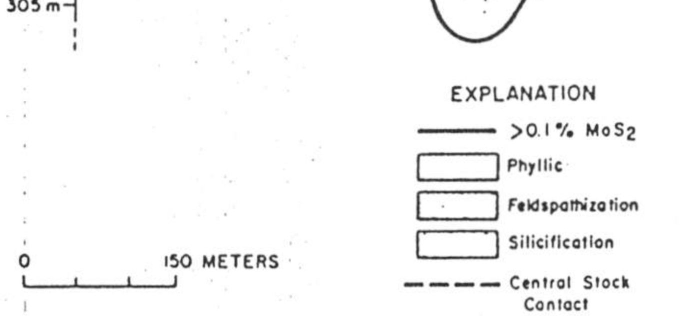

FIG. 9. Generalized hydrothermal alteration distribution along section 105,200 east.

Mineralization (Table 4)

The Kitsault deposit is a stockwork of quartz veins that contain significant molybdenite and pyrite with minor scheelite, galena, sphalerite, chalcopyrite, sulphosalts, and carbonate minerals. The mineralization is directly related to the later phases of the Lime Creek Intrusive Complex. Most of the pyrrhotite was formed during the hornfels development, whereas minor amounts are present in later hydrothermal veins.

Disseminated molybdenite in aplites is the earliest molybdenum event. Closely following emplacement of the aplite was stage I mineralization, which consists of three types of veining, formed from hydrothermal solutions developed by the crystallization of the Central stock. Quartz veins that have potassium feldspar alteration envelopes are the earliest recognized veins in this group. Next came the formation of quartz-molybdenite veins which were followed by quartz-pyrite veins, with or without scheelite.

After stage I, the intrusion of the Northeast Porphyry and related Intramineral dikes took place and was followed by stage II mineralization which again consisted of three types of veins similar to those of stage I. No apparent difference has been identified in the order, style, or characteristics between these two stages of mineralization except for the crosscutting relationships of the Intramineral dikes.

Next came the emplacement of the third vein set (stage III) starting with quartz veins with associated potassic alteration envelopes followed by quartz-molybdenite veins that are characteristically wide with ribbons of molybdenite. These veins are cut by quartz-pyrite veins with or without scheelite.

Following stage III mineralization are polymetallic sulfide veins of stage IV which are characterized by through-going quartz veins that may contain one or more of the following minerals: sphalerite, galena, chalcopyrite, lead-bismuth sulphosalts, tetrahedrite,

TABLE 4. Summary of the Relationship between Phases of the Lime Creek Intrusive Complex and Mineralization

Geologic history of the Kitsault Deposit		
Glaciation—removal of upper portions of the orebody		
Basalts (1.6 ± 0.8 m.y.) dikes and flows		
Lamprophyres (36.5 ± 1.2 m.y.)		
	Stage IV mineralization	Carbonate Quartz-polymetallic
	Stage III mineralization	Quartz-pyrite-scheelite Quartz-banded molybdenite Quartz
	Stage II mineralization	Quartz-pyrite-scheelite Quartz-molybdenite Quartz
Lime Creek Intrusive Complex	Northeast Porphyry (48.3 ± 1.6 m.y.)	Intramineral dikes
	Stage I mineralization	Quartz-pyrite-scheelite Quartz-molybdenite Quartz
	Central stock—aplites (53.3 ± 1.4 m.y.)	
	Southern stock	
	Border stock	
	East Lobe	
Jurassic to Cretaceous Bowser Lake Formation		

scheelite, molybdenite, pyrite, and carbonate. After the base metal stage, fluorite veins and then calcite veins formed. The last-recognized veins contain gypsum and anhydrite which may be supergene.

Several other general characteristics of the mineralization are not summarized in the above description. Stage III banded molybdenite veins are more continuous and wider than any of the other molybdenite veins seen at the property. These veins are commonly several centimeters wide and traceable for tens of meters and in places up to 100 m along strike. The only other vein type that is more consistent in its lateral extent is the polymetallic sulfide veins, which may be traced up to a few hundred meters along strike and which extend for a considerable distance beyond the orebody. Molybdenite becomes less abundant in quartz veins toward both the footwall and the hanging wall of the orebody. The few pyrite-bearing molybdenite veins observed at Kitsault are typically younger than the quartz-molybdenite veins but slightly older than the quartz-pyrite veins in any one stage of mineralization. These veins probably represent a transition from the molybdenite depositional period into the pyrite depositional period. Barren quartz veins are not common on the hanging-wall side of the orebody and quartz-pyrite veins are not common on the footwall side.

Molybdenite: The most significant mode of occurrence for molybdenite, probably representing 80 to 90 percent of the total molybdenite present, is as individual grains less than 0.05 mm in diameter disseminated in quartz veinlets up to 5 mm wide. The second most abundant occurrence is as ribbons up to 2 mm wide within quartz veins up to 10 cm thick. Individual ribbons within veins probably contain 80 to 90 percent molybdenite. The next most abundant occurrence is as molybdenite paint on fracture surfaces. Other occurrences are as crystals up to 5 mm in diameter disseminated in aplite dikes and as rare clots of molybdenite up to 2 cm wide in the polymetallic veins. The rarest occurrence is molybdenite disseminated in the matrix of the breccia dikes found within the southwestern part of the deposit.

In plan, molybdenite occurs in an annular zone (Fig. 10) around a central core of silicified rock. In section, the zones form a vertical cylinder (Fig. 11). Whether these zones ever connected to form a domal configuration similar to Climax-type deposits is conjectural, since the upper parts of the deposits have been removed by glaciation. Mineralization extends deeper in the southwestern part of the deposit (Fig. 11), whereas it is shallowest in the northeast quadrant of the orebody. The northeast part of the orebody may be partly destroyed by the intramineral Northeast Porphyry stock.

Molybdenite zoning indicates that the 0.10 percent and 0.20 percent MoS_2 zones are generally continuous throughout the deposit (Figs. 12 and 13). Higher grade zones, particularly the 0.30 percent and 0.40 percent MoS_2 zones, are highly erratic.

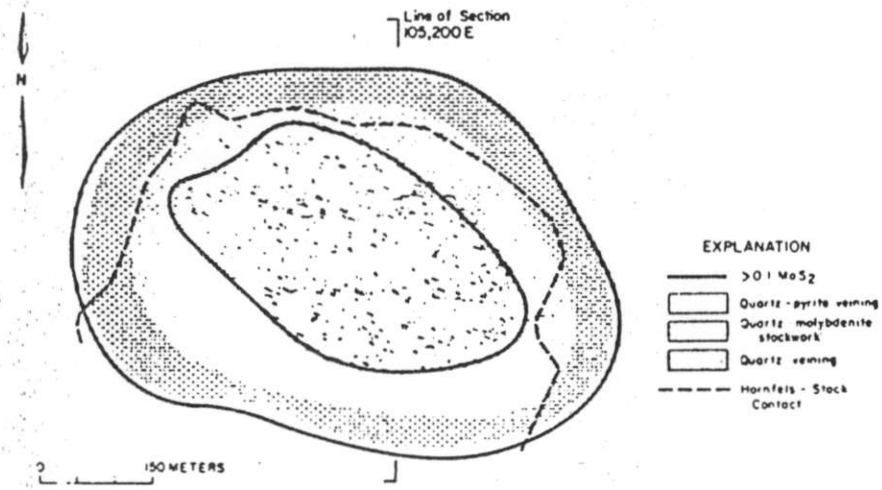

FIG. 10. Generalized plan of mineral zoning.

forming localized pods that are not continuous over great distances. With depth even the 0.20 percent MoS_2 zone becomes less continuous. As shown on the cross section (Fig. 13), the boundaries of the 0.10 percent zone are generally regular, whereas the 0.20 percent and 0.30 percent zones are erratic and sinuous. Mineable reserves are placed at 115 million tons of 0.19 percent MoS_2 (AMAX, 1982).

Pyrite: Pyrite is commonly found in quartz veins, as fracture coatings, disseminated in intrusive rocks, and as erratically distributed clots and aggregates in polymetallic veins. Within quartz veins and as fracture coatings, individual disseminated grains vary in size from less than 0.05 mm to as much as 3 mm. Aggregates of pyrite up to 2 cm wide are most common in the polymetallic veins. Pyrite is most abundant on the hanging-wall side of the molybdenite zone (Figs. 12 and 13). Information is sketchy about pyrite distribution, but it probably occurs in a shell that mimics the shape of the molybdenite zone and may average approximately 1 percent.

Pyrrhotite: Pyrrhotite is most abundantly disseminated through the hornfels aureole surrounding the Lime Creek Intrusive Complex and probably formed during metamorphism. Rare quartz-pyrrhotite veins are scattered throughout the Kitsault deposit, both within the molybdenite zone and within the barren central zone. Also present in the hornfels aureole are isolated 1- to 10-cm-wide quartz-pyrrhotite and pyrrhotite veins that appear to predate the thermal metamorphism and have a more regional extent than do the other pyrrhotite veins.

Scheelite: Scheelite commonly occurs in quartz-pyrite veins on the hanging-wall side of the molybdenite zone (Figs. 10 and 11). Individual scheelite grains are generally less than 2 mm across, have an average size of approximately 1 mm, and are errat-

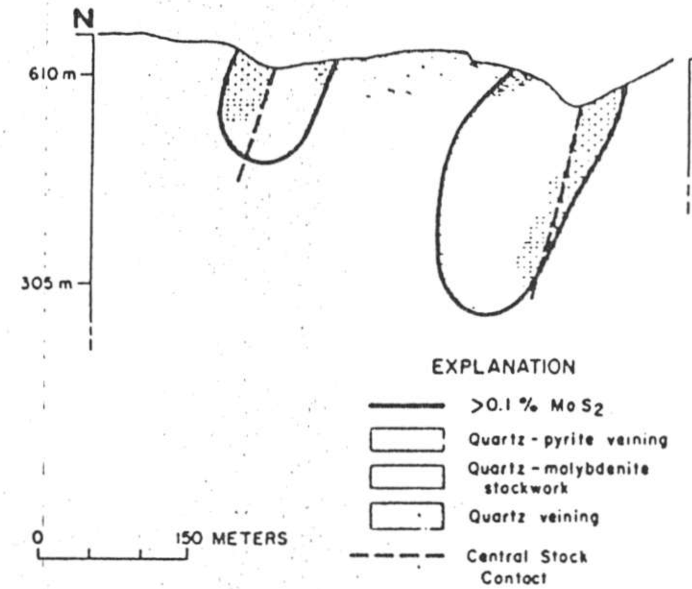

FIG. 11. Generalized mineral zoning along section 105,200 east.

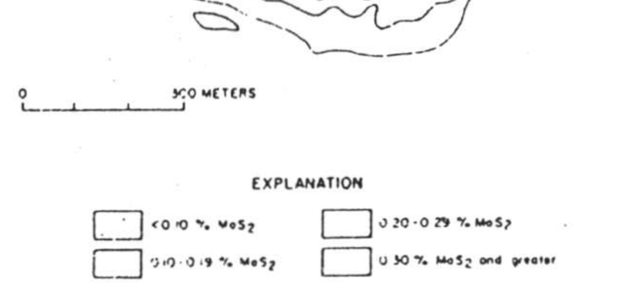

FIG. 12. Ore-zone plan for the 534-m elevation.

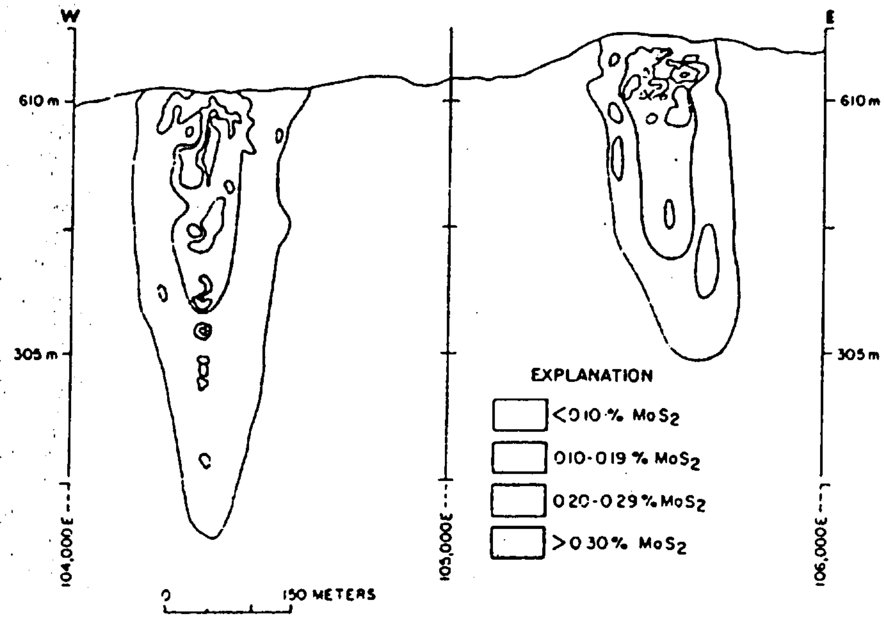

FIG. 13. Ore-zone section 107,400 north.

ically disseminated through the veins. Quartz-scheelite veins that have no apparent pyrite are less common. Minor amounts of scheelite have also been detected in the polymetallic sulfide veins. Scheelite is apparently free of molybdenum, as indicated by a strong blue-white fluorescence. The approximate grade within the scheelite zone is 0.01 percent WO_3.

Base metals: Base metals mineralization is found predominantly in polymetallic sulfide veins. The one exception is the presence of some galena intimately associated with molybdenite. Holland (1976) summarized the character and probable distribution of galena associated with the molybdenite. Microprobe studies suggest that individual grains of galena have a size of approximately 10 microns. Possibly 20 percent of the galena occurs as inclusions encapsulated within the molybdenite lamella, while the other 80 percent occurs as attachments on the edges of molybdenite crystals. Silver appears to be directly associated with lead, probably in solid solution in the galena. Average lead grade for the molybdenite zone is approximately 0.026 percent, whereas the silver grade is approximately 4.9 ppm or 0.15 oz per ton.

Late-stage polymetallic sulfide veins occur throughout the deposit but are most common in the western and northwestern parts. These veins may contain any of the following minerals: chalcopyrite, tetrahedrite, pyrite, sphalerite, galena, lead-bismuth sulfosalts, molybdenite, fluorite, and carbonate. Three lead-bismuth sulfosalt minerals, all members of the bismuthinite-aikinite solid solution series, have been identified: cosalite ($2PbS \cdot Bi_2S_3$), aikinite ($2PbS \cdot Cu_2S \cdot Bi_2S_3$), and neyite ($7PbS_3 \cdot Bi_2S_3 \cdot Cu_2S$). All sulfides within the polymetallic veins occur as clots or concentrations up to a few centimeters in length, although in places, these veins may contain no perceivable sulfides.

Gangue minerals: White, green, and purple fluorite is found in polymetallic sulfide veins, quartz veins, and monomineralic veins that are most abundant in the western part of the deposit. The latter two vein types appear to be younger than the polymetallic veins.

Calcite veins up to a few centimeters wide are common throughout the deposit and appear to be the latest truly hydrothermal event identified at Kitsault. Although no chemical analyses of the carbonate have been performed, the mineral is probably calcite. Gypsum-anhydrite occurs as fracture coatings throughout the deposit and probably is of supergene origin.

Genetic Synthesis

Upper Jurassic to Lower Cretaceous Bowser Lake Formation graywackes and argillites host the Lime Creek Intrusive Complex. The earliest member of the complex is the East Lobe, which was followed in turn by the Border and Southern stocks. These first three members of the complex were emplaced prior to molybdenum mineralization. Associated with these phases of the complex, and possibly the later phases, is a broad aureole of biotite hornfels that developed in the host sedimentary rocks surrounding the intrusive rocks.

The first ore-related intrusive phase was the 53(?)-m.y.-old Central stock and related aplites. Associated with this stock is stage I mineralization, consisting of a central zone of quartz veins surrounded by a

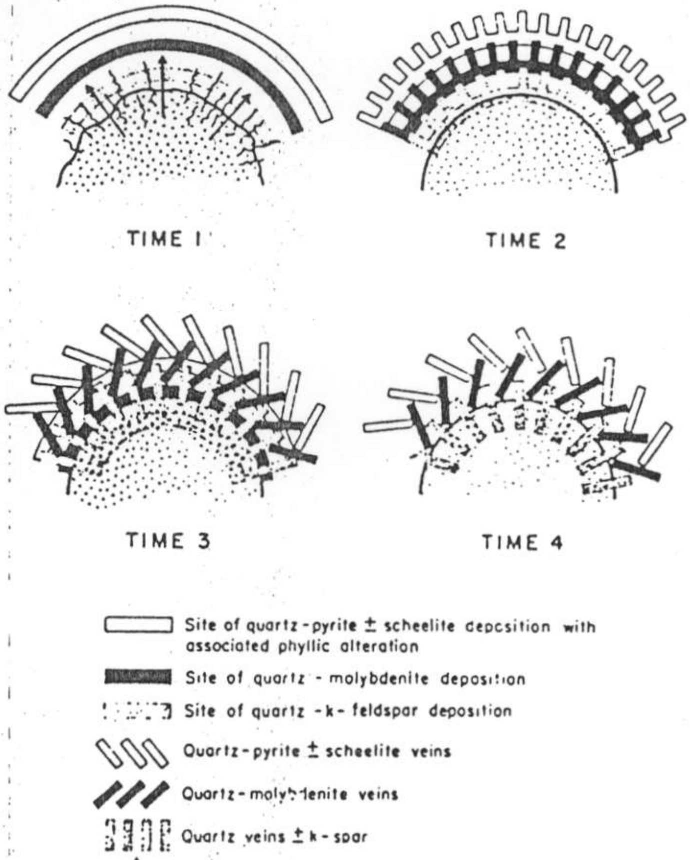

FIG. 14. Diagrammatic formation of mineralization at Kitsault.

quartz-molybdenite zone that generally straddles the stock contact. Peripheral to the quartz-molybdenite zone is a quartz-pyrite-scheelite zone. These zones are typically annular in plan and probably were arcuate in section before erosion. Potassic alteration, characterized by secondary alkali feldspar and minor disseminated fine-grained biotite, in envelopes on quartz veins, occurs within the quartz-molybdenite zone. Interior to the potassic alteration is a silicified zone containing abundant quartz veins with minor wall-rock replacements. The quartz-pyrite-scheelite veins commonly contain quartz-sericite-pyrite alteration envelopes. Although weakly developed, this area corresponds to the phyllic alteration common in most porphyry deposits. Because the surrounding rock is hornfels, propylitic alteration is poorly developed. The above first three alteration types are usually vein envelopes, between which the rock is either commonly propyliticallv to argillically altered or unaltered.

The above-described vein stage indicates apparent vein age relationships with the quartz veins and associated potassic alteration being the oldest, quartz-molybdenite veins next, followed by the youngest vein set consisting of quartz-pyrite-scheelite. Figure 14 is an attempt to explain this apparent age relationship. During crystallization of the Central stock, hydrothermal fluids collected at some location(s) within the solidifying intrusive mass. At some point, conditions were correct for the movement of these fluids upward and outward into the crystallized and fractured shell of the Central stock and surrounding fractured hornfels. The initial sites of mineral deposition are shown in the diagramatic sketch (Fig. 14) labeled Time 1. Quartz deposition occurred throughout the system but was barren of sulfides nearest the center of the intrusion. Outward from the quartz zone, a zone of molybdenite deposition existed, and farther still, a zone of pyrite and scheelite deposition. Because scheelite is such a minor constituent of the system, many pyrite veins formed without any tungsten minerals. As the system evolved, the site of deposition retreated inward as shown by Time 2. The evolution of the system produced a continual migration of the sites of deposition toward the center, so that the sites of mineral formation retreated and produced veins that were superimposed upon previous veins as shown by Time 3. Time 4 presents the exhaustion of the hydrothermal system, showing the crosscutting vein relationships, thus giving the apparent relationship of early quartz veins followed by quartz-molybdenite followed by quartz-pyrite for any one location.

After the intrusion of the Central stock and development of stage I mineralization, the Northeast Porphyry and related Intramineral dikes were emplaced approximately 48(?) m.y. ago. As the Northeast Porphyry crystallized, hydrothermal fluids again were concentrated within the crystallizing magma until a point was reached in which these fluids migrated from their collection area(s) outward into the surrounding fractured rock, in this case the Northeast Porphyry shell, the Central stock, and the hornfels aureole. Again, three vein types developed with associated alteration assemblages similar to those described for stage I. Stage I and II mineralizations are identical and can only be distinguished in areas where Intramineral dikes exist so that the crosscutting relationships between can be identified.

After the completion of stage II, stage III mineralization developed. This stage of mineralization is essentially identical to stage I and II events except that the quartz-molybdenite veins are wider and contain continuous ribbons of molybdenite.

The last mineralizing event recognized at Kitsault consists of the polymetallic veins and later carbonate veins. This base metal episode most likely represents the final stage of the hydrothermal activity at Kitsault.

The next intrusive event recognized at Kitsault is the emplacement of the 36-m.y.-old lamprophyre dike swarm. The final igneous event at Kitsault was the 1.6-m.y.-old volcanic flows and their connecting feeder dikes. Recently glaciation and erosion have