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Kiruna-type Deposits: Their Origin and Relationship to Intermediate Subvolcanic Plutons in the Great Bear Magmatic Zone, Northwest Canada*

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Abstract

Magnetite-apatite-actinolite rocks, similar to those at Kiruna, Sweden, and the St. Francois Mountains, Missouri, are associated with seven epizonal plutons that intrude andesitic stratovolcanoes of a broadly folded, early Proterozoic continental magmatic arc located in the northwestern Canadian Shield. The plutons, mainly medium-grained quartz monzonite-monzodiorite-diorite (IUGS) sheets and laccoliths 5 to 25 km in diameter, are spatially, temporally, and compositionally related to host andesitic stratovolcanoes. They were emplaced at 2 to 3 km depth, are compositionally heterogeneous, metasomatically altered, and had plagioclase as the liquidus phase. In addition they have kilometer-wide alteration halos comprising an inner zone of nearly complete wall-rock albitization, an intermediate zone of magnetite-apatite-actinolite veins, pods, breccias and wall-rock replacement, and an outer zone of disseminated sulfides. One pluton (Balachey) has a halo that is more or less completely outside the body, but another (Rainy Lake) has a halo that is partly superimposed over it. Separation of iron phosphate and silicate melts by liquid immiscibility is not supported by: (1) the gradual replacement of plagioclase by chessboard albite toward the roof of the Rainy Lake pluton, (2) the chemical trends in the Rainy Lake intrusion, (3) the mineralogical zoning, low temperature mineralogy, and replacement textures of the magnetite-apatite-actinolite, and (4) the relationship of the magnetite-apatite-actinolite veins and bodies to the plutons. However, all available data are compatible with a deuteric origin. It is concluded that high temperature, low initial water content, and shallow-level emplacement by intermediate plutons are necessary for the development of Kiruna-type deposits.

Introduction

KIRUNA-TYPE deposits are variable concentrations of magnetite-fluorapatite-actinolite found in volcano-plutonic terranes from the Proterozoic to the Cenozoic. The best known and probably largest deposits are those found near Kiruna, Sweden (Frietsch, 1978; Geijer and Odman, 1974), but other well-known deposits occur in Missouri (Snyder, 1969), Chile (Bookstrom, 1977), and at numerous locations around the Pacific Ocean basin (Park, 1972).

There have been many detailed studies on the mineralogy and occurrence of the deposits, but to date no general model for their genesis has been accepted. In fact, the number of models for their origin approaches the number of deposits. For example, the origin of Kiruna-type deposits has been ascribed to hydrothermal, or late magmatic, processes (Crane, 1912; Geijer, 1915, 1930; Geijer and Odman, 1974; Bookstrom, 1977; Frietsch, 1978), liquid immiscibility (Daly, 1915; Badham and Morton, 1976; Lundberg and Smellie, 1979; Smellie, 1980), exhalative sedimentary processes (Hegemann and Albrecht, 1954; Paràk, 1973, 1975, 1985), and remobilization of iron and phosphorus from older sedimentary rocks (Landergren, 1948; Park, 1961; Frutos and Oyarzun, 1975).

A folded 1.87-b.y.-old subduction-related magmatic arc exposed in the northwestern Canadian Shield at Great Bear Lake contains thick sequences of calc-alkaline andesite interpreted as ancient stratovolcanoes (Hildebrand, 1984). Emplaced into, and in some cases just beneath, the andesites are intermediate concordant plutons, collectively termed the "early intermediate intrusive suite." All of the plutons have concentrations of magnetite-apatite-actinolite and similar spatial, temporal, and compositional relationships to their respective host andesites. This paper focuses on two of the plutons, the Rainy Lake Intrusive Complex and the Balachey pluton, in order to understand the genesis of Kiruna-type deposits.

Regional Geology

The plutons lie along the western margin of Great Bear magmatic zone (Fig. 1), the youngest magmatic belt of the 2.1- to 1.8-b.y.-old Wopmay orogen (Hoffman, 1980; Hoffman and Bowring, 1984). The zone, at least 800 km long by 100 km wide, contains thick successions of subgreenschist facies volcanic and sedimentary rocks (Hoffman and McGlynn, 1977) dated by U-Pb on zircon at 1.87 to 1.86 b.y. (Bowring and Van Schmus, in press). The volcano-sedimentary sequences lie unconformably on an older, deformed

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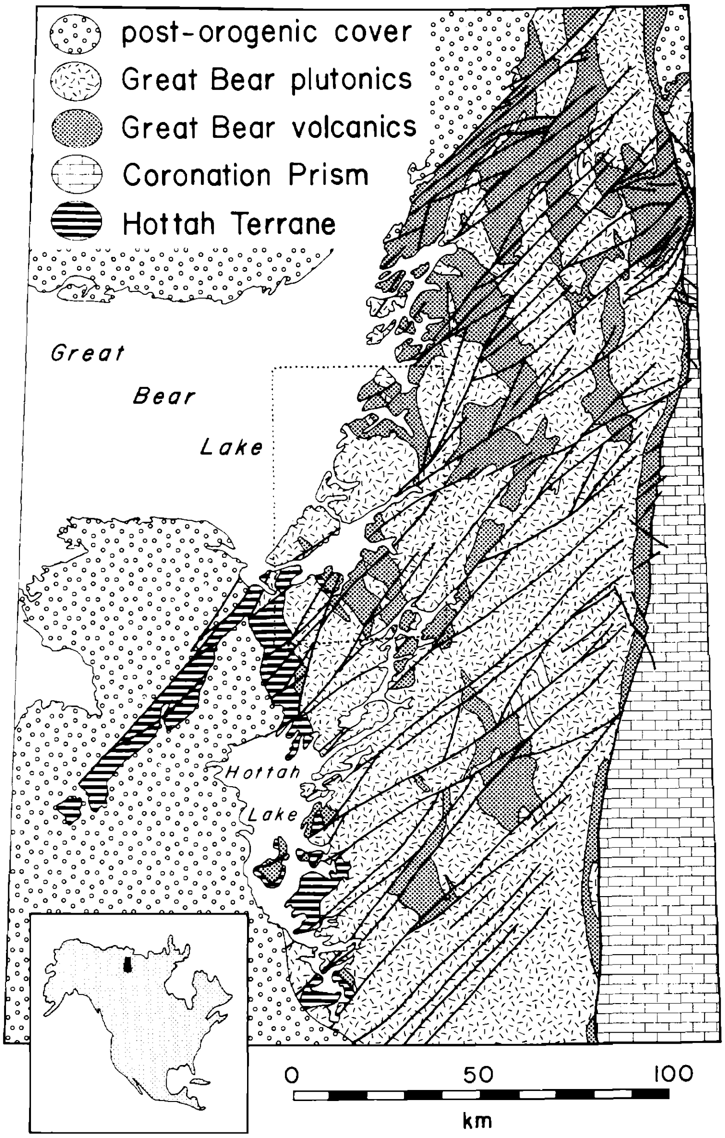

FIG. 1. Regional tectonic map showing distribution of volcanic and plutonic rocks in the northern part of the Great Bear magmatic zone, basement to the west (Hottah terrane) and to the east (Coronation prism), younger cover, and the location of Figure 2.

sialic basement complex (Hildebrand et al., 1983; Hildebrand, 1984) and are cut by biotite-hornblende and hornblende-bearing granitoid plutons, some of which are demonstrably synvolcanic. The volcanic rocks are mainly calc-alkaline and form a compositional series ranging continuously from basalt to rhyolite. Based on major and trace element chemistry, mineralogy, eruptive styles, and regional tectonic setting, the supracrustal sequences of the area are interpreted to represent part of a continental magmatic arc related to eastward directed subduction of oceanic lithosphere (Hildebrand, 1981, 1982a; Hildebrand and Bowring, 1984). Shortly after 1.86 b.y. the entire zone was folded about northwest-trending axes, oblique to the zone, and then intruded by a suite of mainly biotite-bearing granitoid bodies whose age is about 1.84 b.y. (Bowring and Van Schmus, in press). Later (1.84–1.80 b.y.), the entire Great Bear magmatic zone was out by a swarm of northeast-trending, right-lateral transcurrent faults that belong to a regional system of conjugate transcurrent faults producing east-west shortening and north-south extension.

The local host rocks for the early intermediate intrusive suite are a diverse assemblage of volcanic and sedimentary rocks that crop out in two areas separated by faults and younger granitoid plutons (Fig. 2). Individual stratigraphic units are not correlative

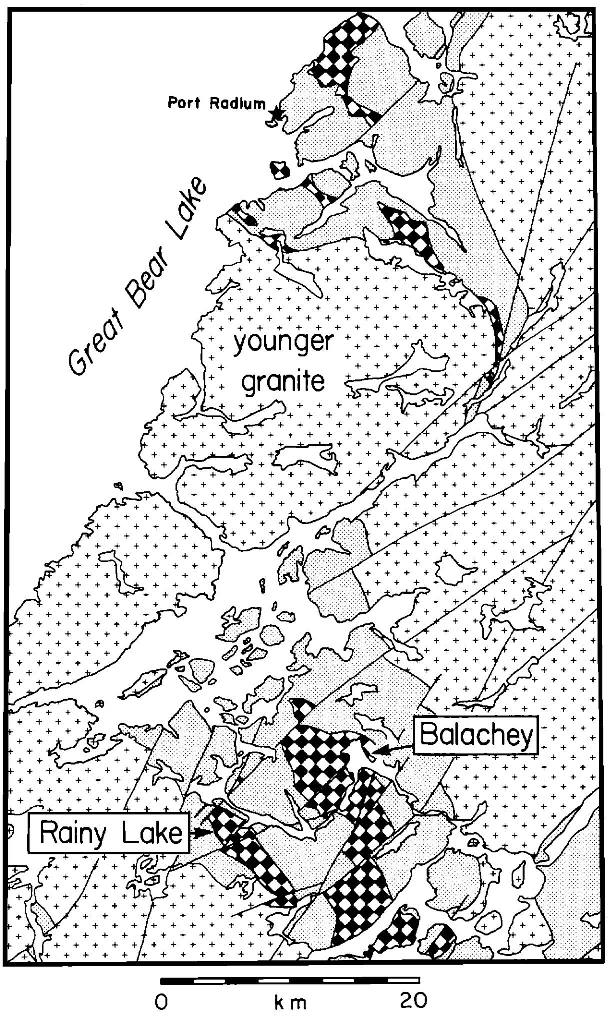

FIG. 2. Simplified geologic map showing the distribution of supracrustal rocks (screened), early intermediate intrusive suite (checkered), and younger granitoid plutons (crosses) along the eastern shore of Great Bear Lake. Balachey pluton and the Rainy Lake Intrusive Complex are labeled.

between the areas, but similarities in U-Pb ages, rock types, and regional stratigraphic position suggest that volcanism in both areas was roughly contemporaneous.

The geology of the northern area can be divided into two main eruptive periods (Hildebrand, 1981, 1982b): development of large andesitic stratovolcanoes, and subsequent emplacement of large volume ash-flow tuff sheets and associated cauldron collapse. The stratovolcanoes, up to 3 km thick and comprising mainly augite- and hornblende-bearing, plagioclase porphyritic andesite, are folded and exposed in oblique cross sections.

At least five sill-like intermediate plutons intrude the stratovolcano complex both at high stratigraphic levels and at its base. Each one of the plutons has a zoned alteration halo comprising an inner zone of intensely albitized wall rock, an intermediate zone of magnetite-apatite-actinolite veins, pods, and disseminations, and an outer pyritic zone. In some cases the sulfide zone hosted rich, but now mined out, polymetallic veins containing native Ag and Bi, Ni-Co arsenides, and pitchblende. It was one of these vein systems, located at Port Radium, which provided the uranium ore used in the Manhattan Project (Anonymous, 1977). Boulders of plutonic rock, similar in mineralogy and texture to one of the plutons, occur in conglomerate near the base of the ash-flow tuff sequence. This indicates that the pluton was emplaced prior to eruption of the tuffs, during or very shortly after andesitic volcanism. In fact, the composition and location of the plutons suggest that they all may be subvolcanic intrusions related to andesitic volcanism.

The geology of the southern area is complex in detail but can be divided into two cycles, each related to collapse of a major caldera (Hildebrand, 1984, 1985a). Initially, voluminous rhyolitic magma was erupted as ash flows. This led to collapse of the first cauldron, which was then filled with fluvial and lacustrine sedimentary rocks and several kilometers of andesitic lavas and breccias, tuff, and epiclastic rocks. The second cauldron, caused by eruption of dacitic magma, formed soon afterward and the topographic depression remaining after collapse was filled by fluvio-lacustrine sedimentary rocks and andesitic lavas and associated breccias.

The southern area was intruded by two intermediate plutons similar to those of the northern area: the Balachey pluton and the Rainy Lake Intrusive Complex. The Balachey pluton intrudes the postcollapse andesites of the first cauldron cycle and the Rainy Lake pluton intrudes the underlying intracauldron facies tuff and fluvio-lacustrine deposits deposited in the same cauldron.

The age of emplacement of the Balachey pluton is tightly constrained by both stratigraphy and geochronology because much of the northeastern margin of the intrusion is unconformably overlain by deposits of coarse mesobreccia related to collapse of the second major ash-flow cauldron whose outflow sheet lies on postcollapse andesites of the first cauldron cycle (Hildebrand, 1984, 1985a). This indicates that it was emplaced during or shortly after eruption of the andesites. Populations of discordant zircon from a pluton interpreted to be resurgent emplaced into the center of the second cauldron (Hildebrand, 1984, 1985a) yield an age of 1,868 ± 2 m.y. (Bowring and Van Schmus, in press). The U-Pb upper intercept age of the Balachey pluton is 1,868 ± 8 m.y. (Bowring and Van Schmus, in press). Therefore, the pluton is synvolcanic and its age, as constrained by both U-Pb geochronology and stratigraphic arguments, is about 1,868 m.y.

The Rainy Lake Intrusive Complex has not been dated and its age is not constrained by field relations, but its compositional and textural similarities to the andesites and the Balachey pluton suggest that it is roughly coeval with both. Thus, both the Balachey pluton and the Rainy Lake Intrusive Complex are considered to be temporally related to postcollapse andesites of the first cauldron cycle.

Like the plutons in the northern belt, there is no evidence to suggest that either the Balachey or Rainy Lake bodies vented to the surface from their present level of emplacement; however, their close compositional and temporal relationship to the andesites indicates that the lavas and plutons may represent part of the same batch of magma. If so, they might be similar in composition and size to bodies that at deeper levels were the source of the erupted andesites. Possibly both plutons were able to rise and invade the volcanic edifice because they did not erupt and thus dehydrate.

The Balachey Pluton

This northwest-trending pluton crops out continuously over a length of 20 km and a width of 1 to 6 km (Fig. 3). The major rock types of the body are medium- to coarse-grained, seriate, hornblende quartz monzonite (IUGS nomenclature) in the northwest and quartz monzodiorite in the southeast. Locally, there is a plagioclase porphyritic border phase. Contacts between internal phases are gradational, and moderate mineralogical variations (2–10%) occur on scales ranging from kilometers to centimeters. A common feature present throughout the intrusion is the occurrence of fractures along which actinolitic amphibole is concentrated.

All contacts of the Balachey pluton with surrounding country rocks are sharp and, like the body itself, trend northwest. Along the entire southwestern margin and part of the northeastern margin the pluton intrudes lavas, tuffs, and sedimentary rocks of the postcollapse andesite pile, along with small related intrusions of monzonite and diorite, which are all strongly altered up to 2 km from the contact. The contact dips away from the pluton at about the same inclination as bedding in the lavas and sedimentary rocks (about 30°). Rocks younger than the pluton are folded; both sides of the pluton are flanked by northwesterly trending synclines. Therefore, Hildebrand (1984) argued that the Balachey pluton is folded, occupies the core of a northwesterly plunging anticline, and was intruded as a large sill. The lower contact of the Balachey pluton is not exposed, but by analogy with other plutons of the early intermediate intrusive suite which are exposed in oblique cross section and are concordant, the lower contact of the Balachey pluton is probably fairly flat. Thus, the pluton is inferred to be sill-like and folded into a broad anticline (Fig. 4).

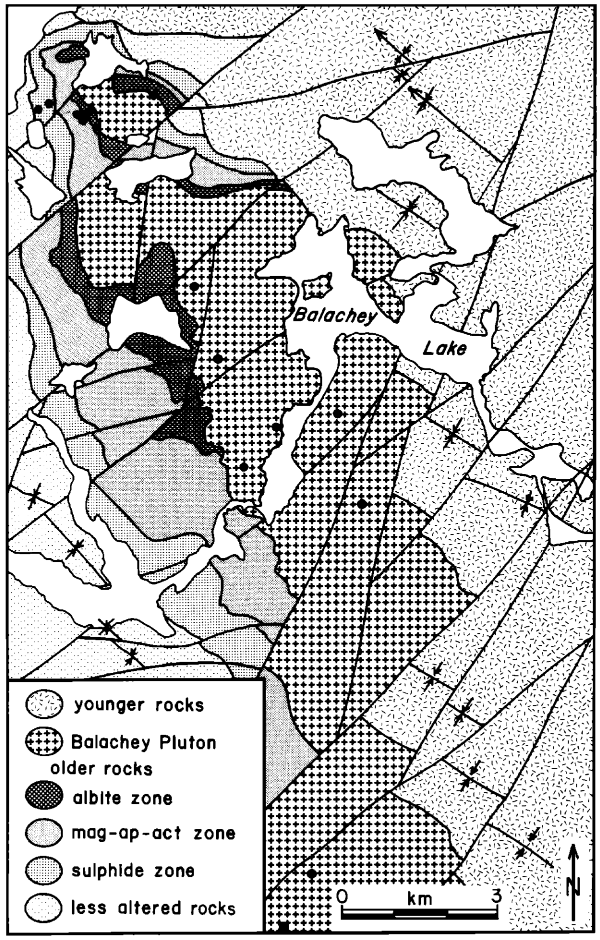

FIG. 3. Geologic sketch map of the northwest half of the Balachey pluton showing the distribution of rocks younger than the pluton and alteration zones in rocks older than the pluton. The Balachey pluton occupies the core of a northwest-plunging anticline. Locations of the samples in Tables 1 and 2 are indicated by dots.

Petrography

The main part of the intrusion is massive and consists dominantly of euhedral, seriticized plagioclase phenocrysts, 1 to 4 mm long, in a matrix of quartz and microperthite, typically forming granophyric intergrowths. Concentric shells of sericite outline original zoning in the plagioclase phenocrysts. Quartz along with microperthite appear to replace plagioclase in many places. Fibrous green amphibole, probably actinolite or actinolitic hornblende, is subhedral, replaced by chlorite along cleavage planes, and forms clots 2 to 4 mm across. Some clots are partly replaced by epidote. Anhedral Fe-Ti oxides are mostly concentrated within the clots of amphibole, but sparse

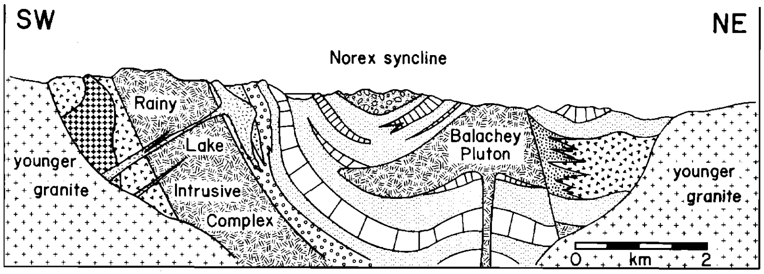

FIG. 4. Schematic cross section (not to scale), modified after Tirrul (1976), showing major folds of the southern area.

hexagonal plates of hematite are scattered throughout. Hexagonal prisms of apatite less than 0.5 mm in diameter and tiny subhedral crystals of zircon are common accessory minerals.

Samples collected from near the roof of the pluton have plagioclase phenocrysts that are partly replaced by an interlocking mosaic of anhedral quartz and albite. Vestiges of original phenocrysts occur, but most phenocrysts have been completely replaced around their margins such that they no longer appear euhedral. Instead, they have margins that grade into and interlock with a groundmass mosaic of quartz and albite. Felted mats and irregular clots of actinolite form pseudomorphs of ferromagnesian minerals, perhaps hornblende or pyroxene. The borders of the clots and aggregates are ragged and fuzzy. Opaque Fe-Ti oxides are much less common than in the main body of the pluton. Minute apatite needles occur in every thin section examined.

Whole-rock chemistry

Eight samples from the Balachey pluton were analyzed at the Memorial University of Newfoundland for major and trace elements and the results are listed in Table 1. The major elements were analyzed by atomic absorption spectrometry except P_2O_5 which was determined colorimetrically. Trace element abundances were determined by X-ray spectrometry on a Phillips 1450 instrument using pressed powder pellets. For the most part, ten rare earth elements were determined in each of three samples by first separating the rare earth elements from other oxides by cation exchange techniques and then analyzing the residue by X-ray fluorescence on the same Phillips 1450 instrument.

The analyses show that the Balachey pluton is of typical calc-alkaline intermediate composition. Silica content of the pluton ranges from about 60 to nearly 66 percent and the least silica-rich samples overlap compositionally with postcollapse andesitic lavas of the first cauldron cycle. Rare earth element analyses exhibit light rare earth element enrichment patterns and have the high overall abundances (Fig. 5) typical of high K andesites from Cenozoic continental magmatic arcs. The patterns are nearly identical to the most siliceous samples of lava from the postcollapse andesite pile except that samples from the pluton have larger Eu anomalies.

Alteration of wall rocks

Wall rocks of the Balachey pluton are strongly altered for a distance of at least 1 km out from the pluton, assuming that the contact continues to dip at 30° beneath the surface. Three alteration zones (Fig. 3) were mapped in the field: an inner zone of intense bleaching and albitization, an intermediate zone of magnetite-apatite-actinolite, and an outer zone of mainly pyrite. The criteria used to define the zones were as follows: (1) the boundary between the inner and intermediate zones was placed at the first appearance of the assemblage magnetite-apatite-actinolite; (2) the boundary between the intermediate and outer zones was mapped at the disappearance of the magnetite-apatite-actinolite assemblage; and (3) the outer margin of the sulfide zone was placed at the disappearance of visible gossan. Mapped in this manner, albite is present in all three zones and sulfides occur in the outer part of the magnetite-apatite-actinolite zone. The alteration zones are truncated along the northwest side of the intrusion by the unconformity at the younger cauldron margin.

The inner, or albite zone, is characterized by nearly complete albitization of the postcollapse andesitic lavas and sedimentary rocks. Most original textures are obliterated and the rocks weather white to pale pink. Nearly all bedded rocks are intensely brecciated; however, vestiges of bedding can still be seen within individual fragments. A fine-grained, pre-Balachey monzonitic intrusion in this zone is completely albitized adjacent to fractures, which gives the rock a striped to mottled appearance. Andesitic lavas within the albite zone are commonly replaced by granoblastic-polygonal albite with only a few specks of chlorite. Hildebrand (1982a) compared the altered rocks with relatively unaltered samples from outside the halo and concluded that virtually all elements originally present in the lavas and sedimentary rocks, including the so-called "immobile elements," have been mobilized

TABLE 1. Major and Trace Element Analyses, Balachey Pluton

Sample no.	J-79-93	H-79-40	J-79-62	J-79-92	J-79-66	J-79-61	H-80-26	H-80-24
SiO_2	65.4	65.5	60.5	64.3	65.7	62.5	64.0	63.0
TiO_2	0.33	0.34	0.59	0.45	0.45	0.44	0.58	0.63
Al_2O_3	15.4	15.9	14.1	15.5	15.5	14.4	14.1	14.4
$Fe_2O_3^*$	4.86	4.12	6.49	4.54	3.65	5.59	5.80	6.74
MnO	0.10	0.04	0.36	0.09	0.11	0.11	0.10	0.15
MgO	1.94	1.51	3.33	1.53	1.56	2.98	2.24	2.80
CaO	1.02	3.71	4.76	2.11	2.09	3.32	3.74	3.80
Na_2O	3.00	3.25	2.45	2.98	3.43	3.08	2.61	2.61
K_2O	4.98	4.03	4.15	5.16	5.13	4.19	4.07	4.16
P_2O_5	0.08	0.10	0.14	0.09	0.08	0.09	0.07	0.11
L.O.I.	2.41	0.64	2.88	2.30	1.90	2.17	1.33	1.55
Total	99.52	99.14	99.69	98.99	99.60	98.87	98.64	99.95
Nb	14	12	13	13	12	13	9	13
Zr	169	187	185	179	184	156	162	203
Y	30	36	25	38	32	31	31	31
Sr	134	280	264	199	214	229	222	271
U	9	5	4	7	1	6	2	1
Rb	184	142	160	177	132	148	155	155
Th	14	17	15	17	17	22	19	14
Pb	10	20	62	24	19	22	18	16
Ga	10	13		14	13	10	14	16
Zn	73	29	125	45	70	90	59	84
Cu	20	22	63	19	22	30	0	0
Ni	14	13		19	16	27	5	4
Cr	11	14	94	16	11	57	18	20
V	68	59	113	63	58	95	100	115
Ba	1,145	973	834	1,185	1,131	979	1,048	1,077
La	15.06	23.73		16.79				
Ce	36.58	55.91		47.04				
Pr	4.64	6.90		6.13				
Nd	17.74	24.43		23.07				
Sm	3.08	4.91		4.82				
Eu	0.22	0.63		0.72				
Gd	3.36	3.84		3.89				
Dy	4.56	3.65		4.11				
Er	1.94	2.29		2.32				
Yb	2.32	3.13		2.86				

Oxides in weight percent, trace elements in ppm; 0 = not detected; L.O.I. = loss on ignition; $Fe_2O_3^*$ = total Fe as Fe_2O_3

and partially removed (Table 2). The albite zone is entirely outside the pluton at its northwestern end but partly within the southeast side of the intrusion.

The zone of magnetite-apatite-actinolite contains those minerals as pods, veins, disseminations, and as rosettes with albite. Most common are abundant small veins (1-2 cm wide) in which fibrous green amphibole, oriented perpendicular to the vein margins, occurs with interstitial anhedral pink apatite and octahedra of magnetite or martite. Pods of magnetite-apatite-actinolite, up to 2 m across, typically contain coarse blades of amphibole to 30 cm long, magnetite octahedra to 5 or 6 cm, and patches of anhedral apatite ranging up to 20 cm. Rosettes of bladed albite, up to 15 cm in diameter, are common in altered andesite flows and have interstitial chlorite, amphibole, and magnetite. Epidote is another common mineral within this alteration zone and in a few lavas it lines cavities suspected to be vesicles. Some epidote-lined cavities are completely filled with coarse pink apatite.

The sulfide halo comprises abundant gossans up to 10 m across, which in the early 1930s probably attracted prospectors to the area in search of silver and uranium. The pyrite is disseminated throughout the area in concentrations as high as 25 percent. The zone contained local polymetallic veins, now mined out, of native Ag, Bi, and Ni-Co arsenides.

The Rainy Lake Intrusive Complex

The Rainy Lake Intrusive Complex (Tirrul, 1976) is a compositionally and mineralogically zoned, sheetlike pluton about 1.5 km thick and 10 to 11 km across (Hoffman et al., 1976). The pluton was folded after intrusion and is now exposed in oblique cross section on the limb of a major syncline (Fig. 4). It has a flat roof that is roughly concordant with bedding of

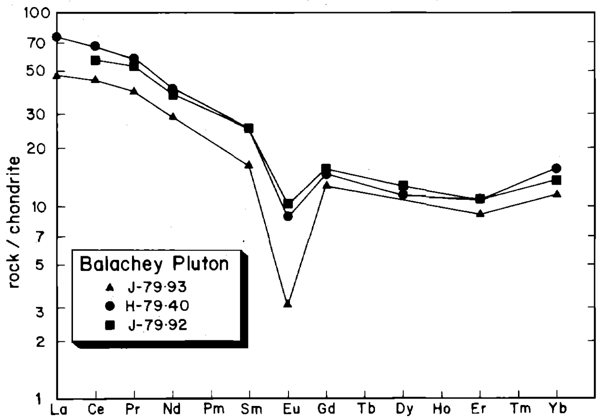

FIG. 5. Chondrite-normalized rare earth elements from the Balachey pluton.

the country rocks and a floor that is slightly convex downward, such that the thickest parts occur near the center (Fig. 6). The pluton is intruded by a younger unrelated syenogranite in the southeast, and therefore, the lower contact of the Rainy Lake Intrusive Complex is not preserved there.

Tirrul (1976) recognized that the pluton was mineralogically and compositionally zoned parallel to its flat roof; he mapped five major divisions. From top to bottom they are: a monzonitic border phase, a syenitic phase that he divided into a fine-grained upper part and a coarse-grained lower part, a central monzonite, and a lower monzodiorite (Fig. 6). In addition, there is a lower border monzonite that presumably was connected to the upper border phase prior to intrusion of younger plutons and erosion. For this study the fine- and coarse-grained syenites are grouped together because there are only minor mineralogical and chemical differences between them. Major mineral phases of 18 samples collected from near the base to the roof of the intrusion are listed in Table 3 and are plotted against height in Figure 7.

Border phase

The upper border phase of the pluton is well exposed in many places and is up to 20 m thick. It comprises about 37 percent intensely seriticized plagioclase phenocrysts up to 1 cm long, 1 to 2 percent relict clinopyroxene phenocrysts, less than 2 percent serpentinized orthopyroxene phenocrysts, and ragged

TABLE 2. Major and Trace Element Analyses of Altered Andesitic Rocks from the Balachey Pluton Halo

Sample no.	H-79-131	H-79-132	H-79-133	H-79-126	H-79-124
SiO_2	59.1	71.3	65.0	59.4	61.5
TiO_2	0.28	tr.	0.00	0.20	0.45
Al_2O_3	18.2	15.5	20.3	17.1	16.6
$Fe_2O_3^*$	3.47	0.65	0.61	4.42	2.73
MnO	0.26	0.07	0.04	0.06	0.12
MgO	3.39	0.39	0.19	1.68	1.42
CaO	4.54	1.41	1.02	3.33	2.14
Na_2O	7.50	8.36	9.36	7.98	8.82
K_2O	1.12	0.37	1.46	0.88	0.88
P_2O_5	0.02	0.01	0.00	0.34	0.38
L.O.I.	2.53	1.82	1.70	3.48	3.12
Total	100.41	99.88	98.68	98.87	98.16
Nb	7	0	0	22	35
Zr	175	35	171	206	203
Y	19	0	6	32	45
Sr	370	83	203	78	45
U	0	0	0	5	5
Rb	25	6	49	9	13
Th	0	0	0	14	12
Pb	6	15	0	3	1
Ga	20	20	20	20	21
Zn	147	24	20	55	15
Cu	8	15	6	13	38
Ni	0	0	0	0	0
Cr	0	0	0	0	0
V	31	6	0	0	122
La	11	5	17	50	64
Ce	11	1	17	72	122
Ba	1,034	262	419	204	163

Samples 131, 126, and 124 are andesitic lavas; 132 and 133 are andesitic sandstones
Oxides in weight percent; trace elements in ppm; 0 = not detected; L.O.I. = loss on ignition
$Fe_2O_3^*$ = total Fe as Fe_2O_3

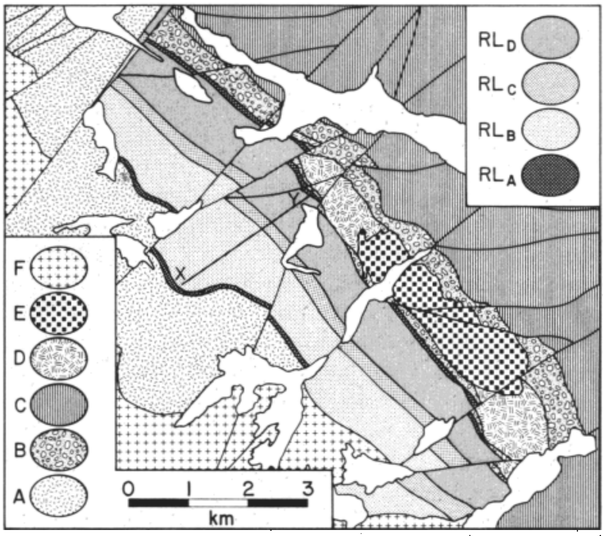

FIG. 6. Geologic sketch map of the Rainy Lake Instrusive Complex showing the surrounding geology. Internal zonation of the pluton: RL_A = monzonitic border phase, RL_B = lower monzodiorite, RL_C = central monzonite, RL_D = upper syenite, A = intracauldron facies tuff and other older rocks, B = postcollapse intracauldron lacustrine and fluvial rocks, C = postcollapse andesitic lavas, breccias, tuff, and epiclastic rocks, D = quartz diorite, E = intrusive plagioclase porphyry, F = younger granite, XY = locations of samples analyzed in this study.

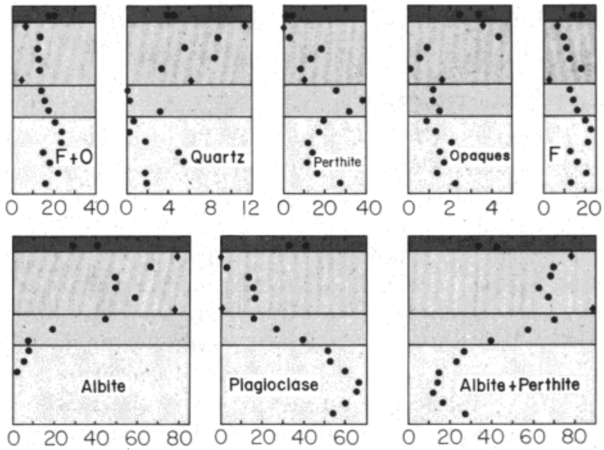

FIG. 7. Modal composition of samples collected from the Rainy Lake Intrusive Complex plotted with height in the intrusion. Vertical axis in this and subsequent diagrams is 1.5 km. Zones are as in Figure 6. F = ferromagnesian minerals, O = opaque minerals, Plagioclase = plagioclase phenocrysts, diamonds = albitite dikes, dots = other samples.

mafic clots (3 mm) of chlorite, amphibole, carbonate, and opaque oxides in a much finer grained groundmass of chlorites, carbonate, chessboard albite, titanite, epidote, amphibole, and minor quartz. Concentric layers of sericite in some of the plagioclase phenocrysts outline original zoning. Under the microscope all original plagioclase appears to have been destroyed, but the microprobe revealed tiny domains of unaltered andesine. Most of the phenocrysts are rimmed with fresh-appearing albite that interlocks with the matrix. Slender needles of apatite, up to 2 mm long, are a common constituent of the groundmass.

Magnetite-apatite-actinolite veins, up to 30 cm across, cut the border monzonite and typically trend normal to the outer contact, locally cutting across it. In the veins coarse, fibrous amphibole is oriented with its long axis perpendicular to the vein margins. The central zone of each vein, like in those around the

TABLE 3. Modal Analyses, Rainy Lake Intrusive Complex

Sample no.	Plagioclase	Perthite	Quartz	Albite	Amphibole	Chlorite	Epidote	Opaques	Apatite	Carbonate	Others[1]
H-79-16	40.5	4.5	4.6	28.6	16.0	0.4		2.4	1.1	0.3	1.6
C-79-27	32.9	1.9	3.8	40.9	13.8	0.2	0.2	3.4	1.4	0.9	0.6
C-79-26			11.3	78.6	1.3	1.1	0.5	3.6		3.6	
C-79-25	2.1	3.2	8.7	66.4	6.8	1.3	1.3	4.4	0.3	0.7	4.8
C-79-24	13.3	18.7	5.5	49.5	10.3	1.0	0.6	0.9	0.1		0.1
C-79-23	15.4	13.5	8.3	49.3	8.0	2.5	1.8	0.6	0.2	0.4	
C-79-22	16.4	8.2	3.4	58.9	10.9	0.7	1.2	0.1	0.2		
C-79-21	0.3	10.5	6.1	77.7	0.2	2.3	0.2	1.6		1.1	
C-79-20	15.4	25.3		44.6	11.1		1.6	1.2	0.2	0.1	0.5
C-79-19	26.8	38.2	0.2	19.0	10.1	0.2	4.0	1.2	0.2	0.2	
C-79-18	39.5	32.1	3.2	7.3	13.0	0.3	2.3	1.5		0.3	0.5
C-79-17	51.5	19.2	0.7	7.6	17.4	0.4	2.2	0.9	0.1		
C-79-16	52.2	17.5	0.3	5.2	18.2	1.1	3.2	1.3	1.0		
C-79-15	59.7	12.3	1.7	2.6	17.6	1.0	2.8	2.1	0.1		0.1
C-79-14	66.4	14.0	4.9		4.9	7.3	0.9	1.5		0.1	
C-79-13	65.6	11.6	5.4		14.7	0.8	0.2	1.7			
C-79-12	59.8	16.2	1.8		0.9	12.2	7.7	1.4			
C-79-11	52.7	27.3	1.9		9.7	0.6	2.7	2.3	0.2		1.6

[1] Others include cpx and opx in H-79-16 and mainly granophyre in other samples

Balachey pluton, is typically filled with anhedral apatite and octahedra of magnetite.

Lower monzodiorite

Except for the lower border phase, seriate monzodiorite is the lowest unit mapped within the pluton. The monzodiorite consists of 50 to 66 percent euhedral, partly sericitized plagioclase phenocrysts ranging in size from 1 or 2 mm up to 1 cm, with interstitial pale green amphibole, opaque Fe-Ti oxides, perthite, granophyre, and alteration products. Modal plagioclase phenocryst content varies systematically from about 53 percent near the base to 66 percent in the central portion and decreases in abundance to about 50 percent near the top of the zone. The plagioclase phenocrysts are tablets of oscillatory zoned andesine that are packed closely together such that each is in contact with its immediate neighbors; there are no overgrowths linking adjacent crystals. The rock is an aggregate of plagioclase phenocrysts and interstitial phases. On some outcrops the phenocrysts define a weak igneous foliation that led Tirrul (1976) to suggest that the monzodiorite is of cumulate origin; in fact, it is an orthocumulate in the nomenclature of Wager et al. (1960).

The pale green amphibole occurs mostly as interstitial clots (3 mm) consisting of fibrous material with random optical orientations, but in a few cases light brown to green pleochroic actinolitic hornblende displays uniform optical orientation and is probably magmatic. The crystals of actinolitic hornblende are 2 to 3 mm across and partly fill areas between plagioclase phenocrysts. Anhedral opaque oxides are ubiquitous in the clots of amphibole but rare in the actinolitic hornblendes. Epidote and chlorite are mostly alteration products of amphibole and are included with it in Figure 7.

Anhedral perthite, about 4 mm across in maximum diameter, is also interstitial and is commonly intergrown with amphibole. In places it appears to have replaced marginal areas of plagioclase phenocrysts. Granophyric intergrowths of quartz and microperthite have a similar mode of occurrence in that they are interstitial, intergrown with amphibole, and appear to replace plagioclase. In other areas quartz does not occur in association with perthite but as small anhedral grains. Tiny prisms of apatite are a common accessory mineral. Zircon was not found in any of the thin sections examined and even 100 kg of rock, collected for U-Pb dating, failed to yield any.

In thin sections made from samples collected progressively upward in the monzodiorite, the plagioclase phenocrysts are more sericitized, have wider rims of albite, contain zoisite or clinozoisite in their central parts, and have albite replacing them along cleavage planes. The clots of amphibole become smaller and the amphiboles themselves become more ragged and felty in appearance. Quartz is sparse near the base and top of the zone (Fig. 7).

Monzonite: The transition from monzodiorite to monzonite is gradational and occurs over a distance of several meters. Mineralogically the change is characterized by an increase in the size of perthite grains to 7 mm and by the appearance of chessboard albite. The abundance of plagioclase phenocrysts decreases regularly from about 40 percent near the base of the zone to about 15 percent near the top. In addition, minor chlorite and amphibole are found in the cores of plagioclase phenocrysts. Both unaltered albite and perthite replace plagioclase to the point where only oval-shaped cores remain. Thus, part of the decrease in modal plagioclase is due to replacement, but even when the effects are restored, there is still a considerable decrease in plagioclase content. Overall, the monzonite appears much fresher in thin section than the monzodiorite. This is because so much of the original plagioclase is now replaced by unaltered albite and perthite.

Syenite: The upper contact of the monzonite with the syenite, like the lower one with the monzodiorite, is gradational over several meters. The contact between the syenite and the upper border phase is sharp. Locally, the syenite transgresses the border phase, reducing its thickness such that it is absent or nearly so.

The syenite weathers pink, probably owing to the presence of finely disseminated hematite. Numerous dikes of fine-grained albitite up to 30 cm across and with gradational margins cut the syenitic phase. Their orientation was not systematically measured during mapping, but many trend perpendicular to the roof of the pluton. Pink fluorapatite, similar to that which occurs in the magnetite-apatite-actinolite veins of the border phase, coats fracture surfaces in the top 10 m of the syenite. The fractures trend nearly normal to the roof of the intrusion.

The syenite differs from the monzonite in that perthite decreases in both abundance and size (from 7 to 4 mm), there is an increase in the abundance of chessboard albite, carbonate appears in amphibole clots, and the modal percent plagioclase is less than 16 percent. The destruction of the plagioclase phenocrysts is so intense that only sparse elliptical relics remain, heavily replaced by chlorite. As in the central monzonite, when the original prealteration size and shape of the plagioclase phenocrysts are taken into account, the syenite contains fewer phenocrysts than any other phase of the intrusion. Apatite has a bimodal abundance, either very common or virtually absent, with no gradation between the two. Quartz content increases dramatically from about 5 percent near the base of the zone to over 10 percent near the top. Granophyre is absent. In general, the amphibole clots are rarer and smaller in the syenite than in lower parts of the intrusion. Fe-Ti oxides are concentrated in the clots as in lower parts of the pluton, but similar to the clots, they become finer and more disseminated upward. However, this is deceiving, because even though the opaque minerals become finer they actually become more abundant in the uppermost parts of the syenite (Fig. 7). Chessboard albite increases in size upward within the syenite, and perthite decreases in size. In the uppermost part of the unit perthite is absent and tiny blebs of quartz are common.

Whole-rock chemistry: Seventeen samples collected from top to bottom through the intrusion (Fig. 6) were analyzed for major and trace elements, also at Memorial University of Newfoundland, using the same methods of analysis as for samples from the Balachey pluton. The results of whole-rock analyses from the pluton are presented in Table 4. Concentrations of many elements are displayed graphically in Figure 8.

SiO_2, Na_2O, Nb, Y, Zr, and the heavy rare earth elements increase from base to top of the body. Other oxides and elements, such as CaO, Al_2O_3, K_2O, Sr, Ba, Rb, MnO, MgO, Cr, and Ni decrease upward. Note that the abundances of most elements in the upper border phase generally fall in between those of the upper syenite and those of the lower monzodiorite. Also of particular interest is the coupled nature of Na_2O and K_2O; that is, as Na_2O increases, K_2O decreases. K_2O, Rb, and Ba decrease with increasing SiO_2.

Alteration: The Rainy Lake Intrusive Complex has an alteration halo similar to that of the Balachey pluton, but the zonation is not as well defined and its spatial relationship to the pluton is different. In part, the halo has been partly destroyed by the intrusion of younger plutons (Fig. 6). Magnetite-apatite-actinolite veins cut the upper border phase and apatite coats fractures in the uppermost portion of the syenite. There are also bodies of magnetite-apatite-actinolite above the roof of the pluton and they are mostly larger than those that occur around the Balachey pluton. Only small gossans remain above the magnetite-apatite-actinolite bodies and there is some controversy among workers in the area as to whether they are related to the pluton or are earlier synsedimentary deposits.

The best exposed bodies of magnetite-apatite-actinolite considered to be related to the Rainy Lake Intrusive Complex are found at the northwest end of the pluton above its roof. The largest is about 50 m across, has sharp outer margins, and is heterogeneous with respect to relative abundances of magnetite, apatite, and actinolite. In places along the contact, massive magnetite-apatite-actinolite occurs, but in other places banded magnetite, apatite, and actinolite or only a thin veneer of apatite or actinolite were found.

Some areas of the body are breccias containing abundant, mostly angular blocks of country rock, some of which are partly replaced by magnetite-apatite-actinolite in a matrix of magnetite-apatite-actinolite. Distinctive blocks found in the breccia are similar in gross appearance to rhythmically interbedded limestone-argillite of the intracauldron fill sequence except that the blocks are composed of alternations of magnetite-apatite-actinolite with argillite. This suggests that the original limestone was replaced by magnetite-apatite-actinolite. Overall, the brecciated zones appear similar to typical zones of ore breccia that occur at Kiruna, Sweden (Geijer and Odman, 1974).

Although much of the body appears at first glance to be massive, close inspection shows that it is banded in many places. The bands are visible because there are slight modal variations in the amounts of magnetite, apatite, and actinolite. Whether or not they reflect original bedding in their host rocks is debatable, but elsewhere in the body as in rocks around the Balachey pluton, it is clear that such a phenomenon does occur (see photographs in Hildebrand, 1984).

Veins of magnetite-apatite-actinolite commonly cut the upper border phase of the pluton. Such veins are up to 30 cm across with marginal zones of actinolite growing normal to the walls and central zones of coarse apatite and octahedra of magnetite. Many veins contain only the assemblages magnetite + apatite or apatite + actinolite.

The amphibole in the veins and larger bodies is actinolite. It has very low Al (IV) K_2O, and Na_2O contents (Table 5). The magnetite is characterized by very low TiO_2, Cr_2O_3, and MnO contents and moderate amounts of vanadium. All of the apatite studied is fluorapatite with fluorine contents around 3 percent. Overall, the compositions of the three mineral phases are similar to those of other Kiruna-type deposits.

Origin of the Magnetite-Apatite-Actinolite

The bodies and veins of magnetite-apatite-actinolite adjacent to the Rainy Lake Intrusive Complex and Balachey pluton led Badham and Morton (1976), based on experimental work by Philpotts (1967), to suggest that an immiscible iron phosphate melt separated from a silicic melt; however, this conclusion appears unlikely for the following reasons:

1. Many of the veins contain only amphibole or amphibole + apatite without magnetite. Thus, there is commonly more silica than iron in the veins.
2. The veins are commonly zoned from apatite in the core to amphibole-magnetite at the margin, a texture incompatible with their derivation from an iron phosphate melt.

TABLE 4. Major and Trace Element Analyses, Rainy Lake Intrusive Complex

	Lower monzodiorite							Central monzonite		
Sample no.	C-79-11	C-79-12	C-79-13	C-79-14	C-79-15	C-79-16	C-79-17	C-79-18	C-79-19	C-79-20
SiO_2	55.0	53.6	53.6	52.8	54.2	55.5	54.8	55.9	58.3	60.8
TiO_2	0.66	0.51	0.63	0.72	0.94	0.92	1.03	0.73	0.86	0.83
Al_2O_3	19.7	20.6	20.5	18.9	19.2	18.7	18.6	17.8	17.0	16.9
$Fe_2O_3^{\circ}$	6.02	5.98	6.04	7.75	7.68	6.75	6.54	7.04	5.38	5.25
MnO	0.29	0.10	0.25	0.22	0.37	0.18	0.28	0.15	0.14	0.06
MgO	2.26	2.24	2.25	2.54	2.58	2.48	2.62	2.18	2.18	1.77
CaO	4.29	5.49	5.42	5.14	5.17	5.49	5.01	3.65	3.68	3.16
Na_2O	3.89	4.18	3.51	3.21	3.68	4.64	4.48	4.14	6.26	7.38
K_2O	4.73	3.51	3.89	3.72	3.72	3.60	4.25	4.69	2.92	2.56
P_2O_5	0.26	0.26	0.27	0.55	0.51	0.51	0.57	0.42	0.48	0.35
L.O.I.	2.66	2.81	2.57	2.81	2.23	1.72	1.82	2.17	1.50	0.90
Total	99.76	99.28	98.75	98.36	100.28	100.55	100.00	98.87	98.71	99.96
Nb	8	3	4	8	4	9	6	14	13	13
Zr	129	64	87	89	83	107	126	167	160	180
Y	25	15	18	24	24	34	35	31	41	36
Sr	530	642	560	579	516	522	495	286	227	202
U	2	0	2	0	1	4	1	0	2	1
Rb	150	110	126	113	120	92	111	109	50	43
Th	10	9	6	1	8	2	10	1	11	11
Pb	13	5	10	21	24	1	22	10	7	21
Ga	20	19	19	21	16	22	15	22	20	20
Zn	275	77	83	170	304	115	306	108	102	43
Cu	8	4	38	38	4	0	0	0	0	6
Ni	13	22	21	9	17	8	16	1	3	6
Cr	18	22	14	10	0	4	0	0	0	0
V	131	104	145	212	193	155	168	148	130	109
Ba	1,028	935	904	1,158	1,614	984	1,160	1,423	819	849
La	20.86	21.94	24.10		22.09	25.87	40.56	23.38	26.55	18.97
Ce	44.99	46.95	52.11		44.14	53.75	80.57	50.72	50.72	44.80
Pr	5.49	5.11	6.43			7.41	10.27	7.41	7.07	6.12
Nd	22.97	21.30	23.55		28.52	31.82	44.43	30.70	30.88	27.44
Sm	3.80	3.85	3.99		5.46	6.54	9.39	6.92	6.15	6.38
Eu	0.84	0.99	1.29		1.69	1.28	1.33	0.99	0.96	1.33
Gd	3.54	2.51	2.92		4.77	5.13	6.46	5.07	4.92	4.45
Dy		2.14	3.46		3.72	4.02	5.80	4.81	5.38	5.63
Er	1.82	1.47	1.33		2.21	2.63	2.09	2.63	2.60	2.69
Yb	1.49	1.20	1.69		2.19	3.28	2.34	3.27	2.10	2.65

Oxides in weight percent; trace elements in ppm; 0 = not detected; L.O.I. = loss on ignition
$Fe_2O_3^{\circ}$ = total Fe as Fe_2O_3

3. Granular magnetite-apatite-actinolite replaces sedimentary rocks and andesitic lava flows.

4. Apatite coats fractures in the upper syenitic phase of the Rainy Lake Intrusive Complex which indicates that it was sufficiently solid to fracture when the apatite crystallized.

5. The composition (low Na_2O, K_2O, and TiO_2) of the amphibole in the veins and bodies suggests crystallization temperatures (Helz, 1979, 1982; Hammarstrom and Zen, in press) too low to maintain an iron phosphate melt. In fact, experiments (I. G. Reichenbach; pers. commun.) show that samples of the magnetite-apatite-actinolite fail to melt completely after 48 hours at 1,150°C under dry conditions at 1 atmosphere.

6. The magnetite contains very small amounts of TiO_2 which is inconsistent with a parental melt that was ever in equilibrium with an intermediate silicate melt.

7. Globules of iron phosphate melt would sink in a silicic melt owing to the large contrast in density between them (Daly, 1915). Therefore, if the magnetite-apatite-actinolite bodies were derived by a process in which an immiscible iron phosphate melt separated from a silicic melt, they should occur near the base of the melt zone not above the intrusive bodies.

If the magnetite-apatite-actinolite bodies are not generated by the separation of an iron phosphate melt

TABLE 4—(*Continued*)

	Upper syenite						Border monzonite	
Sample no.	C-79-21	C-79-22	C-79-23	C-79-24	C-79-25	C-79-26	C-79-27	H-79-16
SiO_2	66.1	61.4	61.1	61.3	64.0	66.0	57.9	
TiO_2	0.92	0.73	0.76	0.86	0.63	0.59	0.65	
Al_2O_3	17.6	16.7	16.1	16.5	14.8	15.3	17.5	
$Fe_2O_3^*$	1.53	4.80	5.33	6.35	4.95	2.06	6.03	
MnO	0.05	0.06	0.10	0.08	0.12	0.04	0.18	
MgO	0.51	1.88	1.66	1.82	1.31	0.49	2.79	
CaO	0.88	2.48	2.22	2.13	2.22	2.49	3.99	
Na_2O	9.41	7.82	5.80	5.95	7.72	8.88	6.01	
K_2O	0.72	1.28	3.14	3.24	0.64	0.38	2.27	
P_2O_5	0.03	0.44	0.44	0.51	0.46	0.02	0.32	
L.O.I.	1.37	1.19	2.12	1.64	1.78	2.56	2.68	
Total	99.27	98.78	98.77	100.38	98.63	98.81	100.32	
Nb	19	17	14	16	20	19	11	7
Zr	247	208	213	199	271	260	150	143
Y	25	38	38	43	58	23	30	27
Sr	54	138	165	150	72	68	288	388
U	1	1	4	3	2	9	3	4
Rb	15	42	86	82	4	58	104	347
Th	0	13	12	8	11	12	10	12
Pb	5	6	15	23	4	15	10	17
Ga	23	19	21	20	22	21	18	12
Zn	49	44	53	62	58	126	125	139
Cu	2	0	17	16	0	25	0	4
Ni	0	1	4	5	4	3	26	55
Cr	0	0	0	0	0	0	58	131
V	24	58	90	85	117	44	151	183
Ba	112	479	1,002	869	74	87	687	1,153
La			20.65		107.81	19.72	28.63	31.75
Ce	15.61	47.62	47.45	47.52	234.18	37.09	63.59	65.50
Pr	2.07	6.49		7.17	24.89	4.13	7.50	7.57
Nd	7.76	28.61	28.00	28.57	94.60	18.81	30.33	31.63
Sm	1.67	5.82	6.47	5.59	13.78	4.27	5.54	6.32
Eu	0.27	1.08	1.42	1.02	1.30	1.06	1.25	1.32
Gd	1.36	5.02	5.40	5.42	7.47	3.45	4.03	4.77
Dy	1.92	5.55	5.09	4.33	7.14	3.03	1.55	4.90
Er	1.58	2.62	2.44	2.54	3.05	1.55	1.68	2.12
Yb	1.98	3.34	2.49	2.67	3.21		2.23	2.06

Oxides in weight percent; trace elements in ppm; 0 = not detected; L.O.I. = loss on ignition
$Fe_2O_3^*$ = total Fe as Fe_2O_3

from a silicate melt, to what process do they owe their origin? I take a somewhat traditional view and suggest that all available evidence indicates that they result from the exsolution of a volatile phase late in the crystallization history of the plutons. The following discussion relies heavily on data from the Rainy Lake Intrusive Complex because complete sections through it are available for study and because relationships within the body are well exposed.

As an initial condition it is assumed that for much of its crystallization history, the Rainy Lake Intrusive Complex behaved as a closed system after intrusion. That is, there were no influxes of new magma into the chamber after initial intrusion nor was there a reservoir of hotter, more mafic magma beneath it. These are reasonable assumptions to make in this case because there is no evidence for late-stage mixing of the Rainy Lake melt with a more mafic melt nor are there any of the textual features commonly associated with periodically refilled magma chambers. The approach used here is to estimate some of the parameters of the Rainy Lake magma, such as composition, H_2O content, and temperature at the time of intrusion in order to constrain the origin of the magnetite-apatite-actinolite segregations.

The best estimate of the original composition of the Rainy Lake magma comes mainly from the similarity of the border phase to the andesites just above its roof. The following lines of evidence indicate that the original magma that cooled to form the Rainy Lake

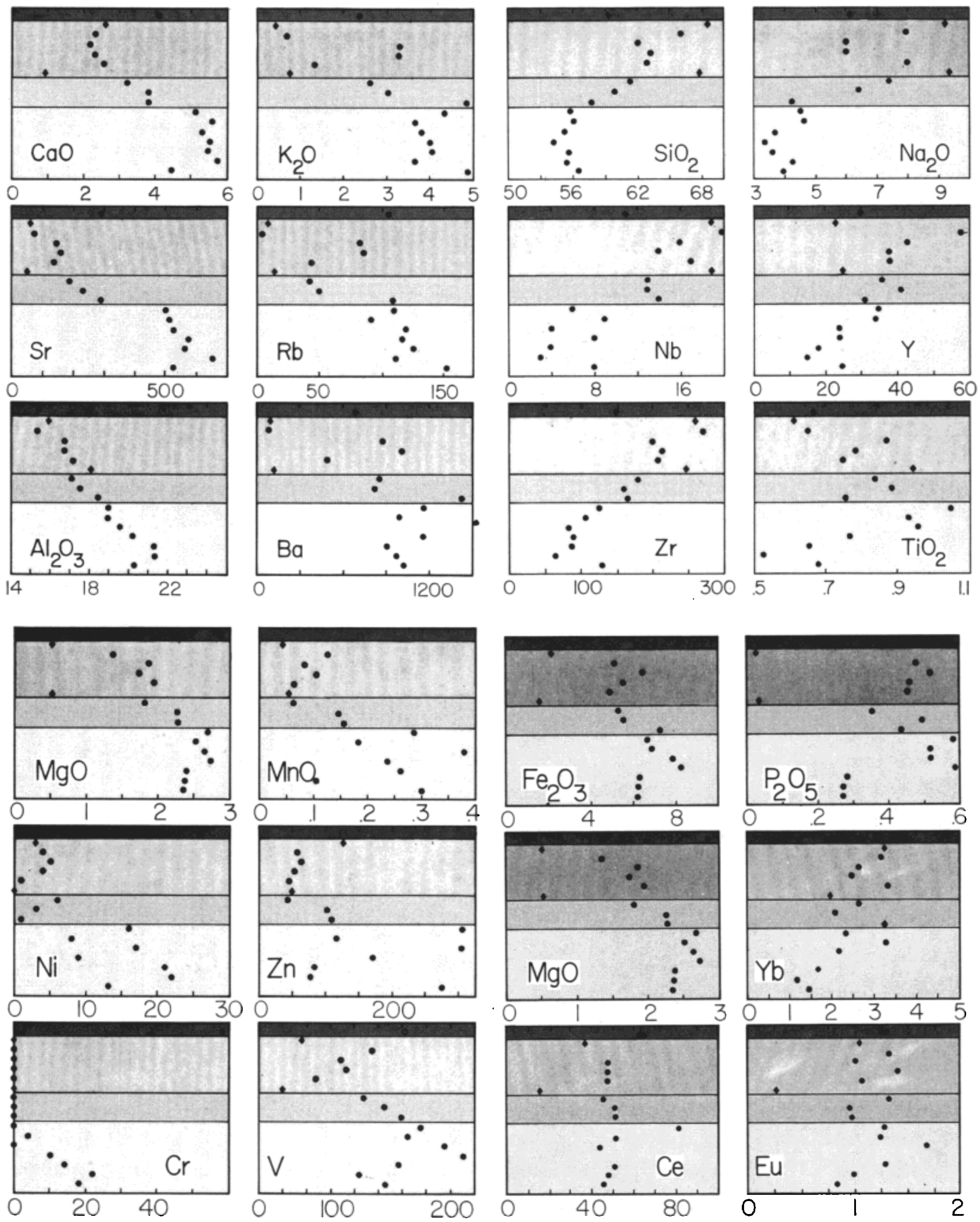

FIG. 8. Anhydrous whole-rock major and trace element analyses of the Rainy Lake Intrusive Complex plotted with height in the intrusion. The vertical axis is 1.5 km in height. Symbols and zones as in Figures 6 and 7.

Intrusive Complex was andesitic: (1) the upper border phase of the intrusion is very similar to postcollapse andesitic lavas of the first cauldron cycle in that both the lavas and the border phase contain substantial quantities of large oscillatory zoned andesine, and lesser amounts of pyroxene, in a much finer groundmass; (2) the composition of the border phase, neglecting the elements most mobile during alteration, is similar to the andesites; and (3) there is a close spatial, and probably temporal, relationship of the pluton with the andesites. Therefore, the Rainy Lake magma is assumed to be of silicic, high K andesitic composition.

Next it is necessary to constrain the depth of emplacement of the pluton. This can be estimated from the thickness of the overlying sedimentary and volcanic rocks as the top of the andesite pile is marked by a thick section of conglomerate and breccia interpreted to be related to the destruction of the andesite stratovolcano just prior to, or during collapse of, a major ash-flow caldera (Hildebrand, 1984). Because the Balachey pluton and, by inference, the Rainy Lake Intrusive Complex predate the caldera, the thickness of sedimentary and volcanic rocks above the roof of the complex could not have been much greater than at present, i.e., about 3 km. Geobarometry on magmatic amphiboles within the intrusion using the empirical hornblende geobarometer of Hammarstrom and Zen (1985, in press) supports this conclusion because most have Al_{total} approximately equal to 1.

In order to estimate the original H_2O content of the Rainy Lake magma one can use published experimental data on andesitic magmas, but to do this the crystallization sequence must be ascertained. For example, if one knows that plagioclase is the liquidus phase in an andesitic melt and that it crystallized between about 0.5 and 10 kb, then the melt contained 2 percent or less H_2O (Hamilton et al., 1964; Marsh, 1976). Alternatively, if an andesitic magma emplaced at 1 kb is saturated with respect to H_2O, then orthopyroxene and clinopyroxene would both crystallize prior to plagioclase (Sekine et al., 1979). As stated earlier, the border phase of the pluton contains 37% plagioclase phenocrysts, minor relict clinopyroxene and minor altered orthopyroxene phenocrysts. This implies that when the magma first intruded, it was a relatively homogeneous mixture of plagioclase, orthopyroxene, and clinopyroxene crystals plus melt and that those parts adjacent to the country rocks quenched to form the border phase. Because the proportion of plagioclase to clinopyroxene and orthopyroxene is very large and because the plagioclase phenocrysts do not contain inclusions of either mineral, plagioclase was likely the first mineral to crys-

TABLE 5. Mineral Analyses of Magnetite-Apatite Activities

Sample	Kiruna	RLBP-1	RLA-1	FEMTN	Balach	RLMRP
			Apatite analyses			
F	3.86	2.80	3.05	3.61	3.13	3.03
Cr_2O_3	0.02	0.00	0.00	0.02	0.00	0.00
FeO	0.04	0.88	0.78	0.07	0.21	0.09
MnO	0.04	0.02	0.02	0.00	0.01	0.03
MgO	0.00	0.00	0.00	0.00	0.00	0.00
CaO	54.45	52.30	52.95	52.76	51.86	54.03
SrO	0.03	0.05	0.04	0.02	0.07	0.03
Cl_2O	0.04	0.20	0.08	0.33	0.34	0.83
P_2O_5	40.62	38.95	40.20	39.81	39.61	40.43
Total	99.10	95.20	97.12	96.62	95.23	98.47
			Oxide analyses			
TiO_2	0.12			0.04	0.34	0.96
FeO	31.01			30.28	31.21	31.69
Fe_2O_3	68.52			65.91	68.12	67.04
MnO	0.03			0.09	0.07	0.20
Cr_2O_3	0.01			0.02	0.05	0.00
V_2O_3	0.27			0.05	0.46	0.29
Total	99.96			96.39	100.25	100.19
			Amphibole analyses			
SiO_2		54.54	51.74			53.86
TiO_2		0.04	0.09			0.09
Al_2O_3		0.65	4.03			0.56
Cr_2O_3		0.12	0.08			0.08
FeO		16.88	16.29			18.49
MnO		0.13	0.40			0.20
MgO		14.18	14.01			13.12
CaO		12.11	11.92			11.96
Na_2O		0.00	0.00			0.00
K_2O		0.09	0.13			0.07
Total		98.74	98.68			98.43

RLBP-1 = magnetite-apatite-actinolite vein cutting Rainy Lake border phase
RLA-1 = amphibole-apatite vein in upper syenite, Rainy Lake pluton
FEMTN = magnetite-apatite vein cutting andesitic lava, quarry near Iron Mountain, St. Francois Mountains, Missouri
Balach = magnetite-apatite body adjacent to Balachey pluton
RLMRP = magnetite-apatite-actinolite body above roof of Rainy Lake pluton

tallize. Another line of evidence which suggests that plagioclase was the first liquidus phase occurs in the lower monzodiorite where all other mineral phases are interstitial to the plagioclase phenocrysts, thus indicating that the interstitial minerals grew after plagioclase had accumulated in the lower part of the intrusion.

It could be argued that the plagioclase crystals did not crystallize from the host melt but are artifacts from the source region, or originated elsewhere and were incorporated into the melt during ascent. This would invalidate any estimate of H_2O content. However, even without the phenocrysts, the melt fraction is of andesitic composition and therefore must have contained little H_2O (less than 4%) in order for it to rise within 3 km of the surface (Burnham, 1979a and b). Furthermore, the plagioclase phenocrysts show no evidence of resorption and are compositionally typical of those known to have crystallized from andesitic melts. There is no evidence to suggest that they did not crystallize from their host magma; thus, the following discussion assumes that plagioclase was the liquidus phase and that when it began to crystallize the melt contained 2 percent H_2O or less.

The distribution of plagioclase phenocrysts in the Rainy Lake Intrusive Complex indicates that the crystals were mechanically concentrated in the lower part of the magma chamber. Because the size and shape of the phenocrysts throughout the intrusion are not much different from those in the border phase and because there are no overgrowths other than late albite on the plagioclase phenocrysts in the lower monzodiorite, there was little growth of plagioclase between the time of intrusion and their concentration in the lower portion of the magma chamber. This suggests that accumulation of the phenocrysts in the lower part of the chamber must have been fairly rapid. In fact, the observed distribution of plagioclase phenocrysts within the body closely resembles sinusoidal distribution patterns of olivine found in lava lakes (Moore and Evans, 1967; Evans and Moore, 1968) and some mafic sills (Murata and Richter, 1961; Simkin, 1967). Such distribution curves originate from the interplay between crystal settling and solidification both from the roof downward and the floor upward (B. D. Marsh, pers. commun.; Gray and Crain, 1969). That is, settling crystals can be trapped by the downward solidification of the roof if the growth rate of the roof zone exceeds the settling velocity of the crystals. Such a mechanism leads to a decrease in observed phenocryst distribution from the top downward. In the case of the floor of the chamber progressive crystallization leads to an increase in modal abundance of settled phenocrysts upward. The end result is a somewhat sinusoidal distribution curve. My calculations indicate that plagioclase phenocrysts found in the intrusion were 0.34 g/cm^3 denser than their host magma and settled (Hildebrand, 1985b). The exact relationship between crystal settling, convection, and solidification in the Rainy Lake Intrusive Complex will be dealt with in a forthcoming report.

The interplay between crystal settling rates and solidification rates controls the distribution of plagioclase in the body, but it alone cannot be responsible for the overall mineralogical and chemical layering; namely, it is impossible to create the overall chemical trends (Fig. 9), such as decreasing Rb, Ba, and K_2O with increasing silica, by separation of any observed or even reasonably hypothesized mineral phase or phases. Moreover, since the pluton solidified both from the base upward and the roof downward, the most evolved compositions should occur some distance in from the roof and floor, as observed in some mafic intrusions, yet in the Rainy Lake pluton the most silica rich samples occur in the uppermost part. In order to understand the chemical variations in the pluton, it is important to recall that the composition of the lower monzodiorite mainly reflects the concentration of plagioclase phenocrysts there. The consistent break for many elements at the monzodiorite-monzonite boundary is a function of the decrease in the volume of plagioclase phenocrysts and an increase in perthite and albite. Both minerals clearly replace plagioclase to some degree. Compositions of the upper syenite are remarkable for their high Na_2O contents, but as stated above such an increase cannot be the result of some sort of liquid-crystal fractionation involving any combination of observed phases. This can be visualized in the system albite-anorthite-orthoclase (Fig. 10) where removal of plagioclase, orthopyroxene, and clinopyroxene will force the compositions of residual liquids to move toward the orthoclase apex; yet, samples of the monzonite and the syenite plot progressively closer to the albite apex as a nearly direct function of their height in the intrusion. Note that samples of altered andesitic rocks from within the albite zone of the Balachey halo plot in the same region as samples from the syenite. Likewise, in the system albite-orthoclase-quartz, fractionating melts move progressively closer to the granite minimum with time, but such is not the case with the Rainy Lake intrusion (Fig. 10).

An additional line of evidence that clearly indicates that the upper part of the intrusion is not part of any fractionation scheme is found in the rare earth element distribution patterns. The overall trends of the rare earth elements are clearly not the result of any sort of liquid-crystal fractionation because there is little or no increase in light rare earth elements as would be expected with any liquid-crystal fractionation involving known phenocrystic phases. In fact, quite the opposite occurs as there is an increase in heavy rare earth elements upward through the pluton. Thermogravitational diffusion as advocated by Hildreth

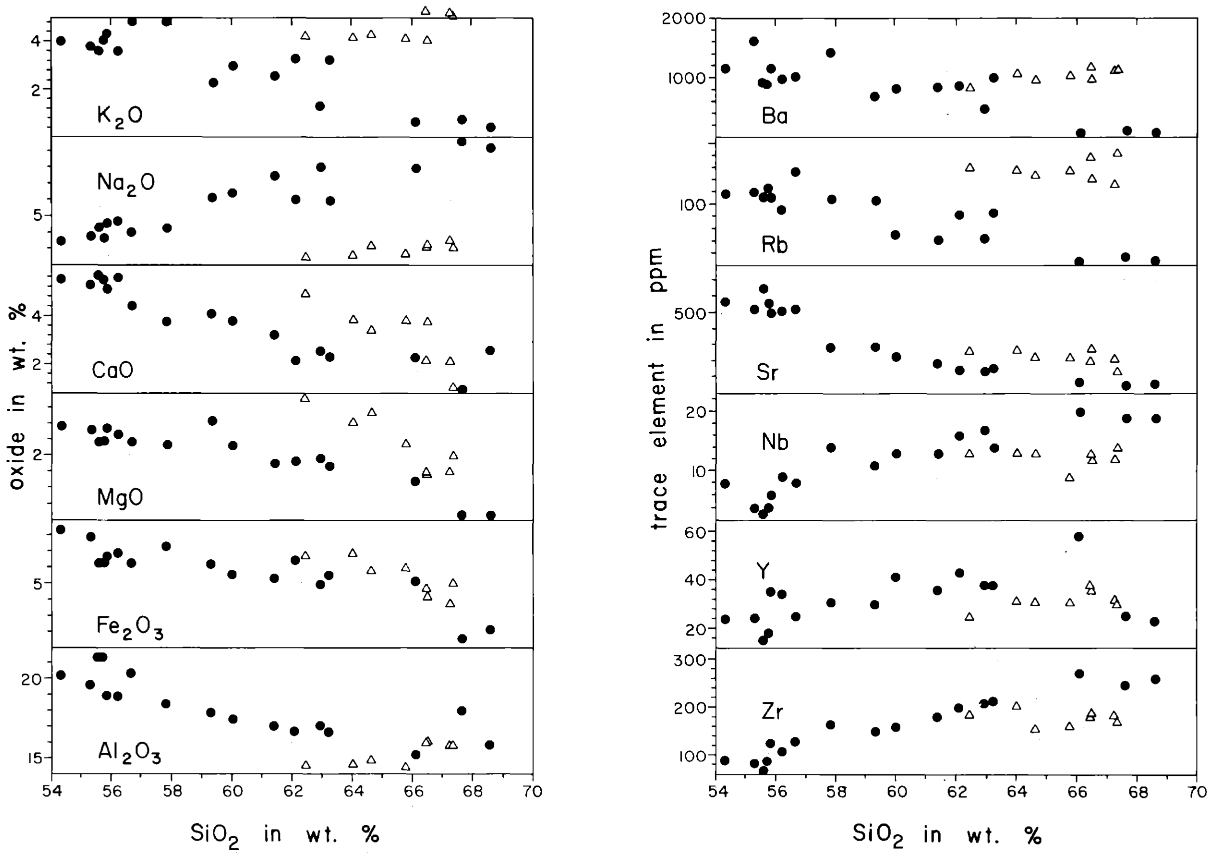

FIG. 9. Harker variation diagrams for selected oxides (wt % anhydrous) and trace elements (ppm) in the Rainy Lake (dots) and Balachey (triangles) plutons. Note that in the Rainy Lake body, as silica increases, K_2O, Rb, and Ba decrease.

(1979, 1981) can apparently produce an increase in heavy rare earth elements toward the top of a magma chamber in magmas of certain composition, but at the same time it creates a lower zone enriched in light rare earth elements, a feature not seen in the data from the Rainy Lake Intrusive Complex. Furthermore, the large variation in plagioclase content in the pluton should produce variations in the concentrations of Eu (Arth, 1976), a feature found only in the lower part of the Rainy Lake complex.

All of the above, coupled with the evidence of replacement textures within the syenite, suggest that the present composition of the syenite is not the result of fractionation but rather resulted from the alteration of already solid, or nearly solid, rock by fluids. There can be little doubt that a volatile phase would eventually exsolve from the Rainy Lake melt because such a phenomenon is a natural and necessary result of the crystallization of calc-alkaline melts emplaced at shallow crustal levels (Burnham, 1979a and b; Burnham and Ohmoto, 1980). As already shown from phase relations, the melt had a low initial H_2O content ($\leq$2%) and was crystallizing interstitial amphibole so the exsolution of volatiles probably did not occur until the very latest stages of crystallization. Because crystallization proceeded inward from both the roof and floor, the volatiles would be concentrated in the more central, latest crystallizing, portion of the chamber. As a volatile phase exsolves from a melt it rises, due to the density contrast, and flows upward through the overlying solidified or mostly solidified melt. This explains why only the upper half of the intrusion is intensely altered.

Exsolving volatiles increase the internal pressure of the chamber and eventually, when the roof rocks can no longer contain such pressure, they fail along fractures oriented normal to the horizontal roof of the body (Koide and Bhattacharji, 1975; Burnham and Ohmoto, 1980; Knapp and Norton, 1981) and volatiles stream out of the intrusion along them. Such fractures, filled with magnetite-apatite-actinolite, are common in the border phase of the Rainy Lake intrusion. The rapid dehydration would not only lead to rapid quenching of any remaining melt but could eas-

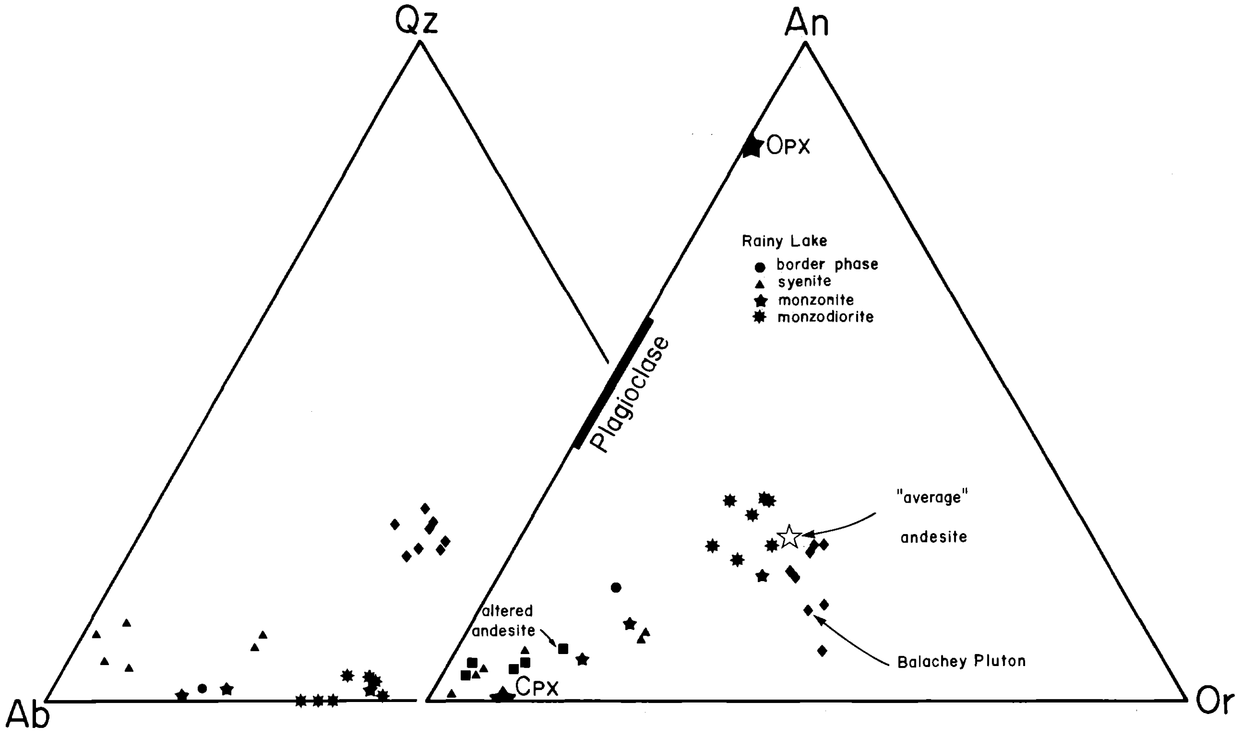

FIG. 10. Cation normative compositions of samples of the Balachey pluton, the Rainy Lake Instrusive Complex, and some albitized andesitic rocks from within the albite zone of the Balachey pluton (Table 2) plotted in the systems albite-anorthite-orthoclase (Ab-An-Or) and albite-orthoclase-quartz (Ab-Or-Qtz). Average andesite is an average composition of postcollapse andesites.

ily create the intensely brecciated zones above its roof. Similar breccias, also attributed to volatile streaming, occur above other epizonal intrusions (Fiske et al., 1963).

The most intensely altered areas of the upper part of the intrusion, which appear as the albitite dikes discussed earlier, are interpreted to represent major zones of fluid migration. Note that the two samples of the dikelike bodies are markedly lower in total iron, phosphorus, and magnesium than any other part of the intrusion. This suggests that the zones may have been a major source of the constituents for the magnetite-apatite-actinolite veins and bodies. Mass balance calculations show that the amounts of iron, magnesium, and phosphorus in the veins and bodies are small compared to those lost from the intrusion.

Because the alteration in the upper part of the Rainy Lake Intrusive Complex is so similar, both in composition and mineralogy, to the albite alteration halo around the Balachey pluton, it is reasonable to relate the two zones to a common origin and to suggest that for some reason, perhaps related to different depths of emplacement or cooling histories, the albite zone related to the Rainy Lake is telescoped over the upper part of the intrusion itself. Without fluid inclusion data it is not possible to determine the composition of the volatile phase responsible for the alteration or the controls on mineral zoning, but some insight can be gained from experimental work and elemental mobility within the system itself. Experimental work (Killinc and Burnham, 1972) indicates that in melts with the compositions of the Rainy Lake and Balachey plutons an exsolving fluid phase would be enriched in chlorine; such fluids at high temperatures are able to transport all the necessary constituents for the alteration associated with the plutons (Burnham and Ohmoto, 1980). The rare earth element data from the Rainy Lake Intrusive Complex are compatible with this conclusion in that the upper part of the body is depleted in light rare earth elements, which can be complexed and mobilized relative to heavy rare earth elements, by chlorine-dominated fluids (Taylor and Fryer, 1980, 1982, 1983). Seyfried and Mottl (1982), although working on seafloor basalts, have shown experimentally that the type of alteration found in the plutons described here is the result of low water to rock ratios, low pH, chlorine-rich, high-temperature systems. This contrasts with the typical low-temperature and high water to rock ratios commonly associated with subsolidus hydrothermal convection.

Discussion

The magnetite-apatite-actinolite bodies described here are so much like other worldwide occurrences described in the literature that they probably originated by the same mechanism. In the Mesosoic to Paleogene arc of Chile there are large numbers of such deposits. Bookstrom (1977) related those at El Romeral to alteration associated with intermediate epizonal plutons. Fiske et al. (1963) described magnetite-apatite-actinolite breccias above the roof of the Tatoosh pluton, which underlies Mount Rainier in the Cascade Range, and suggested that they resulted as volatiles streamed out of the pluton. Crane (1912) and, more recently, Panno and Hood (1983) relate the well-known Pilot Knob deposits of Missouri to hydrothermal replacement of ash-flow tuffs and sedimentary rocks, but the heat source for the alteration has not been found due to the flat-lying nature of the volcano-sedimentary sequences (Sides et al., 1981). Although they have been metamorphosed and deformed to varying degrees after deposition, the classic Kiruna ores (see references in Introduction) are remarkably similar to those described here in terms of mineralogy, textures, and setting. The common occurrence of intensely altered and albitized rocks in the footwall at Kiruna (Geijer, 1915), interpreted in part to represent subvolcanic intrusions, suggests generation by deuteric processes as originally hypothesized by Geijer (1930).

For a number of years Paràk (1973, 1975, 1985) has argued that Kiruna-type deposits are not magmatic in origin but rather are metamorphosed chemical sediments. His arguments are based mainly on the seemingly strata-bound, or bedded, nature of the deposits and the presence of sedimentary structures; however, similar features occur in both the Great Bear magmatic zone (Hildebrand, 1984) and the St. Francois Mountains (Panno and Hood, 1983). In both areas it is clear that such features result from replacement of older sedimentary and volcanic rocks.

J. Hoover Mackin (1968) related magnetite deposits in the Iron Springs region of Utah to deuteric alteration of intermediate composition laccoliths. Magnetite veinlets within the intrusions occur in a zone intermediate to the border phase and the central portions. He convincingly demonstrated that the iron deposits outside the pluton formed by deuteric processes related to the cooling of the intrusions. In accordance with the model presented here he showed that not only iron, but phosphorus, fluorine, and magnesium were selectively removed from the intrusion.

The famous, and somewhat enigmatic, magnetite-apatite flows associated with an andesitic volcano (Frutos J. and Oyarzùn M., 1975; Henriquez and Martin, 1978) at El Laco, Chile, deserve a brief discussion because they are often cited as direct evidence that iron phosphate melts exist in nature. Most visitors to El Laco with whom I have spoken report that they look in every way like lava flows. I have no reason to doubt their observations, yet there are several lines of evidence that suggest that they originated in a manner similar to the deposits described here: (1) they are riddled with large gas cavities in which magnetite and hematite crystals sublimated (Henriquez and Martin, 1978; see also photographs in Park, 1961); (2) there are meter-high sublimate pipes of magnetite ± apatite near the vents (R. F. Martin, pers. commun.); (3) they apparently extend only a hundred meters or so from the vent areas; and (4) the magnetite contains only small amounts of TiO_2 (Frutos J., and Oyarzùn M., 1975). These observations indicate that the flows may have originated when a pluton beneath the associated andesitic volcano dehydrated at a rapid rate and the volatile phase, enriched in iron and phosphorus, streamed to the surface as a supercritical fluid. Upon arrival at the surface the fluid phase might sublimate magnetite and apatite at such a rate and temperature that the material could be fluid enough to flow downslope. The fluid phase possibly reached the surface because the pluton may have been emplaced at a shallower level than those discussed in this paper.

In summary, Kiruna-type deposits are composed of magnetite-apatite-actinolite typically associated with intermediate composition plutons and Na_2O metasomatism. They tend to occur above the roof of the magma bodies, thereby ruling out an origin by iron phosphate-silicate melt immiscibility because iron phosphate melts are much denser than silicate melts; instead, they are interpreted to be the products of high-temperature, chlorine-dominated fluids generated during volatile exsolution.

Although several facets of the model presented here are poorly understood, particularly the mechanisms of transport and deposition, it appears difficult to refute the observation that the common link between most Kiruna-type deposits is an intimate association with intermediate plutons, in many cases related to andesitic volcanoes of continental-arc settings. Thus, a critical factor in the development of Kiruna-type deposits is that an intermediate pluton must contain low enough H_2O so that it can rise to high crustal levels. Basaltic magmas typically contain too little H_2O to exsolve a fluid phase, but when they do, iron loss and albitization can occur (Eldson, 1982). Although many rhyolitic magmas have enough water, they commonly do not contain enough magnesium and phosphorus.

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July 15, November 25, 1985

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