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Altered rocks and magnetite-apatite-actinolite deposits associated with the Mystery Island intrusive suite, Echo Bay, District of Mackenzie

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ALTERED ROCKS AND MAGNETITE-APATITE-ACTINOLITE DEPOSITS ASSOCIATED WITH THE MYSTERY ISLAND INTRUSIVE SUITE, ECHO BAY, DISTRICT OF MACKENZIE

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CONTENTS

Tables

Figures

Plate

1. Geologic map of the distribution of altered rocks associated with the Mystery Island intrusive suite in the Echo Bay area with sample locations.

ALTERED ROCKS AND MAGNETITE-APATITE-ACTINOLITE DEPOSITS ASSOCIATED WITH THE MYSTERY ISLAND INTRUSIVE SUITE, ECHO BAY, NORTHWEST TERRITORIES

Abstract

Magnetite-apatite-actinolite deposits occur as pervasive replacement, veins, pods and breccias within wall rocks to the plutons of the Mystery Island intrusive suite at Echo Bay, Northwest Territories. The plutons and their altered wall rocks host previously-mined pitchblende, native Ag, Ni-Co arsenide veins. Although numerous studies were carried out on the pitchblende, native Ag, Ni-Co arsenide veins, the origin of the altered rocks which host them remains uncertain.

The plutons of the Mystery Island intrusive suite intrude a complex of andesitic stratovolcanoes of the LaBine Group, within the 1.87 Ga Great Bear magmatic zone of Wopmay orogen. The plutons are compositionally heterogeneous, sheet-like bodies of intermediate composition and were emplaced at a depth of 2 to 3 km. At 1.84 Ga the stratovolcanoes and plutons were folded such that the tops and bottoms of the plutons are exposed. After 1.84 Ga, the area was cut by northeast-trending transcurrent faults and mafic magmas.

All of the plutons of the Mystery Island intrusive suite are metasomatically altered. The plutons have haloes of altered wall rock characterized by three zones: 1) an inner zone of albite; 2) an intermediate zone of magnetite-

apatite-actinolite; and 3) an outer zone of disseminated sulphides. The albite zone is characterized by pervasive replacement of the host rock by very fine- to coarse-grained albite. Albitized rocks generally occur within 100 m of the pluton roofs, but extend locally up to 1 km above the plutons. The magnetite-apatite-actinolite zone is defined by the presence of at least two of the three minerals: magnetite, apatite or actinolite. These minerals occur as disseminated crystals, veins, pods, and breccias above the plutons, and locally, within and below them. The mode of occurrence of magnetite, apatite and actinolite varies with original lithology. In andesitic lava flows, these minerals are present disseminated throughout the rock. In sedimentary rocks, albite, actinolite, apatite and magnetite replace individual beds. Andesite flows, sedimentary rocks and plutons are cut by veins of magnetite-apatite-actinolite or magnetite-actinolite. Hydrothermal breccias occur locally, near pluton contacts. The pyrite zone is characterized by the presence of disseminated pyrite crystals or pods up to several cemtimeters in diameter which form visible rusty patches on weathered outcrop surfaces, or extensive gossans where pyrite is locally abundant. Chalcopyrite occurs locally.

Whole-rock geochemistry of the altered wall rocks shows that two of the plutons are Na-matasomatized, as indicated by high Na contents which do not correlate with SiO_2*. One of the plutons is K-metasomatized locally, as indicated by elevated* K_2O *not correlative with an increase in* SiO_2*. One pluton is relatively unaltered and shows a normal magmatic trend of increasing* K_2O *and decreasing* Na_2O *with increasing* SiO_2 *content. Profiles of* SiO_2*,* Na_2O *and* K_2O *with height in some of the plutons show a regular. antithetic variation of*

Na_2O and K_2O. One pluton is reversely zoned, and K_2O and SiO_2 decrease with increasing height in the pluton. Gd, Dy, Be, Yb, Y, Sm, MgO and Na_2O increase with decreasing K_2O; Ba and Rb correlate positively with K_2O in andesitic lava flows above the Glacier Lake pluton.

Whole-rock $\delta^{18}O$ and δD of altered rocks are not zoned, and range from +5.7 to +12.3‰ and -70 to -57‰ respectively for the plutons. $\delta^{18}O$ and δD range from +5.3 to +11.7‰ and -92 to -56‰ respectively for altered andesitic lavas and their cogenetic andesitic porphyries and volcaniclastic rocks. Most $\delta^{18}O$ and δD are higher than +6 and -70‰, respectively, consistent with alteration under low water to rock ratios by magmatic fluids. Lower values suggest involvement of a minor component of evolved meteoric water, evolved seawater, or connate water. Based on stable isotopic data from whole-rock samples and mineral separates, the magnetite-apatite-actinolite deposits formed from fluids of a dominantly magmatic origin, having $\delta^{18}O$ of about +5.0 to +12.0‰ and δD of -60 to -30‰. The effects of the hydrothermal system which deposited the pitchblende, native Ag, Ni-Co arsenide-bearing veins on the isotopic composition of the altered rocks associated with the Mystery Island intrusive suite are difficult to evaluate, since fluids responsible for formation of the quartz veins may have ranged in time from lighter than to the same as those which formed the MAA zone alteration. However, no large-scale zoning of $\delta^{18}O$ or δD occurs around the veins.

Overall, the formation of magnetite-apatite-actinolite veins, pervasive replacement of rocks by albite and magnetite-apatite-actinolite, and *hydrothermal brecciation by magmatic fluids is consistent with geologic and isotopic data. Thus, it is inferred that these deposits formed by replacement in a hydrothermal system dominated by magmatic fluids exsolved by cooling epizonal plutons of the Mystery Island intrusive suite.*

I. INTRODUCTION

The Echo Bay and Camsell River areas are best known for their rich pitchblende, native Ag, Ni-Co arsenide vein deposits. These veins occur within the alteration haloes of several sill-like intermediate composition plutons known as the Mystery Island intrusive suite, and in one location, within one of the plutons. Despite a large number of studies of the pitchblende, native Ag, Ni-Co arsenide veins in the Echo Bay and Camsell River areas, few workers have examined the plutons of the Mystery Island intrusive suite or their altered and mineralized wall rocks. Badham and Morton (1976) carried out a study of the magnetite-apatite-actinolite deposits which form part of the alteration haloes associated with similar plutons in the Camsell River area. They concluded that the deposits formed by the injection of iron magmas formed as immiscible melts separated from a magma of intermediate composition. However, based on detailed geological, petrographical and geochemical data, Hildebrand (1986) concluded that magnetite-apatite-actinolite deposits in the Camsell River area were formed by deuteric-hydrothermal processes. A geological, petrographical, geochemical and stable isotopic study was undertaken in the Echo Bay area to determine the distribution of altered rocks, their relationship to the plutons of the Mystery Island intrusive suite, and the source of the fluids responsible for their formation.

Location

Echo Bay is located on the eastern shore of Great Bear Lake, Northwest Territories, 270 km north-northwest of Yellowknife (Figs. 1 and 2). The Echo Bay study area is within the Canadian National Topographic System map sheets 86L/1 (Echo Bay), 86K/4 (Vance Peninsula), and 86F/13 (Moody Lake), and includes the abandoned townsite of Port Radium.

Previous work

Geology of the Echo Bay - Camsell River area

Evidence of mineralization in the Echo Bay area was first recorded by J.M. Bell in 1900 (Bell, 1901), who noted the presence of "*cobalt bloom and copper green stain*". In 1929, Gilbert LaBine visited Echo Bay with E.G. St. Paul and located several minor occurrences of copper, cobalt and bismuth (The Staff, Eldorado, 1946). The following year, LaBine returned to the area and discovered the pitchblende and silver deposit which he called Eldorado. Eldorado began production three years later, and was the only known occurrence of pitchblende in Canada at that time (The Staff, Eldorado, 1946).

Numerous studies of Eldorado and related deposits in the Echo Bay and Camsell River areas were subsequently carried out, the most comprehensive by Kidd (1932) and Furnival (1935; 1939a, b), who studied the general geology of the area as well as the mineralogy, texture and paragenesis of the mineralized veins. Large-scale mapping of the Echo Bay area was completed by Robinson (1933), Riley (1935), Feniak (1947) and Furnival (1939a).

In 1944, Eldorado was taken over by the Canadian government and the Port Radium/Echo Bay area was mapped at the 1:4800 scale by Joliffe and Bateman (1944), Thurber (1946), Feniak (1947) and Fortier (1948), all of the Geological Survey of Canada. Mursky (1973) compiled large scale maps of the Port Radium area produced during the 1940's and 50's. More recently, Hoffman and Bell (1975), Hoffman et al. (1976), Hoffman (1978) and Hildebrand (1983a) mapped the lithologies of the Echo Bay area. More detailed mapping was carried out in the Camsell River area by Shegelski and Murphy (1973), Padgham et al. (1974) and Hildebrand (1983b). Robinson and Morton (1972) attempted to date rocks of the Port Radium and Echo Bay formations by K-Ar and Rb-Sr methods, but were unsuccessful due to thermal resetting at about 1400 m.y.

The first study of intermediate plutons of the Mystery Island intrusive suite in the Echo Bay area was that of Furnival (1939a; b), who provided a detailed description of the mineralogy, alteration, structure, stratigraphy and age relationships of one of the plutons. More recently, Cherer (1988) studied the petrology and geochemistry of three of the plutons of the Mystery Island intrusive suite in the Echo Bay area. In the Camsell River area (Fig. 3), Tirrul (1976) mapped mineralogical and compositional zoning within, and altered wall rocks above, one of two intermediate composition plutons similar to the plutons of the Mystery Island intrusive suite. Hildebrand (1983b; 1984b; 1986) mapped and studied in detail the geology, petrography and geochemistry of these plutons and associated magnetite-apatite-actinolite deposits in the Camsell River.

The origin of the magnetite-apatite-actinolite deposits at Great Bear Lake was first investigated by Badham and Morton (1976), who completed a geological and geochemical study of the deposits near Camsell River. They concluded that the magnetite-apatite-actinolite bodies were formed as immiscible liquids separated from intermediate silicate melts, and were intruded as a volatile-rich "crystal mush" at about 600°C. Hildebrand (1982; 1983b; 1986) mapped plutons and associated altered and mineralized rocks in the Camsell River area and recognized zoned alteration haloes within, and adjacent to, the plutons. He divided altered rocks into three zones: 1) an inner zone of albite; 2) an intermediate zone of magnetite-apatite-actinolite; and 3) an outer zone of pyrite. Hildebrand (1986) concluded that the mineralization was the result of replacement and brecciation of the country rocks by high-temperature, highly acid, chlorine-dominated fluids derived from epizonal plutons.

Pitchblende, Ag, Ni-Co arsenide vein deposits

Numerous geological, geochemical, and isotopic studies were carried out on the silver and pitchblende veins at Echo Bay and Camsell River (Kidd, 1932; Riley, 1935; Furnival, 1935, 1939a, 1939b; Campbell, 1955; Badham, 1972, 1973a, 1973b, 1975; Jory, 1964). The veins were dated by Jory (1964), who determined a U-Pb model age for pitchblende of 1429 ± 29 m.y. Thorpe (1971;1974) determined a Pb-Pb model age of 1625 m.y. for galenas and a U-Pb model age of 1445 m.y. for pitchblende, and attributed the discrepancy to updating of the pitchblende. Miller (1982) determined a U-Pb model age of 1500 ± 10 m.y. to 1424 ± 29 m.y. for pitchblende.

Robinson (1971) carried out geochemical and fluid inclusion studies of the veins. Robinson and Ohmoto (1973) presented data on mineralogy, fluid inclusions, $\delta^{18}O$ and $\delta^{13}C$ of vein carbonates, and $\delta^{18}O$ for quartz and hematite. They concluded that the veins were deposited in seven stages by seawater at temperatures of 200° to 95°C. Robinson and Badham (1974) determined the $\delta^{18}O$ and $\delta^{13}C$ of carbonates and $\delta^{34}S$ of sulphides from the veins, and concluded that the veins were formed by seawater at 200°C. More recently, Changkakoti et al. (1986a) determined $\delta^{18}O$ and $\delta^{13}C$ of carbonates, $\delta^{18}O$ of quartz, and δD of fluid inclusions in quartz, dolomite and calcite. They concluded that the veins were deposited by magmatic fluids with increasing input of meteoric water towards the final stages. Shegelski (1973), Shegelski and Scott (1975) and Changkakoti et al. (1986b) carried out detailed fluid inclusion studies of the veins, and concluded that they were deposited by boiling saline fluids from 450° to 90°C.

Current work: objectives and methods

This study presents the results of a detailed mapping, petrographic and stable isotopic study of the plutons of the Mystery Island intrusive suite and associated altered and mineralized rocks in the Echo Bay area (Fig. 4). The objective of this study was to understand the genesis of the alteration haloes, the origin of the magnetite-apatite-actinolite mineralization, and their relationship to the plutons of the Mystery Island intrusive suite. Excellent exposure of the plutons and their altered wall rocks in oblique cross-section allowed a unique assessment of geologic and geochemical variations with depth and distance from plutonic contacts.

The plutons of the Mystery Island intrusive suite and their altered wall rocks in the Echo Bay area were mapped at 1:15 000 scale to determine: 1) the distribution of altered rocks; 2) age relationships between the plutons and the alteration haloes; and 3) compositional variation within the alteration haloes. Outcrop in the area is excellent, up to 80 percent. Most outcrops were examined throughout the alteration zones, and in some areas, all outcrops were examined. Locally, detailed mapping at the outcrop scale was carried out to document relationships between rocks pervasively replaced by magnetite-apatite-actinolite and veins and pods of these minerals.

Petrography and geochemistry of the altered rocks were used to determine mineralogical and chemical variations within the plutons and their altered wallrocks. Stable isotopic analysis of the plutons, their wallrocks, and minerals from the magnetite-apatite-actinolite and pyrite zones were carried out to determine the isotopic composition of the fluids responsible for alteration.

II. GEOLOGIC SETTING

Regional geology

Wopmay orogen

The Mystery Island intrusive suite and associated magnetite-apatite-actinolite deposits are located within the Great Bear magmatic zone of Wopmay orogen (Hoffman, 1980, Hoffman and Bowring, 1984), an early Proterozoic orogenic belt located in the northwesternmost part of the Canadian Shield (Fig. 1). The Great Bear magmatic zone is the youngest magmatic belt within Wopmay orogen. Wopmay orogen formed as Hottah terrane, an exotic microcontinent, collided with the western margin of the Archean Slave craton at 1.88 Ga during the Calderian orogeny (Hildebrand and Bowring, 1991; Bowring and Grotzinger, 1992). The collision thrust rift-related, shelf-rise and overlying foredeep rocks deposited on the Slave craton, and 2.0 to 2.55 Ga gneissic rocks and 1.90 Ga volcanic and sedimentary cover of the Grant-Akaitcho groups (Hildebrand et al., 1991) eastward to produce a thrust-fold belt (Tirrul, 1983; King, 1986; Hoffman, 1987; Hoffman et al., 1988). Eastward subduction following collision led to continental arc magmatism of the Great Bear magmatic zone from 1.88 to 1.84 Ga (Bowring, 1984).

Great Bear magmatic zone

The Great Bear magmatic zone (Figs. 1 and 2) is a northerly-trending belt of continental arc rocks about 100 km across and 900 km in length (Hildebrand and Bowring, 1984; Hildebrand et al., 1987). The zone outcrops for 450 km along strike. Deformed rocks of Hottah terrane form the basement beneath most of the Great Bear magmatic zone. The Great Bear magmatic zone comprises minor amounts of tholeiitic basalt, mafic to felsic calc-alkaline volcanic rocks, ash-flow caldera-related rocks, lesser volcanogenic sedimentary rocks, and related plutons (Hoffman and McGlynn, 1977; Hoffman, 1972, 1982; Hildebrand, 1981, 1984; Hildebrand et al., 1987). Intermediate composition rocks are dominant. The Great Bear magmatic zone is synclinal, such that the oldest rocks outcrop in the east and west (Hoffman and McGlynn, 1977; Hildebrand and Bowring, 1984; Hildebrand et al., 1987).

Rocks of the Great Bear magmatic zone were intruded by a suite of biotite- and hornblende-bearing granitic plutons at about 1.843 Ga (Bowring, 1984). Shut-down of arc magmatism of the Great Bear magmatic zone was followed by oblique folding during a period of dextral transpression, possibly due to ridge subduction (Hildebrand et al., 1987) which folded rocks of the Great Bear magmatic zone about northwest-trending axes to expose oblique cross-sections through the crust. In the western part of the zone, large andesitic stratovolcanoes up to 3 km thick and synvolcanic epizonal plutons are exposed in oblique cross-section (Hildebrand, 1984a, b). Large syenogranitic plutons intruded the Great Bear magmatic zone after folding (Hildebrand et al., 1987). After cessation of all magmatism, the zone and its basement were cut by northeast-trending conjugate transcurrent faults (Fig. 2) (Hoffman, 1984; Tirrul, 1983). East-west-trending diabase dykes of the Cleaver dykes (Hoffman, 1982) postdate transcurrent faulting. The Cleaver dykes are cut by gabbroic sheets of several ages known as the Western Channel diabase.

General Geology (Echo Bay area)

Excellent exposure of the rocks in the Echo Bay area has allowed a thorough understanding of the geology in the area. Much of the area is mapped in detail, particularly within previous mining camps. The following geological descriptions are based largely on the accumulated results of previous workers in the Echo Bay area.

Labine Group

Host rocks to the Mystery Island intrusive suite in the Echo Bay area belong to the LaBine Group, a succession of silicious to intermediate lava flows, pyroclastic rocks, and related sedimentary rocks (Hoffman and McGlynn, 1977). Rocks of the LaBine Group (Figs. 3 and 4; Table 1) outcrop on the western margin of the Great Bear magmatic zone. They unconformably overly rocks of the Bell Island Group (Hildebrand and Roots, 1985), which represents a pre-Calderian cover sequence on Hottah terrane (Hildebrand et al., 1990). The LaBine Group was probably deposited in a continental to marginal marine environment, as indicated by rare marine sedimentary rocks and features such as mud cracks, ripple marks and herringbone cross-beds

(Hildebrand, 1981; 1984a). In the Echo Bay area, the LaBine group comprises the Port Radium, Echo Bay and Cameron Bay formations, and is described in detail by Hildebrand (1981; 1984b).

Port Radium Formation

The Port Radium Formation (Table 1) is the oldest unit of the LaBine Group in the Echo Bay area. It consists of at least 1 200 m of fine- to coarse-grained sedimentary rocks (Hildebrand, 1981). The base of the formation is truncated by the Richardson pluton (Fig 5). In general, the sequence coarsens upwards, from fine-grained sedimentary facies to subaerial conglomerates and air-fall tuff (Hoffman and Bell, 1975). However, the dominant rock type is laminated to thinly bedded, gray siltstone to fine sandstone. Graded beds and cross-bedding are present locally. The Port Radium Formation is conformably overlain by the Echo Bay Formation.

Echo Bay Formation

The Echo Bay Formation (Table 1) consists of subaerial, plagioclase porphyritic and amygdaloidal, hornblende- and augite-bearing andesitic lava flows, rare rhyodacite flows, epiclastic rocks and breccias (Hildebrand, 1981; 1984). The exposed section of the Echo Bay Formation in the Echo Bay area is nearly 3000 m thick, and lies conformably upon the Port Radium Formation. The lower 400 m of the formation consists of intercalated epiclastic rocks and lava flows, whereas the upper part of the formation is composed mostly of lava flows with minor amounts of epiclastic rocks (Hildebrand, 1981).

Epiclastic rocks of the Echo Bay Formation consist of volcanogenic sandstone, conglomerate, debris flow deposits, and reworked tuffs (Hildebrand, 1981). The lava flows which comprise most of the Echo Bay Formation are plagioclase porphyritic, and contain from 5 to 45% subhedral to euhedral, platy plagioclase phenocrysts up to 6 mm in length. Minor amounts of hornblende, and less commonly, augite, are also found as subhedral to euhedral phenocrysts up to 5 mm in length. Some of the flows contain up to 20 % quartz-filled amygdules up to 1 cm in diameter, which locally contain chlorite and calcite. Some flows have flow-top breccias.

Cameron Bay Formation

The Cameron Bay Formation (Table 1) consists of at least 4000 m of volcanic rocks and fine- to coarse-grained sedimentary rocks of volcanic and plutonic provenance (Hildebrand, 1981; 1982; 1983a). The volcanic rocks are dominantly tuffs, with lesser amounts of lava flows. Rocks of the Cameron Bay Formation also interfinger with andesites of the Echo Bay Formation (Hoffman and Bell, 1975; Hildebrand, 1983a). The Cameron Bay Formation is separated from the underlying Echo Bay Formation by local unconformities formed during synvolcanic erosion, and characterized by highly ferruginous conglomerate. Boulders of similar composition to plutons of the Mystery Island intrusive suite are found in a conglomerate in the Echo Bay area (Hildebrand, 1981). A conglomerate mapped above the Contact Lake pluton contains fragments of altered andesite, some of which contain abundant magnetite, as well as abundant vitreous quartz grains (Reardon, 1990). Thus, the altered rocks above the Contact Lake pluton were eroded and at least one of the plutons was probably exposed before the termination of volcanism of the Echo Bay Formation. A small intrusive body similar to the plutons of the Mystery Island intrusive suite cuts the Cameron Bay Formation near Cameron Bay (Hildebrand, 1984). The Cameron Bay Formation is overlain by volcanic and sedimentary rocks of the Feniak Formation and the Sloan Group (Hoffman and Bell, 1975; Hoffman, 1978).

Mystery Island intrusive suite

The Mystery Island intrusive suite (Hildebrand, 1981) comprises five semi-concordant, epizonal plutons: the Bertrand Lake, McLeod Lake, Contact Lake, Glacier Lake and Tut plutons (Figs 3 and 4). Two synvolcanic plutons similar in composition to the plutons of the Mystery Island intrusive suite occur in the Camsell River area (Fig. 3). Although the stratigraphy of the hostrocks of these plutons is not directly correlative between the Echo Bay and Camsell River areas, similar U-Pb ages, rock types and regional stratigraphic positions suggest that volcanism in both areas was roughly contemporaneous (Hildebrand, 1986).

The plutons of the Mystery Island intrusive suite are sill-like in cross-section, up to 10 km across, and up to 2 km thick. The plutons were emplaced at two distinct stratigraphic levels within the LaBine Group (Hildebrand, 1984). The Bertrand Lake pluton (Figs. 4, 5) was emplaced within the Port Radium Formation and the lowermost part of the conformably overlying Echo Bay Formation. The other plutons were intruded approximately 1 km above the Bertrand Lake pluton, within andesitic lava flows of the Echo Bay Formation. Younger granitic plutons of the Great Bear batholith truncate some of the plutons.

Plutons of the Mystery Island intrusive suite are intermediate in composition, consisting of fine- to medium-grained seriate diorite - monzodiorite - monzonite - quartz monzodiorite - quartz monzonite (IUGS, Streckeisen, 1973). Locally, the plutons contain more quartz, and are granodioritic to granitic (Cherer, 1988).

All of the plutons contain 30 to 50% subhedral to euhedral, seriate plagioclase phenocrysts, that are weakly to very strongly sericitized, and locally epidotized. Interstitial cloudy, anhedral alkali feldspar up to 3 mm in length comprises 10 to 30% of the rock. Quartz occurs as 1 to 4 mm interstitial, anhedral grains and comprises 5 to 25% of the rock. Hornblende (20 to 30%) and biotite (5 to 15%) are the primary mafic minerals, and are partially to completely altered to chlorite. Some biotite is altered to magnetite along cleavage planes. Minor euhedral to subhedral 1 to 2 mm clinopyroxene phenocrysts are present near plutonic margins. Very fine-grained magnetite less than 1 mm and very fine-grained euhedral apatite and subhedral zircon are ubiquitous accessory minerals. Most of the plutons contain minor amounts of riebeckite, and pods and veins of tourmaline are present locally. Quartz, calcite and chlorite veinlets occur throughout the plutons.

Bertrand Lake pluton

The Bertrand Lake pluton outcrops from the shore of Great Bear Lake eastward beyond Mile Lake, and on a displaced section on Mystery Island (Figs. 4 and 5). The upper contact of this pluton is sharp, generally trending parallel to bedding within the Port Radium and Echo Bay Formations. The lower contact is truncated by the Richardson pluton.

Internally, the pluton is compositionally heterogeneous, consisting of fine- to medium-grained diorite to quartz-diorite to the west and monzonite to the east. It generally comprises about 50% subhedral plagioclase phenocrysts and 15 to 35% anhedral alkali feldspar. The pluton contains 5 to 12% fine-grained, anhedral quartz. The mafic minerals are dominantly subhedral hornblende with lesser biotite, and constitute 15 to 20% of the rock, but up to 40% near the lower contact. Accessory minerals are magnetite (2 to 3%), trace zircon and apatite (up to 2% near the lower contact). Minor riebeckite occurs near the centre of the pluton. All samples examined are strongly altered; plagioclase is strongly sericitized and the mafic minerals are completely chloritized. The upper border phase contains 60% plagioclase phenocrysts and minor clinopyroxene. Locally, adjacent to the lower contact, the pluton contains up to 20% epidote.

McLeod Lake pluton

The McLeod Lake pluton crops out in at least three fault-bounded segments between Contact Lake and McLeod Lake (Figs. 4 and 6). The upper contact is sharp and regular, and the lower contact is completely truncated by the Richardson pluton. Only the northernmost part of the pluton was mapped during this study.

The pluton is homogeneous and consists of moderately altered, medium-grained quartz monzonite, containing 35% partially sericitized, subhedral plagioclase, 20 to 30% anhedral potassium feldspar, 10 to 20% anhedral quartz and minor granophyre. Mafic minerals, mostly hornblende and lesser biotite, comprise 15 to 30%, are strongly chloritized, and are more abundant towards the bottom of the pluton. Accessory phases are magnetite, apatite, titanite, epidote and riebeckite.

Contact Lake pluton

The Contact Lake pluton outcrops along the north side of Contact Lake (Figs. 4 and 6). The upper contact is sharp and locally irregular. The lower contact is sharp where exposed, but is mostly truncated by the intrusion of the Richardson pluton.

The pluton is zoned internally, consisting of fine- to medium-grained seriate quartz monzodiorite to quartz monzonite, and granite near the lower contact at Contact Lake (Cherer, 1988). The pluton comprises of 35 to 45%

weakly to strongly sericitized and epidotized, subhedral plagioclase, 15 to 35% anhedral potassium feldspar, and 10 to 25% quartz. Mafic minerals consist of 10 to 20% subhedral, chloritized hornblende, less than 5% chloritized biotite, and minor clinopyroxene locally. The pluton contains 1 to 3% magnetite, up to 3.5% epidote and 1.6% calcite locally (Cherer, 1988), minor granophyre, and trace apatite, titanite, zircon, and riebeckite.

Glacier Lake pluton

The Glacier Lake pluton outcrops in two areas separated by a right-lateral transcurrent fault with greater than 2 km separation. The pluton crops out at Echo Bay (Figs. 4 and 7) and southeast of Glacier Lake (Fig. 8). Both the upper and lower contacts of the pluton are sharp.

A fine-grained, clinopyroxene-bearing border phase occurs at the lower contact. The pluton shows little internal compositional variation and consists of fine- to medium-grained, seriate quartz monzodiorite - quartz monzonite to monzogranite comprised of 40% weakly to strongly sericitized plagioclase, 30% potassium feldspar, 15 to 25% quartz, and 10 to 15% chloritized hornblende and biotite. Granophyre occurs locally. The pluton contains minor magnetite, up to 2.5% riebeckite, and up to 1% apatite, titanite, zircon, calcite and epidote.

Tut pluton

The Tut pluton (Figs. 4 and 8) is exposed over 18 km^2 on the shore of Great Bear Lake and occupies the core of a syncline (Hildebrand, 1984). The upper and lower contacts are, therefore, not extensively exposed. Where exposed, contacts are sharp.

The pluton consists of seriate to porphyritic fine- to medium-grained quartz monzodiorite - quartz monzonite - monzogranite - granodiorite and contains at least one small area of diorite in sharp contact with the main body of the pluton. The pluton comprises 30 to 40% moderately to strongly sericitized, subhedral plagioclase phenocrysts, 20 to 30% anhedral alkali feldspar, 15 to 30% anhedral quartz, less than 2 to 4% chloritized biotite, 5 to 25% chloritized hornblende, 1 to 2% magnetite, and trace riebeckite, apatite, titanite, calcite, zircon. Rare, discontinous veins of specular hematite up to 3 cm wide occur locally.

Richardson pluton

The 1.84 Ga Richardson pluton (Figs. 5 and 6) (Bowring, 1984) is a coarse-grained biotite syenogranite of the Great Bear batholith. It comprises the southwestern portion of the map area and truncates the lower contacts of the Bertrand Lake and Contact Lake plutons. The pluton has sharp contacts and shows no visible evidence of extensive alteration within the pluton itself or within the adjacent wall rocks.

Structural geology (Echo Bay area)

Rocks of the Great Bear magmatic zone underwent two periods of compressive deformation and a later period of extension. Cessation of arc magmatism in the Great Bear arc at 1.84 Ga was followed by a period of dextral transpression which folded the arc about northwest-trending, gently plunging axes (Hoffman and McGlynn, 1977; Hildebrand and Bowring, 1991). The folds are asymmetrical and have wavelengths of 1 to 15 km (Hildebrand, 1984). Northeasterly-dipping limbs are longer, and expose large parts of the Great Bear magmatic zone in oblique cross-section. The plutons of the Mystery Island intrusive suite in the Echo Bay area are exposed on the southern limb of a fold, except the Tut pluton, which occurs in a syncline (Hildebrand, 1984). Locally, at Port Radium, siltstones are openly folded on the scale of meters, with some smaller, tight folds and chevron folds. There is no megascopically visible penetrative deformation associated with folding.

Numerous northeast-trending, vertical transcurrent faults cut the Great Bear magmatic zone (Fig. 2) (Hoffman, 1984; Tirrul, 1983). The faults have right-lateral separation of up to several km, and are commonly joined to each other by northwest-trending sinistral and east-trending faults which have smaller separations and are less numerous than the northeast-trending faults (Tirrul, 1983).

Within in the Echo Bay area, the transcurrent faults have right-lateral separation of up to 2 km in the Echo Bay area (Fig. 4). Two major sets of faults related to regional transcurrent faulting are present in the Port Radium area, one at about 045° and a second at about 005°. Numerous smaller veins occur at various orientations. The fault zones are filled with quartz veins and stockworks.

The transcurrent faults were later reactivated, and have undergone several periods of movement, as indicated by multiple generations of breccias (Furnival, 1939). The most recent movement along these faults occurred during a period of extension which resulted in dip-slip movement (Furnival, 1935; Hoffman et al., 1976; Hoffman and McGlynn, 1977) which may be contemporaneous with pitchblende, native Ag, Ni-Co arsenide mineralization (Campbell, 1955; Hildebrand, 1988b; Bowring et al., 1989). West-side down normal faulting is recognized within rocks of the Hornby Bay Group which unconformbly overlie the Great Bear magmatic zone (Hoffman and McGlynn, 1977; McGrath and Hildebrand, 1984; Kerans et al., 1981).

III. PETROGRAPHY AND GEOCHEMISTRY OF ALTERED AND MINERALIZED ROCKS

Although regional metamorphism in the Great Bear magmatic zone is subgreenschist facies, all of the wall rocks of the Mystery Island intrusive suite are moderately to very strongly altered. Zonation of altered rocks associated with intermediate composition plutons in the Camsell River area (Fig. 3) was first mapped by Hildebrand (1986), who recognized three zones above and within the plutons: 1) an albite zone, present within and adjacent to the plutons; 2) a magnetite-apatite-actinolite zone, beyond the albite zone;

and 3) an outer pyrite zone. All three zones are also present, and were mapped in the Echo Bay area.

Albite zone

The albite zone is characterized by pervasive replacement of the host rock by albite; albitized rocks are red-brown to pale pink. Albitized rocks generally occur within 100 m of the plutonic roofs, but locally are found up to 1 km above the plutons. Altered rocks also occur locally within and below the plutons. Extensively altered rocks, found in close proximity to the plutons, are white both on the fresh and weathered surfaces. Veins and pods of albite are present in some highly-altered areas. The albite zone commonly overlaps with the magnetite-apatite-actinolite and pyrite zones.

In thin section, rocks within the albite zone are replaced by fine-grained, equant albite up to 4 mm. In andesitic lavas, the groundmass is replaced first, and plagioclase phenocrysts are partially recrystallized at crystal margins in strongly altered rocks. Extremely altered rocks contain very fine-grained, polygonal albite with minor disseminated chlorite. Chlorite is ubiquitous, and comprises up to 15% of albitized andesitic lava flows. Up to 15% very fine-grained, anhedral epidote is also present in most samples. Minor magnetite occurs as corroded crystals or ragged patches with anhedral titanite. Some andesitic lava flows in the albite zone contain riebeckite within plagioclase phenocrysts. Albitized plutonic rocks contain very fine-grained, anhedral to subhedral, granular unaltered albite around strongly sericited plagioclase (labradorite to andesine) phenocrysts. In sedimentary rocks, very fine-grained, anhedral to subhedral albite preferentially replaces individual beds.

Magnetite-apatite-actinolite zone

The magnetite-apatite-actinolite (MAA) zone is defined by the presence of at least two of the three minerals: magnetite, apatite or actinolite. These minerals also occur as disseminated crystals, veins, pods, and breccias above the plutons, and locally, within and below them. Chemical analyses of mineral phases from veins and pervasively altered rocks were obtained using the Cameca RSX11M microprobe at McGill University (Appendix A).

The mode of occurrence of magnetite, apatite and actinolite varies with original lithology. In andesitic lava flows, these minerals are disseminated and constitute up to 35% of the rock. In sedimentary rocks, albite, actinolite, apatite and magnetite replace individual beds. Some pervasively altered andesite flows and sedimentary rocks are cut by veins of magnetite-apatite-actinolite or magnetite-actinolite (Fig. 9). The most common assemblages of these alteration minerals, in order of abundance, are: 1) actinolite + magnetite; 2) actinolite + apatite; and 3) magnetite + apatite + actinolite. The plutons are cut by veins of actinolite or actinolite-apatite near their upper contacts. MAA breccias, typically present near the plutonic contacts, comprise angular to sub-rounded fragments of country rock up to 1 m in diameter in a matrix of medium- to coarse-grained magnetite (± pyrite, chalcopyrite), actinolite, apatite, epidote and albite (Fig. 10). Actinolite-rich breccias, which occur as pink (albitized?) fragments in a dark, actinolite-magnetite matrix, are also found near plutonic contacts.

In thin section, andesite flows partially replaced by MAA contain fine-grained, secondary actinolite to 3 mm in length within the groundmass, and as overgrowths on hornblende. Actinolite (after the classification of Leake, 1978), is the most common mineral within the MAA zone and comprises up to 35% of the rock. The actinolite contains from 0.02 to 1.34 wt% fluorine, and is commonly chloritized. Locally, fine-grained anhedral epidote comprises up to 25% of the rock. Apatite occurs as subhedral to euhedral crystals less than 1 mm in diameter in the groundmass and within secondary actinolite, and comprises up to 3% of the rock. Magnetite occurs within feldspar, epidote and actinolite as finely-disseminated grains or subhedral crystals to 4 mm, and comprises up to 15% of the rock. The magnetite is partially hematized on rims and along cleavage planes. Where the albite zone and MAA zone overlap, albite is replaced by actinolite, epidote, and magnetite, and less commonly, calcite. Calcite also replaces actinolite, and commonly occurs with secondary titanite, and locally with specularite. Titanium-rich Mg-biotite (4.32 wt.% TiO_2) occurs in a magnetite-poor, actinolite-rich altered andesite flow south of the Tut pluton.

Veins of MAA up to 80 cm wide are discontinuous and generally exposed along strike for less than 1 m. The veins have various orientations, but generally strike E-W and N-S and are steeply dipping. Pods are generally less than 1 cm in diameter, but many are up to several decimeters across. Actinolite is the most abundant mineral and occurs as laths up to 5 cm in length. Magnetite crystals are subhedral to euhedral, up to 8 cm in diameter, but generally less than 1 cm. Apatite occurs as dark pink to mauve, subhedral to euhedral crystals up to 5 cm in length.

Magnetite in the MAA zone is characterized by low titanium (less than 0.5 wt.% TiO_2), low Cr_2O_3, and about 0.5 wt.% V_2O_5. Badham and Morton (1976) reported average values for magnetites from the Camsell River area of 0.12 ±0.03 wt.% V and 0.55 ±0.03 wt.% Ti from wet chemical analyses. All vein magnetite is partially altered to hematite (martite) on rims and along cleavage planes. Hematite (martite) contains less than one percent impurities. Primary hematite (specularite) also occurs in some of the veins, and is similar in composition to the martite. A single occurrence of ilmenite from an actinolitized andesite flow is manganese-rich (6.4 wt.% MnO). A titanium-manganese-iron mineral, possibly pyrophanite, observed in trace amounts in two samples of magnetite- and actinolite-rich altered andesite flows.

Fluorapatite, which occurs as fine to coarse, pink to mauve, subhedral to euhedral crystals in the field, is usually interstitial to magnetite, but also occurs within magnetite and actinolite. Apatite from four samples of pervasively replaced andesitic lava flows and MAA veins have fluorine contents of about three percent, similar to the fluorapatites in the Camsell River area (Hildebrand, 1986). Fluorine-rich chlorite and biotite are present in some veins. F-rich talc occurs in a specularite- and pyrite-bearing magnetite-actinolite vein, and replaces actinolite in an actinolite vein within the Tut pluton. A vein within the Port Radium Formation above the Bertrand Lake pluton contains chloritized actinolite, epidote, quartz and hematite-lined vesicles less than 4 mm in diameter. Minor amounts of titanite and carbonate are present in all vein and breccia samples studied in thin section. Minor pyrite is present in some veins.

In sedimentary rocks, beds are preferentially replaced by albite, actinolite or magnetite, and the replaced rocks contain up to 45% actinolite and up to 25% magnetite. Fluorine-rich Mg-biotite (2.76 wt% F) occurs in siltstone of the Port Radium Formation which is replaced by MAA. Limy beds at Port Radium are replaced by very fine-grained, massive magnetite. Where the albite zone and MAA zones overlap, albite is an early mineral, and is replaced by actinolite, epidote and ragged magnetite. Actinolite is also replaced by magnetite and minor subhedral titanite. Magnetite is partially hematized.

Pyrite zone

The pyrite zone is characterized by the presence of disseminated pyrite crystals or pods up to several centimeters in diameter which form visible rusty patches on weathered outcrop surfaces, or extensive gossans where pyrite is locally abundant. Veins of pyrite up to 1 cm wide are also observed. The pyrite zone occurs principally above the plutons, but locally within and below them. The zone is irregular and discontinuous, and is generally found at some distance above the roofs of the plutons. However, one gossan, more than 1 km across, is present directly above the northern portion of the Glacier Lake pluton (Fig. 8). The pyrite zone commonly overlaps the MAA zone, and in one outcrop north of Port Radium, pyrite is disseminated throughout magnetite-apatite-actinolite rock which is cut by a pyrite vein.

In thin section, pyrite occurs as finely disseminated, subhedral to euhedral crystals less than 0.5 mm across. Titanite is commonly present in rocks of the pyrite zone as anhedral crystals adjacent to pyrite and magnetite. One sample is cut by a 0.1 mm pyrite-titanite veinlet. Pyrite also replaces magnetite within the MAA zone locally, and is itself replaced by hematite.

A possible subzone of the pyrite zone east of Port Radium (Fig. 8) is characterized by the presence of finely-disseminated chalcopyrite within the groundmass and within amygdules in andesitic lava flows. The zone is subparallel to stratigraphy. Higher concentrations of pyrite and chalcopyrite are present in sedimentary rocks than in andesitic lavas and porphyries. This may be due to differences in permeability and/or composition of the two lithologies.

Distribution of alteration

All of the plutons of the Mystery Island intrusive suite have associated zoned alteration haloes, although the zones are somewhat irregular and discontinuous. The type and distribution of alteration varies slightly with each pluton, and detailed descriptions of the alteration associated with each of the plutons are given below (see Plate 1).

Bertrand Lake pluton

Alteration adjacent to the Bertrand Lake pluton (Fig. 5) consists of albitization and replacement of sedimentary rocks of the Port Radium Formation by actinolite. Alteration within andesitic lava flows of the Echo Bay Formation is present as small veinlets and disseminations of actinolite, and, less commonly, actinolite-magnetite. Apatite was observed, but is uncommon. At the upper contact of the body, intense alteration within the pluton is present as numerous small veins of actinolite, apatite, actinolite-magnetite and actinolite-magnetite-apatite, particularly in a small plug just above the pluton northwest of Mile Lake. Alteration associated with the Bertrand Lake pluton is much less extensive than for the other plutons.

McLeod Lake pluton

Only the northernmost portion of the pluton was mapped in detail. Alteration is not extensive, and consists of albitization close to, and within plutonic contacts, and localized areas of MAA and pyrite which are not extensive (Fig. 6 and Plate 1).

Contact Lake pluton

Rocks above the Contact Lake pluton (Fig. 6) show the most spectacular example of alteration in the Echo Bay area. Most alteration is concentrated within a zone roughly parallel to the roof of the southeastern half of the pluton, although there is minor alteration both below and within the pluton.

Above the pluton, alteration extends outward in a narrow zone which has a core of intensely albitized andesite overlapping a broader area of intense magnetite-apatite-actinolite alteration. Albitized andesitic lava flows pervasively replaced by MAA are cut by pods and veins of actinolite-magnetite-apatite which are generally 1 to 5 cm wide, but range up to 15 cm wide. This area of intensely altered rock may reflect the presence of an upward protusion of the pluton below the surface, or an area of localized fluid flow. Locally MAA constitutes up to 20% of the rock, which also contain fine- to coarse-grained albite. Subhedral, mauve apatite crystals up to 5 mm comprises up to 5% of the rock. Pyritic alteration is also well-pronounced as gossans greater than 50 m in width, which overlap both the albite and MAA zones.

Glacier Lake pluton

Alteration near the Glacier Lake pluton (Figs. 7, 8) is manifested by large, irregular zones of intense pyritization above the pluton. Other alteration consists of minor disseminated actinolite and veins less than 3 cm wide of actinolite within the pluton and in andesitic lava flows near the upper and lower contacts of the pluton. The MAA zone is restricted to a narrow U-shaped zone near the southern end of the pluton (Fig. 7), where large veins of coarse actinolite-magnetite-apatite up to 80 cm wide contain magnetite crystals to 8 cm. Directly below the pluton, pervasive albitization, magnetite-apatite-actinolite alteration and breccias are present in a narrow, elongate zone adjacent to a narrow extension of the pluton perpendicular to the lower contact (Fig. 7).

Tut pluton

The upper contact of the Tut pluton is not exposed, since the pluton outcrops in the core of a syncline (Hildebrand, 1984). At the southwestern contact, extensive albitized zones are present both within the pluton and the country rocks (Fig. 8). Near Glacier Lake, actinolite pods and veins up to 1.5 m are present within the pluton. In two locations, zones up to 3 m across of breccia comprising subrounded, very fine-grained pink fragments to several centimeters in diameter in an actinolite- and magnetite-rich matrix occur near pluton contacts. Discontinuous veins of specular hematite to 3 cm wide are also found locally within the pluton.

All three types of alteration are found southwest of the pluton, and extend west to the shore of Great Bear Lake and south to Port Radium. However, albitic alteration increases westward toward Great Bear Lake, and MAA occurs east of the lake, about 500 m from the shore. The pyrite zone is present east of the MAA zone. This suggests the former presence of another pluton to the west, possibly an extension of the Bertrand Lake pluton. In 1989, a small, fault-bounded portion of a pluton very similar in texture and composition to the Mystery Island intrusive suite was identified on Cobalt Island at Port Radium (Fig. 8) (Reardon, 1990).

Whole-rock geochemistry of altered rocks

Thirty samples from the Labine Group and Mystery Island intrusive suite were analyzed for major, trace and rare earth elements at the Geological Survey of Canada. Major and minor elements (SiO_2, TiO_2, Al_2O_3, Cr_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5) were obtained by X-ray fluorescence wavelength dispersive analysis on fused disks, except FeO, which was obtained by rapid chemical methods. H_2O, CO_2, C and S were obtained by wet chemical methods. Fe_2O_3 was calculated using Fe_2O_3T (XRF) - 1.11134 (volumetric). The rare earth element values were determined by ICPMS, ICPES and GFAA. Major, trace and rare earth element data are listed in Table 2. All data used in the plots were recalculated to 100% on a volatile-free basis. See Plate 1 for sample locations.

Andesite

The susceptibility of the andesitic lava flows to alteration is reflected in their volatile contents. Andesite lava flows of the Echo Bay Formation have variable water contents ranging from 0.9 to 4.8 wt.%. CO_2 contents are also variable, ranging from 0.1 to 4.7 wt.%. Elemental variation is greater in the andesites as compared to the plutons.

Major, minor, and trace elements for altered andesitic lavas ranging from 56 to 60 wt.% SiO_2 within the alteration haloes of the Glacier Lake pluton were plotted against Na_2O and K_2O. Samples with limited ranges of SiO_2 were used to eliminate the effects of magmatic differentiation on elemental variation. Gd, Dy, Be, Yb, Y, Sm, MgO and Na_2O increase with decreasing K_2O (Fig. 11). The two samples with low K_2O occur within the MAA zone; the other two samples occur further above the pluton roof. Most of these variations are due to substitution of these elements in feldspars. The higher MgO content of the low K_2O samples in the MAA zone, however, is probably due to their increased actinolite content.

Plutons

Of the four plutons of the Mystery Island intrusive suite studied in detail (Tut, Glacier Lake, Contact Lake, Bertrand Lake), the Tut pluton is least altered, and shows a normal magmatic trend of increasing K and decreasing Na with increasing SiO_2 content (Fig. 12). One sample from the Tut pluton is albitized, and has 5.3 wt.% Na_2O (Fig. 12). The presence of albite in this sample was confirmed by XRD analysis. The Bertrand Lake and Contact Lake plutons are Na-matasomatized, as indicated by high Na contents which do not correlate with SiO_2 content. However, part of the Glacier Lake pluton is K-metasomatized, as indicated by elevated K_2O contents not correlative with an increase in SiO_2 content. Six samples from the Contact Lake pluton, ranging in SiO_2 content from 63 to 65 wt.% SiO_2, and five samples from the Glacier Lake pluton ranging from 67 to 68 wt.% SiO_2 were used to evaluate the effects of Na- and K-metasomatism, respectively (Fig. 13). Samples with limited ranges of SiO_2 were used to eliminate the effects of magmatic differentiation on elemental variation. In both plutons, only Na and K vary antithetically, and no regular variations among other elements are observed.

Profiles of SiO_2, Na_2O and K_2O with relative height in the pluton for the Glacier Lake pluton (Fig. 14a) show a regular, antithetic variation of Na_2O and K_2O. SiO_2 is constant at 68 wt.% +/-1 wt.%, except one sample from near the top of the pluton, which is slightly depleted in SiO_2 (65.5 wt.%) and K_2O (5 wt.%), and enriched in Na_2O (2.5 wt.%) relative to the other samples. The Contact Lake pluton is reversely zoned, and K_2O and SiO_2 decrease with increasing height in the pluton (Fig. 14b). Na_2O contents range from 2 to 3 wt.% and increase steadily with height in the pluton, except one albitized sample near the top of the pluton which has a slightly higher Na_2O content (Fig. 14b).

V. PITCHBLENDE, NATIVE AG, NI-CO ARSENIDE VEIN DEPOSITS

The Echo Bay area is best known for its silver and uranium deposits. Several mines (Fig. 3) have operated in the area, and have produced more than 15 million ounces of silver and over 14 million pounds of U_3O_8 (McNiven, 1967). However, the origin of the mineralization remains obscure. These deposits are classified as Ag - sulpharsenide deposits (Bastin, 1939), and are similar to those of the Cobalt-Gowganda camp (Andrews et al., 1982); Jáchymov, Czechoslovakia (Mrna, 1963), Kongsberg district, Norway (Neumann, 1944); Khovou, U.S.S.R (Kroutov, 1972); Chalanches, France (Ypma, 1972); and Saxony (Rosler and Bauman, 1970).

Mineralogy and paragenesis

Quartz-carbonate veins, many of which contain sulphides, are found throughout the study area. The principal minerals of non-economic veins in the Echo Bay area are quartz, calcite, siderite, chalcopyrite, hematite and pyrite. Minor amounts of nickel-cobalt arsenides are present locally. Most of the veins contain strongly chloritized, or, less commonly, hematized fragments of country rock. The veins are divided into several types according to their mineralogy: 1) quartz (± carbonate), 2) quartz + hematite (± carbonate) 3) quartz (± carbonate) + chalcopyrite (± pyrite) (Reardon, 1990). In all veins quartz was deposited first, followed by hematite or sulphides. Most of the veins contain carbonate, usually siderite, which is younger than quartz. Where carbonate and sulphide minerals are both present, the sulphides are found within the carbonate. Veins of calcite and siderite are common and many contain chalcopyrite. Locally, veins of siderite cut quartz-siderite-sulphide veins.

The mineralogy and paragenesis of economically mineralized veins in the Echo Bay area were studied by numerous workers (see "Previous work - pitchblende, Ag, Ni-Co arsenide vein deposits"), and therefore will not be discussed in detail. Based on fluid inclusion work, the veins were deposited during at least five stages of hydrothermal activity by saline fluids ranging from 15 to 35 wt.% NaCl equivalent, at temperatures of 90°to 450°C (Changkakoti et al., 1986b). Calculated $\delta^{18}O$ of the ore fluids range from +0.47‰ to +9.12‰ (Changkakoti et al., 1986b).

Distribution and geometry

The vein system within the Echo Bay area is complex. Quartz and quartz-carbonate veins are present throughout the study area, but are more abundant in the Port Radium area than elsewhere. Kidd (1932) described two sets of faults in the Port Radium area, one at about 045° and a second at about 005°, as well as smaller veins at various directions. The veins dip steeply to the northwest, are up to 15 m wide, and are traced up to 450 m along strike.

Furnival (1935; 1939a; 1939b) described the structural geology of the Contact Lake area (Figs. 4 and 6). There the dominant trend of the veins is 075°, and they dip steeply to the southeast. Furnival (1939b) noted that veins in the Contact Lake pluton followed older altered zones which contain chlorite, garnet, epidote actinolite, pyrite, magnetite, hematite and arsenopyrite and later veins of magnetite and hematite. Since the mineralized veins pass from altered granodiorite into unaltered granodiorite, and displace the magnetite-hematite veins, the altered zones cannot be related to the pitchblende, Ag, Ni-Co arsenide veins. Elsewhere in the Echo Bay and Camsell River areas, the mineralized veins occur within the magnetite-apatite-actinolite and pyrite zones (Hildebrand, 1988b; Reardon, 1989). Pitchblende, native Ag, Ni-Co arsenide vein mineralization may be localized by the altered wallrocks of the Mystery Island intrusive suite, as suggested by Hildebrand (1988).

Age relationships

Kidd (1932) noted that the veins at Port Radium were subjected to repeated fracturing. Furnival (1935) recognized two major periods of movement: one which predates and one which postdates the 1.7 Ga Hornby Bay Group. Campbell (1955) argued that many of the veins filled faults and tension fractures related to the NE-trending transcurrent faults, and proposed that a major period of fracturing was followed by three periods of extension, the last involving a dip-slip movement contemporaneous with mineralization.

Jory (1964) described a diabase dyke in the Eldorado mine (Fig. 3) at Port Radium which intersects and is diverted by quartz veins. The dyke is brecciated by later movement on the veins and healed by vein mineralization. Jory (1964) also reported that a diabase sill in the mine is not offset by quartz veins, but is affected by late mineralization. Robinson (1971) concluded that diabase dykes in the Eldorado mine are younger than the initial development of the vein structures but older than most of the vein minerals. In agreement with Jory, Robinson (1971) concluded that a diabase sill in the mine cut all but the latest stages of mineralization. The cross-cutting relationships of the veins and diabase dykes and sills described by Jory (1964) and Robinson (1971) suggest that faulting and vein formation at Port Radium took place before and after the emplacement of the dykes, and that the youngest period of vein formation is contemporaneous with mineralization.

Since most mineralized veins strike northeast, it might seem reasonable to relate them to northeasterly-striking transcurrent faults. However, the largest transcurrent faults in the area are not known to be mineralized, although they contain quartz stockworks up to 30 m wide (Furnival, 1935). Whereas strike-slip faults only develop dilatant zones at bends (Crowell, 1974), it is difficult to explain how mineralized veins, up to 1.5 km long and with features characteristic of extension, would be generated along such faults.

Along the western side of the Great Bear magmatic zone, a number of workers have identified west-side-down normal faults which juxtapose rocks of the lower Hornby Bay Group against rocks of Wopmay orogen (Kerans et al., 1981; Hildebrand, 1982; Hoffman, 1984; McGrath and Hildebrand, 1984; Ross and Kerans, 1989). The presence of mineralization in northeasterly-striking fault zones may be explained by relating the timing of mineral deposition to west-side-down normal faulting, as proposed by Campbell (1955) and later by Hildebrand (1988b). The hydrothermal cells which were responsible for the mineralization may have been driven by 1663 +/-8 Ma (Bowring and Ross, 1985) magmatism of the lower Hornby Bay Group (Hildebrand, 1988b).

Robinson and Ohmoto (1973) argued that diabase dykes and sills, actinolite-magnetite veins and pitchblende, native Ag, Ni-Co arsenide veins are closely related in time, and were formed at about 1450-1400 Ma based on: K-Ar ages of 1400 Ma (1405 Ma new standardized age, Steiger and Jager, 1978) for a diabase sill in the Port Radium area (Wanless et al., 1970), and

1420 Ma (1425 Ma new standardized age) for actinolite-magnetite veins in the Echo Bay mine (Robinson and Morton, 1972); a U-Pb age of 1.450 Ma on pitchblende from mineralized veins at Port Radium (Jory, 1964); and cross-cutting relationships, as described above. Thorpe (1971) reported a Pb-Pb age for galena in mineralized veins of 1625 Ma.

IV. STABLE ISOTOPE GEOCHEMISTRY

Stable isotope analyses of hydrogen, oxygen, carbon and sulphur were carried out on whole-rock samples and mineral separates from the Port Radium and Echo Bay Formations, Mystery Island intrusive suite, and magnetite-apatite-actinolite veins and pervasively altered wall rocks. Samples locations are indicated on Plate 1. Isotopic compositions are reported in per mil deviation from SMOW (Standard Mean Ocean Water) for oxygen and hydrogen, PDB (Belemnitella americana Peedee Formation) for carbon and CDT (Canon Diablo Troilite) for sulphur. Analytical methods are described in Appendix B.

Wall rocks

Oxygen and hydrogen

Whole-rock samples from the LaBine Group, Mystery Island intrusive suite and Richardson pluton were analyzed for their oxygen and hydrogen isotope ratios by standard techniques. Isotopic compositions and water contents of whole-rock samples are given in Table 3. Variation of $\delta^{18}O$ within the plutons and their altered wall rocks is limited; $\delta^{18}O$ ranges from +5.7 to +12.3‰ (Fig. 15). Seventy whole-rock hydrogen analyses were carried out on samples from the Port Radium Formation, Echo Bay Formation, the Mystery Island intrusive suite and the Richardson pluton. δD range from -92 to -56‰ (Fig. 16).

Port Radium Formation

Six samples of fine-grained sedimentary rocks of the Port Radium Formation, two carbonates and one siltstone at Port Radium, and two siltstones from above and below the Bertrand Lake pluton were analyzed. $\delta^{18}O$ ranges from +7.8 to +11.4‰, with a mean value of +8.4‰. δD of sedimentary rocks from the Port Radium Formation ranges from -84 to -62‰.

Echo Bay Formation

Andesitic lava flows and cogenetic intrusive porphyries range in $\delta^{18}O$ from +6.9 to +11.7‰. Volcanogenic sandstone from the Echo Bay Formation ranges from +7.8 to +9.2‰. Andesitic lavas, related porphyries and volcanogenic sandstone from the Echo Bay Formation range in δD from -92 to -56‰.

Mystery Island intrusive suite

Plutons of the Mystery Island intrusive suite have $\delta^{18}O$ ranging from +5.7 to +12.3‰. The mean value is +9.1‰. Five samples through the southern portion of the Glacier Lake pluton (Fig. 7) were analyzed for $\delta^{18}O$. $\delta^{18}O$ range from +10.7 to +12.7‰, and no trend is evident. Similarily, four samples through the Contact Lake pluton (Fig. 6a) show no trend for $\delta^{18}O$, and range from +8.6 to +11.2‰. Average, unaltered intermediate plutons have $\delta^{18}O$ from +8.0 to +9.0‰ (Hoefs, 1980). The δD of plutons of the Mystery Island intrusive suite ranges from -91 to -60‰.

Cameron Bay Formation

Sedimentary rocks and tuffs of the Cameron Bay Formation range in $\delta^{18}O$ from +10.1 to +12.7‰. The higher values for these rocks as compared to the plutons of the Mystery Island intrusive suite and altered andesitic lava flows may reflect their original composition, since sedimentary rocks have higher average $\delta^{18}O$ than igneous rocks. It may also be due to their greater susceptibility to alteration due to greater permeability. Volcanic and sedimentary rocks of the Cameron Bay range in δD from -76 to -60‰.

Richardson pluton

One sample of the Richardson pluton was analyzed, and has a $\delta^{18}O$ of +10.4‰. This value is slightly higher than typical values for unaltered granitic plutons, which have $\delta^{18}O$ values between +6.0‰ and +10.0‰. (Hoefs, 1980). The pluton has a δD value of -71‰.

Magnetite-apatite-actinolite zone

Magnetite, apatite, actinolite, biotite, epidote, talc and quartz from the MAA zone were analyzed for their oxygen and hydrogen isotopic compositions. Sample locations are shown on Plate 1.

Oxygen

Analyses of mineral separates from 14 veins and pervasively altered rocks were carried out on actinolite, epidote, talc, biotite, apatite, quartz and magnetite (in part martite). The data are presented in Table 4a and b.

Actinolite ranges in $\delta^{18}O$ from +6.4 to +9.6‰. Epidote has $\delta^{18}O$ of +4.1‰ and +5.4‰; quartz from the same sample has a $\delta^{18}O$ of +12.4‰. Talc has a $\delta^{18}O$ of +12.3‰. Biotite has a $\delta^{18}O$ of +9.7‰. Apatite ranges in $\delta^{18}O$ from +6.5 to +8.0‰.

Nine samples of magnetite (all in part martite) have $\delta^{18}O$ from -3.1‰ to +4.5‰ (Table 4b). The lower δ-values obtained for the magnetite do not indicate equilibrium with other minerals in the assemblage. One sample of martite was analyzed, and has a $\delta^{18}O$ of -2.2‰. The martitization of the magnetite may have occurred after the formation of the veins, possibly by circulating groundwaters, or late in the formation of the veins at lower temperatures, since fractionation of oxygen between water and magnetite decreases with decreasing temperature. Because of the finely-intergrown nature of the hematite in magnetite, the values obtained for the magnetites can only be considered as a minimum value.

Hydrogen

Hydrous minerals were analyzed for δD and water content (Table 4a). Twelve actinolites range in δD from -82 to -53‰. One biotite, which occurs with magnetite and actinolite, has a δD value of -112 ‰. Talc has a δD value of -55‰. Epidote, which occurs with actinolite and quartz, has a δD value of -93‰.

Pyrite zone

Sulphur

Pyrite and chalcopyrite from gossans, pods and veins within the pyrite and chalcopyrite zones were analyzed for $\delta^{34}S$ (Table 5). Robinson and Ohmoto (1973) determined a $\delta^{34}S$ value of +4.1‰ to +5.1‰ for disseminated pyrite in the Port Radium Formation and and Robinson and Badham (1974) reported a $\delta^{34}S$ value of 3.5‰ and +5.1‰ for pyrite and of +4.0‰ for chalcopyrite in tuffs and at the Terra Mine, in the Camsell River area (Fig. 3). Both pyrite and chalcopyrite show enrichment in $\delta^{34}S$ with respect to the average of zero per mil for sulphides from undifferentiated basic rocks (Ohmoto and Rye, 1979). Pyrite from within the magnetite-apatite-actinolite zone has similar $\delta^{34}S$ to those of sulphides in the pyrite zone (Table 5). Pyrite in a magnetite-hornblende vein at Port Radium has $\delta^{34}S$ of +2.15‰ (Robinson and Ohmoto, 1973). Massive sulphides in wall rocks at the Silver Bay Mine in the Camsell River area (Fig. 3) have distinctly lower $\delta^{34}S$ of -8.4‰ to -10.2‰ (Robinson and Badham, 1974).

Most of the $\delta^{34}S$ for pyrite and chalcopyrite at Echo Bay are typical for igneous rocks and are consistent with a magmatic source for the sulphur whether the sulphides are a primary component of the rocks or were introduced later by magmatic fluids, since magmatic fluids from arc volcanoes of andesitic composition typically have positive $\delta^{34}S$ (SO_2), from 0‰ up to +11.6‰ (Taylor, 1986). However, one value for chalcopyrite (+10.8‰) is unusually high. Therefore, the sulphides may actually have greater variation which is not evident due to the limited number of analyses.

Quartz-carbonate veins

Knowledge of the fluids which formed the quartz-cabonate veins in the Echo Bay area is necessary in order to assess the influence of these fluids on the isotopic composition of rocks in the area. Calcite and siderite from unmineralized veins in the Port Radium area were analyzed for $\delta^{18}O$ and $\delta^{13}C$ (Table 6), and chalcopyrite from quartz and calcite-chalcopyrite veins was analyzed for $\delta^{34}S$ to compare them with the results from the pitchblende-bearing veins.

Oxygen and carbon

Calcite from a calcite pod in andesitic porphyry has a $\delta^{18}O$ of +9.1‰ (Table 6). $\delta^{18}O$ for two calcite from chalcopyrite-bearing quartz-carbonate veins are +7.0‰ and +10.7‰. Siderite from a chalcopyrite-bearing quartz-carbonate vein has a $\delta^{18}O$ of +14.2‰. Siderite from a quartz-carbonate vein has a $\delta^{18}O$ of +16.6‰ These values are similar to those obtained by Robinson and Ohmoto (1973), Robinson and Badham (1974) and Changkakoti et al. (1986a).

$\delta^{13}C$ data obtained for calcite and siderite in quartz-carbonate (+/- chalcopyrite) veins (Table 6) are also comparable to those of Robinson and Ohmoto (1973), Robinson and Badham (1974) and Changkakoti et al. (1986a). Calcite from a calcite pod in andesitic porphyry has a $\delta^{13}C$ of -5.7‰. Calcite from chalcopyrite-bearing quartz-carbonate veins have $\delta^{13}C$ of -5.6 and -4.2‰. Siderite from a similar vein has a $\delta^{13}C$ of -2.2‰. Siderite from a quartz-carbonate vein has a $\delta^{13}C$ of -2.9‰.

Sulphur

Chalcopyrite from a pyrite- and chalcopyrite-bearing quartz vein has a $\delta^{34}S$ value of +5.6‰ (Table 6). Sulphides in the pitchblende, native Ag, Ni-Co arsenide veins at Echo Bay have a wide range of $\delta^{34}S$ from -26.0‰ to +26.9‰, but massive and banded chalcopyrite, which occurs with dolomite, has a limited range of +3.7 to +7.9‰; chalcopyrite which occurs with calcite has a $\delta^{34}S$ value of +13.5‰ (Robinson and Ohmoto, 1973; Robinson and Badham, 1974).

Hydrothermal Fluids

Whole-rock oxygen and hydrogen isotopic data were used to characterize the nature and origin of fluids responsible for the formation of the alteration haloes associated with the Mystery Island intrusive suite. Most whole-rock $\delta^{18}O$ and δD are higher than +6‰ and -70‰, respectively, consistent with alteration by magmatic fluids. Lower values suggest involvement of a minor component of evolved meteoric water, evolved seawater or connate water. Stable isotopic data for mineral separates of actinolite, epidote, biotite, apatite, quartz and magnetite were used to calculate a range of fluid isotopic compositions for $\delta^{18}O$ and δD, based on known isotopic fractionations between minerals and water for a range of temperatures. The data indicate that the fluids which deposited these minerals ranged from about +4.0‰ to +12.0‰ for $\delta^{18}O$ and from -30‰ to -10‰ for δD, assuming a temperature of 300° to 400°C. This temperature was based on temperature estimates for the formation of MAA in similar deposits determined by mineral assemblages and stable isotopic data (Research Group of Porphyrite Iron Ore of the Middle-lower Yangtze Valley, 1977; Ripley and Ohmoto, 1979). These values fall within the range of magmatic fluids, and are distinctly higher in $\delta^{18}O$ and δD than meteoric water or seawater (see Taylor, 1986). However, mixing of a small component of meteoric water, seawater, or connate water cannot be ruled out, and some input of such surficial waters is probable.

Estimation of the effects of overprinting during the formation of later quartz veins on these results is difficult, since fluids responsible for formation of the quartz veins may have been slightly lighter or the same as those which formed the MAA zone alteration. Robinson and Ohmoto (1973) calculated a $\delta^{18}O$ of +1.0‰ for the fluids which deposited the pitchblende-bearing veins at Port Radium, based on isotopic data from mineral separates of quartz, hematite, calcite and dolomite. Robinson and Badham (1974) calculated a $\delta^{18}O$ of +2.0‰ based on isotopic data for calcite and dolomite. However, Changkakoti et al. (1986a) calculated a range of $\delta^{18}O$ for the mineralizing fluids, from +9.12‰ (early fluids) to +0.47‰ (late fluids) from the $\delta^{18}O$ of quartz, calcite and dolomite. No zoning is evident in the wall rocks surrounding the veins.

V. CONCLUSIONS

Geologic, textural and mineralogic evidence indicate a hydrothermal origin for the alteration and mineralization of rocks in the Echo Bay area. A close spatial association of the altered rocks to the plutons of the Mystery Island intrusive suite is demonstrated by the zonation of altered rocks above the plutons and the occurrence of similar alteration within the plutons. Alteration occurs both as pervasive replacement of the rocks, and as veins and breccias. Where these two occur together, the veining and brecciation is preceeded by replacement. This is probably due to sealing of the rocks by hydrothermal alteration and subsequent fracturing due to increasing hydrostatic pressure. Some MAA breccias contain eroded and rotated fragments, also typical of explosive hydrothermal brecciation. Coarse-grained, pegmatitic veins are common, and also suggest formation of MAA veins from a fluid phase. The occurrence of riebeckite within the plutons and the wallrocks suggests that Na-rich fluids penetrated both the plutons and their wallrocks. Hydrothermal fluids produced both Na- and K-metasomatism within the plutons and their wall rocks.

Stable isotopic data for the Mystery Island intrusive suite and altered wall rocks demonstrate that the alteration was produced by dominantly magmatic fluids. However, a component of other fluids, possibly evolved surface waters, is possible. The calculated isotopic composition of the hydrothermal fluids responsible for formation of the MAA zone is about +4 to +12.0‰ for $\delta^{18}O$, and -30 to -10‰ for δD.

Pitchblende, native Ag, Ni-Co arsenide veins are spatially, but not temporally related to the plutons of the Mystery Island intrusive suite and their altered wallrocks; the greatest concentration of pitchblende, native Ag, Ni-Co arsenide veins occurs where the MAA and pyrite zones overlap. Both the plutons and their alteration haloes are offset by the faults which contain these veins. Geologic evidence indicates at least two periods of movement on the faults, and that the youngest veins are mineralized. Overprinting of the isotopic signatures associated with the Mystery Island intrusive suite by the hydrothermal system which deposited the pitchblende, native Ag, Ni-Co arsenide veins is not evident.

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APPENDIX A - Electron Microprobe Analyses

Quantitative mineral analyses were carried out by the author at McGill University, Montréal with the Cameca RSX11M electron microprobe using an accelerating voltage of 15 kV, a beam current of 8 nA and a beam diameter of approximately 1 micron. Analyses were obtained from standard polished thin sections carbon coated before analysis. Standards used were SWOL for Fe, Mg, and Si; OLIV for Mn; and DIOP for Ca. Data were acquired for until a standard deviation of less than 2 wt.% was achieved. The ZAF correction technique was used for data correction.

APPENDIX B - Stable Isotope Analyses

Stable isotope analyses were completed for whole-rock samples by the author and John Sekerka at the Geological Survey of Canada in Ottawa. Mineral separate analyses were completed by the author. Bulk fluid inclusion analyses were carried out by Bruce Taylor (Geological Survey of Canada) and the author at the GSC, Ottawa. Mass spectrometer analyses were carried out by John Sekerka at the Geological Survey of Canada for deuterium, and by Gilles St. Jean and Margaret McLaren at the University of Ottawa for oxygen, carbon and sulphur.

Whole-rock samples were trimmed to remove all weathered surfaces, split to less than 2 cm size, and crushed in either a cyclone crusher or jaw crusher. This material was then split into two fractions, one of which was pulverized in a tungsten puck pulverizer for three to five minutes, depending on sample hardness.

Oxygen for isotopic analysis was liberated from approximately 10 mg of powdered sample by reaction with BrF_5. The oxygen was converted to CO_2 by passing it over a hot carbon rod. To liberate hydrogen, 80 to 120 mg of powdered sample (whole-rock) or unpowdered sample (mineral separates) was heated incrementally under vacuum until fused. Hydrogen was produced by passing the H_2O over hot uranium metal. Volumetric measurements of the hydrogen yields were recorded to determine water contents. CO_2 from calcite was liberated by reaction with H_3PO_4 at 25°C for 24 hours; siderite was reacted for 72 hours. Routine precision is approximately 0.2 ‰ (1 σ) for $\delta^{18}O$, 1.0‰ (1 σ) for δD and 0.1‰ for $\delta^{13}C$.

Figure captions

Figure 1. Generalized geology of the northwestern Canadian Shield (modified from Hoffman, 1989) showing the major structural provinces the study area of this report.

Figure 2. Geology of the northern Great Bear magmatic zone, after Hildebrand, 1986. The box outlines the area shown in Figure 3.

Figure 3. General geology of the Echo Bay and Camsell River areas with previous mine locations. 1 = Eldorado, 2 = Echo Bay, 3 = El Bonanza and Bonanza 4 = Contact Lake, 5 = Terra, 6 = Northrim, 7 = Norex, 8 = Smallwood (after Changkakoti et al., 1986a).

Figure 4. General geology of the Echo Bay area showing plutons of the Mystery Island intrusive suite.

Figure 5. Geology of the Bertrand Lake pluton showing alteration zones. Inset of Mystery Island, a fault-displaced section of the Bertrand Lake pluton.

Figure 6. Geology of the Contact Lake pluton showing the distribution of altered rocks. Alteration is more extensive above the southern part of the pluton, between the Contact Lake and McLeod Lake plutons. Note the unconformity ( ) which truncates the alteration zones at the southeastern end of Echo Bay.

Figure 7. Geology of the southern part of the Glacier Lake pluton showing the distribution of altered rocks. Magnetite-apatite-actinolite occurs beneath the pluton adjacent to a narrow extension perpendicular to the bottom of the pluton.

Figure 8. Geology of the Port Radium area, southern Tut pluton and the northern part of the Glacier Lake pluton showing simplified alteration zones. Note the fault-bounded portion of an intermediate pluton, possibly of the Mystery Island intrusive suite, which outcrops on Cobalt Island. Zones of altered rocks are subparallel to the shoreline of Great Bear Lake north of Port Radium. Note the displacement of the plutons and alteration zones along faults.

Figure 9. Sketch of pervasively altered volcanogenic sandstone, replaced by actinolite and albite, actinolite and minor magnetite, and cut by veins of (magnetite)-apatite-actinolite, Port Radium.

Figure 10. Sketch of hydrothermal breccia with magnetite matrix in andesitic porphyry, Port Radium. Fragments up to several decimeters across are angular to sub-rounded and have altered

(albitized?) rims. The matrix is mostly magnetite, with epidote, albite, pyrite, chalcopyrite and minor bornite.

Figure 11. Plots of K_2O vs. Na_2O,MgO, Gd, Dy, Be, Yb, Y, Sm for andesitic lava flows above the southern part of the Glacier Lake pluton ranging from 56 to 60 wt.% SiO_2. Gd, Dy, Be, Yb, Y, Sm, MgO and Na_2O increase with decreasing K_2O. The two samples with low K_2O occur within the MAA zone; the other two samples occur further above the pluton roof. Most of these variations are due to substitution of these elements in feldspars. The higher MgO content of the low K_2O samples in the MAA zone, however, is probably due to their increased actinolite content.

Figure 12. Plot of Na_2O vs. SiO_2 for the Tut (O), Bertrand Lake (X), Glacier Lake ( ), Contact Lake (Δ) and McLeod Lake ( ) plutons. Boxes indicate samples plotted in Figure 13. The Tut pluton is least altered, and shows a normal magmatic trend of increasing K and decreasing Na with increasing SiO_2 content. However, one sample is albitized. The Bertrand Lake and Contact Lake plutons are Na-matasomatized, as indicated by high Na contents which do not correlate with SiO_2 content. Part of the Glacier Lake pluton is K-metasomatized, as indicated by elevated K_2O contents not correlative with an increase in SiO_2.

Figure 13. a) plot of Na_2O vs. K_2O for the Glacier Lake pluton; b) plot of Na_2O vs. K_2O for the Contact Lake pluton. In both plutons, only Na and K vary antithetically. No regular variations among other elements are observed.

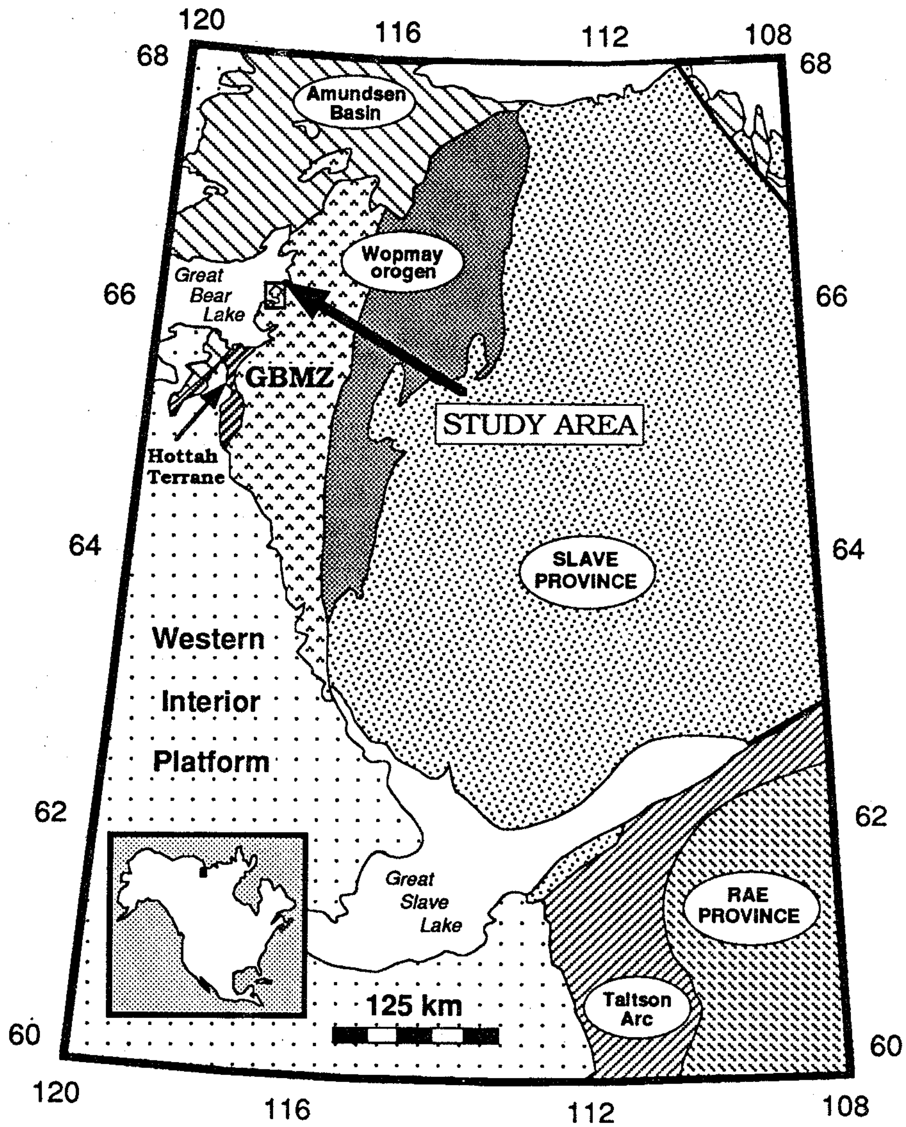
Figure 14. a) plots of SiO_2, K_2O and Na_2O vs. height in the southern part of the Glacier Lake pluton; b) plots of SiO_2, K_2O and Na_2O vs. height in the Contact Lake pluton. Na_2O and K_2O vary antithetically in both plutons. The Contact Lake pluton is reversely zoned, and K_2O and SiO_2 decrease with increasing height in the pluton Na_2O contents range from 2 to 3 wt.% and increase steadily with height in the pluton, except one albitized sample near the top of the pluton which has a slightly higher Na_2O content.

Figure 15. Histogram of $\delta^{18}O$ data for altered andesitic lava flows, cogenetic andesitic porphyries and plutons of the Mystery Island intrusive suite.

Figure 16. Histogram of δD data for altered andesitic lava flows, cogenetic andesitic porphyries and plutons of the Mystery Island intrusive suite.

Tables

Table 1.	Table of formations, LaBine Group, after Hildebrand (1984).
Table 2.	Major, minor and trace element analyses for andesitic lava flows of the Echo Bay Formation and plutons of the Mystery Island intrusive suite. Major elements in weight % and trace elements in ppm. All data were recalculated to 100% on a volatile-free basis. EB, Echo Bay Formation; MIIS, Mystery Island intrusive suite.
Table 3.	$\delta^{18}O$ and δD (‰, SMOW) and water content (wt.%) data for whole-rock samples.
Table 4a.	$\delta^{18}O$ and δD (‰, SMOW) and water content (wt.%) data for silicate minerals from magnetite-apatite-actinolite veins and pervasively altered rocks.
Table 4b.	$\delta^{18}O$ (‰, SMOW) for magnetite and martite from magnetite-apatite-actinolite veins and pervasively altered rocks.
Table 5.	$\delta^{34}S$ (‰, CDT) of pyrite and chalcopyrite from the pyrite zone and chalcopyrite subzone.
Table 6.	a) $\delta^{18}O$ (‰, SMOW) and $\delta^{13}C$ (‰, PDB) for calcite and siderite; b) $\delta^{34}S$ (‰, CDT) for chalcopyrite from quartz-carbonate-sulphide veins.



120
116
112
108
68
68
Amundsen
Basin
Wopmay
orogen
Great
Bear
Lake
66
66
GBMZ
STUDY AREA
Hottah
Terrane
64
64
SLAVE
PROVINCE
Western
Interior
Platform
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62
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Slave
Lake
RAE
PROVINCE
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Taltson
Arc
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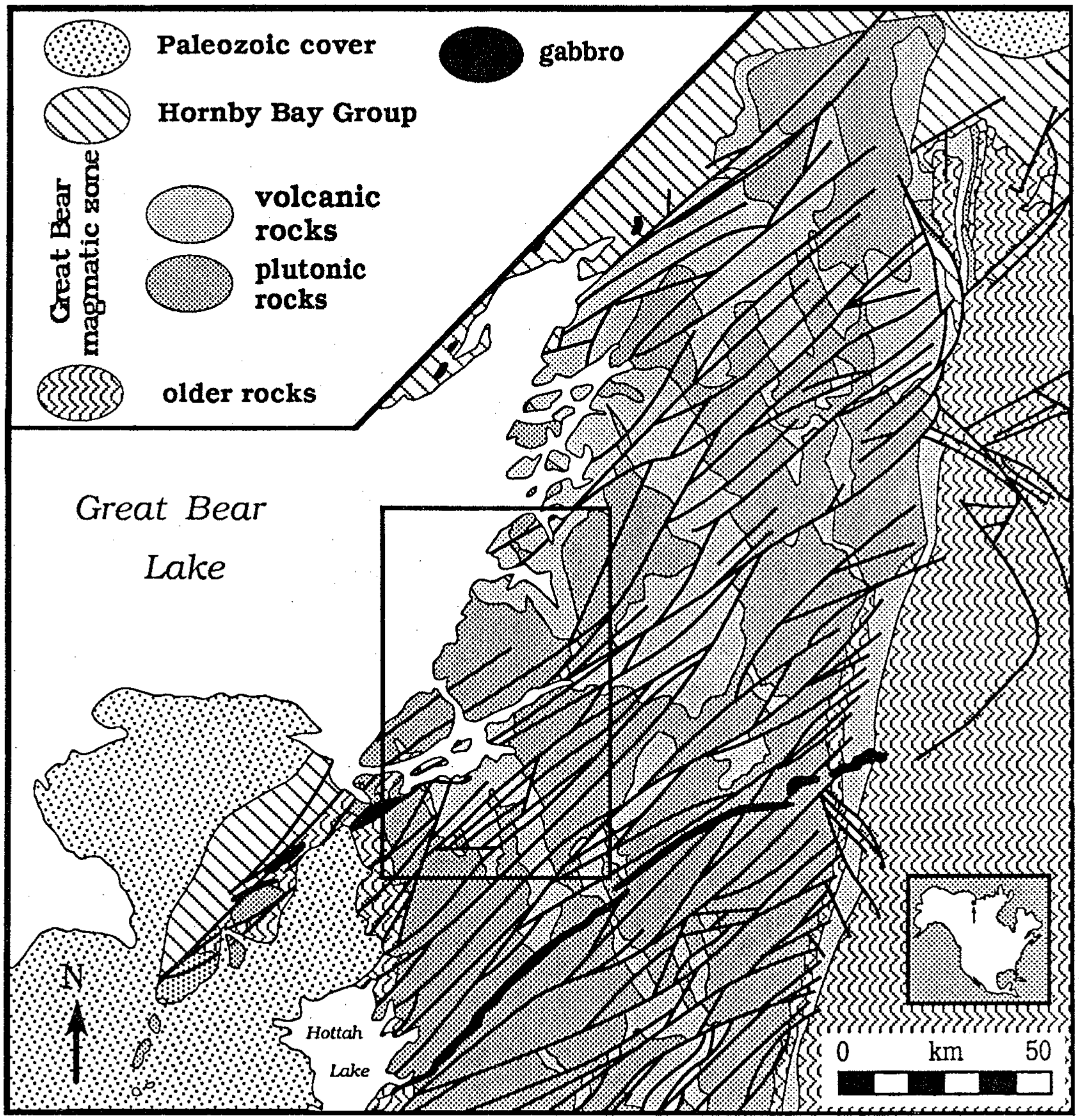
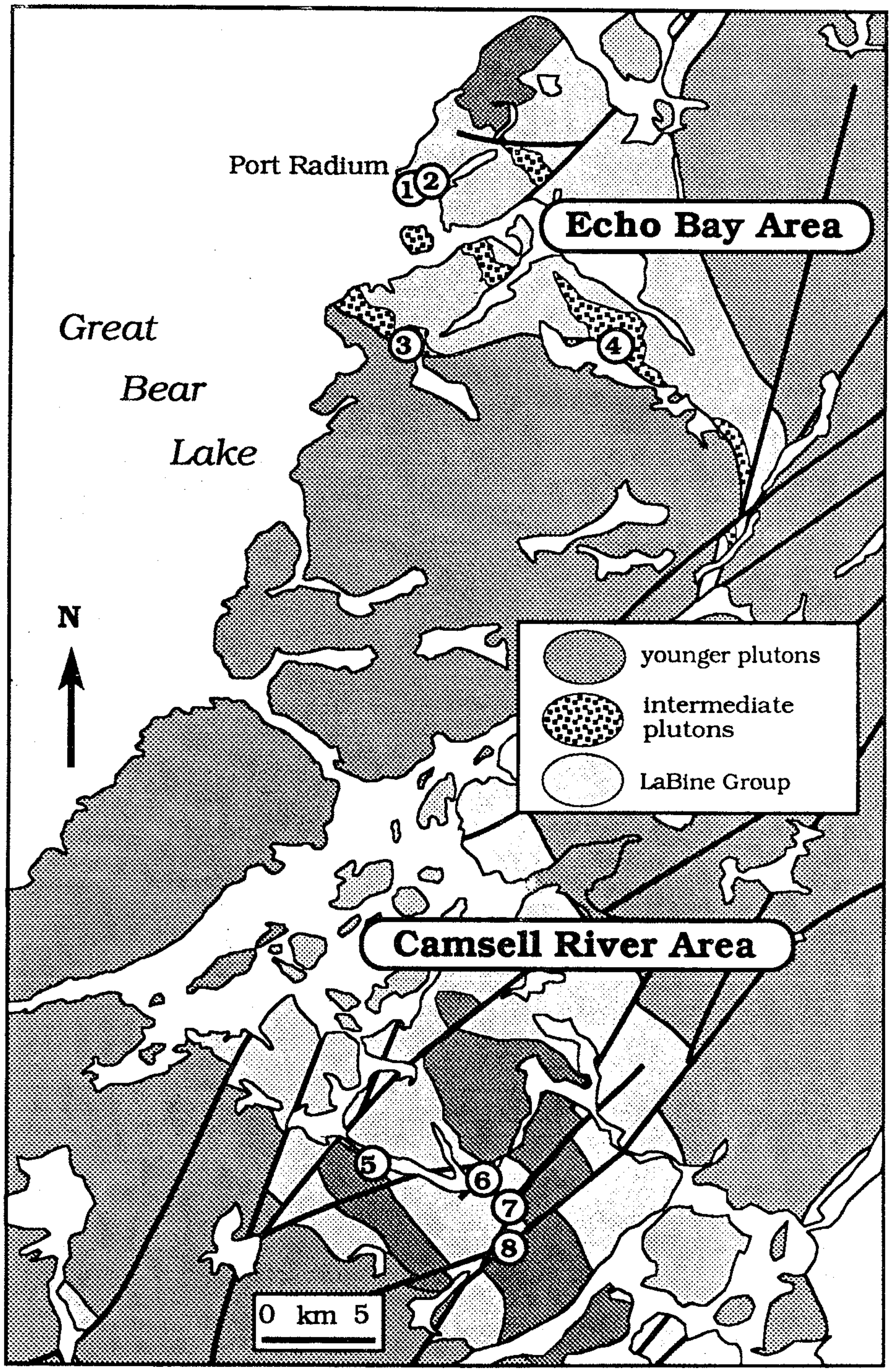
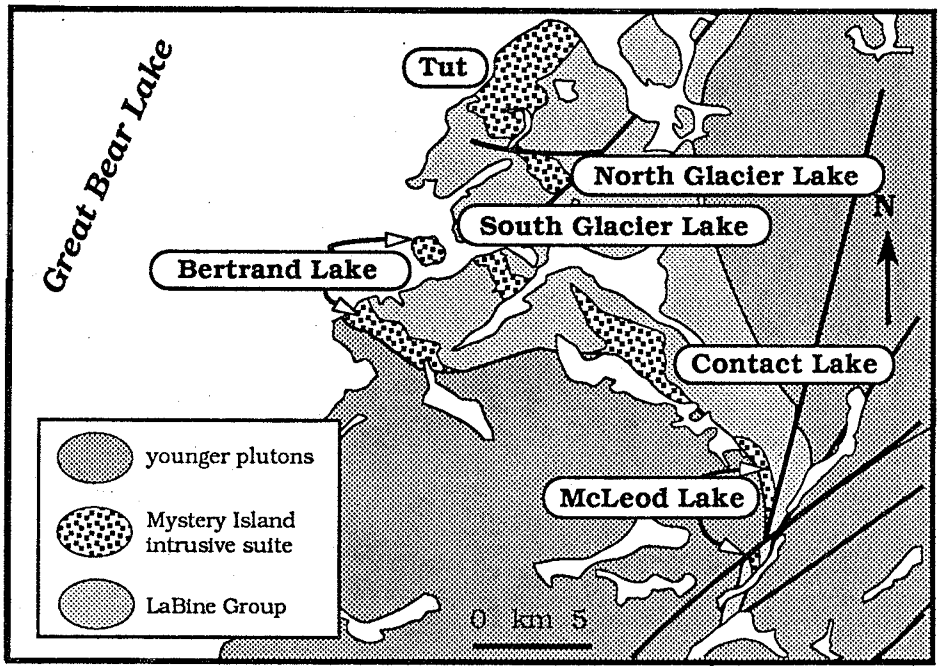

Paleozoic cover
gabbro
Hornby Bay Group
Great Bear magmatic zone
volcanic rocks
plutonic rocks
older rocks
Great Bear Lake
Hottah Lake
N
0 km 50



Port Radium
Echo Bay Area
Great Bear Lake
N
younger plutons
intermediate plutons
LaBine Group
Camsell River Area
0 km 5
1
2
3
4
5
6
7
8



Great Bear Lake
Tut
North Glacier Lake
South Glacier Lake
Bertrand Lake
Contact Lake
McLeod Lake
N
younger plutons
Mystery Island intrusive suite
LaBine Group
0 km 5

LEGEND - Figures 5 to 8

LITHOLOGIES

gabbro and diabase

younger granite

diorite

Altered rocks associated with the
Mystery Island intrusive suite

albite

magnetite-apatite-actinolite

pyrite

Mystery Island intrusive suite

LaBine Group

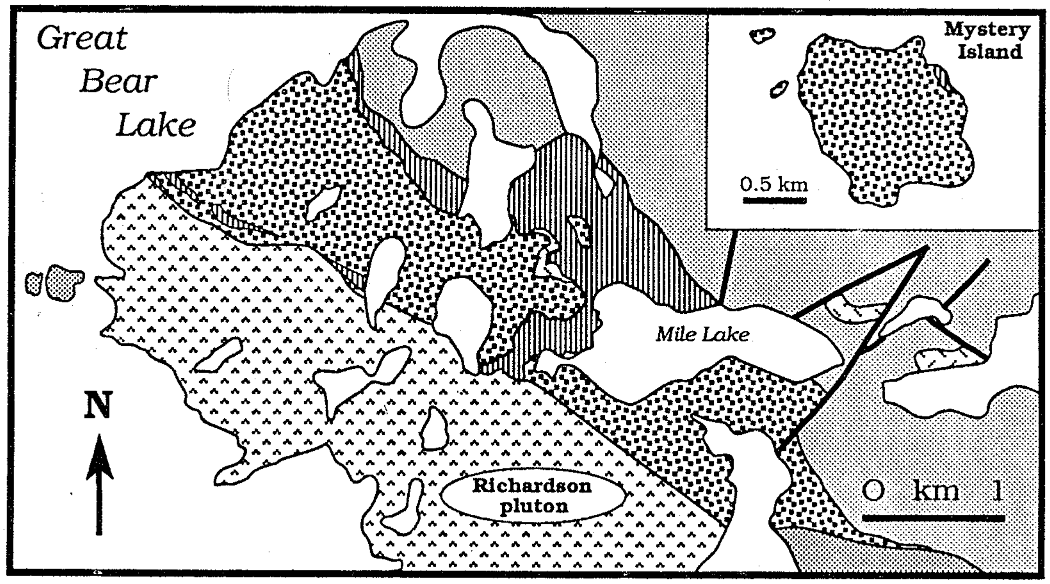
Port Radium Formation

SYMBOLS

geologic contact

fault

unconformity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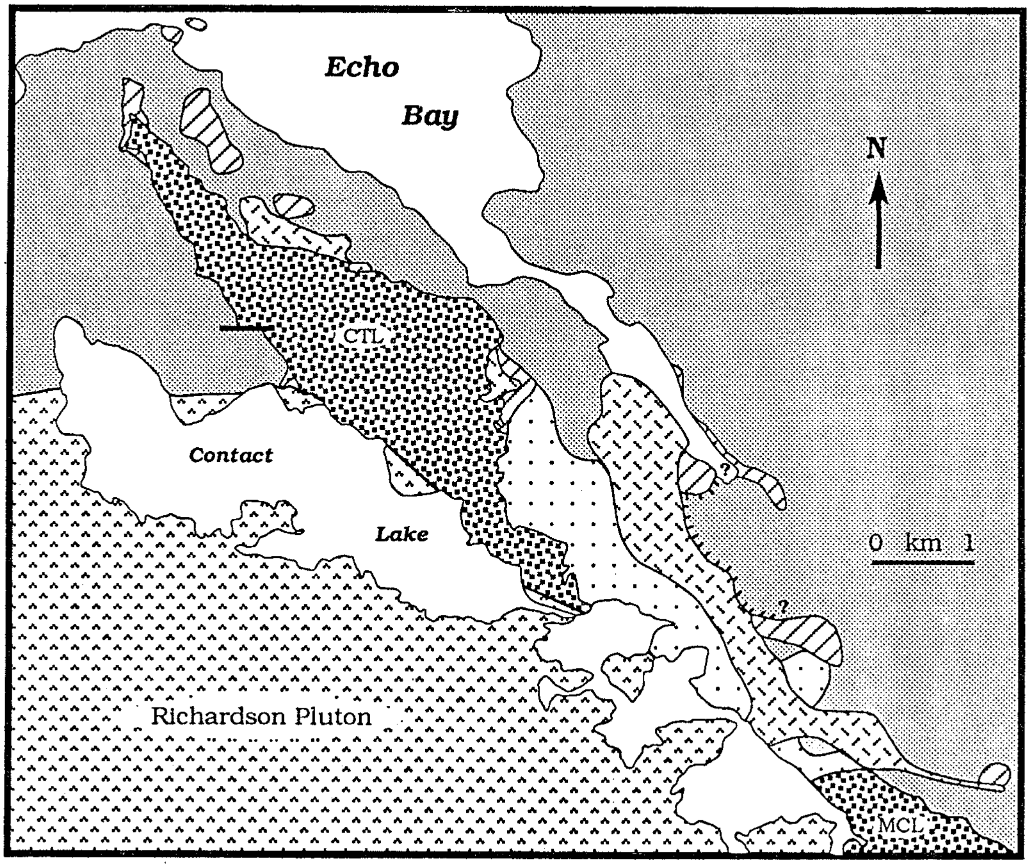
Lake
Mystery
Island
0.5 km
Mile Lake
N
Richardson
pluton
0 km 1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Bay
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CTL
Contact
Lake
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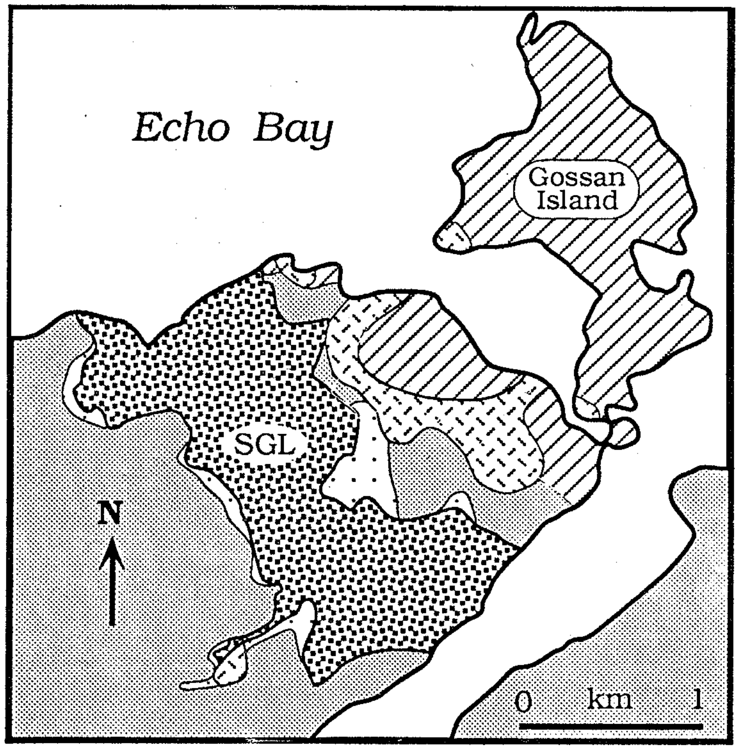
Richardson Pluton
MCL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Gossan Island
SGL
N
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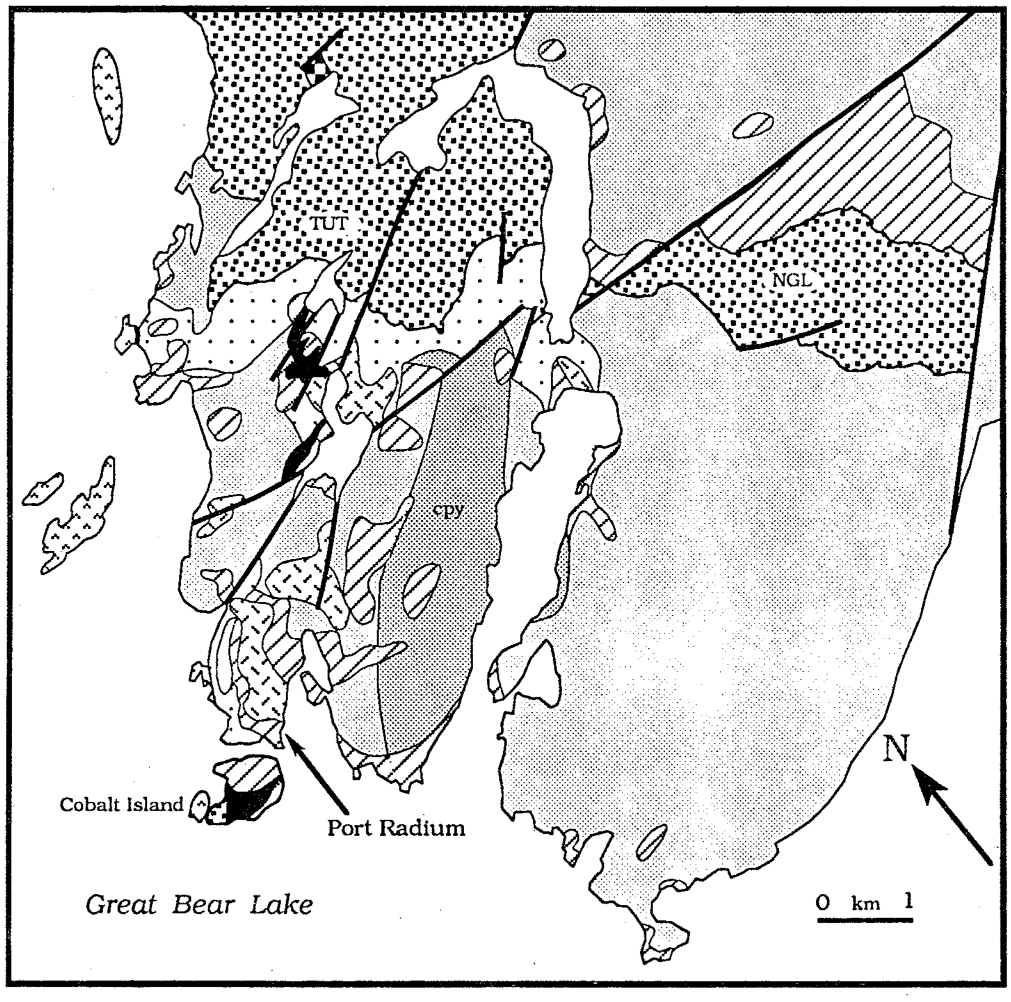
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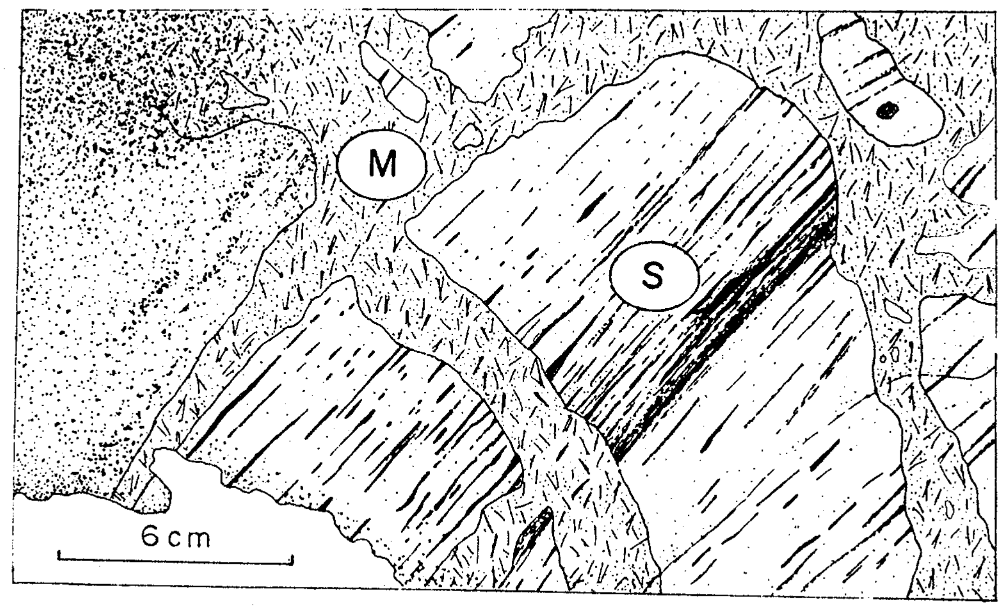
NGL
cpy
Cobalt Island
Port Radium
N
Great Bear Lake
0 km 1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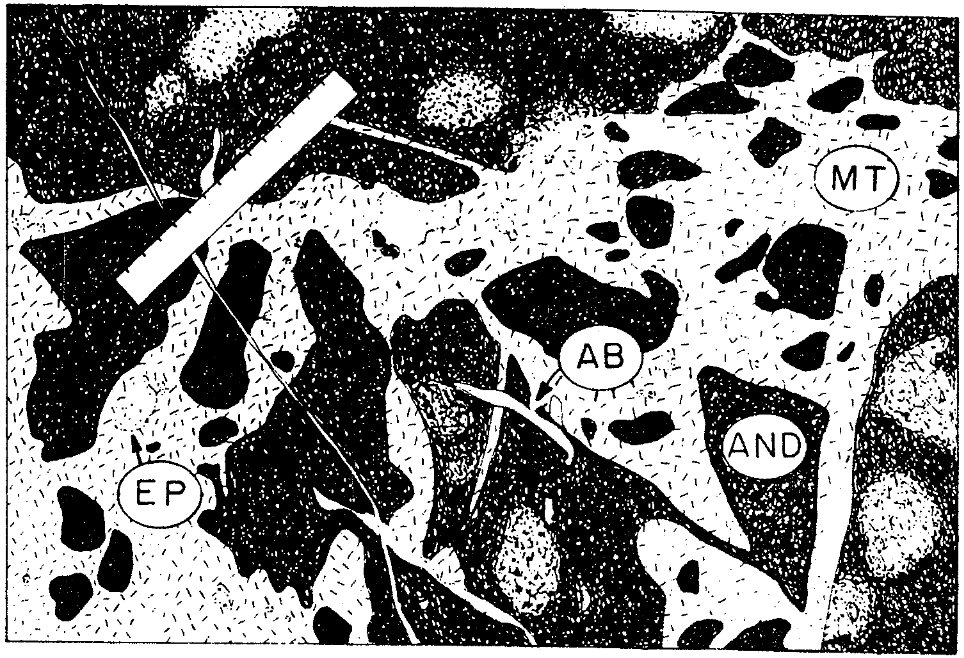
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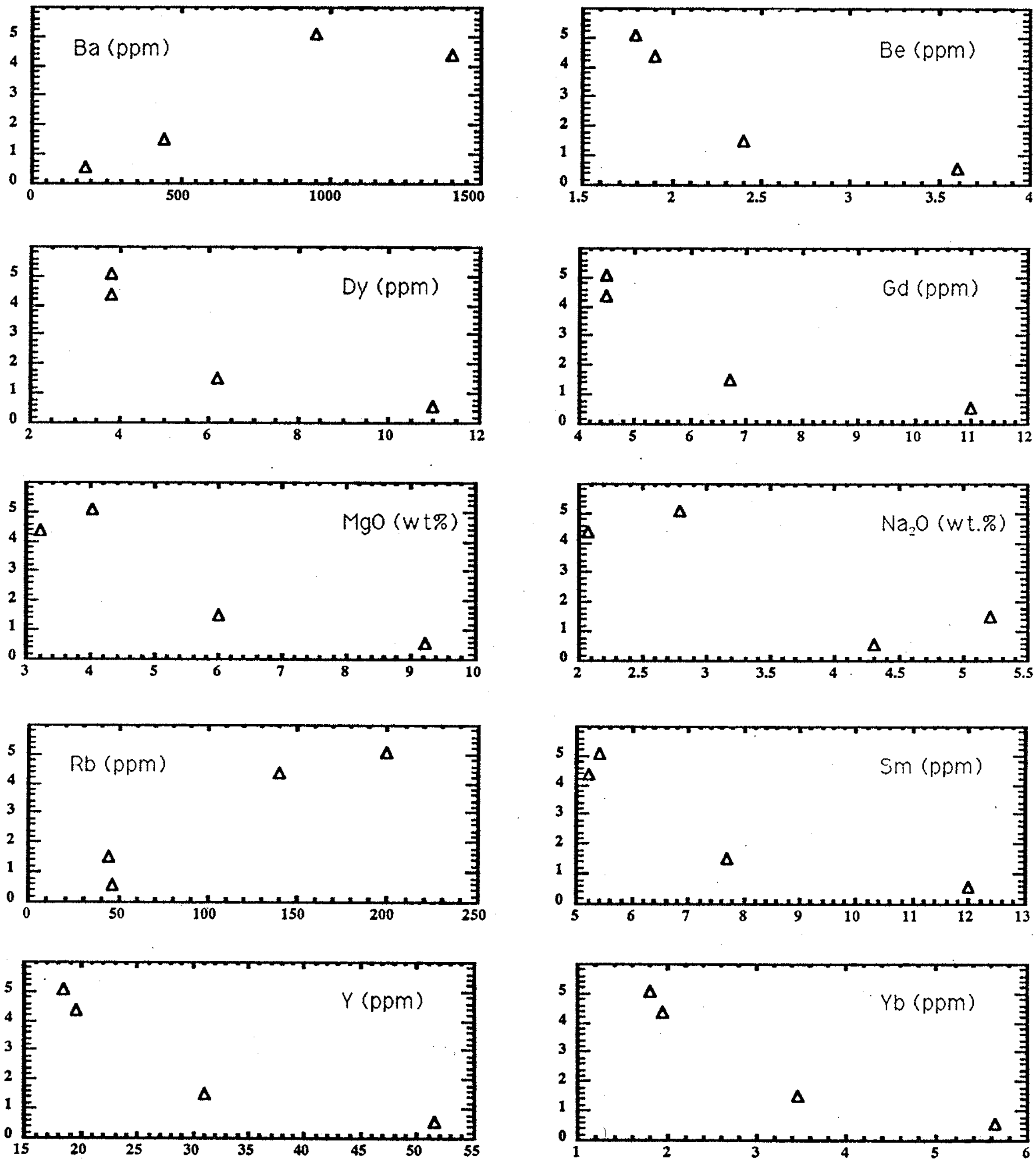
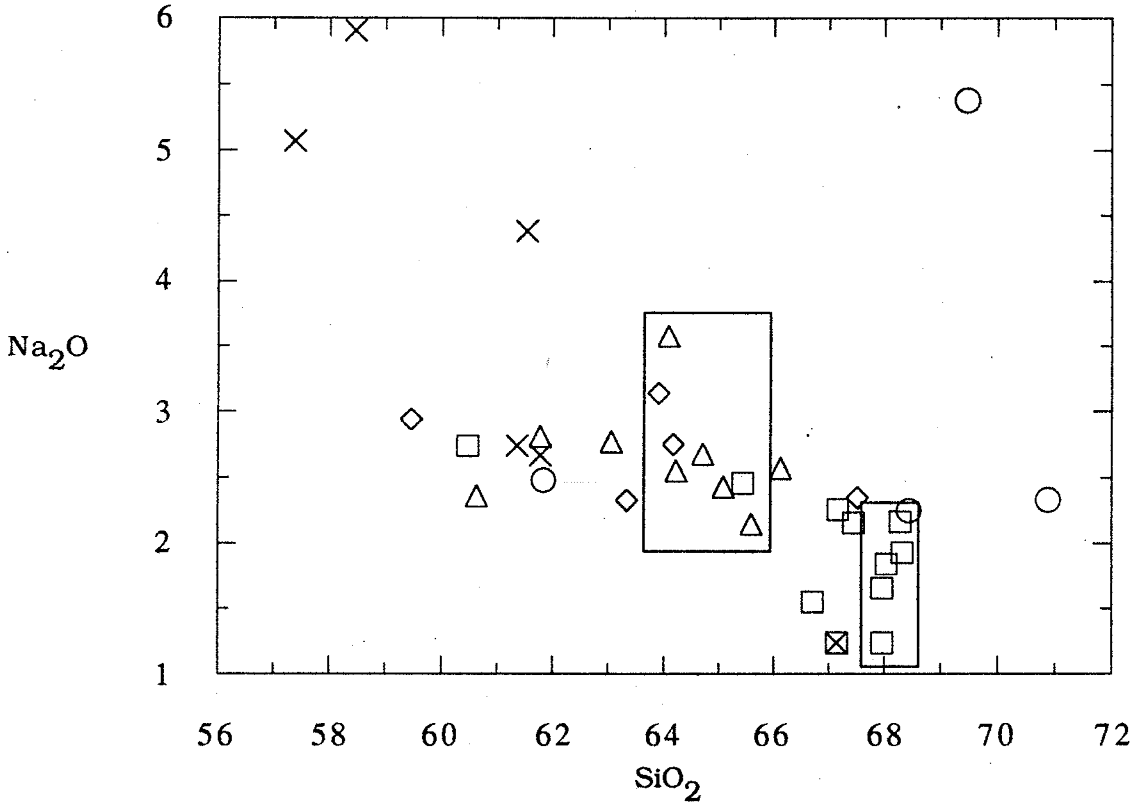

Ba (ppm)
Be (ppm)
Dy (ppm)
Gd (ppm)
MgO (wt%)
Na_2O (wt.%)
Rb (ppm)
Sm (ppm)
Y (ppm)
Yb (ppm)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Na_2O
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60
62
64
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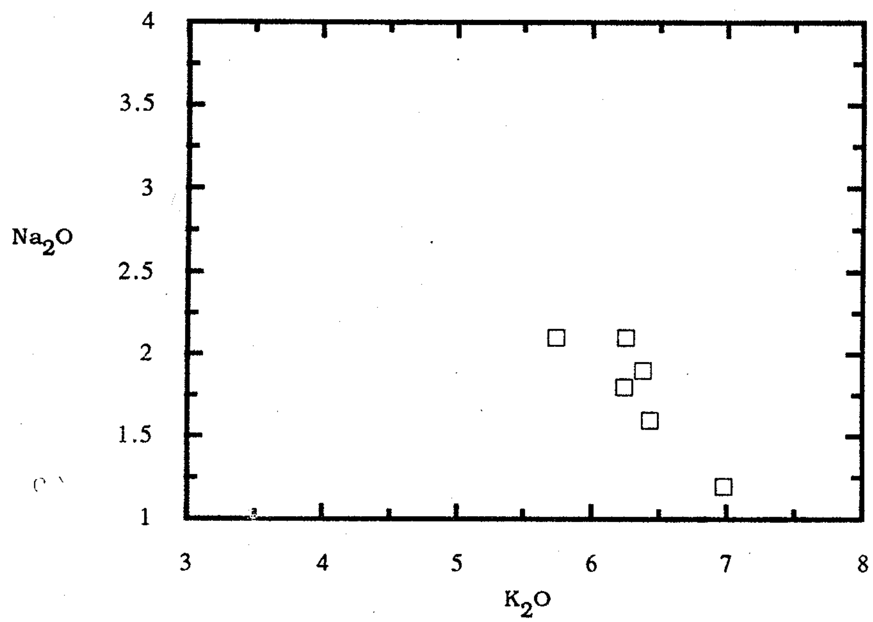
68
70
72
SiO_2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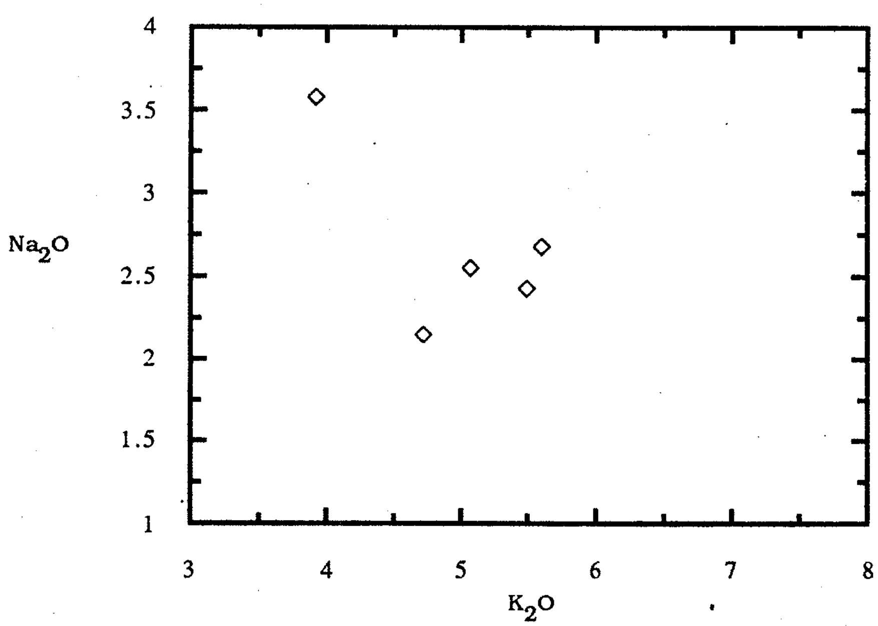
K$_2$O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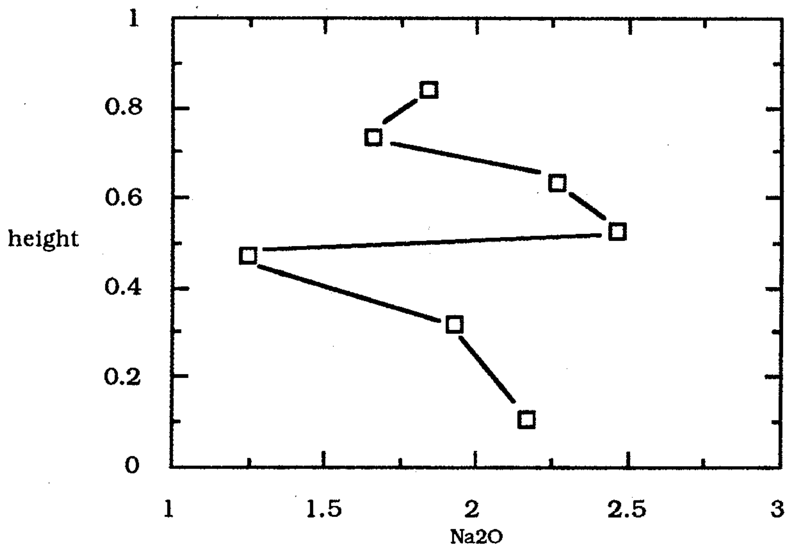
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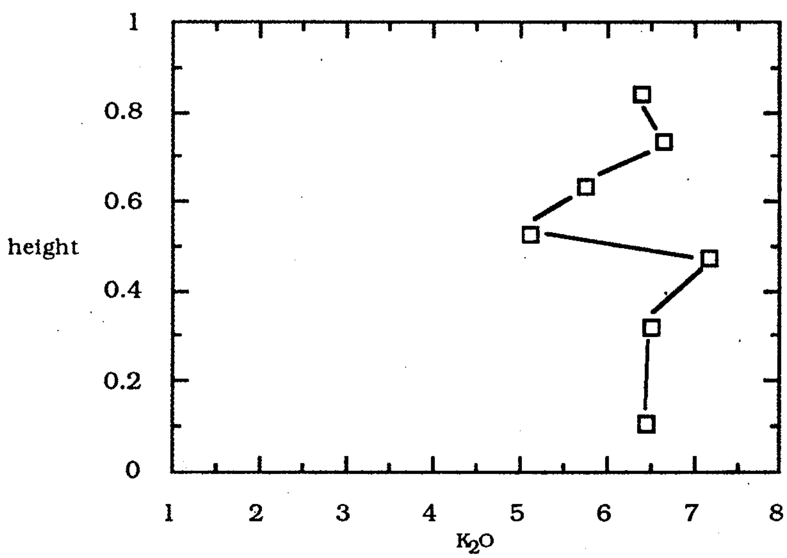
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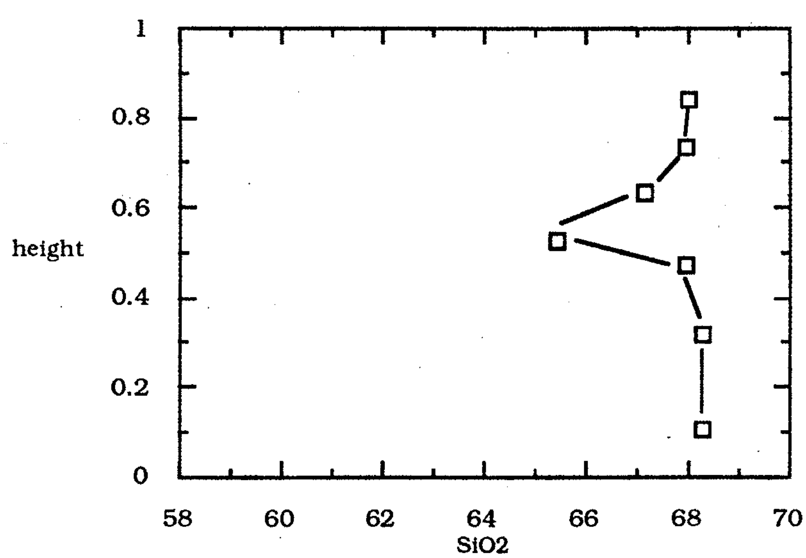
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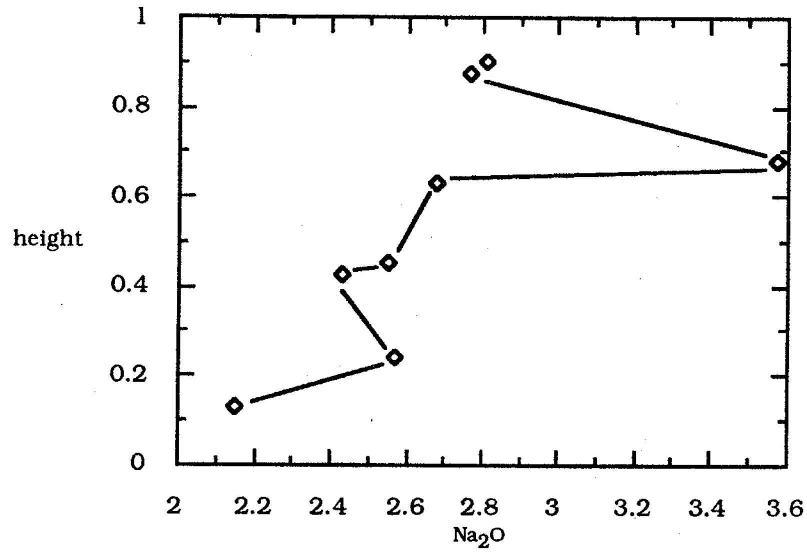
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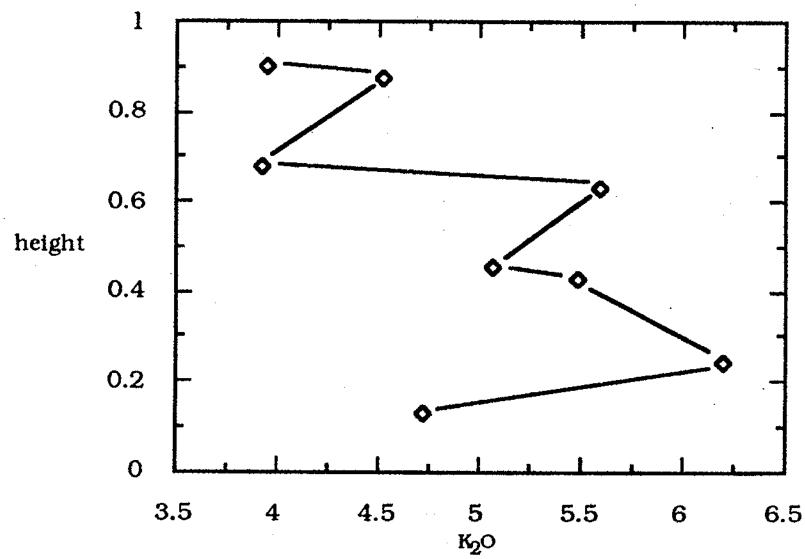
Na_2O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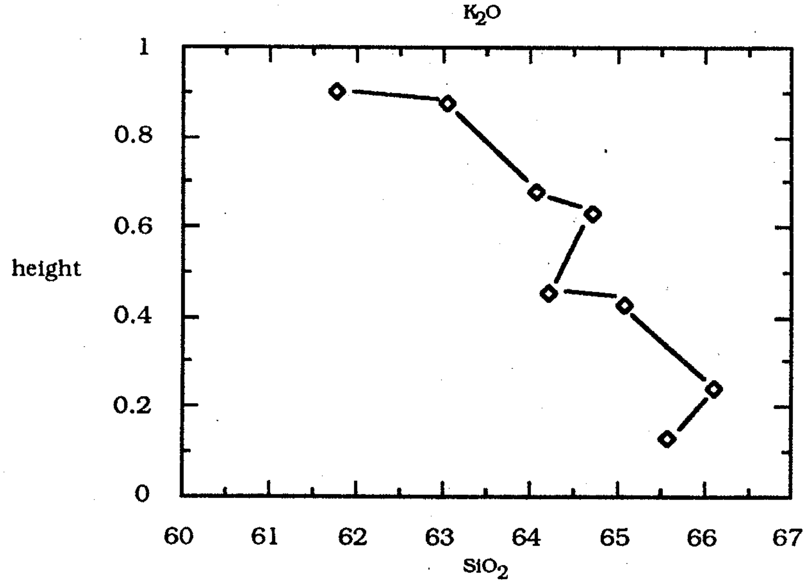
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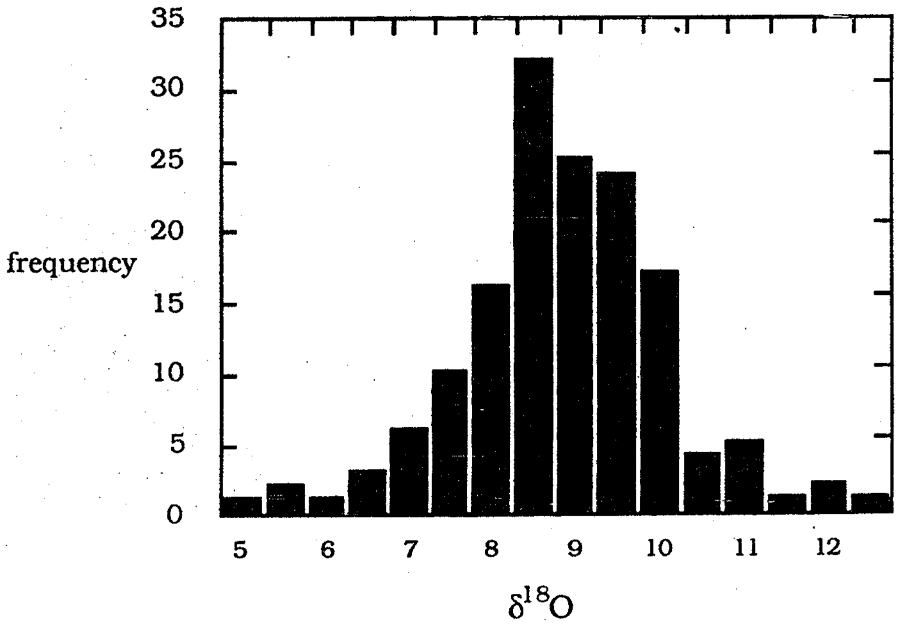

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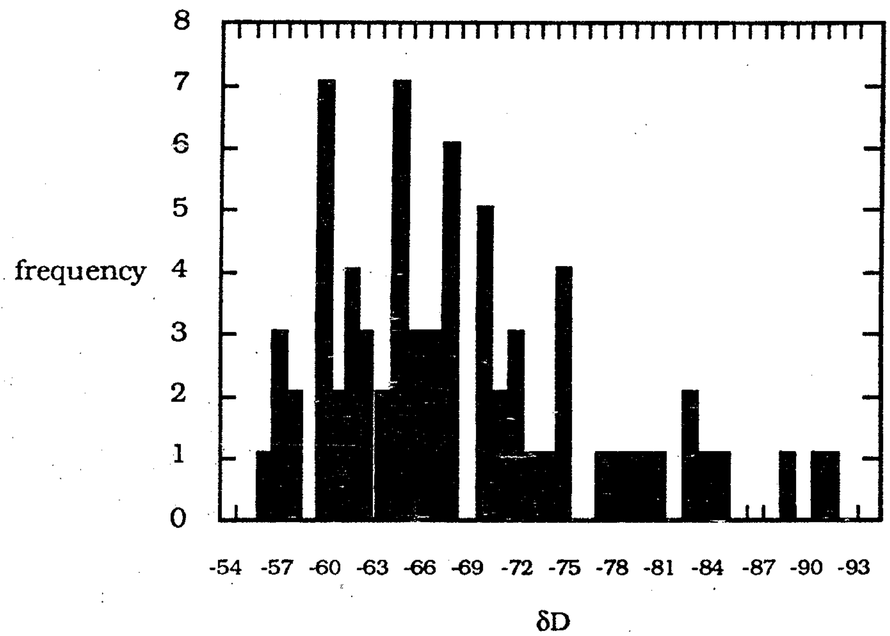
δ18O



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-78
-81
-84
-87
-90
-93
δD

LaBine Group	Cameron Bay Fm	Planar and crossbedded, volcanic-lithic and feldspathic sandstone and gritstone; ripple laminated siltstone and mudstone with mudcracks; hematitic polymictic conglomerate of mainly volcano-plutonic provenance; thin beds and erosional remnants of ashstone; local talus and explosion breccias; cauldron collapse breccias interfingered with ash flow tuff. The formation is divided into 12 members which are described in detail by Hildebrand (1984a, 1984b).
LaBine Group	Echo Bay Fm	**Sparkplug Lake Member:** porphyritic andesite flows and breccia. This member distinguished only by its stratigraphic position above the Mackenzie Tuff.
LaBine Group	Echo Bay Fm	**Suprise Lake Member:** porphyritic (hornblende-augite-plagioclase) andesite flows and breccia; many flows are trachytic; some flows are oxidized to a brick-red colour; also thin sedimentary beds and minor laharic breccia.
LaBine Group	Echo Bay Fm	**Cobalt Porphyry Member:** intrusive hornblende-plagioclase porphyry and microdiorite.
LaBine Group	Echo Bay Fm	**Mile Lake Member:** porphyritic lava flows with intrbedded volcanogenic sandstone and conglomerate; andesitic lapilli tuff and ashstone.
LaBine Group	Port Radium Fm	Thin-bedded, fine grained sandstone and siltstone with at least two carbonate beds less than 1 m thick; all exposures are within the alteration halos of the Mystery Island intrusive suite.

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TYPE	P	P	P	P	P	P	P	P	P	P	P	P	P
SiO2	57.00	58.46	60.70	61.38	61.78	67.16	66.20	67.10	66.00	63.80	65.40	66.40	64.50
TiO2	0.99	0.79	0.53	0.62	0.60	0.37	0.47	0.48	0.49	0.55	0.52	0.52	0.50
Al2O3	17.60	16.98	17.86	17.24	14.79	14.69	14.30	14.80	14.40	15.10	14.60	14.40	15.00
Fe2O3	2.53	2.43	2.10	2.18	2.17	1.94	1.20	1.20	1.10	1.30	1.00	0.10	1.20
FeO	2.38	3.65	5.21	5.02	4.63	3.90	3.20	3.10	3.90	4.80	4.30	5.40	4.00
MnO	0.34	0.28	0.44	0.43	0.18	0.08	0.08	0.07	0.11	0.10	0.09	0.10	0.10
MgO	4.03	3.72	3.55	2.71	3.78	1.85	1.63	1.30	1.51	2.12	1.47	1.61	1.77
CaO	6.80	4.81	1.94	4.78	5.03	1.23	1.42	1.79	1.32	2.21	2.05	0.89	1.21
Na2O	5.07	5.91	4.32	2.74	2.67	1.24	2.10	1.90	1.20	2.40	2.20	1.80	1.50
K2O	2.56	2.78	3.12	2.63	4.37	7.42	6.25	6.38	6.98	4.98	5.62	6.24	6.81
P2O5	0.27	0.19	0.22	0.28	0.00	0.13	0.11	0.10	0.10	0.12	0.12	0.12	0.11
S							0.00	0.00	0.00	0.01	0.01	0.03	0.00
H2O	2.12	4.34	2.98	2.74	2.34	2.98	1.90	1.10	2.00	1.80	1.50	1.90	2.20
CO2							1.00	0.50	0.90	0.50	0.60	0.50	0.90
total	102.14	104.34	102.97	102.75	102.34	102.99	99.86	99.82	100.01	99.79	99.48	100.01	99.80
Nb	8	9	5	4	13	20	0	0	0	0	0	0	2
Zr	139	132	136	110	166	237	226	225	232	210	245	243	233
Y	28	27	18	20	29	18	7	8	0	9	8	32	8
Sr	271	185	296	438	299	125	126	161	106	181	178	111	84
Rb	97	92	95	93	162	281	230	291	254	215	258	258	287
Ba	864	714	1247	1098	896	1332	808	798	998	873	918	760	977
Pb	173	21	7	14	22	12	13	29	16	42	28	20	15
Zn	402	275	375	251	192	60	76	47	38	180	52	43	75
Cu	48		9	12	10	24	41	34	19	150	34	43	25
Ni	3	17	4		41	24	14	15	15	20	16	17	15
Co	0	0	0	0	0	0	16	13	13	21	17	13	14
Cr	9	84			122	23	43	40	47	58	39	36	47
V	155	195	104	98	124	80	66	61	65	90	72	68	66
Be							2.9	2.5	2.6	2.4	2.6	2.9	3.2
La	0.0	15.1	0.0	0.0	33.7	10.1	35.0	53.0	57.0	98.0	100.0	170.0	26.0
Yb		2.3			1.8	2.0	1.9	2.0	2.0	1.9	2.1	2.1	2.3

	C-87-8	C-87-9	C-87-10	C-87-11	C-87-12	C-87-13	C-87-14	C-87-15	C-87-16	C-87-17	C-87-18	C-87-19	C-87-20
TYPE	P	P	P	P	P	P	P	P	P	P	P	P	P
SiO2	65.70	64.10	64.40	64.30	63.00	62.90	62.60	61.40	59.30	63.00	62.40	63.00	66.10
TiO2	0.50	0.50	0.53	0.45	0.61	0.50	0.62	0.60	0.62	0.59	0.57	0.54	0.50
Al2O3	14.30	14.90	14.80	15.50	15.40	15.20	15.10	15.40	15.40	15.40	15.20	14.50	14.70
Fe2O3	1.20	1.30	3.30	1.40	2.40	1.40	2.60	2.00	3.10	1.10	1.10	1.90	0.80
FeO	4.20	5.60	2.10	3.80	3.50	4.00	4.00	4.10	3.40	4.10	5.80	4.80	4.30
MnO	0.10	0.22	0.28	0.26	0.18	0.22	0.23	0.25	0.24	0.23	0.19	0.15	0.08
MgO	1.90	2.20	1.94	2.05	2.43	1.50	2.07	2.73	2.32	2.68	2.97	2.60	1.39
CaO	0.61	2.05	1.31	3.05	2.91	3.30	2.95	3.64	4.92	2.99	2.66	3.43	1.82
Na2O	1.60	2.10	2.50	2.40	2.50	2.60	3.50	2.70	2.70	3.10	2.30	2.70	2.30
K2O	6.43	4.61	6.05	5.42	4.97	5.44	3.83	4.40	3.79	5.23	5.12	4.39	5.79
P2O5	0.12	0.14	0.14	0.14	0.15	0.13	0.16	0.14	0.17	0.14	0.16	0.14	0.12
S	0.00	0.00	0.02	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00
H2O	2.20	2.50	1.80	1.50	1.30	1.60	1.70	1.90	1.60	1.30	1.60	1.50	1.40
CO2	0.40	0.40	0.80	0.20	0.20	0.70	0.50	0.90	1.60	0.20	0.20	0.20	0.40
total	99.27	100.62	99.98	100.48	99.58	99.49	99.87	100.17	99.18	100.07	100.32	99.86	99.70
Nb	0	0	0	0	0	0	0	0		0	0	0	0
Zr	254	210	209	225	179	209	265	185	6	202	267	231	238
Y	0	0	0	0	0	0	0	0		0	1	0	0
Sr	81	184	94	283	284	231	279	258		275	225	276	185
Rb	276	159	182	184	184	170	129	91	304	141	162	115	272
Ba	814	1036	1864	1635	1138	1067	1854	1588	1000	1444	1000	1100	825
Pb		17	17	24	14	27	16	30	129	21	13	18	22
Zn		160	210	110	130	91	110	140	171	75	93	86	43
Cu		36	19	60	16	14	26	22		24	76	21	38
Ni		12	7	9	15	12	14	15		22	24	18	16
Co		18	15	18	22	15	17	21		20	21	21	17
Cr		46	50	44	51	45	73	67		90	77	61	38
V		80	77	83	98	80	110	110	0	84	110	100	69
Be		2.5	2.2	2.0	1.9	2.2	2.0	1.8		1.8	1.8	1.8	2.7
La		26.0	53.0	47.0	61.0	25.0	45.0	40.0	0.0	43.0	55.0	31.0	58.0
Yb		1.8	1.9	1.9	1.9	1.7	2.0	1.6		1.5	1.7	2.0	1.9

* Recalculated to 100% P = pluton A = andesite D = dacite

	88-R062	88-R085	88-R088	88-R099	88-R156	88-R302	89-R410	89-R512	H-77-53 *	H-77-53b *	H-77-80 *	H-77-51 *	H-77-96 *
TYPE	P	P	P	P	P	P	P	P	A	A	A	A	A
SiO2	65.70	59.80	68.50	67.00	58.70	59.00	69.90	59.50	57.65	59.03	59.42	59.98	60.42
TiO2	0.53	0.69	0.66	0.46	0.67	0.77	0.38	0.67	0.68	0.48	0.73	0.74	0.79
Al2O3	14.50	15.90	16.50	14.60	14.80	15.70	14.30	15.30	17.43	15.52	15.90	18.19	17.94
Fe2O3	0.40	2.80	0.40	1.40	0.00	1.90	1.40	2.20	2.26	2.12	2.34	2.30	2.34
FeO	5.80	3.70	1.30	2.50	8.50	5.20	1.60	4.50	7.61	8.52	7.86	3.51	3.45
MnO	0.14	0.30	0.13	0.09	0.65	0.18	0.08	0.18	0.34	0.47	0.47	0.18	0.16
MgO	1.93	3.06	0.65	1.65	4.16	3.74	1.55	3.27	4.23	3.72	3.92	2.78	1.88
CaO	0.41	4.04	1.32	2.17	3.80	3.59	0.58	5.93	1.62	3.20	1.26	3.72	5.01
Na2O	2.10	2.40	5.30	2.20	2.90	2.30	2.30	2.70	4.08	4.06	3.81	2.97	3.69
K2O	5.74	3.74	3.71	5.65	4.15	4.40	6.15	3.63	3.81	2.59	4.20	5.37	4.03
P2O5	0.12	0.15	0.02	0.10	0.19	0.19	0.13	0.20	0.28	0.28	0.08	0.26	0.29
S	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
H2O	2.10	2.10	0.80	1.40	2.10	1.80	1.40	0.50					
CO2	0.30	0.90	0.30	0.60	0.30	0.60	0.30	0.60					
total	99.90	99.80	99.70	100.00	100.20	99.70	100.30	99.50	99.99	99.99	99.99	100.00	100.00
Nb	0	0	6	0	0	0	0	0	10	14	10	10	11
Zr	280	180	260	220	140	360	240	190	149	137	162	162	163
Y	18	19	13	20	18	19	19	20	18	45	24	27	25
Sr	76	270	96	230	290	380	140	350	129	62	64	555	553
Rb	220	120	120	210	150	130	300	20	119	43	89	124	126
Ba	800	1200	340	840	1500	1100	690	810	1028	511	1499	1624	1150
Pb	11	7	9	9	8	9	11	7	9	18	9	6	21
Zn	39	120	23	53	350	120	42	84	211	136	340	94	144
Cu	110	42	19	10	31	65	7	79	0	24	33	57	49
Ni	15	11	14	4	24	23	8	26	0	0	0	0	0
Co	9	17	10	9	19	16	6	18	88	250	54	17	15
Cr	130	78	97	130	150	130	76	140	173	112	182	107	110
V	56	100	27	49	110	100	35	120					
Be	1.9	2.0	1.6	2.3	1.8	2.0	3.1	2.0					
La	56.0	35.0	25.0	53.0	34.0	29.5	56.0	28.0					
Yb	1.9	1.9	1.5	2.1	1.7	1.8	1.9	2.0					

	H-77-50 *	H-77-15 *	H-77-140 *	88-R010	88-R016	88-R023	88-R024	88-R033a	88-R036	88-R041	88-R051	88-R056	88-R066
TYPE	A	A	D	A	A	A	A	A	A	A	A	A	A
SiO2	60.57	63.59	67.32	60.20	52.90	57.60	62.60	58.00	61.80	56.60	66.90	58.60	53.60
TiO2	0.69	0.49	0.42	0.88	0.76	0.71	0.60	0.67	0.58	0.73	0.54	0.62	0.74
Al2O3	15.35	17.10	17.33	17.30	14.10	15.70	13.60	15.90	11.90	14.60	15.50	13.60	9.60
Fe2O3	2.26	2.05	2.01	1.40	6.30	3.50	2.60	1.80	2.10	1.80	0.90	3.80	0.00
FeO	4.87	3.84	1.57	3.00	8.60	4.80	6.90	5.90	10.40	6.30	2.70	9.00	12.60
MnO	0.27	0.07	0.17	0.20	0.19	0.30	1.11	0.17	0.14	0.16	0.10	0.18	0.27
MgO	4.95	1.26	2.06	1.09	5.33	3.10	2.31	4.18	5.29	3.89	1.66	3.23	8.77
CaO	4.27	1.88	1.62	2.74	1.07	4.26	0.18	2.16	0.27	4.55	0.98	0.99	4.63
Na2O	2.30	3.99	1.85	7.90	3.10	2.00	0.00	2.70	0.00	2.70	4.70	4.00	4.10
K2O	4.31	5.59	5.56	1.37	3.08	4.19	5.30	4.40	1.99	4.89	3.41	2.89	0.57
P2O5	0.16	0.15	0.10	0.76	0.29	0.21	0.14	0.16	0.16	0.19	0.02	0.23	0.04
S	0.00	0.00	0.00	0.00	0.05	0.01	0.57	0.05	0.52	0.02	0.00	0.33	0.02
H2O				1.20	3.60	2.10	3.10	2.50	4.80	1.60	1.50	2.30	2.60
CO2				1.30	0.60	1.60	1.40	1.60	0.20	1.10	1.10	0.40	1.60
total	100.00	100.01	100.01	99.60	100.30	100.40	100.70	100.40	100.30	99.30	100.10	100.20	99.30
Nb	11	17	20	10	0	0	0	0	0	0	0	6	0
Zr	166	213	233	150	110	160	180	160	140	120	240	110	81
Y	29	30	32	32	13	20	18	18	15	19	4	24	52
Sr	305	216	107	130	89	360	55	340	18	340	80	45	59
Rb	125	183	210	36	76	140	190	170	100	200	99	80	46
Ba	880	1198	870	480	900	1400	1200	700	290	950	600	500	180
Pb	16	16	5	4	10	12	12	19	8	8	14	120	11
Zn	260	48	62	45	140	240	110	90	50	41	15	190	110
Cu	0	0	0	47	190	50	23	16	11	15	30	21	26
Ni	0	0	0	9	150	12	31	11	49	14	1	19	17
Co	197	10	3	5	34	18	14	4	15	17	4	14	8
Cr	147	65	33	69	420	110	180	63	240	89	140	110	330
V				46	160	130	82	100	110	140	1	200	160
Be				1.3	2.1	1.9	2.2	2.1	1.9	1.8	1.5	2.8	3.6
La				42.5	23.0	31.5	27.0	13.0	19.5	27.5	6.9	32.5	15.0
Yb				2.7	1.3	2.0	1.8	1.9	1.4	1.8	0.5	2.0	5.7

* Recalculated to 100%   P = pluton   A = andesite   D = dacite

	88-R083a	88-R148	88-R150	88-R177	88-R180	88-R182	88-R186	88-R222	88-R303	H-77-93	89-R404	88-R019
TYPE	A	A	A	A	A	A	A	A	A	A	A	A
SiO2	54.80	63.20	53.70	51.90	46.00	59.40	56.80	70.80	53.50	70.20	67.30	61.50
TiO2	0.66	0.62	0.73	0.59	0.98	0.59	0.72	0.27	0.90	0.51	0.54	0.71
Al2O3	13.10	15.50	15.00	13.60	15.70	16.50	16.50	7.80	16.90	13.20	17.40	15.00
Fe2O3	7.10	2.50	2.00	1.30	12.50	0.60	1.20	3.00	1.60	0.90	0.70	8.10
FeO	5.40	4.60	8.10	5.70	8.60	6.80	5.60	11.30	7.70	2.50	1.40	1.70
MnO	0.22	0.14	0.27	0.15	0.14	0.07	0.21	0.26	0.36	0.23	0.12	0.15
MgO	5.76	1.67	5.65	3.22	2.67	3.19	2.07	1.36	3.93	1.43	1.07	1.80
CaO	2.35	1.04	6.85	8.46	5.69	5.87	4.35	0.07	4.87	1.74	0.78	0.82
Na2O	5.00	3.80	2.50	4.50	5.60	2.50	6.60	0.00	4.20	4.10	8.50	0.30
K2O	1.48	4.82	3.20	1.57	0.52	1.91	1.39	0.33	2.86	2.72	0.70	7.19
P2O5	0.02	0.22	0.26	1.56	0.02	0.18	0.33	0.08	0.22	0.17	0.14	0.25
S	0.12	0.00	0.00	0.02	0.00	0.34	0.24	0.97	0.01	0.00	0.00	0.00
H2O	2.20	1.10	1.60	1.60	1.50	2.00	1.60	3.60	1.90	1.20	0.90	2.10
CO2	1.60	0.20	0.10	4.70	0.30	0.10	2.30	0.20	0.20	0.40	0.20	0.60
total	100.00	99.60	100.20	99.00	100.20	100.10	100.10	100.10	99.30	99.40	99.90	100.40
Nb	0	0	0	0	0	0	0	0	0	8	5	0
Zr	120	170	95	92	98	140	180	110	120	180	210	190
Y	31	24	17	54	17	18	25	10	19	16	13	25
Sr	160	210	480	380	380	300	150	7	380	53	110	64
Rb	44	160	100	63	11	98	31	16	110	96	39	220
Ba	440	1400	1100	520	60	410	800	270	820	370	150	1300
Pb	7	7	6	9	6	74	39	81	25	14	2	5
Zn	160	82	160	90	200	100	180	950	320	200	29	39
Cu	37	16	22	14	23	95	93	340	13	6	22	6
Ni	19	1	42	20	31	17	11	22	7	9	7	0
Co	10	11	25	12	15	20	14	110	17	8	4	6
Cr	97	70	180	80	86	83	54	65	32	150	42	64
V	330	74	160	140	580	110	100	43	150	36	26	97
Be	2.4	2.3	1.5	3.0	1.5	1.6	1.9	0.6	1.5	1.4	1.8	2.2
La	11.5	38.0	20.0	130.0	13.5	24.0	36.5	36.0	20.5	14.0	17.5	20.0
Yb	3.5	2.4	1.5	4.3	1.0	1.6	2.3	0.7	1.7	1.8	1.4	2.2

ABBREVIATIONS:

AREA:

BTL	Bertrand Lake area
CBF	Cameron Bay Formation
CTL	Contact Lake area
MCL	McLeod Lake area
NGL	North Glacier Lake area
PR	Port Radium area
SGL	South Glacier Lake area
TUT	Tut pluton area

TYPE:

AND	andesite
BRC	breccia (volcanogenic)
CRB	sedimentary carbonate rock
DCT	dacite
DRT	diorite
DYK	dyke (granitic)
GRD	granodiorite
MNZ	monzonite
MZD	monzodiorite
MZG	monzogranite
POR	andesitic porphyry
QMD	quartz monzodiorite
QMZ	quartz monzonite
SLT	siltstone
SYT	syenite
TUF	tuff
VSS	volcanogenic sandstone

ZONE:

	albite zone
A	magnetite-apatite-actinolite zone
M	pyrite zone
P	

sample	area	type	zone	$\delta^{18}O$	δD	wt.% H_2O
77-015	CTL	and		10.2	-63	
77-019	CBF	sed		10.1	-63	1.2
77-022	CBF	tuf		11.1	-66	1.7
77-042	CBF	tuf		12.7	-73	1.1
77-051	BTL	and		9.6	-66	1.1
77-052	BTL	mnz		7.9	-79	
77-053	BTL	and		10.3	-65	
77-081	BTL	sed		11.4	-60	1.8
77-093	CTL	and		10.2	-70	0.9
77-095	PR	and			-70	
77-096	PR	and		8.8	-81	1.4
77-124	BTL	ptn		8.8	-58	
77-135	BTL	sed		8.6	-57	2.7
77-140	CTL	dct		12.1	-66	
77-154b	CBF	tuf		9.6	-60	1.2
77-170	NGL	mnz			-64	
77-172	CBF	sed		11.2	-75	1.1
77-239	CBF	drt			-60	1.9
77-226	CBF	tuf		10.9	-63	1.5
80-069	CTL	syt		10.4	-71	
87-009	CTL	ptn		11.2	-65	1.9
87-011	CTL	ptn		8.9	-72	1.1
87-013	CTL	ptn		8.6	-71	1.3
87-015	CTL	ptn		9.0	-65	1.2
88-001	CTL	and		8.7		
88-002	CTL	dyk	A	10.4		
88-003	CTL	and	P	8.2		
88-010	CTL	and	P	10.3		
88-013	CTL	and		11.7		
88-016	CTL	and	P	9.4		
88-019	CTL	and		10.5	-68	1.5
88-022	SGL	and	P	10.3		
88-023	SGL	and	P	9.5	-56	
88-024	SGL	and		9.5		
88-028	SGL	and	AP	9.0		
88-031	SGL	dyk	AP	10.7		
88-033a	SGL	and	P	9.9		
88-034	SGL	and	P	9.1		
88-035	SGL	and	P	8.6		
88-036	SGL	and	M	8.4		
88-037	SGL	and	M	7.1		
88-041	SGL	and	M	7.5		
88-042	SGL	and		9.2		
88-043	SGL	and		9.4		
88-044	SGL	mnz		8.8		
88-049	SGL	mnz	A	8.4		
88-050	SGL	and		8.0		
88-051	SGL	and	M	9.7		
88-052	SGL	mnz		8.9		
88-053	SGL	and		8.1		
88-056	SGL	and		8.5		

sample	area	type	zone	$\delta^{18}O$	δD	wt.% H_2O
88-056	SGL	and	P	8.5	-67	
88-057	SGL	and	M	8.6		
88-062	SGL	mnz		9.0	-64	1.4
88-066	SGL	and	M	8.2		
88-068	SGL	and	M	8.9		
88-070	SGL	mzd		9.8		
88-075	BTL	qdt		12.3		
88-076	BTL	drt		8.1	-65	
88-081	BTL	mnz		8.8		
88-083a	SGL	and	MP	10.0	-65	1.5
88-085	TUT	drt		8.3	-60	
88-087	TUT	drt		8.7	-62	1.5
88-088	TUT	mzg		10.3	-75	0.6
88-089	TUT	mnz		9.4	-60	1.3
88-091	TUT	qmd		7.7		
88-099	TUT	mzd		9.5	-67	0.9
88-112	NCTL	and	P	8.5	-61	
88-124	NCTL	and	P	9.1		
88-128	NCTL	qmd		9.0		
88-130	NCTL	and	M	8.9	-70	
88-135	SCTL	and	MP	7.3		
88-141	SCTL	and	M	7.2	-68	1.2
88-142	SCTL	and	A	8.8		
88-148	SCTL	and		9.4		
88-150	SCTL	and	M	7.2	-80	
88-156	MCL	qmz		9.2	-70	1.5
88-162	SCTL	and	P	8.1	-78	
88-166	SCTL	and	A	7.4		
88-172	CTL	and	A	9.5		
88-174	CTL	and	AM	9.4		
88-176	CTL	and		9.2		
88-177	CTL	and	AM	9.6		
88-180	CTL	and	M	7.7	-85	1.0
88-182	CTL	and	AMP	6.3	-92	1.4
88-185	CTL	and	AM	7.8		
88-186	CTL	and	P	8.9		
88-188a	CTL	and	M		-72	0.7
88-188b	CTL	maa	M	7.0		
88-189	CTL	and	M	8.1		
88-196	CTL	and	M	8.2		
88-197	CTL	and		10.0	-65	
88-198	CTL	qmz		9.8	-77	0.9
88-204	BTL	drt		5.8	-83	1.5
88-207	BTL	and		5.3	-65	1.7
88-212	CTL	and?	M	6.9	-75	1.2
88-216	BTL	drt		7.8		
88-219	BTL	slt		7.8		
88-222	NGL	brc	P	8.8		
88-226	CTL	and		8.7		
88-227	CTL	and	AM	9.9		
88-231	CTL	and	M	6.5		

sample	area	type	zone	$\delta^{18}O$	δD	wt.% H_2O
88-234	SGL	and	M	8.4		
88-243	SGL	mzd		8.5	-61	1.4
88-257a	BTL	mzd		9.4	-72	0.8
88-263b	BTL	por		10.1	-60	1.8
88-269	BTL	mnz		8.5	-83	
88-302	SCTL	qmz		9.5		
88-303	SCTL	and		9.3	-74	1.3
88-305	SCTL	qmz		8.7		
88-306	SCTL	and		8.2		
88-308	NGL	and	P	9.5		
89-013	PR	sed	MP	8.1		
89-019	PR	ptn		9.9		
89-162	PR	sed	P	9.2		
89-173	PR	por	AM	7.8	-89	0.5
89-191	PR	por		10.5	-58	
89-226	PR	sed		8.7	-68	
89-234	PR	por		8.9		
89-291	PR	por?			-62	
89-294	PR	and		7.8		
89-313	PR	and		9.4	-70	
89-323	PR	and		9.0		
89-338	TUT	and		8.3		
89-352	TUT	grd		8.7		
89-404	TUT	and	A	8.6		
89-410	TUT	qmz		11.0	-62	1.0
89-423	TUT	and	AM	10.4		
89-432	TUT	and		10.4		
89-447	MCL	grd		9.7	-67	1.1
89-449	MCL	and	MP	9.0	-60	1.9
89-469	TUT	por		10.0	-68	0.9
89-506	NGL	and		9.2		
89-508	NGL	and		8.9	-57	2.7
89-512	NGL	qmz		7.8	-91	0.7
89-538	TUT	mzd		8.5	-68	1.5
89-548	TUT	and		8.7		
89-549	TUT	and		8.4		
89-576	SGL	and		9.9		
89-578	SGL	mnz	A	9.6		
89-580	SGL	mnz		9.7		
89-582	SGL	qmz		9.7		
89-584	SGL	mnz		8.7		
89-586	SGL	mnz		10.0		
89-588	SGL	qmz		9.8		
89-590	SGL	qmz		10.4		
89-592	SGL	mnz		9.0	-68	
89-594	SGL	dyk		9.9		
89-596	SGL	dyk		9.7		
89-598	SGL	and		8.7		
89-603	PR	crb	A	9.1	-84	0.6
89-604	PR	crb		6.7	-62	0.5
89-608	BTL	and		9.8	-57	
89-620	BTL			9.3		

sample	mineral	type	$\delta^{18}O$	δD	wt.% H_2O
89-193 -AC	actinolite	VEIN	+ 6.4	- 80	
89-446 -AC	actinolite	VEIN	+ 6.6	- 53	
88-256 -AC	actinolite	VEIN	+ 6.9	- 72	2.60
88-115 -AC	actinolite	PAR	+ 7.0	- 78	
88-153 -AC	actinolite	PAR	+ 7.0	- 80	
89-495 -AC	actinolite	VEIN	+ 7.1	- 80	
88-248 -AC	actinolite	PAR	+ 7.4	- 67	2.30
89-059b-AC	actinolite	PAR	+ 7.7	- 82	1.34
89-124 -AC	actinolite	PAR	+ 7.9	- 78	
89-426 -AC	actinolite	PAR	+ 8.5	- 65	
89-600b-AC	actinolite	VEIN	+ 9.4	- 80	1.65
89-445b-AC	actinolite	PAR	+ 9.6	- 74	
88-153 -EP	epidote	PAR	+ 4.1	- 93	2.50
88-256 -EP	epidote	VEIN	+ 5.4		
				-112	2.60
89-059b-BT	biotite	PAR	+ 9.7		
				- 55	
88-083b-TC	talc	VEIN	+ 12.3		
88-115 -AP	apatite	PAR	+ 6.5		
88-248 -AP	apatite	PAR	+ 6.5		
88-256 -AP	apatite	VEIN	+ 6.9		
89-600b -AP	apatite	VEIN	+ 7.3		
89-445b -AP	apatite	PAR	+ 7.5		
89-059b -AP	apatite	PAR	+ 8.0		
88-256 -QZ	quartz	VEIN	+12.4		

sample	mineral	type	$\delta^{18}O$
89-124 -MT	magnetite	PAR	- 3.1
88-083b-MR	martite	VEIN	- 2.2
88-083b-MT	magnetite	VEIN	- 0.5
89-446 -MT	magnetite	VEIN	+ 1.0
89-445b-MT	magnetite	PAR	+ 2.3
89-193 -MT	magnetite	VEIN	+ 2.4
89-059b-MT	magnetite	PAR	+ 3.6
88-153 -MT	magnetite	PAR	+ 4.1
89-600b-MT	magnetite	VEIN	+ 4.2
88-188b-MT	magnetite	PAR	+ 4.5

sample	description	mineral	$\delta^{34}S$
89-429b	calcite-chalcopyrite pod	chalcopyrite	+ 4.2
89-483b	calcite-chalcopyrite pod	chalcopyrite	+ 10.3
89-373	gossan	pyrite	+ 0.8
89-360	pyrite pod in MAA zone	pyrite	+ 2.7
89-143	pyrite pod	pyrite	+ 4.4
89-276	gossan	pyrite	+ 4.8

sample	description	mineral	$\delta^{18}O$	$\delta^{13}C$
88-245b	chalcopyrite-bearing quartz-carbonate vein	calcite	+ 7.0	- 5.6
88-263a	chalcopyrite-bearing quartz-carbonate vein	calcite	+ 10.7	- 4.2
89-008	calcite pod in andesitic porphyry	calcite	+ 9.1	- 5.7
89-021b	quartz-siderite vein	siderite	+ 16.6	- 2.9
89-188b	chalcopyrite-bearing quartz-carbonate vein	siderite	+ 14.2	- 2.2

sample	description	mineral	$\delta^{34}S$
89-459	chalcopyrite and pyrite -bearing quartz vein	chalcopyrite	+ 5.6