

## PETROGENESIS OF THE LATE ARCHEAN SYENITIC MURDOCK CREEK PLUTON, KIRKLAND LAKE, ONTARIO: EVIDENCE FOR AN EXTENSIONAL TECTONIC SETTING

STEPHEN M. ROWINS\*

*Ottawa–Carleton Geoscience Centre, Department of Geology, University of Ottawa, Ottawa, Ontario K1N 6N5*

EION M. CAMERON

*Geological Survey of Canada, Ottawa, Ontario K1A 0E8, and Ottawa–Carleton Geoscience Centre, Department of Geology,  
University of Ottawa, Ottawa, Ontario K1N 6N5*

ANDRÉ E. LALONDE AND RICHARD E. ERNST

*Ottawa–Carleton Geoscience Centre, Department of Geology, University of Ottawa, Ottawa, Ontario K1N 6N5*

### ABSTRACT

The Murdock Creek pluton has a spatial, temporal and possible genetic relationship to major Archean lode-gold deposits at Kirkland Lake in the Abitibi greenstone belt of Ontario. It is a compositionally zoned body comprising a thin mafic margin of clinopyroxenite, meladiorite, melamonzodiorite, and melasyenite, and an extensive felsic core of alkali feldspar syenite. A coeval hornblende unit with lamprophyric affinities outcrops throughout the pluton. Quantitative modeling using Pearce element ratio (PER) diagrams demonstrates that the various rock-types were derived from a common parental magma by fractional crystallization, principally of diopside, plagioclase, and alkali feldspar. Accumulation of early fractionated minerals in the pluton's margin produced cumulate mafic rocks. A chemically evolved liquid (*i.e.*, residual) physically expelled from the spaces between the earlier-formed crystals yielded alkali feldspar syenite in the core of the pluton. Fractional crystallization caused an increase in incompatible light rare-earth elements (*LREE*) and large-ion lithophile elements (*LILE*) and in the ratios K/Rb, La/Yb from mafic through felsic fractions. There is a complementary decrease in compatible transition elements (Sc, V, Cr, Co, Ni), whereas coherent ratios, such as Th/U, and the *LILE* ratios K/Sr, K/Ba, Rb/Sr, and Rb/Ba, are relatively constant. The parental potassic mafic alkaline magma was derived by partial melting during extension-induced upwelling of *LILE*- and *LREE*-enriched upper mantle. Subsequent separation of early-formed amphibole from the partial melt enabled a dry, more buoyant syenitic liquid to rise in the Kirkland Lake – Larder Lake fault zone (KLF). Fractional crystallization occurred during ascent and subsequent to final emplacement at mid-crustal levels. Enhanced K<sub>2</sub>O, *LILE* and *LREE* contents, and depletions in Nb, Ta, and Ti, are geochemical characteristics of all units. These are typical of, but by no means unique to, igneous rocks formed in modern subduction-related island-arc settings. Moreover, the low Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, SiO<sub>2</sub>, and high MgO whole-rock contents are more akin to alkaline rocks formed in rift environments far from subduction zones. Thus, recent tectonic models suggesting that Archean subduction processes are necessary for the genesis of these rocks may need revision. Gold mineralization in this important camp is shown to be consistent with an extensional tectonic regime.

*Keywords:* Pearce element ratios, syenite, fractional crystallization, rift environment, cumulate, hornblende, lamprophyre, lode gold deposits, Abitibi greenstone belt, Murdock Creek pluton, Kirkland Lake, Ontario.

### SOMMAIRE

Le pluton de Murdock Creek montre des liens spatiaux, temporels, et possiblement génétiques avec les importants gisements d'or archéens que l'on retrouve dans les roches vertes de la ceinture métavolcanique de l'Abitibi, près de Kirkland Lake en Ontario. Ce pluton est zoné et comprend une mince bordure mafique composée de clinopyroxénite, méladiorite, mélamonzodiorite et mélasyéénite, et une zone centrale importante et plus felsique, composée de syénite à feldspath alcalin. Une hornblende contemporaine, d'affinité lamprophyrique, affleure à plusieurs endroits dans le pluton. Un modèle quantitatif fondé sur les rapports élémentaires de Pearce indique que ces différentes roches sont dérivés d'un magma commun par une cristallisation fractionnée du diopside, plagioclase et feldspath alcalin. La cristallisation précoce et l'accumulation des minéraux mafiques sont responsables de la bordure mafique du pluton, alors que le coeur de syénite à feldspath alcalin provient de l'expulsion du liquide résiduel des

\*Present address: Department of Geology, University of Western Australia, Nedlands 6009, Australia.

interstices des minéraux mafiques. Les processus de cristallisation fractionnée expliquent bien l'augmentation que l'on observe, vers l'intérieur du pluton, des teneurs en éléments incompatibles comme les terres rares légères et les éléments lithophiles de grand rayon, et des rapports K/Rb et La/Yb, et aussi, la diminution en teneur des éléments compatibles (Sc, V, Cr, Co, Ni). Les rapports cohérents comme Th/U et ceux d'éléments lithophiles K/Sr, K/Ba, Rb/Sr, et Rb/Ba sont relativement constants. Le magma original, étant potassique, mafique et alcalin, s'est formé par anatexie du manteau supérieur enrichi en éléments lithophiles à grand rayon et en terres rares légères, dans une zone d'extension et de soulèvement. La séparation subséquente de l'amphibole de ce magma anatectique a permis au liquide syénitique, relativement sec et léger, de monter le long de la zone de faille de Kirkland Lake – Larder Lake. Les fortes teneurs en K<sub>2</sub>O, en éléments lithophiles à grand rayon, et en terres rares légères, et les appauvrissements en Nb, Ta, et Ti, sont des caractéristiques géochimiques distinctes pour toutes les roches du pluton. Quoique ces signatures soient courantes dans les arcs de subduction modernes, elles ne sont pas exclusives à ce milieu tectonique. D'ailleurs, les faibles teneurs en Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, SiO<sub>2</sub>, ainsi que l'enrichissement en MgO, sont plutôt typiques des roches alcalines associées aux milieux de rift, éloignés des zones de subduction. Les modèles tectoniques récents qui font appel aux processus de subduction à l'Archéen pour expliquer l'origine de ces roches, pourraient donc être à revoir. La minéralisation aurifère dans cette importante région minière est associée avec un régime tectonique d'extension.

*Mots-clés:* rapports d'éléments de Pearce, roches ultrapotassiques, syénite, cristallisation fractionnée, milieu de rift, cumulats, hornblendite, lamprophyre, dépôts d'or archéen, ceinture verte de l'Abitibi, pluton de Murdock Creek, Kirkland Lake, Ontario.

## INTRODUCTION

Late Archean syenitic plutons (~2680 Ma) near Kirkland Lake, Ontario, in the southern part of the ~2.7 Ga Abitibi belt, show a strong spatial coincidence with gold mineralization, carbonatization, and the Kirkland Lake – Larder Lake fault zone (KLF) (Fig. 1). This coincidence has led to suggestions of a genetic link between syenitic magmas and ore-forming fluids (Colvine *et al.* 1984, 1988, Cameron & Carrigan 1987, Cameron & Hattori 1987). However, the relationship, if any, is not as obvious as it might first appear, because the gold ore postdates syenitic magmatism but is known to be contemporaneous with related lamprophyric magmatism (Wyman & Kerrich 1988). Gold mineralization is locally controlled by faults, the precursors of which also controlled the intrusion of individual plutons (Cameron 1990). Despite the spatial association amongst these geological elements, few studies have directly addressed the petrological and geochemical features of the Archean syenites at Kirkland Lake, or those that occur in other Archean lode gold "camps" (*e.g.*, Matachewan, Sinclair 1982; Lac Shortt, Morasse *et al.* 1988).

The purpose of this contribution is three-fold. Firstly, we seek to demonstrate through geochemical modeling using Pearce element ratio (PER) diagrams and systematic variation in trace-element abundances, that the rock types comprising the Murdock Creek pluton are related by fractional crystallization from a common source of potassic mafic alkaline magma whose progenitor was a mantle-derived lamprophyric magma. This is the first study, to our knowledge, to use the PER technique to model igneous fractionation in syenitic rocks. Secondly, we seek to investigate the geodynamic setting of the pluton using whole-rock geochemistry, and determine whether Archean subduction processes are requisite for the formation of the potassic alkaline igneous rocks in the Kirkland Lake area. Finally, we examine the connection between alkaline magmas, gold-bearing fluids, carbona-

tization, and the KLF. Previously, it has been proposed that the alkaline magmas were the immediate source of gold-bearing fluids. It is now argued that the connection is less direct, with the gold and the alkaline plutons both being the result of interlinked processes.

## GEOLOGICAL SETTING

The Abitibi belt is the largest and economically most important Archean granite–greenstone terrane of the Canadian Shield, with gold production in excess of 3.9 billion grams (Hodgson & MacGeehan 1982). Of that, 652 million grams (Grabowski *et al.* 1987) have been recovered from seven mines in the Kirkland Lake camp, making it the second largest Archean gold camp in North America. The rocks of the greenstone belt in the region mainly comprise a thick succession of komatiitic, tholeiitic and calc-alkaline basalts, with lesser amounts of sedimentary rocks, belonging to the Larder Lake, Kinojevis, and Blake River groups, respectively (Jensen & Langford 1985). These form the southern limb of an elongate, east-plunging synclinorium (Fig. 1), metamorphosed to low-grade subgreenschist and greenschist facies (Jolly 1974). The youngest unit, the Blake River Group, has been dated at 2703 ± 2 Ma and 2701 ± 2 Ma by U–Pb on zircon (Nunes & Jensen 1980, Corfu *et al.* 1989).

The most prominent feature of the district is the east-trending Kirkland Lake – Larder Lake fault zone (KLF), at the western termination of an east–west regional strike-slip fault, the Larder Lake – Cadillac fault. Cameron (1990) has suggested that the KLF is a series of strike-slip (pull-apart) basins formed by extension of the lithosphere at a strike-slip termination. The KLF is largely filled by the Timiskaming Group (Hewitt 1963, Cooke & Moorhouse 1969, Hyde 1980), a 2677 ± 2 Ma (Corfu *et al.* 1991) sequence of interbedded sedimentary and alkaline volcanic rocks that unconformably overlie the basaltic rocks cited above. The southern margin of the KLF is a fault contact against uplifted Larder Lake Group basalts, whereas the north-

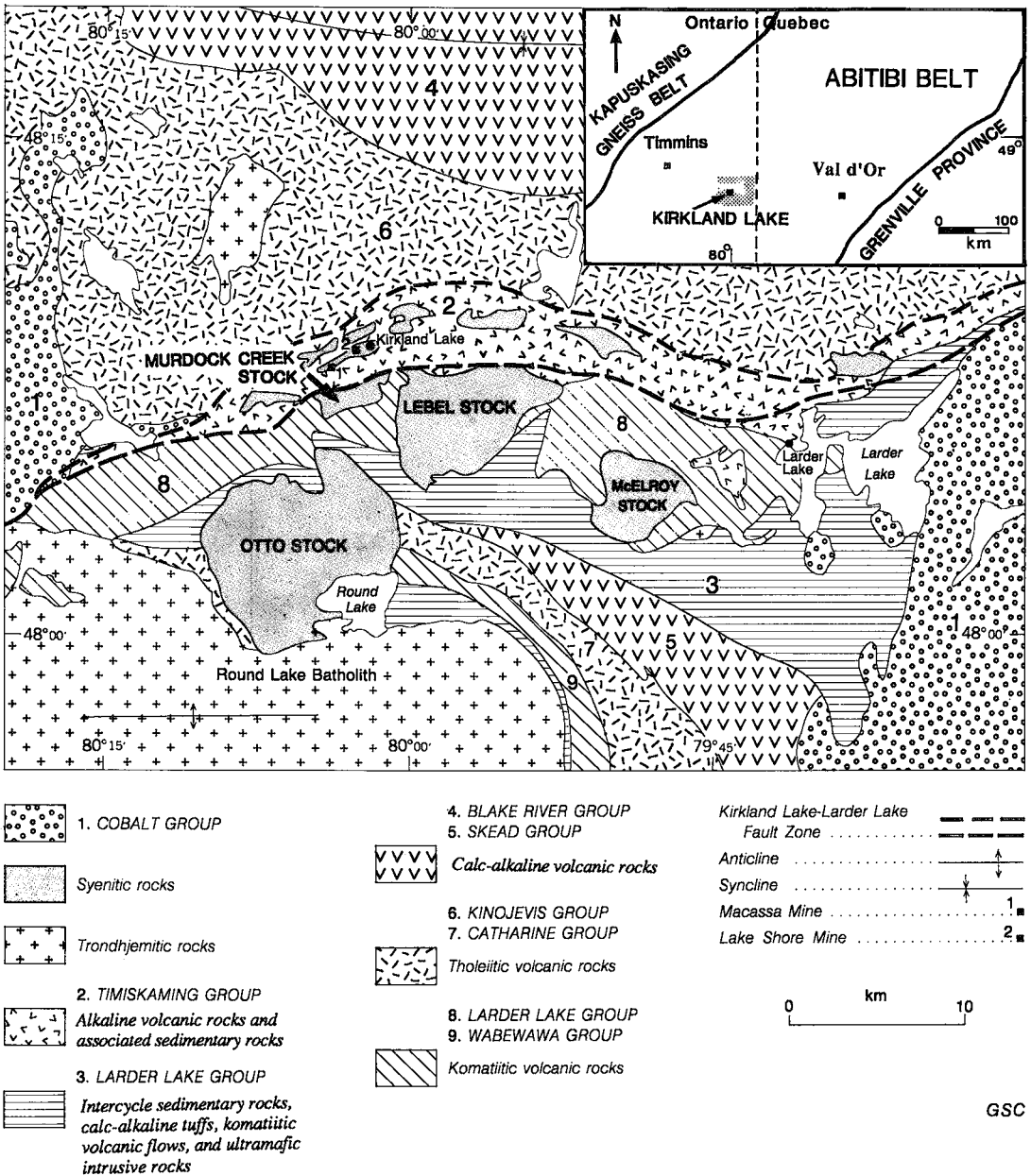


FIG. 1. Geology of the Kirkland Lake area (modified from Jensen 1978).

ern margin is, in part, an unconformity of Timiskaming rocks over Kinojevis basalts, and elsewhere, a fault.

The district is also notable in containing numerous composite syenitic plutons, which are uncommon elsewhere in Archean terranes. The area is one of the world's oldest major centers of alkaline magmatism. The large, subcircular plutons south of the KLF (Fig. 1) appear to have been forcefully emplaced as diapirs into the

surrounding supracrustal rocks, whereas the smaller syenitic plutons *within* the KLF are elongate parallel to the margins of the strike-slip basins, a form suggesting passive intrusion into extensional fractures (Cameron 1990). The Otto stock, one of the large, round plutons south of the KLF, has been dated by the conventional U-Pb technique (zircon) at  $2680 \pm 1$  Ma (Corfu *et al.* 1989), and by the ion probe U-Pb technique (zircon) at

2671 ± 8 Ma (Ben Othman *et al.* 1990). Calc-alkaline (also called shoshonitic) lamprophyres occur throughout the area and are commonly associated with syenitic plutons, which they both predate and postdate. A dike set that cross-cuts syenite has been dated by the U-Pb method (titanite) at 2674 ± 2 Ma (Wyman & Kerrich 1988).

Carbonatization of rocks within, and proximal to, the KLF is extensive and structurally controlled (Thomson 1950). Syenitic plutons are affected to varying degrees, but are also, in some places, observed to cut carbonatized zones. This feature, together with the occurrence of pebbles of carbonatized rock in the upper beds of the Timiskaming Group (Hewitt 1963), suggest a long period of infiltration by a CO<sub>2</sub>-rich fluid.

#### GEOLOGY OF THE MURDOCK CREEK PLUTON

Since outlines of the geology and structure of the

Murdock Creek pluton are given by Rowins *et al.* (1989, 1991), only a summary is presented here. Typical modes of the different plutonic units are summarized in Table 1.

#### Field relations

The Murdock Creek pluton (Fig. 2) is a crudely elliptical body, elongate in an east-west direction, parallel to the strike of the KLF. It intrudes komatiitic basalts of the Larder Lake Group. At the contact, there is a heterogeneous zone of intermingled clinopyroxenite and altered basaltic country-rock. West of the north-trending Lake Shore fault, rock units and contacts are well preserved, with only minor shearing and alteration, in contrast to those in the east, which are obscured by post-emplacement faulting and alteration. It is primarily from this unaltered western portion of the pluton that the samples used in this study were collected.

TABLE 1. MODAL MINERALOGY OF MURDOCK CREEK ROCK-UNITS

ROCK-UNIT <sup>a</sup>	AS	MAS	MS	MM	MD	CP	HB
<b>Primary Minerals</b>							
K-Feldspar (Vol. %)	66-80	42-45	44-57	8-12	0-2	0-1	<3
Plagioclase	0-2	1-3	5-13	38-45	26-30	0-10	6-40
Clinopyroxene	11-27	28-30	15-24	15-22	31-35	53-62	10-15
Biotite	0-9	9-13	7-12	16-27	15-20	14-27	5-11
Amphibole	—	—	—	—	—	—	50-70
Magnetite	1-4	4-5	1-3	1-2	2-4	1-6	<1
<b>Secondary Minerals</b>							
Biotite	0-2	2-5	1-3	<2	3-4	1-5	0-2
Amphibole <sup>b</sup>	0-2	<1	1-6	1-10	4-10	1-13	0-1
Quartz	—	—	—	—	—	—	tr
Chlorite	0-1	<1	0-1	0-1	0-1	0-1	—
Epidote	0-1	<1	1-2	<2	<2	0-1	0-2
Calcite	0-2	0-1	<1	<1	0-1	0-2	0-1
Sericite	<1	<1	<1	<1	0-1	0-1	0-1
Rutile/Titanite	tr	tr	tr	tr	tr	tr	—
<b>Accessory Minerals</b>							
Apatite	<2	1-2	<2	<2	1-2	1-3	<1
Titanite	<2	<1	0-1	<1	0-1	<1	<1
Zircon	tr	—	tr	tr	tr	tr	tr
Sulfide minerals <sup>c</sup>	tr	tr	tr	tr	tr	tr	tr
Plag. Composition			A <sub>16-18</sub>		A <sub>30-34</sub>		A <sub>10-15</sub>
Color Index (CI) <sup>d</sup>	22±9	53±4	38±12	46±8	68±8	>85	>60

Modal ranges are based on 1000 counts per thin section in conjunction with visual estimation techniques for coarse-grained samples; tr = trace amounts.

<sup>a</sup> Rock-units as follows: AS, alkali feldspar syenite; MAS, melanocratic alkali feldspar syenite; MS, melasyenite; MM, melamonzodiorite; MD, meladiorite; CP, clinopyroxenite; HB, hornblende.

<sup>b</sup> Secondary amphibole varieties include magnesian hastingsite, actinolite, tremolite, and magnesio-riebeckite. Terminology after Leake (1978).

<sup>c</sup> Primary sulfide minerals include pyrite, chalcopyrite, bornite, and covellite.

<sup>d</sup> Color Index (CI) = total mode - quartz, plagioclase, alkali feldspar, apatite, calcite, and sericite (after Streckelsen 1976).

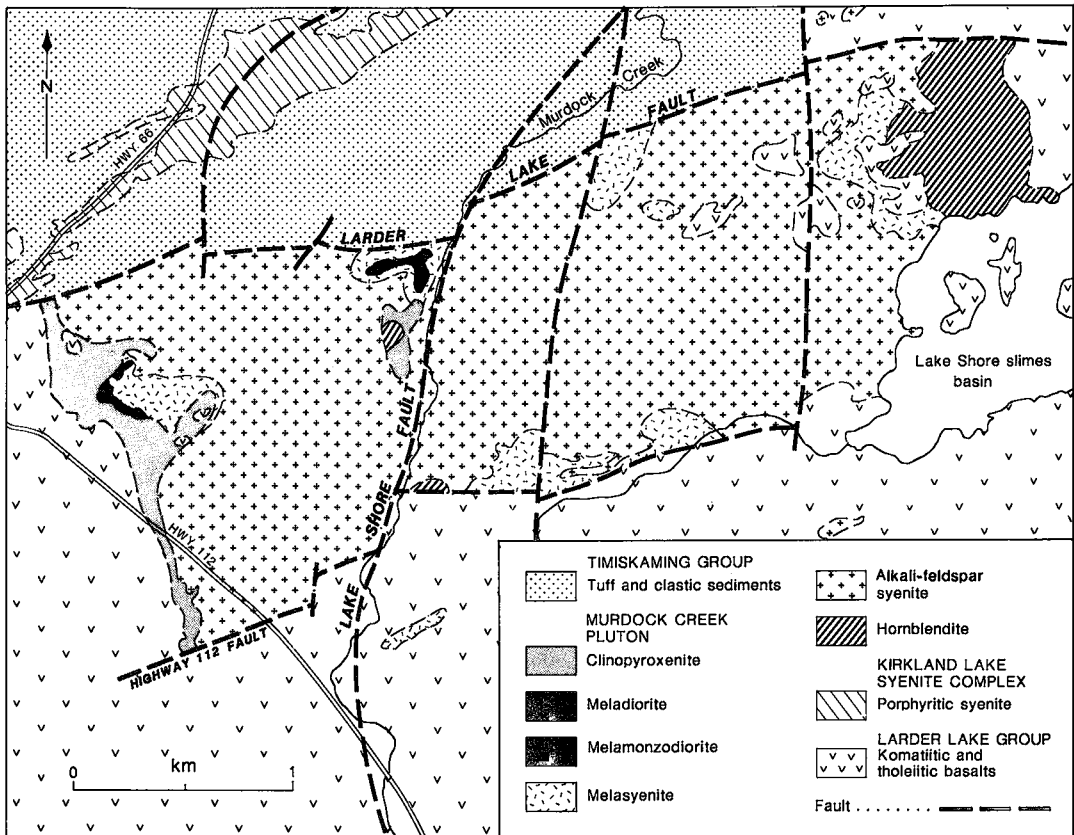
Six plutonic units are defined using the IUGS nomenclature (Streckeisen 1976). A thin, mafic margin of clinopyroxenite, meladiorite, melamonzodiorite, and melasyenite encloses an extensive felsic core of alkali feldspar syenite (Fig. 2). Melanocratic alkali feldspar syenite is not distinguished from normal alkali feldspar syenite in Figure 2, because the two units are intergradational. An intrusive hornblendite unit outcrops throughout the pluton, in addition to forming a large (700 × 500 m) body at the northeastern extremity of the pluton. However, because hornblendite is cut by late dikes of alkali feldspar syenite, the hornblendite is interpreted to be coeval with the other rocks. Except for the hornblendite, all rock types generally exhibit gradational contacts in the field. Less commonly observed abrupt contacts are produced by the movement of unconsolidated magma into earlier solidified rock-units.

Rare dikes of pegmatitic alkali feldspar syenite are usually associated with small shear zones, several meters wide, within the alkali feldspar syenite core of the intrusion. These shear zones are interpreted as pressure-release conduits along which volatile-rich fluid and melt

were forcefully expelled during the final stages of magma consolidation. Other features of late-magmatic volatile build-up, such as miarolitic cavities, were not observed.

*Petrography of the mafic margin*

Massive, fine- to medium-grained clinopyroxenite consists almost entirely of slightly pleochroic, pale green, subhedral to euhedral, equant crystals of diopside, which produce a cumulate texture, although gravitational settling of crystals is not implied. Primary zonation (*i.e.*, growth zoning) is absent, but metasomatic reaction with a late Na-rich vapor phase has produced bright apple-green aegirine-augite along some grain boundaries and fractures (*e.g.*, Fig. 3a in Rowins *et al.* 1991). Primary Mg-rich biotite, plagioclase, magnetite, apatite, titanite, and rare alkali feldspar fill the interstices. The modal abundance of primary biotite is not uniform and can reach 27% (Table 1). Typical primary inclusions in diopside include anhedral magnetite, euhedral apatite and titanite, and subhedral flakes of highly pleochroic,



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FIG. 2. Geology of the Murdock Creek pluton (Thomson 1950, Rowins *et al.* 1989, 1991).

light tan to dark brown biotite. Clinopyroxenite grades gradually into meladorite, which generally retains the massive, fine- to medium-grained texture, although a slight primary foliation may be imparted to the rock by the preferential alignment of plagioclase laths. Mineralogically, meladorite is identical to clinopyroxenite, except that plagioclase ( $An_{30-34}$ ) is now relatively abundant, and the rock possesses a hypidiomorphic-granular texture. Melamonzodiorite is the least abundant rock-type. It is markedly heterogeneous, varying from fine to medium grained, and from syenitic to clinopyroxene-rich over tens of centimeters. Medium-grained plagioclase and laths of perthitic alkali feldspar may possess ragged and sutured crystal margins, indicative of minor recrystallization. In leucocratic variants, diopside, biotite, apatite, and titanite tend to occur together in 0.5- to 6-mm long lenticular clots interstitial to larger feldspar crystals (e.g., Fig. 3c in Rowins *et al.* 1991). Melasyenite is a medium-grained, massive- to trachytic-textured rock, and the most mafic variants can appear slightly porphyritic, with perthitic alkali feldspar laths up to 1 cm long. Toward the core of the pluton, this rock type becomes more leucocratic, its textures and mineral distributions becoming increasingly homogeneous, with the slightly porphyritic appearance giving way to a more evenly colored pink melasyenite. Subhedral alkali feldspar grains are usually larger than those of less abundant plagioclase ( $An_{16-18}$ ), and they typically display Carlsbad twinning and vein- and bleb-type perthitic intergrowths. The wide range in size of alkali feldspar crystals presumably resulted from movement in a viscous, partially crystallized syenitic magma or crystal mush, which produced substantial granulation of crystal edges. Other rock textures and proportions of primary ferromagnesian minerals and accessory phases are comparable to those in meladorite and melamonzodiorite.

#### *Petrography of the felsic core*

Hypidiomorphic-granular alkali feldspar syenite exhibits considerable diversity in terms of mineral proportions, with the most melanocratic variants marking the transition from the mafic margin to the felsic core. Alkali feldspar grains commonly display Carlsbad twinning and perthitic exsolution intergrowths of the vein, bleb, patch, and interlocking varieties. Pale green, columnar to equant diopside and strongly pleochroic, tan-brown biotite, together with rare plagioclase, are typically interstitial to larger perthitic alkali feldspar laths. In trachytic-textured variants, perthitic alkali feldspar grains possess ragged margins rimmed by fine-grained polygonal albite or, alternatively, clear films of recrystallized albite if granulation is less severe. Diopside and primary Mg-rich biotite [see Tables 1 and 2 in Rowins *et al.* (1991) for compositions] are compositionally and texturally very similar to those in the other plutonic units, as are the variety of accessory minerals (Table 1).

#### *Petrography of intrusive hornblendite*

Small bodies of medium- to coarse-grained hornblendite contain the *only* primary amphibole encountered in the rock types studied. Variable proportions of amphibole and plagioclase, the former ranging in composition from edenitic hornblende to magnesio-hastingsitic hornblende (Rowins *et al.* 1991), yield a range of rock types. Ultramafic rocks (*sensu stricto*) possessing a cumulate texture defined by equant, euhedral, twinned hornblende crystals, commonly grade into more plagioclase-rich rocks exhibiting a porphyritic or hypidiomorphic-in-equigranular texture. Here the rock is more accurately termed a hornblende meladorite or "dioritic" hornblendite. However, for the sake of simplicity, these rocks are here collectively referred to as hornblendite. Typical primary inclusions in hornblende include subhedral pale green diopside and subhedral flakes of greenish brown biotite, plus euhedral apatite and subhedral magnetite. In the hornblende cumulates, the intercumulus groundmass consists principally of anhedral plagioclase ( $An_{10-15}$ ), subhedral diopside, Mg-rich biotite or phlogopite, magnetite, apatite, and rare anhedral alkali feldspar. This mineral assemblage is *identical* to that in the other rock types of the Murdock Creek pluton, an observation that is considered important for the petrogenetic interpretation of these rocks. Rowins *et al.* (1991) also reported that the compositions of diopside and biotite in the hornblendites are very similar to those in the other plutonic units. The variety of, and textures displayed by, secondary replacement minerals and accessory phases are likewise very similar (Table 1).

#### WHOLE-ROCK GEOCHEMISTRY

##### *Analytical methods*

Whole-rock samples were analyzed for major elements and Cr, Rb, Sr, Y, Zr, Nb, and Ba by X-ray fluorescence spectroscopy (XRF) at the Geological Survey of Canada. Results were calibrated against standard rock samples; concentrations of major elements are accurate to better than 1% of the reported concentration, with the exception of FeO and MnO ( $\pm 2\%$  relative). Trace-element concentrations obtained by XRF are accurate to  $\pm 10\%$  of the given value, except for Rb ( $\pm 2\%$  relative). The  $Fe^{3+}/Fe^{2+}$  ratio was determined by titration employing the Wilson (1960) method;  $H_2O$  and loss-on-ignition (LOI) were obtained with a Leco furnace; the concentration of  $CO_2$  was obtained by combustion followed by infrared detection, and that of S by ion chromatography, considered accurate to  $\pm 5\%$  of the reported concentration.

Concentrations of Sc, V, Co, Ni, Cu, Zn, As, Mo, Sb, Hf, Ta, Au, Th, U, and the rare-earth elements (REE) were determined by instrumental neutron-activation analysis (INAA) on 10–15 g of sample (Bondar-Clegg

TABLE 2. REPRESENTATIVE MAJOR- AND TRACE-ELEMENT DATA ON ROCKS OF THE MURDOCK CREEK PLUTON

ROCK-UNIT <sup>a</sup> SAMPLE	AS 87104	AS 87118	MAS 88217	MS 87131	MS 89293	MM 88295	MM 89227	MD 88288	MD 89142A	CP 87130	CP 88297	HB 88329	HB 89509	AUG-S <sup>b</sup> P2	FEL-S <sup>c</sup> P1
SiO <sub>2</sub>	55.5	57.2	49.5	54.0	53.9	46.1	53.2	49.2	46.7	41.7	44.1	47.8	47.9	48.2	56.6
TiO <sub>2</sub>	0.76	0.61	1.15	0.80	0.69	1.19	0.88	0.90	1.05	1.56	1.37	0.81	0.83	0.90	0.61
Al <sub>2</sub> O <sub>3</sub>	13.0	15.3	10.6	14.1	13.7	9.5	13.0	11.4	12.2	5.3	9.5	7.5	7.4	12.6	18.9
Fe <sub>2</sub> O <sub>3</sub>	4.2	4.1	6.4	4.4	2.7	7.0	4.7	4.0	5.2	8.8	5.6	3.1	2.6	na	na
FeO (FeOT)	3.4	2.6	6.0	4.1	4.7	7.8	4.6	6.2	6.5	7.9	8.1	5.9	5.9	na	na
MnO	7.1	6.2	11.7	8.0	7.1	14.0	8.8	9.8	11.2	15.7	13.1	8.7	8.2	7.8	3.7
MgO	0.14	0.13	0.23	0.16	0.16	0.21	0.17	0.19	0.21	0.28	0.22	0.18	0.15	0.13	0.08
CaO	4.59	3.26	7.35	5.67	6.91	9.26	6.54	8.44	9.20	12.51	11.50	15.95	16.10	6.6	0.90
Na <sub>2</sub> O	6.83	5.03	10.50	7.18	6.93	10.29	8.86	9.15	10.36	16.78	12.04	11.95	12.33	7.2	1.9
K <sub>2</sub> O	3.4	4.3	2.9	3.9	4.2	2.3	4.3	2.8	2.4	0.5	1.6	0.7	0.9	3.1	4.4
P <sub>2</sub> O <sub>5</sub>	8.26	5.97	3.37	4.09	3.73	3.15	2.18	3.50	3.20	1.75	3.04	3.01	3.15	5.5	7.5
H <sub>2</sub> O	0.66	0.50	1.02	0.52	0.47	0.63	0.61	0.65	0.82	1.46	0.77	0.19	0.13	0.52	0.22
CO <sub>2</sub>	0.6	0.5	0.7	1.1	1.3 <sup>d</sup>	1.3	0.9 <sup>d</sup>	1.5	1.3	1.2	1.6	1.8	1.2 <sup>d</sup>	5.2 <sup>d</sup>	3.6 <sup>d</sup>
CO <sub>2</sub>	0.1	0.3	0.1	0.1	na	0.7	na	0.3	0.3	0.3	0.3	0.2	na	na	na
TOTAL	99.44	99.80	99.82	100.12	99.39	99.43	99.94	99.23	99.14	100.04	99.74	99.09	98.59	97.75	98.41
S	114	<50	200	<50	400	600	300	<50	200	214	1300	<50	200	121.6	119.7
Sc	20.6	15.0	31.6	22.6	18.0	40.6	20.7	29.5	23.7	64.5	43.3	42.3	37.9	28.3	8.1
V	na	na	290	na	183	370	218	220	284	na	340	180	202	367	91
Cr	190	130	150	300	323	310	242	460	394	440	460	1200	1230	318	80
Co	31	29	44	37	41	52	na	48	na	80	56	53	na	50	24
Ni	33	33	39	51	78	57	44	100	109	90	92	230	262	96	18
Cu	na	na	35	na	na	100	na	85	na	120	15	na	19	16	16
Zn	200	150	120	140	158	130	139	120	136	210	280	69	70	99	56
As	1.6	5.3	0.8	3.3	2.0	1.7	2.6	4.3	1.8	1.5	1.9	1.2	1.0	8.7	3.5
Pb	185	146	78	131	116	112	92	147	102	70	111	113	112	166	206
Sr	1869	2133	1934	1587	1660	799	2681	1546	2871	669	795	316	277	682	562
Y	61	54	78	71	21	70	30	67	24	40	30	14	24	24	21
Zr	174	193	139	225	106	158	165	188	87	109	93	72	42	156	285
Nb	<2.0	<2.0	14.0	<2.0	<2.0	19.0	2.0	35.0	<2.0	<2.0	25.0	4.0	<2.0	6	10
Mo	1	1	0.5	3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	na	na
Sb	0.1	0.4	0.1	0.2	0.4	0.2	0.2	0.4	0.1	0.1	0.2	0.2	0.2	3.6	3.1
Ba	3262	3221	3992	2159	2815	1850	1302	1565	3382	2141	2349	1094	1218	132	817
La	97	92	86	75	37	44	52	61	45	74	33	12	11	na	na
Ce	164	153	170	121	98	100	120	120	110	147	79	44	35	na	na
Sm	13.0	12.0	17.5	10.0	9.5	12.9	12.7	13.6	13.1	18.0	10.9	6.2	6.1	na	na
Eu	4.0	3.0	3.0	2.0	2.0	3.0	2.0	3.0	3.0	5.0	2.0	2.0	2.0	na	na
Tb	1.5	1.4	1.6	1.4	0.9	1.4	1.2	1.2	1.2	2.5	1.1	0.7	0.8	na	na
Yb	1	1	3	3	1	3	3	2	1	3	1.8	0.7	1	na	na
Lu	0.3	0.3	0.4	0.4	0.1	0.4	0.3	0.2	0.3	0.5	0.4	0.1	0.1	na	na
Hf	4	4	3	5	1	1	2	2	0.5	3	2	2	0.5	na	na
Ta	<0.5	0.7	0.5	0.6	0.7	0.7	0.9	0.5	0.5	<0.5	0.5	0.5	0.6	na	na
Au (ppb)	4	1	1	1	1	1	8	1	1	4	1	1	1	6	17
Th	3.8	7.4	3.1	11.0	3.4	3.4	4.9	3.2	1	2.1	1.7	1.7	1.8	9	26
U	0.6	1.5	0.04	2.5	0.9	0.9	1.3	0.8	0.1	0.3	0.5	0.4	0.3	2.6	3.2
Agpaitic index <sup>e</sup>	0.95	0.88	0.79	0.77	0.81	0.76	0.72	0.74	0.61	0.51	0.62	0.59	0.65	0.87	0.81
CIPW Norm															
Or	36.98	35.27	19.91	24.16	22.03	18.60	12.88	20.67	18.90	5.20	17.95	17.75	18.58	32.48	44.32
Ab	24.79	34.69	20.02	31.65	30.79	11.37	35.96	16.45	11.31	—	0.23	3.63	0.30	9.58	31.69
An	1.72	4.81	5.95	8.89	7.22	6.29	9.95	8.20	12.79	7.05	9.76	8.42	7.13	4.22	7.99
Ne	2.16	0.92	2.45	0.73	2.75	4.38	—	3.92	5.01	2.29	7.20	1.24	3.77	9.01	3.01
Lc	—	—	—	—	—	—	—	—	—	4.03	—	—	—	—	—
Di	22.07	13.28	31.48	18.56	19.32	32.55	23.88	26.38	26.59	52.85	35.97	39.34	42.19	22.42	—
Hy	—	—	—	—	—	—	1.57	—	—	—	—	—	—	—	—
Ol	2.01	1.80	5.48	5.87	9.72	10.43	4.83	12.86	11.93	8.15	14.29	20.25	18.75	7.00	4.05
Mt	6.10	5.96	9.30	6.39	3.89	10.17	6.87	5.81	7.57	12.79	8.13	4.50	3.76	5.38	1.60
Il	1.45	1.16	2.19	1.52	1.31	2.26	1.68	1.71	2.00	2.97	2.61	1.54	1.58	1.71	1.16
Ap	1.45	1.10	2.24	1.14	1.03	1.39	1.34	1.43	1.80	3.21	1.69	0.42	0.29	1.14	0.48
C	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.62
TOTAL	98.74	99.00	99.02	98.92	98.08	97.43	98.95	97.43	97.90	98.54	97.84	97.09	97.34	92.95	94.91
F.I. <sup>f</sup>	63.93	69.96	42.38	56.54	55.57	34.35	48.84	41.04	35.22	11.52	25.38	22.62	22.65	51.07	79.02

Oxides reported in wt. %; trace-elements in ppm except for gold (ppb); na = not analyzed; FeOT = all iron recalculated as FeO.

<sup>a</sup> Rock-units as in Table 1.

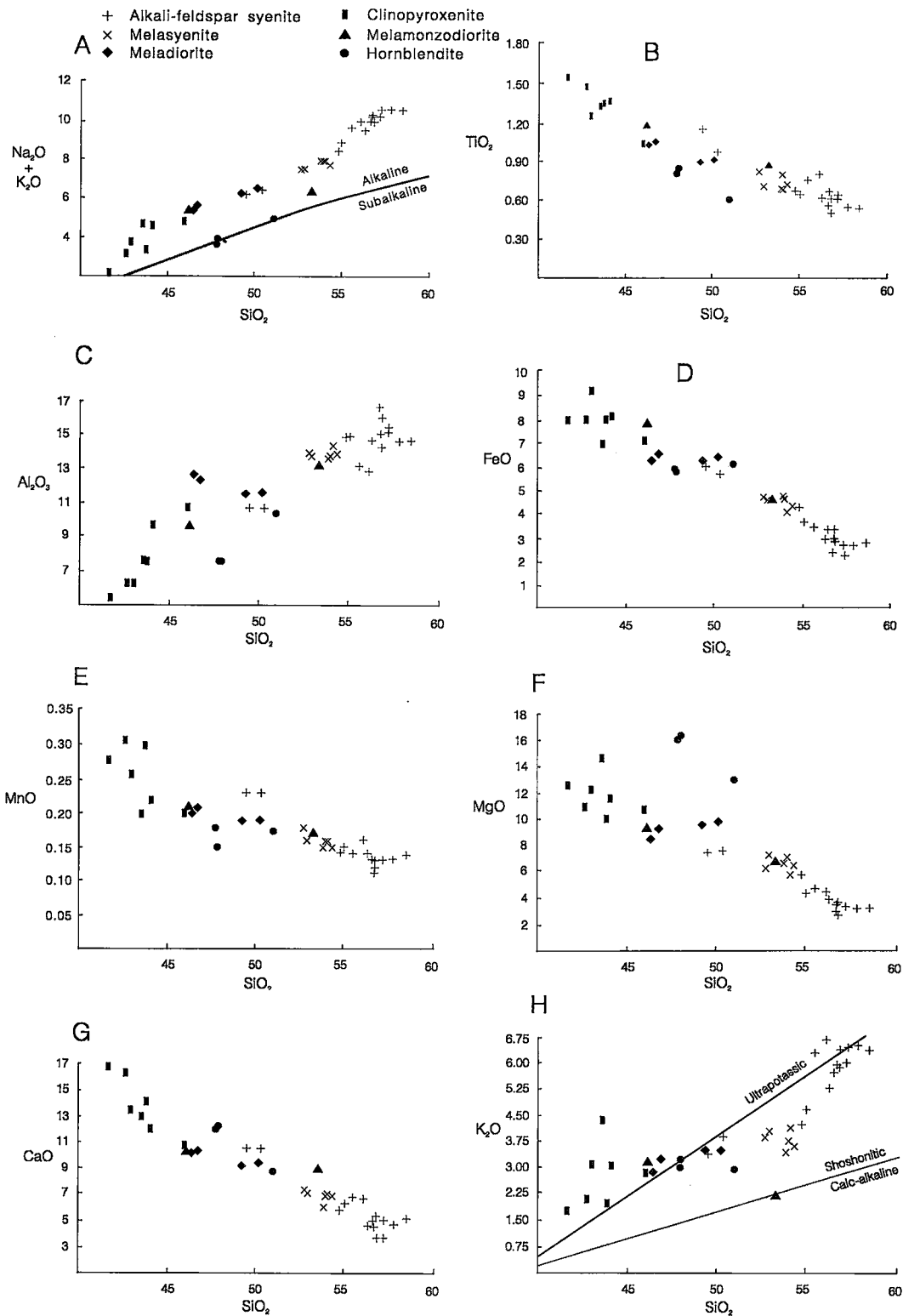
<sup>b</sup> Average augite syenite composition from the Kirkland Lake syenite complex (Macassa mine) (from Table 3 in Kerrich & Watson 1984). For normative calculations, the Fe<sub>2</sub>O<sub>3</sub>/(FeO + Fe<sub>2</sub>O<sub>3</sub>) ratio (0.42) was determined by taking the average Fe<sub>2</sub>O<sub>3</sub>/(FeO + Fe<sub>2</sub>O<sub>3</sub>) ratio of nine augite syenite samples reported in Table 2 of Kerrich & Watson (1984), and then correcting the FeO and Fe<sub>2</sub>O<sub>3</sub> values in the analysis. Note that Ba = 132 ppm (?) appears to be erroneous, as all reported unaltered augite syenite analyses (n = 10) in Table 2 of Kerrich & Watson (1984) have Ba contents ranging between 1660 and 2200 ppm, average = 1850 ppm.

<sup>c</sup> Average felsic syenite composition from the Kirkland Lake syenite complex (Macassa mine) (from Table 3 in Kerrich & Watson 1984). For normative calculations, the Fe<sub>2</sub>O<sub>3</sub>/(FeO + Fe<sub>2</sub>O<sub>3</sub>) ratio (0.27) was determined by taking the average Fe<sub>2</sub>O<sub>3</sub>/(FeO + Fe<sub>2</sub>O<sub>3</sub>) ratio of two felsic syenite samples reported in Table 2 of Kerrich & Watson (1984), and then correcting the FeO and Fe<sub>2</sub>O<sub>3</sub> values in the analysis.

<sup>d</sup> wt. % loss-on-ignition at 1000°C.

<sup>e</sup> Agpaitic index = molecular ratio (Na + K)/Al.

<sup>f</sup> F.I. = normative whole-rock fractionation index (wt. % Or + Ab + Ne + Lc + Kp).





and Company); concentrations are accurate to better than  $\pm 20\%$  of the stated value (except for Au,  $\pm 50\%$ .)

### Major elements

Thirty-seven unaltered samples from the various rock-units comprising the Murdock Creek intrusion were studied; results of whole-rock major- and trace-element analyses for 13 representative samples are reported in Table 2, along with CIPW norms. A complete set of analytical data can be obtained from the Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, Ontario K1A 0S2. Low whole-rock volatile contents ( $H_2O$  and  $CO_2$  or total LOI generally less than 2%) reflect the low proportion of hydrous minerals in the pluton, and the lack of sub-solidus hydration and carbonatization. All samples are slightly undersaturated in  $SiO_2$ , containing several wt.% nepheline (Ne), or, less commonly, olivine (Ol) plus hypersthene (Hy), in the norm (Table 2). The presence of normative nepheline is compatible with the alkalis versus  $SiO_2$  diagram (Fig. 3a), which shows all Murdock Creek rock types to be within Miyashiro's (1978) field of alkaline rocks. Normative leucite (Lc) and potassium metasilicate (Kp;  $KAlSiO_4$ ) in several biotite-rich clinopyroxenite and hornblende samples are consistent with their classification as ultrapotassic igneous rocks *sensu stricto* (see classification in discussion on tectonic setting).

The agpaitic index  $(Na+K)/Al$  (mol. prop.) ranges from 0.51 in clinopyroxenite to 1.0 in a single alkali feldspar syenite sample (87119), indicating that Murdock Creek syenites are of the miaskitic variety (Sørensen 1974). None of the Murdock Creek samples are peralkaline, since they lack modal aegirine and alkali amphibole, have agpaitic indices less than 1.0, and lack normative acmite. The  $K/Na$  ratio generally exceeds unity and, together with high abundances of  $K_2O$ , demonstrates the chemical affinity of Murdock Creek rock types with shoshonitic (mildly potassic; Morrison 1980, Cullers & Graf 1984) and, in some cases, ultrapotassic igneous rocks (especially those of group II of Foley *et al.* 1987).

The compositional continuity of the Murdock Creek rock suite is well illustrated in Harker variation diagrams (Figs. 3b–h). Smooth linear trends characterize all major elements over the entire compositional range. Given the gradational boundaries between rock types, the spatial distribution of plutonic units (mafic margin to felsic core), and the systematic changes in mineral chemistry (Rowins 1990, Rowins *et al.* 1991), this smooth linearity suggests that all Murdock Creek rock units (except hornblende) are cogenetic members of a single fraction-

ation series, a hypothesis that is quantitatively tested below with Pearce element ratios.

The  $FeO_T/(FeO_T+MgO)$  molar ratio is fairly constant throughout, with values typically between 0.30 to 0.40. During crystallization of alkali feldspar syenite, however, slight Fe enrichment occurred, and values approach 0.45. Relatively high, though variable,  $Fe^{3+}/(Fe^{2+}+Fe^{3+})$  ratios (cation proportions), ranging between 0.30 and 0.50, characterize all rock units of the mafic margin, supporting evidence provided by ferromagnesian silicates and opaque oxides for high fugacity of oxygen throughout the pluton's evolution [ $f(O_2)$  between the hematite–magnetite (HM) and nickel–nickel oxide (NNO) oxygen buffer curves; Rowins *et al.* (1991)]. An increase in this ratio during crystallization of alkali feldspar syenite, up to a maximum of 0.68, mimics the increase observed in the  $FeO_T/(FeO_T+MgO)$  ratio.

### Major-element modeling

Pearce element ratio (PER) diagrams (Figs. 4, 5) (Pearce 1968) are X–Y plots of ratios of elements designed to avoid the closure problem that can distort trends on Harker or weight percent oxide–oxide diagrams and lead to erroneous petrogenetic conclusions (Chayes 1964, 1971, Nicholls 1988). Such diagrams allow recognition of cogenetic rock suites and permit the identification and quantification of mineral losses and gains from the system, thereby allowing discrimination among processes of magmatic differentiation such as crystallization, assimilation, and magma mixing (Russell & Nicholls 1988). The denominators of the ratios are common to both axes and are usually single elements that must be conserved (*i.e.*, remain incompatible) during the differentiation process. The numerators may be single elements or complex algebraic combinations of elements. A procedure for designing complex numerators is given in Ernst *et al.* (1988), and a more comprehensive matrix method is given by Stanley & Russell (1989). Briefly, equations were devised based on the mineral stoichiometry (analyzed compositions where possible); these equations sum the contribution from each mineral species to the abundance of particular elements. Appropriately chosen linear combinations of these equations yield equations that isolate the variation in the abundance of specific minerals and allow testing of fractionation hypotheses. The trends on such diagrams have slopes equaling the ratio of the numerator elements accumulated or fractionated during the process causing chemical variation. In Figures 4 and 5, La is used as the conserved element by which the numerators are

Fig. 3. Major oxides plotted against  $SiO_2$  (wt. %). Note that the highly melanocratic alkali feldspar syenite samples 88216 and 88217 plot at  $SiO_2$  values more typical of the less evolved rock-types. Boundary of the alkaline field in Fig. 3a from Miyashiro (1978). Boundaries in Fig. 3h after Peccerillo & Taylor (1976) and Wheller *et al.* (1987).

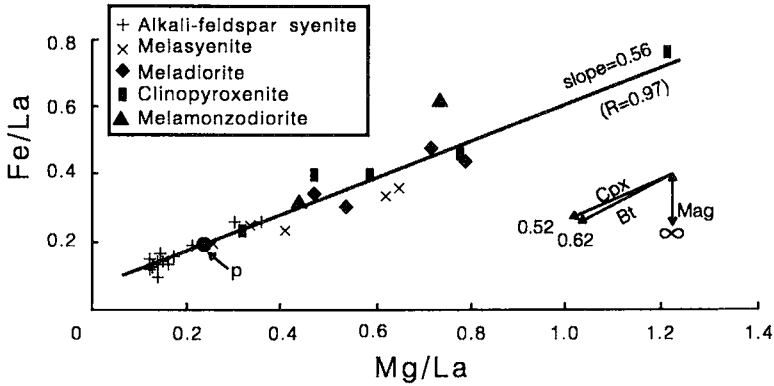


FIG. 4. Murdock Creek data plotted on a Pearce element ratio diagram to test for the effects of clinopyroxene-controlled fractionation. The inset shows the igneous fractionation vectors for clinopyroxene (cpx), biotite (bt), and magnetite (mag) for Murdock Creek rocks. Compositions that are consistent with the clinopyroxene hypothesis define a slope of 0.52. Point "P" on the best-fit line is the assumed position of the parent composition of the Murdock Creek pluton. See text for further discussion.

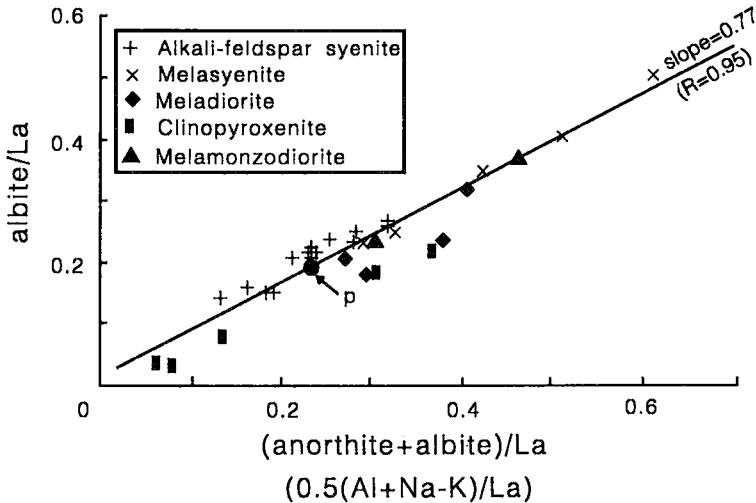


FIG. 5. Pearce element ratio diagram to test the effects of feldspar fractionation on geochemical data from the Murdock Creek pluton. The numerators, albite (Na) and anorthite plus albite [ $0.5(AI + Na - K)$ ], have been constructed from equations based on mineral stoichiometry, which sum the contribution from each mineral species to the abundance of particular elements (e.g., Ernst *et al.* 1988). Note that amongst the four meladiorite samples, there are two clinopyroxenite samples that have plagioclase contents (7 or 8 % modal) only slightly less than the > 10% amount necessary for classification as a meladiorite according to the IUGS scheme (Streckeisen 1976). Point "P" is the assumed parent-composition of the Murdock Creek pluton.

divided. Note that all elements are expressed as molar abundances. The choice of La as the denominator was based on several factors: (1) it occurs at high concentrations relative to its detection limits (2 ppm), and thus any effects of analytical error are minimized; (2) it varies in

a manner consistent with incompatible behavior during differentiation (*i.e.*, lowest concentrations in the mafic marginal rocks and highest concentrations in the felsic core); (3) the major minerals of the pluton have mineral-liquid partition coefficients ( $K_d$ ) for La considerably

less than unity (*e.g.*, Hanson 1980), and (4) particularly La-rich accessory minerals such as allanite and monazite are absent, although the presence of apatite and titanite, which have a  $K_d$  for La significantly greater than one (Mittlefehldt & Miller 1983, Lemarchand *et al.* 1987), could lead to anomalously high concentrations of La in some samples. Fortunately, the overall increase in La concentrations from the mafic through felsic rock-units leads to the conclusion that La behaved incompatibly. In both PER diagrams, hornblende compositions are not plotted because data points lie far off the well-defined main trends, indicating that hornblende bodies are not related to the Murdock Creek parent magma by fractionation of clinopyroxene or feldspar. However, as suggested later, this does *not* preclude a cogenetic relationship through other processes of differentiation.

Because diopside is the principal ferromagnesian mineral in the pluton, a simple PER diagram of Fe/La versus Mg/La (Fig. 4) should be effective in testing for diopside fractionation. Furthermore, because the Fe/Mg ratios of diopside and biotite remained constant throughout crystallization owing to a high magmatic  $f(O_2)$  (Rowins *et al.* 1991), single-mineral vectors covering the entire range of rock compositions can be calculated using *average* Fe/Mg ratios. In Figure 4, the stoichiometry of average Murdock Creek clinopyroxene (see compositions in Table 1 of Rowins *et al.* 1991) requires that the trend have a slope of 0.52 (*i.e.*, Fe:Mg = 0.34:0.66). The calculated slope is 0.56 (correlation coefficient  $R = 0.97$ ), close enough to the theoretical value to confirm clinopyroxene fractionation as the dominant mechanism of fractionation of the ferromagnesian phase. The slightly higher calculated slope likely reflects minor fractionation of biotite and magnetite, since both minerals have higher Fe/Mg than diopside (Fig. 4) and have the capacity to affect the ratio.

Figure 4 also tracks the history of clinopyroxene fractionation and accumulation during differentiation from a hypothesized common parent (point "P" in Fig. 4). The position of this hypothetical parent is based largely upon petrographic evidence, which indicates that the clinopyroxenites are cumulates and therefore enriched in clinopyroxene relative to the parent. Thus, given the geometry of PER diagrams, the composition of the hypothetical parent must plot between the residual liquids (alkali feldspar syenites) and rocks that are accumulative in clinopyroxene (all others).

A plot of normative albite/La (Na/La) versus  $0.5(Al + Na - K)/La$  (Fig. 5) was constructed to test the effects of feldspar fractionation. The numerator of the X-axis ratio,  $0.5(Al + Na - K)/La$ , is designed to show the effects of anorthite plus albite fractionation. This numerator monitors "plagioclase" behavior in all rock types except those alkali feldspar syenite samples in which plagioclase is absent; in this case, the anorthite content is essentially zero, and the albite component is entirely hosted in perthitic alkali feldspar. The line of best fit in this PER diagram has a well-defined slope of

0.77 ( $R = 0.95$ ), suggesting a cogenetic relationship between the rock units. The slope is also a crude measure of the average anorthite content  $[An/(Ab+An)]$  of crystallizing plagioclase during the pluton's evolution ( $\sim An_{23}$ ). This value will be an underestimate in those rocks where plagioclase dominates over alkali feldspar because the slope-calculated plagioclase composition has albite components from both plagioclase *and* alkali feldspar. The numerator does not discriminate between the albite component in plagioclase and that in alkali feldspar. Conversely, it will be an overestimate in the rocks where alkali feldspar is the dominant feldspar. This is in agreement with microprobe data on plagioclase in meladorite ( $An_{30-34}$ ) and in melasyenite ( $An_{16-18}$ ). It should be emphasized that the slope in Figure 5 is controlled by fractional losses or gains of albite and anorthite only; fractionation of any other mineral species will have no effect on this particular vector.

The parent (P) in Figure 5 is located so as to provide a rough balance between accumulated and fractionated rocks (weighted by areal extent). Thus no buried portion needs to be hypothesized. Note also that the hypothetical parent liquid does not need to be located at the same position (relative to samples) on the two PER diagrams because of the non-closed nature of PERs. In terms of the (anorthite + albite)/La ratio, the lowest ratios are found in clinopyroxenites, indicating that these rocks have not gained or accumulated any plagioclase. With the crystallization and subsequent accumulation of plagioclase, the meladorite and the other transitional rock-types, *i.e.*, melamonzodiorite and melasyenite, are produced.

Interestingly, the highest degrees of "plagioclase" accumulation are found in melasyenite samples and one melamonzodiorite sample, although the greatest modal concentrations of plagioclase occur in meladorite samples (Table 1). Once again, this discrepancy arises because the  $0.5(Al + Na - K)$  numerator does not discriminate between the albite component in plagioclase and that in alkali feldspar (the dominant variety of feldspar in melasyenite and a major component of melamonzodiorite). Therefore, the  $0.5(Al + Na - K)$  numerators of melasyenite and melamonzodiorite receive contributions of albite from both plagioclase and alkali feldspar, as opposed to meladorite, which contains essentially only plagioclase. A similar argument explains the decrease or *reversal* observed in the  $0.5(Al + Na - K)/La$  ratio with the transition from melasyenite to alkali feldspar syenite; albite contributions come only from alkali feldspar.

The model to explain the data in both Figures 4 and 5 requires that the pluton be considered in two parts: (1) a marginal region encompassing the transitional mafic units, clinopyroxenite, meladorite, melamonzodiorite, and melasyenite, and (2) the bulk of the pluton (by exposed area), the alkali feldspar syenite core. Relative to the hypothetical parent-composition (P), the suite of marginal rocks has excess clinopyroxene (Fig. 4).

Plagioclase accumulation is observed in the meladiorites, melamonzodiorites, and particularly the melasyenites, whereas the clinopyroxenites (excluding samples 87115, 88297) are slightly depleted in plagioclase. This finding suggests that the mafic marginal units were present as crystal mushes (explaining granulation of feldspars and mineral foliations observed), and that a process or combination of processes (*e.g.*, filter-pressing, flow differentiation, convective fractionation) concentrated early-formed clinopyroxene along the walls of the magma chamber to yield clinopyroxenite. With further cooling and progressive inward crystallization, plagioclase and, later, alkali feldspar, became liquidus minerals. Variable amounts of feldspar and clinopyroxene accumulation resulted in the formation of the remaining mafic marginal units. The last unit to crystallize was the interior alkali feldspar syenite. This unit is depleted in clinopyroxene relative to the parent composition, complementing the formation of the marginal rock-units, which are enriched in this mineral (relative to parent). From the above discussion, it follows that the alkali feldspar syenite crystallized from the chemically evolved liquid (plus small suspended crystals) physically expelled from the spaces between the earlier-formed crystals. Of course, the enrichment of alkali feldspar in alkali feldspar syenite, relative to the hypothetical parent-composition and the more mafic rock-types, is not properly shown in Figure 5 since only its albite component, and not both albite and orthoclase (the potassium feldspar end-member in alkali feldspar) is monitored. In both PER diagrams, the data points for individual rock-types display considerable linear spread along the line of best fit. This is suggestive of a variable degree of separation of cumulus crystals and interstitial liquids during crystallization. For example, early-trapped liquid in a meladioritic crystal mush might be released at a much later stage of crystallization, to mix with more evolved liquids forming alkali feldspar syenite. The resulting alkali feldspar syenite would then have the low concentrations of La associated with meladiorites and hence plot closer to them in the PER diagrams. Many other complications are likely to have occurred during crystallization, and it should be emphasized that the above model is a only a simplified version of what would have been a complex process of crystal-liquid separation (*e.g.*, see discussions on crystal-liquid separation in McCarthy & Hasty 1976, McCarthy & Groves 1979, Irvine 1980, Michael 1984, Huppert & Sparks 1988). Field and petrological evidence that crystal-liquid separation was an efficient physical process in producing the Murdock Creek rock suite includes the strong compositional zonation of the pluton, the significant proportions of cumulate and relatively evolved rocks including alkali feldspar syenite pegmatite, and the lack of strong chemical zoning in minerals (*cf.* Michael 1984, Thompson & Fowler 1986).

PER analysis also can be used to investigate the relationship between hornblende and the hypothetical

Murdock Creek parent, as located in Figures 4 and 5. Hornblende compositions bear a remarkably close geochemical and mineralogical resemblance to lamprophyric rocks, specifically spessartites of the calc-alkaline lamprophyre clan (Rock 1984, 1990). Highly mafic or even ultramafic K-rich rocks of this nature have been referred to as melaspeartites (Rock 1987, and references therein), but in the Kirkland Lake area they could simply be regarded as hornblende-enriched members of a potassic basalt or lamprophyric magma suite, which comprises calc-alkaline lamprophyres plus the highly differentiated syenites and trachytes. A similar intrusive hornblende unit has been identified, along with minette lamprophyres, in the syenitic Otto stock (Smith & Sutcliffe 1988) south of the Murdock Creek pluton (Fig. 1). Lamprophyres, hornblendites and so-called "appinites" in Scotland (Pitcher & Berger 1972, Wright & Bowes 1979, Hamidullah & Bowes 1987, Rock 1990) very commonly occur together (either within individual plugs, or in adjacent but separate plugs) in the vicinity of felsic (syenitic, granitic) plutons, and it appears that a similar igneous environment exists at Kirkland Lake. Differentiation of lamprophyric magmas to yield evolved syenitic magmas has been convincingly demonstrated in a large number of recent petrogenetic studies (*e.g.*, Macdonald *et al.* 1986, Thompson & Fowler 1986, Rock 1987a, Rock & Hunter 1987, Fowler 1988, Němec 1988, Leat *et al.* 1988). In the case of the Murdock Creek pluton, a genetic relationship with hornblende is especially well supported, given (1) the spatial and temporal association, (2) similarities in the compositions of ferromagnesian minerals and inferred conditions of crystallization (Rowins *et al.* 1991), and (3) very similar REE and trace-element characteristics (next section).

Given the above arguments, if hornblende is taken to approximate the composition of the most primitive mantle-derived melt, which subsequently differentiated to produce a "residual" syenitic liquid (the hypothesized Murdock Creek parent), then the composition of the fractionate that must be removed from the hornblende can be determined by subtracting PERs, *e.g.*, Mg/La for hornblende minus Mg/La for hypothesized parent. Such PER differences, calculated for each major element and then converted into the composition of the average fractionate, show that the resulting composition is similar to the hornblende itself. This does not imply that the hornblende and Murdock Creek parent had identical compositions. If a large amount of fractionation occurred in deriving the Murdock Creek parent from the hornblende, then even small differences in composition between the hornblende and its fractionate can lead to large differences in composition between the hornblende and its derivative Murdock Creek "parent". For example, a large amount of fractionation is suggested by the extent of change in light REE contents (La, Ce) from hornblende to clinopyroxenite (assuming that this composition possesses LREE abundances closest to Murdock Creek parent magma), which indicates ap-

proximately 65 to 77% crystallization. We note, however, that because the hornblendite is a cumulate rock in some cases, it may represent a more primitive composition than the lamprophyric melt from which it crystallized. Therefore, the actual difference between the composition of the hypothesized Murdock Creek parent magma and its mafic progenitor is probably not as great as is suggested by using the average hornblendite composition. The 65–77% crystallization range should be regarded as a maximum.

*Trace elements*

Abundances of incompatible elements are conveniently summarized on chondrite-normalized (cn) plots (Fig. 6), or spidergrams (Thompson *et al.* 1984). Spidergrams for all Murdock Creek rock types share remarkably similar geochemical features, consistent with the hypothesis that they are cogenetic members of a single fractionation series. Despite the *pre-emplacment* evolution of the magma (leaving a denser mafic cumulate residuum below) and subsequent fractional crystal-

lization, many of the most important trace-element characteristics have been inherited, almost unchanged, from the most primitive rock-units to the most highly evolved. Consistent features of Murdock Creek spidergrams are marked depletions at Nb, Ta, Ti, Th, and U, and enrichments in the other large-ion lithophile elements (*LILE*) and *LREE*. The tectonic implications of this distinctive pattern are addressed later.

Table 2 shows that abundances of the compatible transition metals Sc, V, Cr, Co and Ni are highest in the most mafic rock-types of the intrusion and decrease fairly regularly with increasing SiO<sub>2</sub> content, a trend consistent with the strong partitioning of transition metals into ferromagnesian silicates and Fe–Ti oxides (Gill 1981, Henderson 1982). Hornblendite samples possess the highest Cr (up to 1230 ppm) and Ni (up to 271 ppm) contents of any rock type in the intrusion. This, together with their high Mg contents (maximum 16.1 wt.% MgO), support the contention that they are magmatic cumulates derived from little-fractionated mantle liquids (see discussion on primary compositions in Rhodes 1981, Rock 1987).

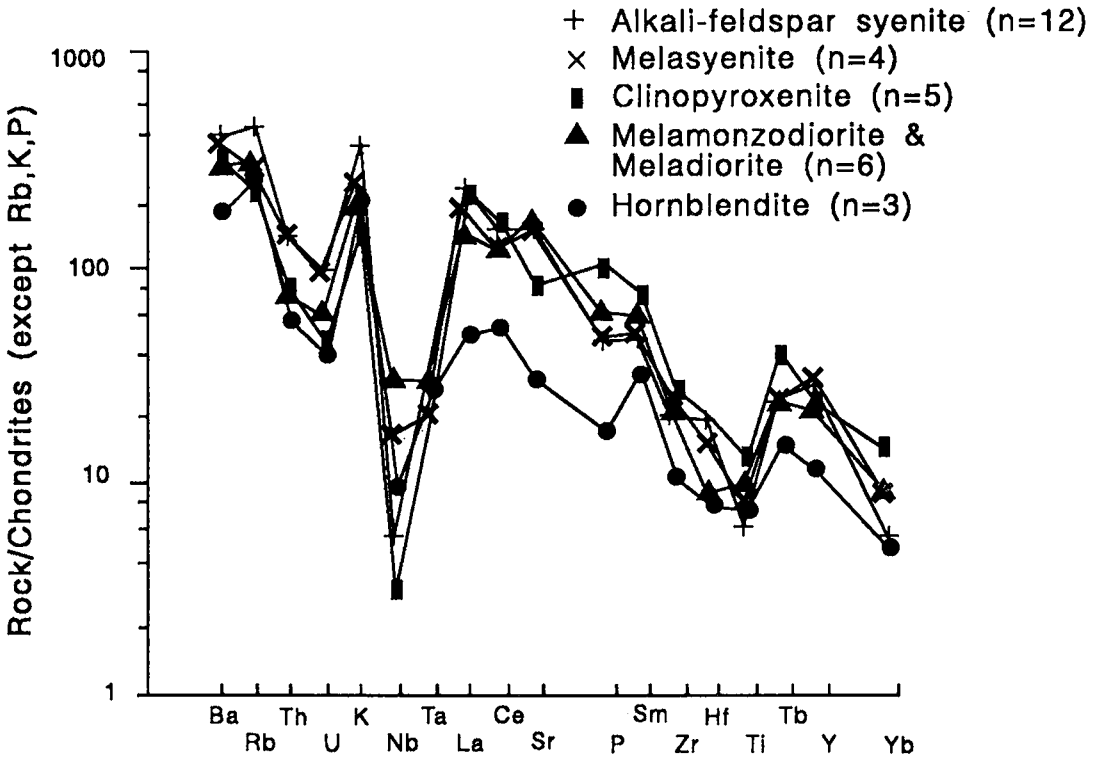


FIG. 6. Chondrite-normalized incompatible element patterns (spidergrams) for rock units of the Murdock Creek pluton. Normalizing factors are from Thompson (1982). Note that Rb, K, and P have been normalized to terrestrial rather than chondritic abundances. Pronounced negative anomalies at Nb, Ta, Ti, and lesser ones at Th and U, and positive anomalies at Ba, Rb, K, Sr, and La are characteristic of all Murdock Creek rock units (n = number of samples averaged).

High-field-strength elements (*HFSE*), such as Nb, Ta, Y, Zr and Hf, lack systematic variation with increasing degrees of magmatic fractionation, probably because of their concentration in accessory mineral phases that remained on the liquidus throughout crystallization: Nb and Ta in Fe–Ti oxides and Ti-silicates (Green 1981, Green & Pearson 1987, Ryerson & Watson 1987), and Zr and Hf in zircon (Watson 1979, Green 1981).

The metallic elements Cu, Zn, As, Mo, Sb, and Au fail to display systematic variation with changing  $\text{SiO}_2$ , and their low concentrations are typical of syenitic rocks (Turekian & Wedepohl 1961, Gerasimovsky 1974, Sorensen 1974). Such low abundances are consistent with the chalcophile nature of these elements (Brownlow 1979) and the uniformly low whole-rock S contents, manifested mineralogically by the scarcity of primary sulfide minerals.

Thorium and U tend to be most abundant in alkali feldspar syenite, in accord with their large ionic radii and resultant incompatibility. The Th/U ratio varies between 3.2 to 7.0, averaging about 4.9, a value just within the magmatic range (Maynard 1983). The relative constancy of the ratio concurs with the maintenance of uniform  $f(\text{O}_2)$  ( $\sim 10^{-12}$  bars) during the pluton's crystallization because of its sensitivity to changes in magmatic  $f(\text{O}_2)$  (Watkins & Haggerty 1967, Barbey & Cuney 1982).

Abundances of Ba, Rb, and Sr are higher than for most rocks of syenitic composition (*cf.* Turekian & Wedepohl 1961, Gerasimovsky 1974). *LILE* abundances generally follow  $\text{K}_2\text{O}$  contents and correlate

positively with  $\text{SiO}_2$ , consistent with their exclusion from clinopyroxene, the main mineral component of the less evolved mafic differentiates. This positive covariation results in fairly constant K/Sr, K/Ba, Rb/Sr, and Rb/Ba ratios, although some deviation is present because of changing proportions of fractionating minerals and the preferential accumulation of one mineral phase over another. The highest K/Rb ratios are found in melasyenite and alkali feldspar syenite (Fig. 7), the opposite of Shaw's (1968) predicted main trend for K/Rb variation during magmatic differentiation. The usual trend of decreasing K/Rb values with progressive differentiation is generally attributed to an increase in the amount of biotite fractionating (or in some cases leucite in volcanic rocks: *e.g.*, Barbieri *et al.* 1968), because biotite preferentially concentrates Rb to a greater degree than other rock-forming minerals (Hanson 1978, Mittlefehldt & Miller 1983). In the case of the Murdock Creek pluton, this reverse trend is best explained as resulting from the *early* crystallization of biotite, which is enriched in Rb relative to K, leaving residual magma impoverished in Rb, followed by later crystallization and accumulation of alkali feldspar crystals depleted in Rb relative to K (the K/Rb ratio of biotite is normally about 1/3 that of coexisting alkali feldspar: Beswick & Eugster 1969). Evidence that alkali feldspar was indeed a primary influence on the K/Rb ratio is shown in Figure 7; two very melanocratic alkali feldspar syenite samples, 88216 and 88217, have K/Rb ratios of 387 and 359, respectively, both values significantly higher than those found

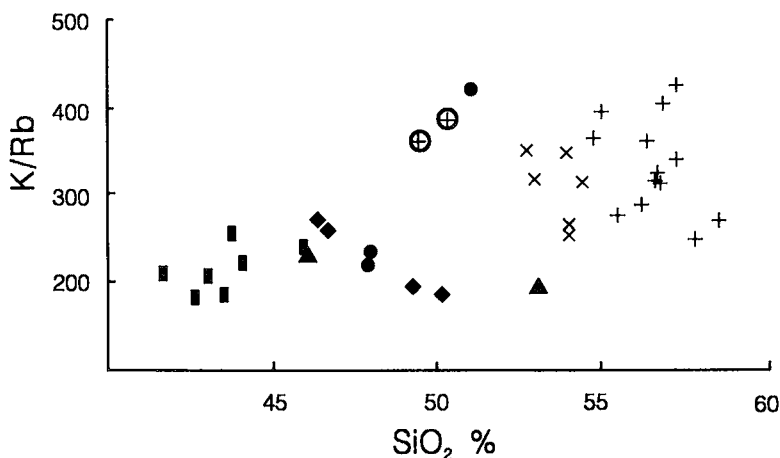


FIG. 7. K/Rb plotted against  $\text{SiO}_2$  (wt.%). The higher K/Rb ratio in melasyenite and alkali feldspar syenite results from early fractionation of biotite and late fractionation and accumulation of alkali feldspar (see text for further discussion). The very melanocratic alkali feldspar syenite samples 88216 and 88217 (circled data points) have respective K/Rb ratios of 387 and 359, both values substantially higher than those found in samples of similar  $\text{SiO}_2$  content but containing much less alkali feldspar, thus demonstrating the large degree of control exerted by alkali feldspar on the ratio. Symbols as in Fig. 3.

in samples of similar SiO<sub>2</sub> content but containing much less alkali feldspar (*e.g.*, meladiorite and melamonzodiorite).

*Rare-earth elements*

Rare-earth-element patterns (Fig. 8) are remarkably similar for all Murdock Creek rock types, with chondrite-normalized La abundances between 150 and 350, and abundances of the heavy rare-earth elements (*HREE*) about 5 to 13 times. Note that hornblendite has a similar *REE* profile but lower chondrite-normalized abundances, consistent with its more primitive character. Alkali feldspar syenite typically displays slight *LREE* enrichment (La content between 70 to 110 ppm) and *HREE* depletion (Yb content 1 or 2 ppm), relative to the less evolved mafic differentiates. These trends result in higher (La/Yb)<sub>cn</sub> ratios (maximum 59) and in *REE* curves with slightly steeper negative slopes. The overall similarity of *REE* spectra, in conjunction with the slight steepening of profiles accompanying progressive crystallization, are consistent with derivation from a common parental magma and a cogenetic relationship through fractional crystallization and mineral accumulation. Clinopyroxene, which dominates the early fractionating assemblage, preferentially incorporates the *HREE* (Schnetzer & Philpotts 1970, Cullers & Graf 1984), whereas biotite and feldspar have only a minor

effect on the *REE* pattern of the melt, except for Eu in the feldspars (Arth & Hanson 1975, Hanson 1980). The negligible or very small negative Eu anomalies in the Murdock Creek *REE* profiles are a common feature of Archean alkaline igneous rocks (Condie 1981, Cullers & Graf 1984). Lack of such anomalies in rocks of the Murdock Creek pluton can be explained by the uniformly high magmatic *f*(O<sub>2</sub>) under which all rock units crystallized. Such conditions would have favored Eu in the trivalent state, thereby preventing its incorporation into the fractionating plagioclase (Drake 1975, Drake & Weill 1975).

*REE* contents in the felsic members of the pluton closely resemble those of other Archean syenites (Fig. 5–17 in Condie 1981). The *REE* patterns for the Murdock Creek rock units also closely match the *REE* profiles of: (1) felsic and augite syenite from within the KLF (Fig. 9), although Murdock Creek rocks tend to possess higher *LREE*<sub>cn</sub> abundances, and (2) trachytic flows and tuffs belonging to the Timiskaming Group, which are suggested to be extrusive equivalents to the Kirkland Lake syenite suite (Cooke & Moorhouse 1969, Ridler 1970). As pointed out by Kerrich & Watson (1984), the higher La abundances of the extrusive rocks (about 400 to 600 times chondrite) are not unexpected owing to the preferential concentration of the *LREE* and other incompatible elements plus volatiles into the explosive extrusive phase of alkaline plutonic–volcanic

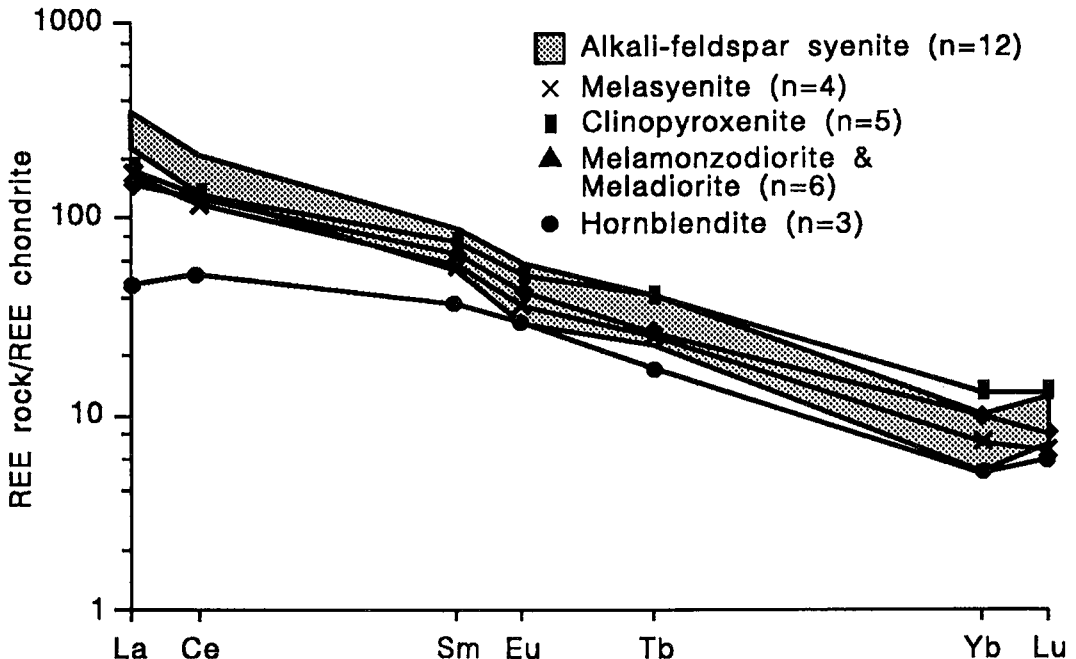


FIG. 8. Average chondrite-normalized *REE* patterns for rock units of the Murdock Creek pluton. Chondrite-normalization factors are those of Haskin *et al.* (1968).

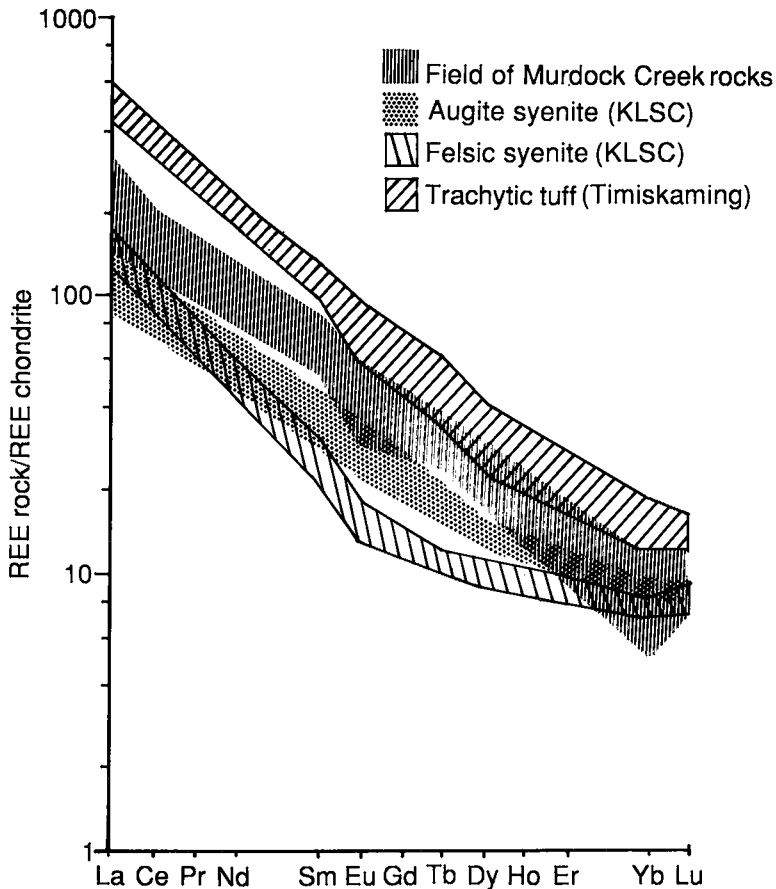


FIG. 9. Chondrite-normalized *REE* fields for rock units of (1) the Murdock Creek pluton (excluding hornblende), (2) augite and felsic syenite from the Kirkland Lake syenite complex (KLSC), and (3) trachytic tuff of the Timiskaming Group. Data for the KLSC and Timiskaming Group rocks from Kerrich & Watson (1984).

complexes (*e.g.*, Carmichael *et al.* 1974). For comparison, the *REE* profiles of hornblende, meladorite, melasyenite, and syenite from the Otto stock, lying just south of the Murdock Creek pluton, are plotted in Figure 10. All these rocks are shown to be *LREE*-enriched and lack Eu anomalies like at Murdock Creek, but felsic members show considerably more variation in *LREE* abundances.

#### CONSANGUINITY OF LATE ARCHEAN POTASSIC ALKALINE IGNEOUS ROCKS IN THE KIRKLAND LAKE AREA

Late Archean (~2680 Ma) composite syenitic plutons within and adjacent to the KLF exhibit many field, petrographic, and mineralogical similarities to one another (comparative descriptions can be found in Burrows

& Hopkins 1923, Thomson 1950, Thomson *et al.* 1950, Lovell 1972, Ploeger & Crockett 1982, Kerrich & Watson 1984, Cameron & Carrigan 1987, Hicks & Hattori 1988, Smith & Sutcliffe 1988, Lévesque 1989, Rowins *et al.* 1989, 1991, Sutcliffe *et al.* 1990). There are, however, surprisingly few published geochemical data available for a direct comparison of the Murdock Creek pluton with other syenitic plutons from this suite, with two exceptions: the Kirkland Lake syenite complex (KLSC) and the Otto stock. The KLSC, within the KLF, has been the subject of numerous studies because this igneous complex hosts most of the gold mineralization. A comparison of the average abundances of major and trace elements in felsic and augite syenite from the KLSC with melasyenite and alkali feldspar syenite from the Murdock Creek pluton reveals a close geochemical resemblance (see samples P1 and P2 in Tables 2 and 3). The KLSC syenite is more felsic, having slightly



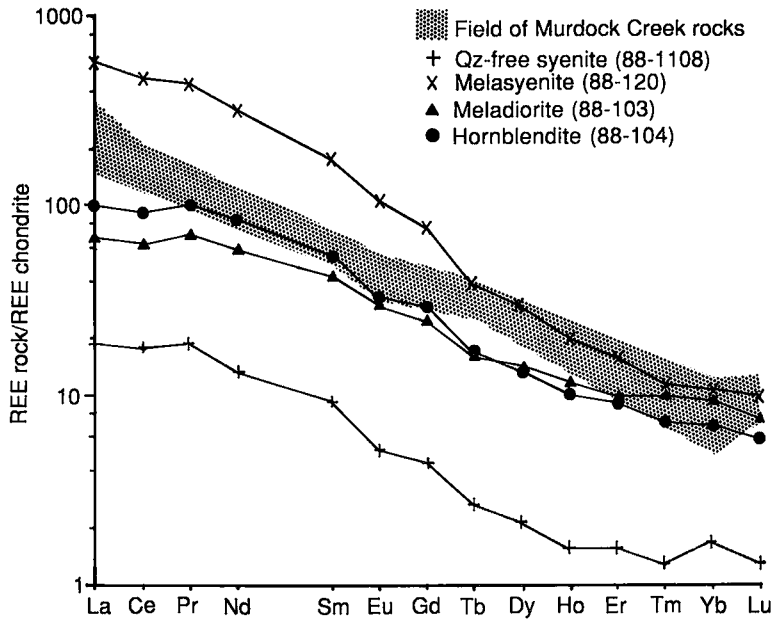


FIG. 10. Chondrite-normalized REE patterns for rock units of the Otto stock. Shaded field includes REE profiles for all Murdock Creek rock types except hornblendite. Data for the Otto stock from Sutcliffe *et al.* (1990).

TABLE 3. INTER-ELEMENT RATIOS OF COMPARABLE ROCK-TYPES FROM THE MURDOCK CREEK PLUTON, OTTO STOCK, AND THE KLSC<sup>a</sup>

ROCK-UNIT <sup>b</sup> # ANALYSES SAMPLE #	MURDOCK CREEK PLUTON				KLSC		OTTO STOCK				AVERAGE SYENITE <sup>c</sup>
	HB	MD	MS	AS	FEL-S	AUG-S	HB	MD	MS	SYEN	
	3	4	6	12	3	3	1	1	1	1	—
	—	—	—	—	P1	P2	88104	88103	88120	881108	—
SiO <sub>2</sub> (wt. %)	48.9 ± 1.8	48.1 ± 1.8	53.6 ± 0.6	56.7 ± 1.0	56.6	48.2	46.1	48.6	51.9	64.2	62.2
K <sub>2</sub> O/Na <sub>2</sub> O	3.2 ± 1.5	1.2 ± 0.1	1.0 ± 0.2	1.5 ± 0.2	1.7	1.8	1.4	0.8	2.9	0.7	1.1
K/Rb	291 ± 111	230 ± 43	311 ± 40	331 ± 60	302	275	216	269	357	712	436
Rb/Sr	0.3 ± 0.2	0.1 ± 0.04	0.1 ± 0.02	0.1 ± 0.03	0.4	0.2	0.2	0.1	0.1	0.2	0.6
Ti/Zr	75 ± 41	49 ± 18	31 ± 9	22 ± 4	14	35	45	49	57	14	7
Zr/Y	4 ± 1	4 ± 1	4 ± 1	3 ± 1	13	7	6	5	3	7	25
Nb/Y	0.2 ± 0.1	0.2 ± 0.2	0.2 ± 0.2	0.1 ± 0.1	0.5	0.3	na	na	na	na	1.8
Cr/Ni	5 ± 1	4 ± 1	4 ± 1	5 ± 1	4	3	5	5	3	2	0.5
(La/Yb) <sub>cn</sub>	10 ± 3	17 ± 10	23 ± 10	45 ± 12	15	15	14	7	52	11	6

na = not analyzed; data sources for the KLSC and the Otto Stock are Kerrich & Watson (1984) and Sutcliffe *et al.* (1990) respectively; ± values = one standard deviation (95 % confidence interval) from calculated average value; <sup>a</sup> KLSC = Kirkiand Lake syenite complex; <sup>b</sup> rock-units as in Table 1; <sup>c</sup> data from Turekian & Wedepohl (1961).

elevated Al<sub>2</sub>O<sub>3</sub> and K<sub>2</sub>O, and lower FeO<sub>T</sub>, MgO, and CaO, relative to the Murdock Creek alkali feldspar syenite. K<sub>2</sub>O/Na<sub>2</sub>O ratios in unaltered KLSC felsic and augite syenite samples typically exceed unity, matching those in Murdock Creek melasyenite and alkali feldspar syenite samples, a clear indication of chemical affinity with ultrapotassic and shoshonitic igneous rocks (*e.g.*, Morrison 1980, Foley *et al.* 1987). Trace-element

abundances and inter-element ratios also are very similar. Comparable rock-types are LILE-enriched, Murdock Creek rocks being slightly more so. The low absolute Zr and Nb contents noted by Kerrich & Watson (1984) in both the felsic and augite syenite of the KLSC also are observed in equivalent syenitic units from the Murdock Creek pluton and result in higher Ti/Zr and much lower Nb/Y ratios than in “normal” syenites

[Table 3; also, see Gerasimovsky (1974), and Floyd & Winchester (1978)]. Furthermore, Zr/Y, K/Rb, and Rb/Sr ratios closely match in equivalent units from the two plutons and are somewhat lower than is the case for most rocks of syenitic composition (Table 3). Cr/Ni ratios in the rock units under consideration also compare favorably, and are higher than in most syenitic rocks. Given the similarity in *REE* patterns (Fig. 9) and the fact that both the Murdock Creek pluton and the KLSC differ from the composition of typical syenitic rocks in precisely the same respects, the case for a consanguineous relationship is very strong.

A comparison of the Otto stock with the Murdock Creek pluton reveals that an intrusive hornblendite unit also is temporally and spatially associated with units of meladiorite, melasyenite and syenite (Sutcliffe *et al.* 1990). These rock types can be either silica-oversaturated or -undersaturated; alkali granite and quartz syenite occur in the central part of the stock, whereas melasyenite in the northern margin may contain up to 40 vol.% nepheline (Currie 1976). Moreover, except for hornblendite, clinopyroxene (aegirine-augite and augite) is usually the dominant primary ferromagnesian silicate (Rowins, unpubl. data; see Table 2 in Sutcliffe *et al.* 1990). Drawing any conclusions from a comparison of major- and trace-element abundances between equivalent units is difficult because only one sample each of hornblendite, meladiorite, melasyenite, and quartz-free syenite was analyzed. Nonetheless, it appears that the Murdock Creek rocks are, in general, more potassic and *LILE*-enriched. The composition of hornblendite and meladiorite closely resembles that of their Murdock Creek counterparts, supporting the case for consanguinity suggested by *REE* patterns (Fig. 10). Melasyenite and quartz-free syenite from the Otto stock also share compositional similarities with Murdock Creek melasyenite and alkali feldspar syenite. Specifically, the low absolute Zr contents noted in KLSC and Murdock Creek rocks also occur in the felsic members of the Otto stock and result in high Ti/Zr ratios (Table 3). Data in Table 3 also show that the Zr/Y, K/Rb, Rb/Sr, and Cr/Ni ratios in Otto melasyenite correlate reasonably well with average Murdock Creek melasyenite, and somewhat less so with the KLSC augite syenite. Zr/Y, K/Rb, Rb/Sr, and Cr/Ni ratios in the quartz-free syenite of the Otto stock do not correlate particularly well with either average Murdock Creek alkali feldspar syenite or KLSC felsic syenite, although precisely how much weight can be attached to these "differences" is uncertain given the limited geochemical data-base.

In summary, it seems that with some exceptions, there is good geochemical evidence for the case of consanguinity among syenitic plutons in the Kirkland Lake area. This is especially true for the Murdock Creek pluton and the KLSC. The geochemical similarity extends to trachytic flows and tuffs belonging to the Timiskaming Group (Fig. 9), and to calc-alkaline lamprophyres, as shown through *REE* patterns and spider-

grams in Ujike (1985), Wyman & Kerrich (1988, 1989), and Ben Othman *et al.* (1990).

#### PETROGENESIS

It is generally accepted that potassic mafic alkaline igneous rocks are products of partial melting of a strongly metasomatized mantle (Lloyd & Bailey 1975, Gupta & Yagi 1980, Bailey 1982, 1987, Lloyd *et al.* 1985, Fitton & Upton 1987, Foley *et al.* 1987, Menzies *et al.* 1987), enriched in K and other incompatible elements, most notably the *LILE*. The metasomatic agent (vapor or silicate melt) may come from the deep mantle or from subducted oceanic ± continental crust and associated sediments (*e.g.*, Armstrong 1991, and references therein).

The evidence presented here suggests that the Murdock Creek pluton has evolved via a two-stage process. In the first stage, primitive mafic alkaline melt (*lamprophyric*), similar in composition to the hornblendite, was produced by partial melting of metasomatically enriched upper mantle. Partial melting was initiated by mantle upwelling during lithosphere extension in response to strike-slip faulting along the KLF (Cameron 1990). This permitted temperatures to exceed the solidus of mantle peridotite, as explained in the model of McKenzie & Bickle (1988) for the generation of basaltic magma. Partial melting, accompanied by uprise of mantle above the carbonate-stable limit (Meen 1987), likely caused the extensive degassing of CO<sub>2</sub> from the mantle (Newton *et al.* 1980, Bailey 1982), which was responsible for widespread carbonatization of rocks within the KLF (*cf.* Groves *et al.* 1988). Early crystallization in the volatile-rich partial melt favored hornblende over clinopyroxene, although small inclusions of primary diopside in cumulus hornblende crystals in hornblendite suggest diopside coprecipitation and the possibility that it preceded amphibole on the liquidus. Separation of hornblende crystals from melt at depth and during ascent (~ 65 to 77% crystallization according to our calculations), achieved through any number of mechanisms of crystal-liquid segregation [see Dawson & Smith (1982) for a review], enabled an anhydrous and relatively buoyant residual melt to separate and rise up the KLF. This pulse of partial melt then underwent extensive fractional crystallization, primarily of clinopyroxene, plagioclase, and alkali feldspar and lesser biotite, magnetite, and apatite, to yield the clinopyroxenite - - alkali feldspar syenite rock series observed. This interpretation finds petrographic support from the textural observation that the interstitial regions between cumulus crystals of hornblende (trapped intercumulus liquid) in hornblendite are composed chiefly of diopside and plagioclase, with lesser biotite and rare alkali feldspar (see Fig. 3f in Rowins *et al.* 1991); recall that such an assemblage of late-crystallizing minerals is identical to that which formed the Murdock Creek pluton.

The coeval relationship between hornblendite and the

much more evolved syenitic members of the pluton might seem unusual but, as noted by Thompson & Fowler (1986), it is not uncommon for a subvolcanic complex of leucocratic rock-types to be surrounded by satellite vents or a radial dike-swarm composed of material from the denser mafic magmas in the lower parts of the system, which were unable to rise through the lighter liquids above them. The hornblendite body at the center of the syenitic Otto stock also is interpreted as a late intrusive phase (Smith & Sutcliffe 1988), and such a scenario as that described above may explain its late appearance in the evolution of that pluton. We note that Sutcliffe *et al.* (1990) also supported a genetic link between hornblendite and the more evolved syenitic units comprising the Otto stock. However, their suggestion that amphibole fractionation and accumulation caused the change in rock compositions from ultramafic to syenitic seems doubtful, given that, like at Murdock Creek, *clinopyroxene* is the dominant primary ferromagnesian silicate in the syenitic units.

#### TECTONIC IMPLICATIONS AND GOLD METALLOGENY

It has recently been proposed by McNeil & Kerrich (1986), Wyman & Kerrich (1988, 1989), Ben Othman *et al.* (1990), Sutcliffe *et al.* (1990), Corfu *et al.* (1991), and Kerrich & Feng (1992) that Archean alkaline igneous rocks in the Superior Province, and, in particular, the potassic alkaline rocks associated with the KLF, formed from subduction-like processes at a destructive plate margin, analogous to plate motions in the Phanerozoic. Cited in support of this interpretation are spidergrams displaying marked depletions in Nb, Ta, Ti and, less commonly, P in conjunction with *LILE* and *LREE* enrichments, a chemical signature typical of shoshonitic and ultrapotassic volcanic rocks formed in modern subduction-related island-arc complexes (Perfit *et al.* 1980, Pearce 1982, Macdonald *et al.* 1985, Thompson & Fowler 1986, Foley *et al.* 1987, Wheller *et al.* 1987, Stolz *et al.* 1988). The patterns are commonly attributed to *LILE* and *LREE* enrichment in a previously Nb-Ta-Ti-depleted mantle source by aqueous fluids or partial melts driven from subducted oceanic crust, the enriched elements being those tending to be mobilized by aqueous fluids.

Despite the tectonic inferences drawn from these geochemical features, there are several reasons why subduction processes may not have been directly involved in the genesis of Archean alkaline rocks at Kirkland Lake. It is now widely established that *LILE* and *LREE* enrichment in the upper mantle may result exclusively from intramantle metasomatism regardless of tectonic setting (*e.g.*, Foden & Varne 1980, Arculus & Johnson 1981, Edgar 1983, Varne & Foden 1986). Furthermore, the cause of the depletion in Ti-group elements in subduction-related magmas is controversial and may not be related to the *LILE* and *LREE* enrichment process in the mantle (*i.e.*, a chemical decoupling of *LILE* and

*HFSE* occurs: Stern & Ito 1983, Foley & Wheller 1990). Briefly, depletion in island-arc-related rocks is usually attributed to either (1) the presence of Ti-group elements in a residual titanate or perhaps a Fe-Ti oxide phase (into which Nb and Ta partition) after partial melting in the mantle (Saunders *et al.* 1980, Green 1981, Morris & Hart 1983, Brophy & Marsh 1986), or (2) an inherent property of the source region, brought about by a previous episode of melt extraction, zone refining or equilibration with a percolating melt or fluid. The former hypothesis was rejected by Ryerson & Watson (1987) on the basis of experimental studies showing that Ti saturation was unlikely over a range of physical conditions in melt compositions varying from basaltic to rhyolitic. Smalley *et al.* (1983) and Briqueu *et al.* (1984) also have suggested that Nb and Ta anomalies in some orogenic magmas are derived independently from a Ti-rich phase. Along the same lines, the negative Ti, Nb, and Ta anomalies in spidergrams are seen to variable extents in continental ultrapotassic rocks (lamproites) and less incompatible-element-enriched continental rocks such as flood basalts and related intrusions (Thompson *et al.* 1984, Foley & Wheller 1990). Indeed, Foley & Wheller (1990) have shown that continental ultrapotassic rocks (lamproites) possess a gradation of *HFSE* abundances that overlap the characteristics of island-arc potassic rocks. Clearly, whatever the mechanism (or mechanisms) responsible for the depletion in Ti-group elements, it must be able to operate in circumstances other than subduction zones. If a "residual Ti-rich accessory phase" model is invoked to explain the pronounced depletions in Ti-group elements in Murdock Creek rocks, then titanite seems the most likely candidate, given the oxidized nature of the pluton's source region in the mantle (Rowins *et al.* 1991) and the relatively shallow level of mantle fusion (due to lithosphere extension and mantle upwelling), conditions that favor titanite stability (Hellman & Green 1979, Green 1980, 1981). Magnetite also is a possible residual phase, but its ability to accommodate Nb, Ti, and Ta is much lower than that of titanite (Green & Pearson 1987).

Some of the most compelling evidence against subduction processes to account for the geochemistry of the Murdock Creek suite comes from the work of Foley *et al.* (1987). They divided ultrapotassic mafic rocks into three principal groups according to geochemistry and tectonic setting. Group-I rocks (lamproites), characterized by low Ca, Na and Al, and high *LILE* contents, and minor or negligible depletions in the *HFSE* on spidergrams, occur principally in continental environments. Group-II rocks (kamafugites), with low Si, Al, and Na, and high Ca and *LILE* (notably Sr) contents, are characteristic of rift zones (*e.g.*, East African rift valley). Group-III rocks occur in orogenic, island-arc environments and have much higher Al contents than the other two groups. Other distinguishing features of this group include high Ca, K, and low Mg and *HFSE* contents. Using the criteria of Foley *et al.*, two biotite clinopyroxene-

nite samples (89221 and 89296) and two hornblendite samples (88329 and 89509) from the Murdock Creek intrusion are ultrapotassic *sensu stricto* ( $K_2O/Na_2O \geq 2$ ,  $K_2O$  and  $MgO \geq 3$  wt.%). On the key major-element discriminant diagrams,  $CaO$  versus  $Al_2O_3$ ,  $CaO$  versus  $MgO$ , and  $Al_2O_3$  versus  $Na_2O$ , these rocks plot exclusively within the rift-related group-II field. This group-II assignment also holds for the other clinopyroxenite and hornblendite samples, which are not ultrapotassic *sensu stricto* but clearly members of the same rock unit. The large Nb, Ta, and Ti troughs in the Murdock Creek spidergrams (Fig. 6) might seem to suggest an association with subduction-related group-III rocks of Foley *et al.*; however, as discussed, depletion of these elements is by no means restricted to subduction zones, a point also made by Foley *et al.* given the observed depletion in Ti-group elements in spidergrams of group-II rocks from the San Venanzo and Cupaello occurrences in Italy.

Field evidence of extensive carbonatization along the KLF suggests a  $CO_2$ -rich melting environment, which supports the classification of the Murdock Creek ultrapotassic rocks as belonging to group II, since complexing with  $CO_2$  readily explains this group's distinctly high Ca and Sr contents. The presence of a free  $CO_2$  fluid or vapor phase is consistent with mantle enrichment under relatively oxidizing conditions (Cameron 1988), as implied by the intrinsically oxidized nature of syenitic plutons in the Kirkland Lake area (Cameron & Carrigan 1987, Rowins *et al.* 1989, 1991) and oxidized ore fluids rising in the KLF (Cameron & Hattori 1987).

Preliminary Sr- and Nd-isotope data on clinopyroxene samples from several syenitic plutons and associated calc-alkaline lamprophyres in the Kirkland Lake area (Hattori & Hart 1990), including the Murdock Creek pluton, also argue against the involvement of metasomatic fluids or melts from a subducting slab. Although the pyroxene shows *LILE* and *LREE* enrichment and *HFSE* depletion, mimicking whole-rock compositions, they have low initial  $^{87}Sr/^{86}Sr$  (0.7009 to 0.7016) and high positive  $\epsilon_{Nd}$  values (+0.8 to +3.0), indicating derivation from a "depleted" mantle source. This "depleted" mantle source must have subsequently undergone *LILE* and *LREE* enrichment without the addition of *HFSE*. Metasomatic fluids or melts from a downgoing slab could have re-introduced *LREE* and *LILE*, but would also have added radiogenic Sr and Nd, raising  $^{87}Sr/^{86}Sr$  and lowering  $^{143}Nd/^{144}Nd$ .

Syenitic plutons within the KLF are elongate in plan view; for example, the KLSC that hosts the main ore-zone at Kirkland Lake has a length-to-width ratio of approximately 6:1. Cameron (1990) has proposed that these plutons were intruded during extension within a strike-slip basin at the western termination of the major Cadillac - Larder Lake fault, which strikes east-west. The orientation of the basin and of the plutons corresponds to that for sinistral transtension (*e.g.*, Sanderson & Marchini 1984). The strike-slip movement may be

related to accretion of the Superior Province (Corfu & Stott 1986, Percival & Williams 1989), and it is possible that subduction processes, during development of the greenstone belts, caused enrichment in some regions of the mantle. However, the isotopic evidence cited above, together with the fact that the episode of partial melting leading to formation of the Murdock Creek magma postdated greenstone-belt volcanism, regional metamorphism, and initial Timiskaming sedimentation, once again mitigate against the involvement of slab components or the existence of an older "fossil" subduction zone beneath the potassic alkaline rocks in the Kirkland Lake area.

The relationship of the alkaline magmatism to gold derives from the association with  $CO_2$  and with the extensional tectonic environment.  $CO_2$  was invariably an important component of the ore fluids for Archean lode-gold deposits (*e.g.*, Ho 1987). At Kirkland Lake, this association is highlighted by the pervasive carbonatization of much of the KLF. Deep,  $CO_2$ -rich fluids are relatively oxidizing and favor the extraction of  $Au^0$  from rocks as  $Au^+$  and the dissolution of sulfide, which acts as a ligand to complex  $Au^+$  (Cameron 1988). Liberation of  $CO_2$  from the mantle is linked to the processes of metasomatism and partial melting that generated the alkaline magmas.

## CONCLUSIONS

Geochemical modeling, including analysis using Pearce element ratios, and systematic trace-element variation over the compositional continuum of rock types constituting the Murdock Creek pluton, indicate a fractional crystallization model, with incompatible elements (*LILE* and *LREE*) and the ratios K/Rb, La/Yb increasing, compatible elements (Sc, V, Cr, Co, Ni) decreasing, and coherent ratios such as Th/U, Zr/Hf, Cr/Ni, and the *LILE* ratios K/Sr, K/Ba, Rb/Sr and Rb/Ba remaining relatively constant throughout crystallization. The increasing K/Rb ratio is explained in terms of changing proportions of crystallizing phases, with different distribution-coefficients for K and Rb. The control of primary mineralogy over element distribution is well illustrated in chemical variation diagrams, *REE* patterns, and plots of chondrite-normalized incompatible elements (spidergrams). Modeling using Pearce element ratios has revealed that the mafic marginal rocks were present as crystal mushes with cumulate-like chemistry (*i.e.*, excess clinopyroxene relative to the parental melt), whereas the later-crystallizing alkali feldspar syenite forming the core of the pluton is depleted in clinopyroxene but enriched in alkali feldspar, the result of having formed from chemically evolved liquid physically expelled from the interstices between earlier-formed crystals accreted along the walls of the magma chamber. The recognition of mineral accumulation in granitic or syenitic rocks is difficult to discern petrographically, unlike the case of layered mafic complexes, where

igneous sedimentary structures and distinct cumulus-intercumulus textural relationships are common (e.g., McCarthy & Robb 1978, Wager & Brown 1968). This study not only demonstrates the effectiveness of PER diagrams in identifying the mechanism of igneous differentiation responsible for pluton evolution, but also highlights the ability of PER to recognize crystal accumulation and depletion in syenitic rock suites.

Consideration of all the geochemical data leads to a petrogenetic model in which (1) a source region in the mantle, which may already be depleted in Ti-group elements, is modified by deeper-mantle-derived volatiles or melts rich in the *LILE* and *LREE*; (2) partial melting, initiated by mantle upwelling *via* lithosphere extension at a major strike-slip termination (pull-apart basins), produced a liquid of potassic mafic alkaline or *lamprophyric* character, and (3) separation of early-crystallizing hornblende occurred at depth or during ascent (or both), permitting anhydrous and buoyant residual melt to ascend to mid-crustal levels *via* the KLF, eventually generating the evolved Murdock Creek rock compositions principally by crystal fractionation of clinopyroxene, plagioclase, alkali feldspar, and lesser biotite. Magnetite, titanite, and apatite were the most common accessory phases in the primary assemblage.

A comparison of the petrographic, mineralogical, and geochemical characteristics of the Murdock Creek pluton, immediately outside the KLF, reveals many similarities with the alkaline intrusive and extrusive rocks within the KLF. A consanguineous relationship with the Otto stock, situated well outside the KLF, also appears likely. We suggest that all were derived by repetitive episodes of small degrees of partial melting of the same metasomatically *LILE*- and *LREE*-enriched source in the upper mantle, resulting in numerous pulses of partial melt (syenitic plutons) of slightly variable major- and trace-element character; yet their overall geochemical coherence is not lost.

Major-element geochemistry of ultrapotassic rocks from the Murdock Creek pluton is more compatible with formation in a rift environment rather than a subduction setting, as recently proposed for the genesis of these rocks in the Kirkland Lake region. The marked depletions in Nb, Ta, and Ti in the Murdock Creek rocks, although a common feature of subduction-related island-arc magmas, are not unique to this environment, and in fact are known in rocks from widely differing tectonic environments in the Phanerozoic.

Gold mineralization in the Kirkland Lake district is the result of several interlinked processes. Strike-slip faulting and localized extension of the lithosphere caused upwelling of deep mantle and partial melting of carbonated peridotite to yield alkaline magmas and CO<sub>2</sub>. Relatively oxidized CO<sub>2</sub>-rich fluid rose up the KLF, and extracted Au<sup>0</sup> from the shear-zone rocks as Au<sup>+</sup>, which was then transported as a soluble sulfide complex. Gold-bearing fluid was later expelled during a compres-

sional phase that followed extension, and the gold deposited along reverse faults within the KLF.

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