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GEOLOGY AND ISOTOPE GEOCHEMISTRY OF THE LIME CREEK MoS_2 OREBODY, ALICE ARM, BRITISH COLUMBIA

David L. Giles and Donald E. Livingston

ABSTRACT

K-Ar dating of the Lime Creek stock, Alice Arm, B.C. indicates that the intrusion of the Main granodiorite occurred about 63 m.y. ago and that the intrusion of the productive kalialaskite and the four phases of stockwork MoS_2 mineralization occurred 53 m.y. ago. Initial strontium isotope ratios of 0.7052 ± 0.0002 for the two principal intrusive rocks and late polymetallic veins indicate that the igneous rocks and mineralizing system were derived from mantle material with a small component of crustal contamination. Sulfur isotope values of $0.0 \pm 1.6^{o}/oo$ for magmatic and hydrothermal sulfides support the concept of a mantle source for the igneous and hydrothermal systems. Syngenetic sedimentary and metamorphic pyrite from the Bowser group host rocks yield light sulfur isotope values of -0.7 to $-3.1^{o}/oo$. An anhydrite veinlet from the deeper part of the stock yields a heavy sulfur isotope value of $+15.6^{o}/oo$. Laboratory data, along with local and regional field derived data, are compatible with a genesis of the deposit within the concepts of plate tectonic theory. The data at hand are compatible with, but insufficient to prove convective fluid flow as the process of hypogene mineralization.

INTRODUCTION

The Lime Creek* ore body in northwestern British Columbia is one of the few commercial primary stockwork-type molybdenite deposits in North America. Others include the Climax, Urad-Henderson, Questa, and Endako ore bodies. They are mined on a low grade-high tonnage basis, and are open pit operations except for Climax and Urad-Henderson.

Much recent geochemical research on both porphyry copper and stockwork MoS_2 deposits has been concerned with dating of micas related to the mineralization and associated igneous rocks. The results appear to show that mineralization and the predominant magmatic events of the deposit are indistinguishable in age (Kirkham 1971; Laughlin et al., 1969; Livingston et al., 1968; Page and McDougall, 1972a,b), except where dating has been in sufficient detail to resolve the analytical overlap (e.g., Moore and Lanphere, 1971).

At Lime Creek, geologic information shows that the Main granodiorite, the major intrusive and dominant host rock for MoS_2 mineralization, was emplaced and had solidified sometime prior to the introduction of MoS_2. The first MoS_2 episode is intimately related to localized bodies of kalialaskite which clearly intrude the older stock. K-Ar dating was undertaken to clarify the age relations between Lime Creek plutonism and the apparently younger hydrothermal event that began with kalialaskite.

Strontium and sulfur isotope studies of numerous porphyry coppers and at least one stockwork MoS_2 deposit in North America show that the igneous and sulfide material in these systems was largely mantle-derived. A similar study was made on selected samples from Lime Creek to provide information on the source of the intrusives and mineralization.

*Also known as "Alice" and "B.C. Molybdenum".

A brief outline is presented here of major features of the geology and mineralization at Lime Creek. The regional geology of the Central Coast Mountains will be briefly described in order to relate the apparent source and age of the Lime Creek intrusive-mineral system to the regional geologic framework, and to the regional evolution from a plate tectonic viewpoint.

The Lime Creek property was formerly owned and operated by B.C. Molybdenum, Ltd., a subsidiary of Kennecott Copper Corporation. It is now owned by American Metal Climax (Can.) Ltd.

REGIONAL GEOLOGIC FRAMEWORK

Alice Arm-Anyox Area

The Lime Creek stockwork MoS_2 deposit is located approximately 500 miles northwest of Vancouver, B.C. (Fig. 1), adjacent to the eastern edge of the Coast Crystalline Complex, and near the head of Alice Arm fiord.

The ore body is associated with one of a group of small, composite and Mo-related calc-alkali plutons (Woodcock, et al., 1966) emplaced in a volcanic and sedimentary terrain flanking the Coast Crystalline Complex (Fig. 2). The oldest rocks in the Alice Arm-Anyox area are a sequence of intermediate volcanic and pyroclastic deposits of probable lower to middle Jurrassic age that belong to the Hazelton group (Souther and Duffel, 1964). Reconnaissance mapping by Carter and Grove (1972) indicates that the Hazelton in the area consists mainly of volcanic breccia, tuff and conglomerate, minor flows, and andesitic pillow lavas, all variably metamorphosed on a regional scale to rocks of the greenschist facies. The Hazelton is unconformably overlain by regionally unmetamorphosed Bowser Group strata of middle and upper Jurassic to lower Cretaceous age. In the Alice Arm area, the Bowser consists of microgreywacke and thin-bedded argillite or siltstone, and these are the immediate host rocks for the Lime Creek stock (Fig. 2).

South and west of Alice Arm, the Hazelton and Bowser strata have moderate to steep dips along a regional northeast strike, whereas north of the Arm the regional trend swings sharply to the northwest. In the Anyox inlier, and marginal to contacts with both the Coast Plutonic Complex and the Alice Arm intrusions (Fig. 2), the sediments have been contact metamorphosed to cordierite-bearing biotite hornfels in an aureole up to one half mile wide.

The major tectonic element bordering the east side of the Coast Crystalline Complex in British Columbia is the Columbian Intermontane Belt. It includes, in the central part of the province, the Bowser basin to the north and a region underlain by Tertiary lavas to the south, separated by the northeast-trending Skeena Arch in the vicinity of Prince Rupert and Hazelton (Fig. 2). From the tectonic viewpoint, the Alice Arm plutons have been emplaced in the southern rim of the Bowser basin, on the northern flank of the Skeena Arch, and are satellitic to the Coast Crystalline Complex.

The Coast Crystalline Complex in the immediate Alice Arm-Anyox area (Fig. 2) consists of large expanses of quartz diorite, granodiorite, and lesser quartz monzonite intrusive into Hazelton and younger sediments. The intrusive rocks are probably a northern extension of the Ponder Pluton, as has been mapped and studied in detail by Hutchison (1970) north of Prince Rupert. Hutchison describes the Ponder Pluton as a parautochthonous, tongue-shaped and recumbent body that shows gradational zones and gneissic layering as well as sharp and discordant intrusive relationships. The latter occurs particularly along the eastern contact of the pluton with Hazelton and younger sediments.

The igneous rock at the contact between the Ponder (?) and Bowser metasediments about 2 miles immediately west of the Lime Creek stock (Fig. 2) is a homogeneous, massive, and medium-grained quartz diorite. A biotite K-Ar date of 47 ± 1.2 m.y. has been obtained from quartz monzonite along Observatory Inlet at about the southern edge of the map area shown in Fig. 2 (Wanless, et. al., 1966).

Lamprophyre dikes invade both the Coast Crystalline rocks and older strata. Although their overall distribution is unknown, the dikes seem to swarm at centers of earlier igneous activity of mineralization in the area. This has been recognized at Anyox (Carter and Grove, 1972) and within the Alice Arm intrusive bodies (Giles, unpub. data). A whole rock K-Ar date on a lamprophyre dike from the Lime Creek stock has yielded 36.5 ± 1.2 m.y. (N.C. Carter, pers. comm.). Latest igneous activity in the Alice Arm area is represented by the remnants of flat-lying phonolitic flows which unconformably overlie Bowser strata a short distance east of the Lime Creek stock (Figs. 2 and 3). Whole rock K-Ar dating of these flows gives a very young 1.6 ± 0.8 m.y. (N.C. Carter, pers. comm.); no evidence is available as to the source area of these alkali lavas.

Coast Crystalline Complex and Environs

The general geology of the Coast Crystalline Complex, which extends in a belt for over 1000 miles along the Coast Mountains of British Columbia (Fig. 1), has been summarized by Roddick, et. al. (1965), Douglas, et.al. (1970), and recently by Roddick (1974). Contrary to earlier "batholithic" concepts, the Complex is now recognized as having a long and varied igneous, metamorphic and structural history. Overall, the belt seems better characterized by paragneiss, diffuse contacts, migmatite, and plastic deformation than by forceful and multiple plutonism, homogeneity, and discordant structure.

In the Central Coast Mountains, a narrow and irregular band of metavolcanics and metasediments stretches obliquely southeastward across the axis of the range from the Alaskan panhandle to the eastern side of the Crystalline Complex near Prince Rupert. Rocks in this metamorphic band vary from greenschist facies on the west to almandine-amphibolite facies on the east (Hutchison, 1970). Most of the rocks are pre-Jurassic and possibly Paleozoic (Roddick, et.al., 1965), but the sequence probably includes metavolcanics of the lower Jurassic Hazelton group.

The rocks of the Crystalline Complex west of the metamorphic band are mainly plutonic, whereas those to the east toward the Alice Arm area are characterized by a complex assemblage of intermediate gneiss, schist, synplutonic rocks and migmatite (Central Gneiss Complex). True gneiss of the Central Gneiss Complex display high-pressure progressive regional metamorphism to the sillimanite grade of the almandine-amphibolite facies. Granite is rare, and homogeneous quartz monzonites are restricted to core areas of gneiss domes or to small epizonal plutons. The gneiss and migmatite underlie and locally grade into the metamorphic band and apparently are the oldest rocks in the region (Roddick, et.al., 1965).

Rocks of the Central Gneiss Complex are in turn intruded by, and commonly gradational into, massive to foliated plutonic rock of mostly intermediated composition. Hutchison (1970) distinguishes four diapirlike plutonic styles in the Prince Rupert area, ranging from autochthonous and migmatitic plutonic complexes to smaller-scale allochthonous and clearly intrusive plutons. All but the latter are rooted in migmatite terranes of the Central Gneiss Complex. The Ponder pluton, which separates Hazelton and younger strata in the Alice Arm area from the high-rank metamorphics of the Central Gneiss Complex further west, is parautochthonous and displays characteristics of both end members.

In summary then, the metamorphic section across the Central Coast Mountain segment of the Coast Crystalline Complex varies from greenschist facies on the west to apparent complete anatexis on the east adjacent to the Alice Arm area, and may incorporate rocks as old as Paleozoic.

Application of plate tectonic concepts to western Canada as discussed by Monger, et.al., (1972) and Petö (1974), suggests that the central metamorphic band, Central Gneiss Complex, and lower Jurassic Hazelton andesitic metavolcanics are probably remnants of a volcanic island arc and the deep metamorphic root associated with a subduction zone. Arc development appears to have taken place in the early Mesozoic, and was the result of large-scale westward overthrusting of the Pacific plate oceanic crust by the continental craton that began in late Paleozoic time. Interaction of the two convergent lithosphere plates lead to trench development at the boundary and the descent of the oceanic slab under the continent along a Benioff (subduction) zone.

The model and the processes involved in such subduction-related oceanic island-arc systems have been adequately described in current literature (eg. Dewey and Bird, 1970; Dickinson, 1970; Isacks et.al., 1968), as has the relation to volcanoplutonic orogenic magmatism and deformation (eg. Coney, 1970; Dewey, 1969; James, 1971). A recent general literature review and critique of the hypothesis has been provided by Meyerhoff and Meyerhoff (1972).

Subsequent to the active island arc processes, uplift or thermal doming of the continental plate margin took place in the Central Coast Mountain region in late Mesozoic and early Tertiary time. This was accomp~~lished~~anied by block faulting, orogenic igneous activity, and continued development of the Skeena Arch-all of which unroofed a lower crustal metamorphic root zone or mobile core now recognized as the high rank Central Gneiss Complex.

Hodder and Hollister (1972) and Monger, et.al., (1972) attribute such regional tension and faulting with uplift as providing direct access to differentiated mantle material under a relatively thin, stretched crust (Souther, 1970). Accordingly, large areas of the Intermontane Belt south of the Skeena Arch are covered by continental plateau basalts, and the belt contains numerous intermediate to silicic calc-alkaline plutonics and ultra-basic bodies of Jurassic to early Tertiary age. As pointed out by Carter (1970) and Sutherland-Brown, et.al., (1971), there is an apparent locallization of calc-alkaline porphyry intrusives in the general area of the Skeena Arch, many of which are copper and/or molybdenum related. The Alice Arm intrusive units are an example of the latter, as are the intrusives of the Granisle copper and the Hudson Bay Mountain molybdenum deposits farther east along the trend of the arch. Continued or renewed access to deep magmatic material may be exemplified by the late Cenozoic lamprophyre dikes and phonolitic lavas in the Alice Arm area.

A generalized application of the plate tectonic hypothesis to copper and molybdenum ore-producing and locallization processes in western British Columbia has been treated by Hodder and Hollister (1972) and by Sillitoe (1972).

GENERAL GEOLOGY AND MINERALIZATION

The Lime Creek stock is a composite pluton, zoned in part, that has been invaded by a complex of dikes, pods, and irregular masses of fine-grained silicic igneous rocks and intrusive breccia. The latter are ore-related and occur for the most part along the northern periphery of the stock. Molybdenite mineralization occurs as a multiple-stage stockwork of MoS_2-bearing veinlets arranged in an annular ore zone (defined as>0.16% MoS_2) that overlaps the northern border of the stock (Fig. 3).

Geologic work to date has indicated that the intrusive phases of the stock are divisible into four major map units, two of which are shown on Fig. 3. These latter units, termed the Main granodiorite-quartz monzonite and the satellitic East quartz diorite, comprise the bulk of the pluton and are the oldest host rocks for MoS_2 mineralization. Kalialaskite and several varieties of intramineral quartz monzonite porphyry and breccia are the volumetrically lesser rock units, confined to the mineralized zone, and mappable only at pit scale or larger.

A detailed description of the various rock types including alteration, mineralization, and structure has been given by Carter (1964), and the reader is referred to that report. The following briefly summarizes some pertinent recent work on intrusive and mineral patterns.

The Main granodiorite body, measuring 2000 by 2800 feet, is texturally and compositionally zoned from quartz diorite at the margin, through predominant granodiorite to porphyritic quartz monzonite in the core area of the pluton. Near-surface primary rock features and zonal relations are almost totally obscured by soil cover or by hydrothermal effects, specifically alkali metasomatism and silicification that are related to MoS_2 mineralization. However, detailed petrographic studies of pit and drill core samples indicate that the premineral stock contained a medium-grained equigranular dioritic border phase. This phase is characterized by a chilled contact zone, abundant biotite and hornblende, zoned plagioclase, and lesser intersertal quartz and alkali feldspar. Toward the core area of the pluton the rock texture becomes progressively seriate porphyritic, with the development of prominent coarse crystals of poikilitic alkali feldspar, increased interstitial quartz, lesser zoned sodic plagioclase, and primary biotite at the expense of hornblende.

The zonal and textural variations appear systematic and are suggestive of progressive inward crystallization and differentiation of a melt having an initial granodioritic composition. Part of the higher level monzonitic core areas of the pluton apparently crystallized in a relatively static and alkali-charged environment. Optically homogeneous alkali feldspar up to 6 cm. in diameter occasionally occur and appear to have grown quietly from intersertal liquid. They have poikilitically enclosed all pre-existing minerals, including quartz grains. The resultant texture has a characteristic "birds eye" appearance on fracture face.

The mafic-rich border zone may have encircled the stock, but it has not been traced completely around the border because of poor exposure and drill information. The very high secondary biotite content within the ore zone along the northern margin (Fig. 3) is interpreted as mainly hydrothermally-reconstituted biotite and/or hornblende reflecting the initially high mafic content of dioritic host rock. Outside of the ore zone along the southern margin, biotite in the quartz diorite border phase has been mostly chloritized. This may be deuteric in part. Evidence does not support any appreciable assimilation of hornfelsed Bowser wallrock to account for the high Fe-Mg budget of the diorite.

The East quartz diorite occupies a small elongate extension off the south-eastern part of the main stock (Fig. 3). This rock differs from the Main granodiorite in having a high hornblende content, diabasic texture, more calcic plagioclase, and an apparent uniform composition. It is relatively unaltered. Nowhere has the contact between the two main plutons been observed, and the age relations are unknown.

Insofar as has been determined by drilling, the contacts of the Main stock in the northern half dip steeply outward or are vertical to a depth of 2000 feet or more. Although moderately fractured, the Bowser wallrock has not been strongly shattered or brecciated near the contact, and although stock and hornfels locally interfinger, dike activity is virtually absent. The Main granodiorite stock appears to have been relatively passively emplaced. The regionally east-northeast trending and steep north-dipping Bowser strata have been warped conformable to the contact only along the western side of the stock.

The Bowser argillites and microgreywackes adjacent to the stock have been contact metamorphosed into a biotite hornfels aureole, approximately 800 feet thick, which grades gradually outward into unaltered sediments. The hornfels has been locally bleached and silicified immediately adjacent to the stock contact. Carbonate filled fractures are common in the hornfels, as are small amounts of disseminated pyrite-pyrrhotite.

The zone of MoS_2 mineralization is a slightly elliptical ring, between 200 and 800 feet thick, confined to the northern half of the stock (Fig. 3). The zone overlaps and roughly parallels the north, east, and west stock contacts both on surface and at depth, whereas the southern segment cuts across the stock and appears to dip vertically. Consequently, the ore zone appears to be the surface trace of a steep-sided conical shell or cylinder. The areas of better grade MoS_2 are along the stock hornfels contact, where shearing and stockwork fracturing are best developed and localized. The southern segment is rather ill-defined and erratic in both rock preparation, alteration and mineralization.

It would appear that the hornfels contact acted as the major premineral ore control. Higher grade ore shoots occur within the ring, and are directly related to zones of intense shearing and faulting, some of which have offset the stock contact at surface and at depth. Clearly post-magmatic but premineral fracture zones were also an important ore control, and perhaps the major control for the southern segment of the ore ring.

The MoS_2 ore ring encloses a central barren zone characterized by little or no molybdenite and by large areas of intense and quartz-K feldspar alteration with minor secondary biotite. The barren altered zone is completely within intrusive rocks. From drilling information, the alteration gradually diminishes with depth to unaltered or weakly altered quartz monzonite in deeper central areas of the pluton.

Recent pit mapping indicates that the molybdenite paragenetic sequence consists of four superimposed but separate episodes of MoS_2 introduction. The first stage is related to the injection of lenticular dikes, pods, and irregular masses of kalialaskite, where the MoS_2 occurs as disseminations and rare rosettes in the matrix and as "paint" on fracture faces. The middle two stages are typical quartz-pyrite-MoS_2-alkali feldspar veinlets in a closely spaced and random stockwork pattern within the Main granodiorite, kalialaskite, and the hornfels. The youngest MoS_2 stage is characterized by banded and throughgoing quartz-MoS_2 veins up to one foot thick. Most of the molybdenite in the Lime Creek ore body resulted from the first two mineral events. Numerous dikes and irregular zones of intramineral quartz monzonite porphyry and related intrusion breccia occur in the ore zone along the northern stock margin. These were apparently emplaced after the kalia-laskite event but before the late stage banded veins. The ore zone averages around two volume percent pyrite, both disemminated and in veinlets; lesser amounts of pyrite with some pyrrhotite and traces of magnetite are dispersed through the high-silica barren zone.

The final stage of mineralization is represented by coarse polymetallic quartz veins that cut the MoS_2 ore zone. The veins are up to 3 feet thick and contain minor amounts of pyrite, galena, sphalerite, molybdenite, tetrahedrite, chalcopyrite, fluorite, gypsum, and ankeritic dolomite, along with a wide variety of lead-bismuth sulphosalts (Woodcock, et.al., 1966).

The kalialaskite is a fine-to medium-grained and slightly vuggy rock, white to dark pink in color, consisting almost entirely of intergrown anhedral quartz and alkali feldspar in varying proportions. Traces of sodic plagioclase have been found, and the average CaO content of the rock is about 0.5%. The alkali feldspar may be either orthoclase or microcline, and graphic intergrowths with quartz are common. The kalialaskite is clearly post-Main stock intrusive, and is sporadically distributed around the contact zone within the MoS_2 ore ring; it is considered the "ore-bringer" igneous event.

The intramineral quartz monzonite porphyry is generally a fine grained greenish rock with numerous small plagioclase phenocrysts in a "dirty" groundmass characterized by abundant dispersed biotite flakes and a semi-granulated texture. As with the kalialaskite, the monzonite occurs as lenses and dikes along the stockhornfels contact. It grades locally into intrusive breccia zones containing inclusions and angular blocks of all younger rocks, most of which are mineralized.

By far the dominant hydrothermal alteration type associated with Lime Creek mineralization is quartz-alkali feldspar ($\pm$ biotite). Sericitic and argillic alteration occur on a lesser scale as replacement of plagioclase and adjacent to shear zones. Metasomatic potash feldspar is found as extensive replacement along borders of stockwork quartz-MoS_2 veins, as large grains and patches with secondary biotite in dioritic host rock, and with pervasive quartz flooding in the central barren zone. Mineralization at Lime Creek is intimately related to high potash activity.

Some argument could certainly be raised that the kalialaskite actually represents some form of quartz-K feldspar metasomatic alteration related to MoS_2 mineralization. However, the rock has igneous textural characteristics, is clearly intrusive into the Main granodiorite stock and the hornfels wall rock, and does not show any features suggestive of replacement. It is considered an intrusive igneous rock.

Section on analytical techniques missing (in preparation).

DISCUSSION OF RESULTS

K-Ar Dating

The K-Ar radiometric date on secondary biotite from within the ore zone is 53.7 ± 1.7 my. (Table 1). The sample (KAA-261) was taken from a nearly pure clot of ragged and intergrown biotite flakes within a dike-like body of kalialaskite. The kalialaskite in the northern ore zone contains numerous such patches, streaks, and clots of biotite believed to be remnants of dioritic host rock. As such this biotite has almost certainly been recrystallized in a biotite-stable environment, and re-equilibrated to the age of both kalialaskite intrusion and the first-recognized MoS_2 episode.

The 53-54 my. age of major MoS_2 mineralization in the ore zone at Lime Creek is well supported by three unpublished K-Ar dates by the British Columbia Bureau of Mines (N.C. Carter; pers. comm.) and by one earlier published date of 53.5 my. (Woodcock, et. al., 1966). These dates are in part on primary biotite from intramineral quartz monzonite porphyry dikes. Hydrothermal sericite from a MoS_2 prospect related to a monzonite stock 3 miles west of B.C. Molybdenum (Fig. 3) yields an unpublished K-Ar date of 52.9 ± 1.7 my. (Giles, unpub. data).

A 63.2 ± 2.1 my. K-Ar date was obtained on primary biotite from the quartz monzonite phase of the main granodiorite in the deeper central area of the Lime Creek stock (Table 1). The quartz monzonite at depth beneath the high-silica zone is essentially unaltered except for locallized bleaching, chloritization and silicification along walls of fractures and occasional quartz-carbonate-pyrite or quartz-anhydrite veinlets. The analytical sample (KAA-134) was taken from composited sections of drill core in the interval 2430-2500 feet.

Although a significantly older date for plutonism relative to mineralization at Lime Creek was not unexpected-based on geologic information - the magnitude of the apparent age difference is somewhat surprising. This would seem to place doubt on the Main granodiorite as being the cogenetic parent or source plutonic pulse for associated mineralization, as has been demonstrated geologically at Climax (Wallace, and others, 1968) or inferred when the ages of magmatism and mineralization were undistinguishable or nearly so (McDowell and Kulp, 1967; Livingston, and others, 1968; Laughlin, and others, 1969; Moore and Lanphere, 1971; Silberman, and others, 1974). At Lime Creek, the small-volume kalialaskite or its deeper parent is the apparent source intrusive for MoS_2, which is clearly comagmatic and time equivalent with that rock type.

Nevertheless, if the above 63.2 my. "igneous" date is valid, it is in apparent conflict with the seemingly well established 53-54 my. age of structurally higher and superimposed MoS_2 mineralization. Obviously the presence of younger secondary biotite in the altered zone of an apparently significantly older host intrusive raises speculation of a blind mineralizer intrusive at depth. However, geologic work and exploratory drilling by B.C. Molybdenum Ltd. has not revealed any additional major blind instrusive in the immediate area that is capable of causing either the widespread biotitic alteration, or the complete re-equilibration of existing secondary biotite to a uniform 53-54 my. date.

A monzonite porphyry body found adjacent to the northeast part of the ore body at depth appears too small and geometrically removed to have had any significant "younging" effect. In fact, this porphyry body is probably intramineral. It is weakly altered and MoS_2-mineralized, and a K-Ar age on slightly chloritized biotite from this rock yields 47 my. (N.C. Carter, pers. comm.).

Similarly, the lamporphyre dikes transecting the orebody, while clearly a postmineral thermal event, are volumetrically small relative to the overall orebody, and they have sharp well-chilled margins, indicating rapid outward heat transfer into a relatively cool host rock. None of the samples of secondary biotite from the ore zone were in proximity to lamprophyre dikes.

Any postmineral thermal event capable of effecting widespread re-equilibration of secondary biotite in the high-level ore zone would seemingly be strong enough to similarly affect primary biotite in deeper parts of the system. Presumably this latter biotite would be closer to the hot source region of the thermal event, and consequently would undergo a greater degree of Ar-loss and probable chloritization. However, the fresh nature of the biotites and their discrepent ages do not support this concept.

The second alternative is that the Lime Creek composite stock was emplaced at around 63 my. ago, differentiated and solidified in situ, and subsequently acted as the focus for an entirely separate mineralizing event from depth around 10 my. later. Under this hypothesis (a) the Lime Creek stock provided the deep channel-ways for ascending solutions and accompanying igneous material, as well as a locus for precipitation of a high-level stockwork MoS_2 ore shell; (b) the primary biotite in quartz monzonite from the deeper central core of the Lime Creek stock was essentially unaffected by these later upward moving solution, and consequently has retained a minimum K-Ar date for Lime Creek plutonism.

Expanding on this argument, there is considerable evidence from the mine area and drill core to indicate that the stock-hornfels contact was a major ore control. On the broad scale, mineralization parallels and is restricted to the steeply-dipping contact for some depth, and it seems probable that ore fluids migrated either up or toward the contact zone at high-level depositional sites. Evidence further suggests that the present level of exposure is not far below the former roof or hood zone of the Lime Creek stock, which probably acted as a "cap" to upward moving solutions. The initial geometry of the MoS_2 ore shell may have been that of an inverted cone or cup draped over the apex and flanks of the stock.

There is no strong evidence to indicate that a sufficent volume of primary ore fluids (or accompanying igneous material) passed upward through the central areas of the stock and then spread laterally outward near the top to form the cup-shaped orebody. Rather, it appears more probable that fluids moved up the peripheral contact zone, and perhaps merged inward at or near the roof, with the deeper igneous core of the stock acting as a relatively impermeable barrier to fluids.

If such fluids and accompanying minor igneous material (kalialaskite) were essentially confined to outer contact avenues at depth, it also seems plausible that igneous biotite deep within the mozonite core area of stock could retain an older plutonic date. This implies that the episode of MoS_2 mineralization at Lime Creek was not a pervasive thermal or "younging" event except at or near zones where mineralization was locallized. As this is not an unrealistic assumption, the weight of evidence suggests to us that - insofar as it is valid - the 63 my. date reflects a minimum age for Lime Creek plutonism (Main granodiorite) and that a separate but partially superimposed period of MoS_2 mineralization took place at about 53-54 my. Clearly further age dating is needed to confirm this interpretation.

Strontium Isotope Ratios

The results of rubidium, strontium, and strontium isotope analyses on whole rock samples of the kalialaskite and Main granodiorite, and on ankeritic dolomite, are given in Table 1. The kalialaskite (KAA-101) was taken from a large irregular mass within the northern ore zone that contained coarse disseminated MoS_2 flakes but was free of secondary biotite and inclusions. Using the measured K-Ar age on nearby secondary biotite from within this rock unit, an initial Sr^{87}/Sr^{86} ratio was calculated at 0.7050 $\pm$ .0002.

The Main granodiorite (KAA-134) is the quartz monzonite phase from the deeper core area of the stock, and is the same sample from which primary biotite yielded a K-Ar age of 63.2 my. The calculated initial Sr^{87}/Sr^{86} ratio is 0.7053 $\pm$ .0002. The ankeritic dolomite (KAA-837) was obtained as coarse crystals from a late polymetallic quartz vein. As the sample contains nil rubidium, no age correction is necessary, and the initial strontium isotope ratio is 0.7054 $\pm$ .0002. The total strontium isotope data is summarized in Fig. 4.

The relative errors listed in Table 1 and shown on Fig. 4 are at the one sigma level, and there is basically little significant difference in the initial strontium isotope ratios; the close overall average is around 0.7052. This value is slightly but definitely enriched over values expected for juvenile basaltic material (.7033), and quite clearly the Lime Creek rocks were not derived from uncontaminated mantle derivatives at around 50 to 60 my. ago.

An alternative possible source for the intrusive material could be through total or partial melting of lower crustal rocks that had an average crustal ratio of about 0.705 in the Coast Complex region at 60 my. ago. Theoretically such an average crust could have been derived exclusively from the mantle through volcanism which took place 260 my. ago. This does not, however, coincide with the known geologic information about Coast Crystalline Complex and environment as reviewed previously. The igneous and metamorphic history of the region appears too complex to allow crustal development solely through reworking of widespread mantle-derived volcanism that took place in mid-Permian time.

Evidence indicates that the backbone or core of the Coast Complex consists of high-rank gneisses and migmatites representing rocks of pre-Jurassic age; probably as old as early Paleozoic in the Central Gneiss Complex. As of 60 my. ago many of these rocks would have developed strontium isotope ratios variously, and in some cases considerably, in excess of 0.705. Consequently, an early Tertiary "average" crustal ratio of 0.705 in the Alice Arm region implies not only considerable dilution with juvenile mantle-derived material, but a rather fortuitous mixing of inhomogeneous ratios within the immediate region where the Lime Creek magmas were generated.

A third potential source for the Lime Creek intrusive material is mantle-derived magma that has been contaminated with local crustal rocks having higher Sr^{87}/Sr^{86} ratios. There are numerous mixing models that could yield the observed ratios, but perhaps the simplest - and the one the writers favor - involves the contamination of a large proportion of juvenile mantle-differentiated material with small amounts of relatively old crustal material. Such contaminating material with high Sr^{87}/Sr^{86} ratios could have been conveniently derived from the basement rocks of the adjacent Coast Crystalline Complex or its buried equivalent under the Alice Arm area. These rocks (specifically the Central Gneiss Complex) show clear evidence nearby of migmatization and partial melting related to a deep crustal root zone. A source for the Lime Creek magmas involving predominantly mantle derivatives is consistent with the timing and events involved in a plate tectonic interpretation for western Canada (eg. Petö, 1974).

The isotope data suggest that the strontium within the dolomite could have been extracted from the kalialaskite at 40 ± 10 my. ago, or from the Main granodiorite any time in the past 60 my. (Fig. 4). On geological grounds, the polymetallic veins are considered to be late stage features of the major hydrothermal event responsible for earlier MoS_2 mineralization. Accordingly, it would appear that the granodiorite rather than the kalialaskite is the logical source for any Sr (and Ca) derived from either of these two rocks.

The rubidium and strontium data could be interpreted to represent an isochron of about 40 my. However, the necessary assumption of consanguinity for isochrons is contrary to our interpretation of the K-Ar dating and is not supported by the vein-like character of the dolomite in sample KAA-837. Therefore, we consider any isochron interpretation of the data as invalid.

Sulfur Isotope

The results of sulfur isotope measurements on ten sulfide (plus one anhydrite) samples are shown in Table 1 and on Fig. 5. Of the sulfides, five are clearly of hydrothermal origin on geological grounds, and consist of pyrite and molybdenite obtained from within and adjacent to the Lime Creek ore zone. The average $\delta^{34}S$ values for these is exactly zero per/mil (Fig. 5), which is the meteoritic standard and the conventionally inferred value for sulfur derived from the mantle or lower crust.

It must be emphasized that significant new developments in the isotope geochemistry of sulfur and carbon (Ohmoto, 1972; Rye and Ohmoto, 1974) shed considerable question on the interpreted ~~opinion~~ ORIGIN of hydrothermal sulfur in a deposit when the argument is based on $\delta^{34}S$ values of a few individual sulfide minerals. Our data was gathered some years ago under certain previous assumptions regarding interpretation of $\delta^{34}S$ data (cf. Ohmoto, 1972, p. 522) now shown to be invalid. We acknowledge not having adequate isotope data on sulfide/sulfate species (or carbon) at Lime Creek to define the fluid variables or the isotope composition of total sulfur in solution ($\delta^{34}S_{\Sigma S}$) necessary for a comprehensive discussion. Nevertheless, our data may be of some ~~suggestive~~ limited use.

The recent work of Ohmoto (1972) clearly demonstrated that for a specific hydrothermal deposit, $\delta^{34}S$ values can show wide variations among coexisting minerals as well as in time and space within the deposit. It is necessary to know not only the total range of $\delta^{34}S$ values in all minerals, but the time/space relations of samples within the mineral system.

The MoS_2 ore zone at Lime Creek is essentially a two sulfide assemblage - pyrite (pyrrhotite) and molybdenite, for which the time and space relationships of the four mineralization stages are resonably well known. Four of the hydrothermal sulfides in Table 1 and Fig. 5 represent pyrite and molybdenite from the first, last and probable intermediate (silicic core) stages, and from scattered areas within the orebody. Insofar as these few samples can be considered representative and coexisting, the very small range between samples and $\delta^{34}S$ values near zero suggest that $\delta^{34}S_{\Sigma S}$ was relatively constant in time and space at about 0 ‰ throughout the MoS_2 mineralization episode at Lime Creek. At an inferred mineralization temperature of $\sim 350^{\circ}C$, Ohmoto (1972) has shown that in the region of the pyrite-pyrrhotite stability fields at low pH ~~fields~~, sulfide $\delta^{34}S$ values will approximate $\delta^{34}S_{\Sigma S}$ at around 0 ‰.

Pyrites obtained from two unaltered samples of the Main granodiorite and the East quartz diorite have an average $\delta^{34}S$ value of -0.5 per/mil. These pyrites occur as tiny sparsely disseminated grains in the intrusive rocks, and are considered magmatic in origin on geologic grounds. As with the hydrothermal sulphides, the near-zero per/mil. value implies either a lower crust or upper mantle origin for the sulfur, and by association is strongly suggestive of predominantly the same origin for the igneous host rock.

Three pyrite samples were taken from unaltered and hornfelsed Bowser group wallrock on the northern periphery of the Lime Creek stock (Fig. 3). These pyrites are considered syngenetic, occuring as thin films and rosettes on bedding planes in unaltered rock or recrystallized as small disseminated cubes in hornfels within the contact aureole. The latter pyrite is frequently intergrown with pyrrhotite. Hornfels sample KAA-156, taken within the hornfels halo at around 400 feet from the contact, shows an apparent relative depletion in S^{34} compared to the two unaltered and unmetamorphosed Bowser pyrite samples well outside the halo (Fig. 5). The development of pyrrhotite within the contact halo is believed due to partial de-sulfurization during recrystallization of the original sedimentary pyrite. This is perhaps the event when S^{34} was lost.

Anhydrite occurs as sparse lavender-colored grains in veinlets and clots in deeper parts of the Lime Creek stock. An anhydrite sample obtained from deep drill core has a δS^{34} value of +15.6 per/mil., which is in accordance with S^{34} enrichment in oxidized sulfur species under hypogene conditions (Field, 1966).

The process of hypogene anhydrite formation has been discussed by Norton (1969; 1972; pers. comm.) within the framework of a hydrothermal convective system developed within the adjacent to stock-like intrusive bodies. According to Norton's model, fluids entering a crackled stock from wall rock on the deep parts of the convection cycle may well be low-calcium acid sulfate solutions. Mass transfer calculations (Hegelson, 1970) indicate that anhydrite will precipitate from reaction of such a solution with a Ca-bearing rock at constant temperature and pressure. A low calcium and a high sulfate content can easily be predicted for pore fluids passing through Bowser strata. Accordingly, it is believed that the anhydrite in the deep Lime Creek stock resulted from the reaction of incoming acid sulfate solutions with the plagioclase of the Main granodiorite.

To what extent such convective fluid flow contributed to major hypogene mineralization is unclear. It is inviting to speculate that pore fluids were at least important in latter stages of the MoS_2 mineral sequence (Taylor, 1974; White, 1974). As such, they may have provided (among others) S^{34}-enriched sulfur from the Bowser wallrock, and Ca (with Sr) from the Main granodiorite plagioclase for the late ankeritic dolomite in polymetallic veins (cf. preceeding section on Sr isotopes). A light stable isotope study could shed considerable light on this situation, as has been recently reported on at Climax (Hall, and others, 1974).

CONCLUSIONS

From the data at hand, we conclude that the Main granodiorite was intruded at least 63 my. ago and was subsequently intruded by the kalailaskite and mineralized with MoS_2 at least 10 my. later at 53 my. ago. The igneous intrusions and the MoS_2 mineralizing materials have principally derived from a mantle source or sources with a small amount of crustal contamination. Four stages of MoS_2 mineralization occurred interspersed with minor but significant intrusions of dikes and breccias. The materials of late poly-metallic veins may well have been derived by hydrothermal leaching of the Main granodiorite. The laboratory data and the local and regional geological setting "fit" with modern plate tectonic concepts and with modern thoughts of convecting hydrothermal systems, but more data needs to be collected to positively support or refute these theories.

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Table I, ANALYTICAL RESULTS

I. K-Ar data (biotite)

Sample No. and location	Ave % K	Ave Ar^{40*} (ppm)	K^{40} (ppm)	Apparent Age (m.y.)
KAA-134 Main granodiorite; DDH 69-1; composite from 2430'-2500'; disseminated books; <1% cht.	5.844	0.0268	7.130	63.2(±2.1)
KAA-261 Kalialaskite; West pit, 1990 level; secondary clot; no cht.	8.067	0.0314	9.842	53.7(±1.7)

II. Sr isotope data (whole rock)

	Rb(ppm)	Sr(ppm)	Rb^{87}/Sr^{86}	$(Sr^{87}/Sr^{86})_t$	$(Sr^{87}/Sr^{86})_o$
KAA-101 Kalialaskite; West pit, 1990 level; no biotite or inclusions	122±1.5	168±1.0	2.127±.025	.7066±.0002	.7050±.0002
KAA-134 Main granodiorite; as above	142±1.5	725±6.0	0.574±.006	.7058±.0002	.7053±.0002
KAA-837 Ankeritic dolomite; East pit, 2060 level; vein	0.7±0.7	829±7.0	0.002±0.002	.7054±.0002	.7054±.0002

III. Sulfur isotope data

PYRITE

	δS^{34} (‰)
KAA-134 Main Granodiorite; as above	+0.5
KAA-135 Bowser group siltstone; mine access road, pole #94	-0.7

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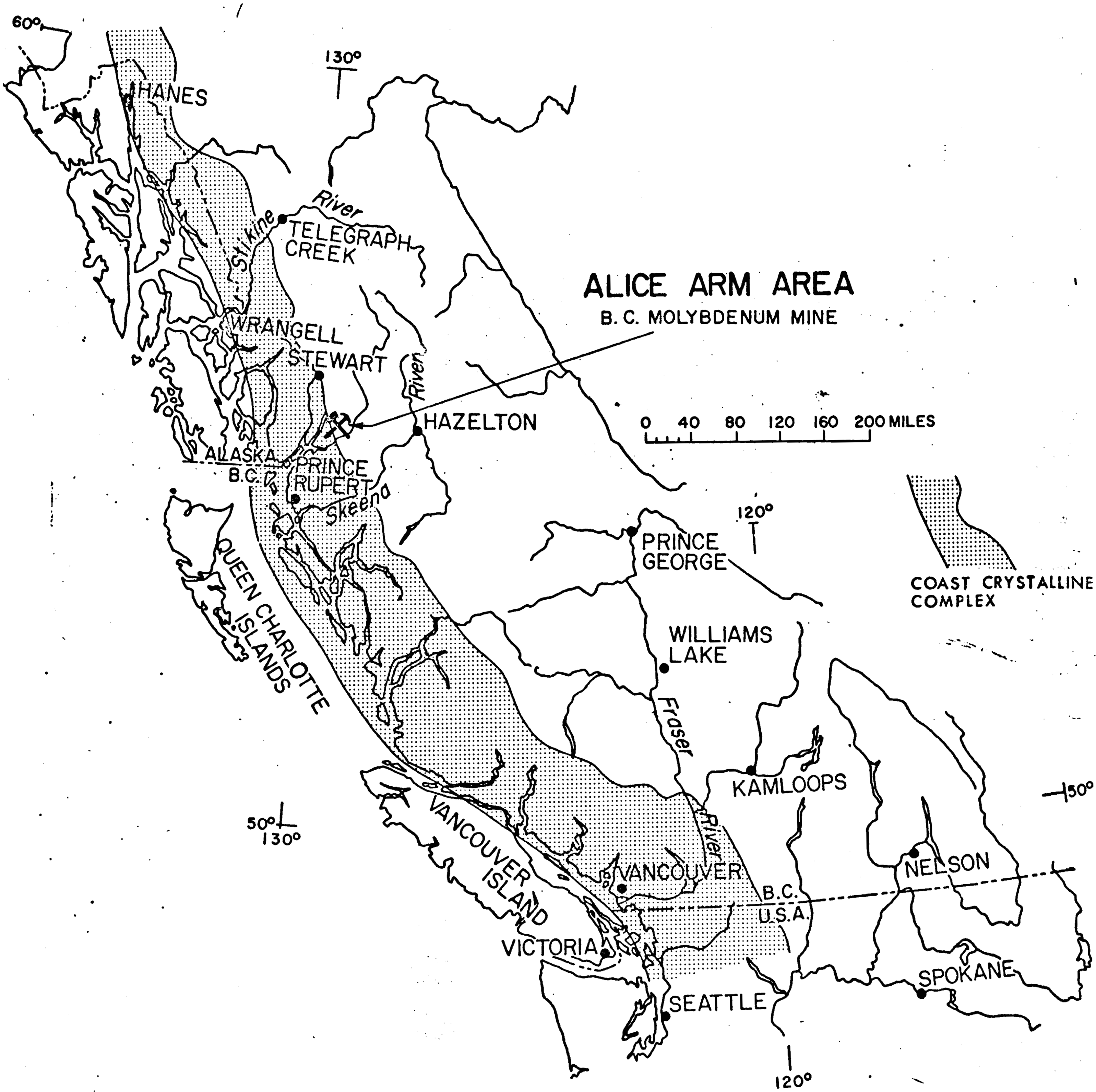
	δS^{34} (‰)
KAA-144 Bowser group argillite; Clary Lake road, pole #6	-1.1
KAA-260 Diorite ore; West pit, 1990 level	+0.4
KAA-5002B Late polymetallic vein; East pit, 2095 level	+1.6
KAA-151 Silicified barren core zone; East pit, 2130 level, with pyrrhotite	-0.8
KAA-156 Bowser hornfels; junction of access road and mine office road; with pyrrhotite.	-3.1
Kx-2058 East Quartz diorite; 500' east of Patsy Creek.	-1.4

MOLYBDENITE

KAA-152 Kalialaskite-related, first MoS_2 episode; West pit, 1990 level	-1.3
KAA-153 Banded vein, fourth MoS_2 episode; East pit, 2025 level	+0.1

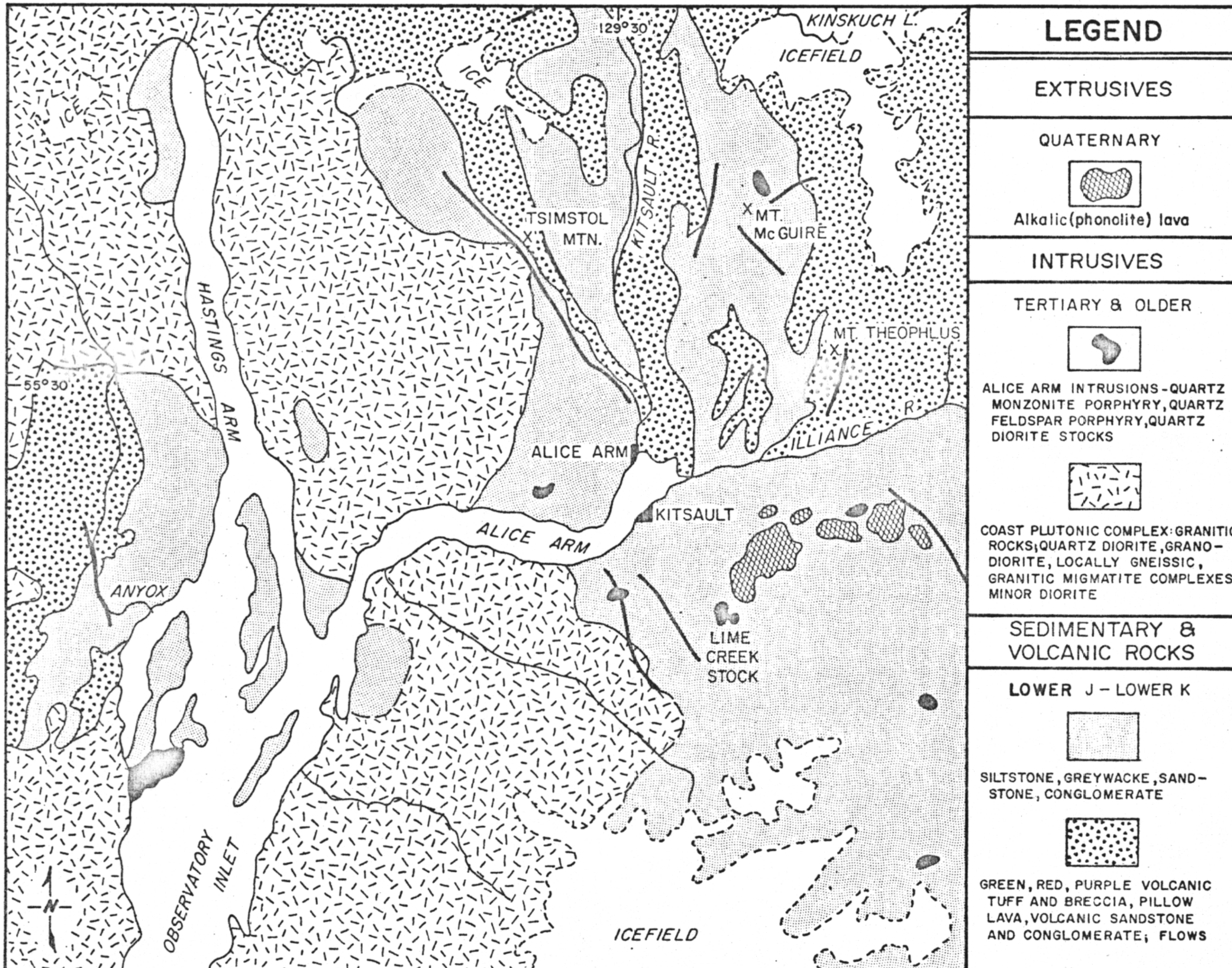
ANHYDRITE

KAA-108 vein and clots; DDH 69-1, 2374'	+15.6



Index map of British Columbia, showing location of Alice Arm area and Coast Crystalline Complex.

Fig. 1



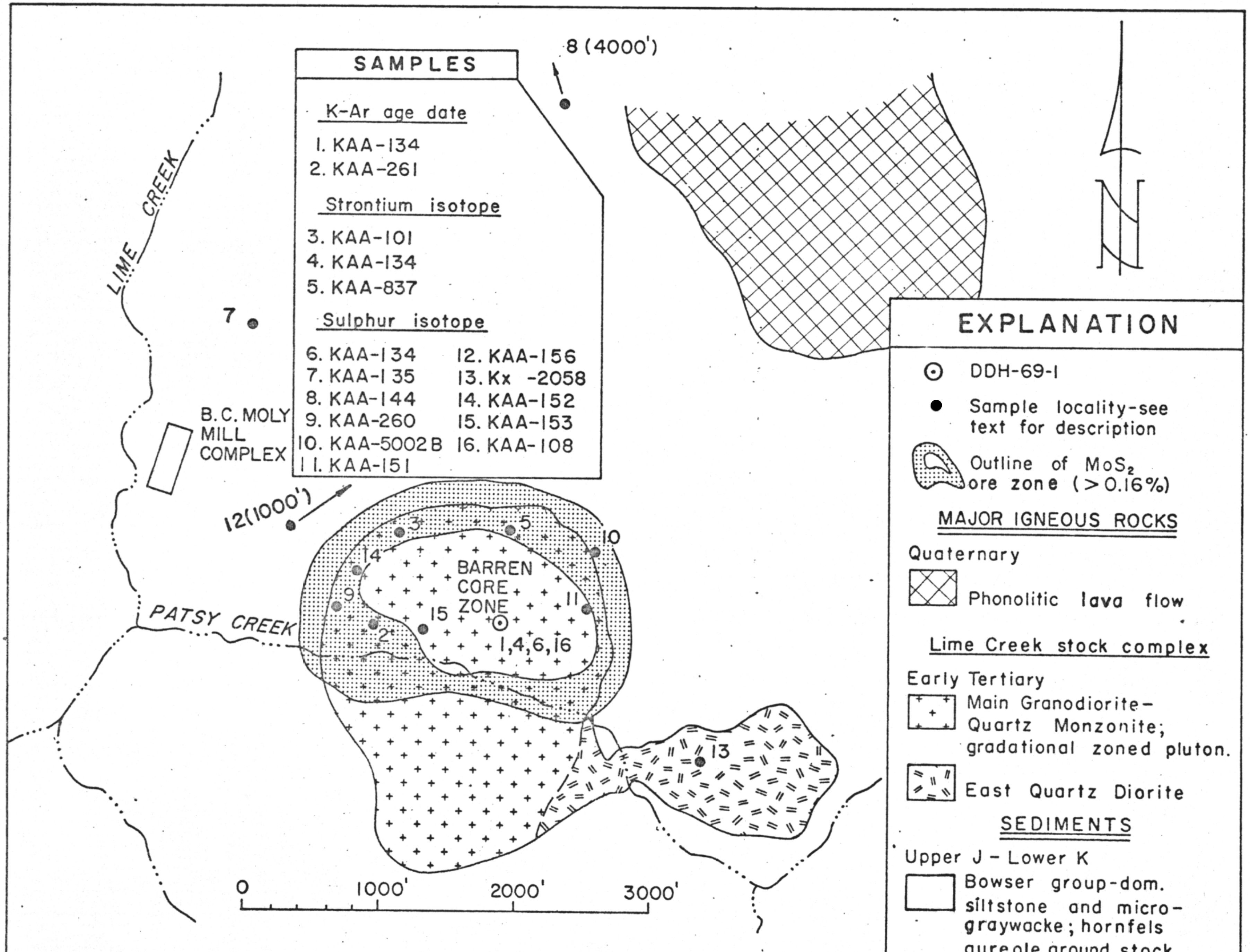
GENERALIZED GEOLOGIC MAP—ALICE ARM AREA, B.C.

0 5 10 15 MILES

SCALE

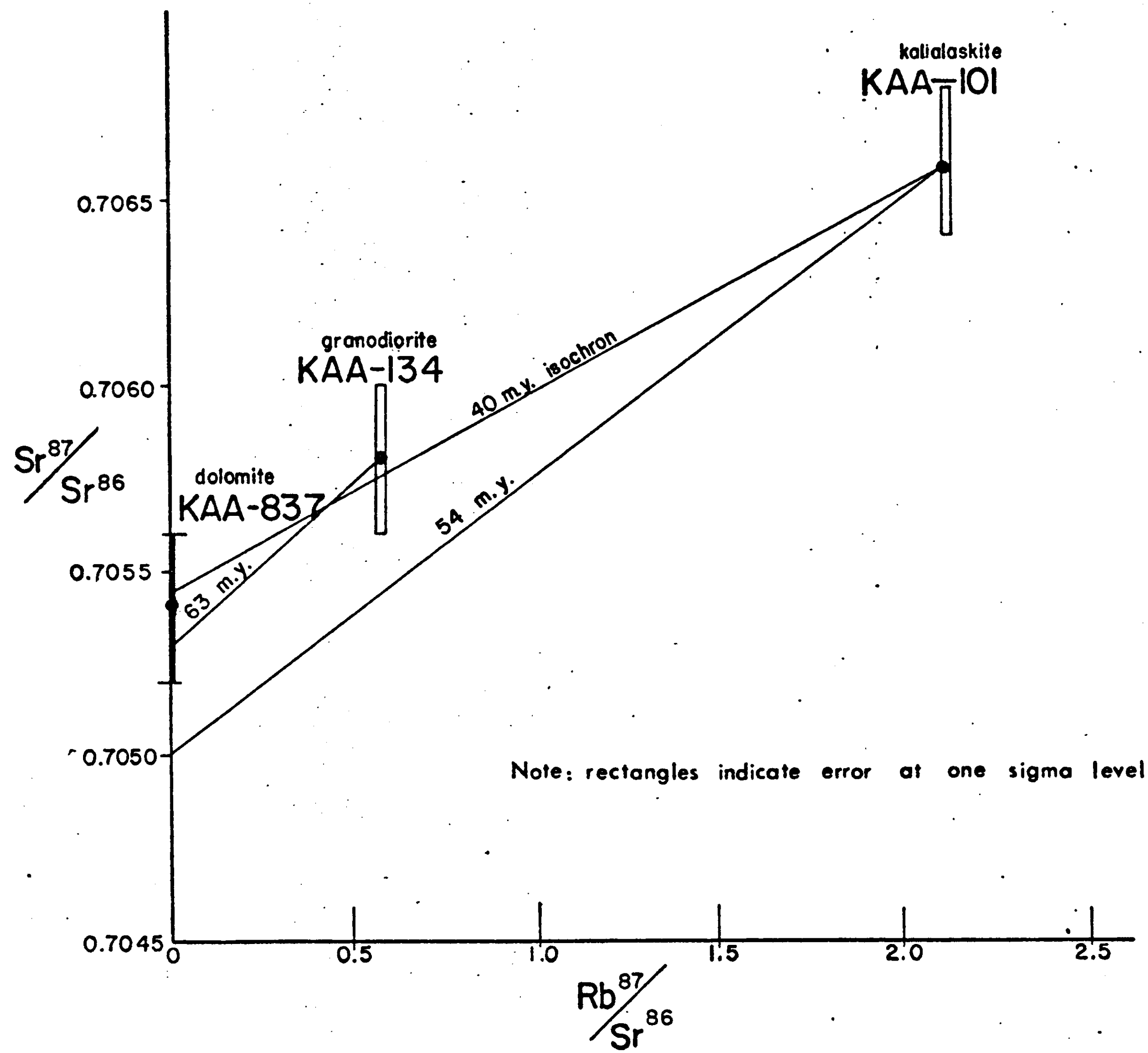
MODIFIED FROM CARTER & GROVE, 1972

Fig. 3



Outline Geological & Sample Location Map–Lime Creek Orebody

Fig. 3



STRONTIUM ISOTOPE DATA

Fig. 4

= analytical precision (±0.2‰)

= range and mean value

SULFUR ISOTOPE DATA

PYRITE

Wallrock
(Bowser)
Argillite; siltstone (KAA-135; KAA-144)
Hornfels contact gureole (KAA-156)
(with pyrrhotite)

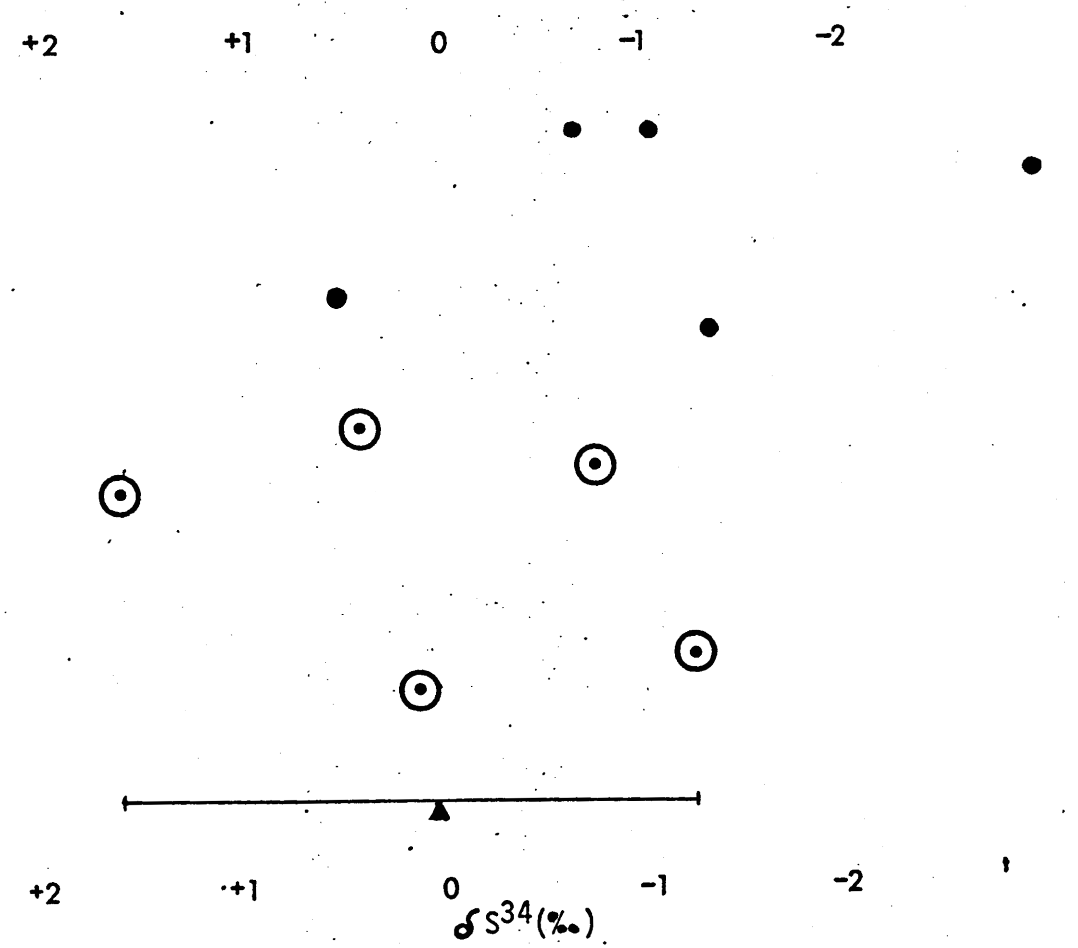
Magmatic
Main granodiorite (KAA-134)
East quartz diorite (Kx-2058)

Hydrothermal
Diorite ore, MoS_2-related (KAA-260)
Barren silicic core (with pyrrho) (KAA-151)
Polymetallic vein (KAA-5002B)

MOLYBDENITE

Kalialaskite (stage #1) (KAA-152)
Banded vein (stage #4) (KAA-153)

HYDROTHERMAL SULPHIDES



NOTE: Circled dots indicate sulphides of certain hydrothermal origin.

Fig. 5