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PERALUMINOUS PLUTONISM: NATURE AND ORIGIN OF THE MOLY MAY LEUCOGRANITE AND ITS COAST PLUTONIC COMPLEX GRANITIC HOST-ROCKS, NORTHWESTERN BRITISH COLUMBIA

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Abstract

The Moly May pluton of northwestern British Columbia is one of several small molybdenite-bearing granitic complexes of Cenozoic age known as the Alice Arm intrusions. These were intruded into the eastern margin of the Coast Plutonic Complex (CPC) and the Bowser Lake Group (greenschist-grade metasedimentary rocks). This pluton consists of three mappable units (aplitic garnet–muscovite leucogranite, medium-grained leucogranite, and coarse-grained to pegmatitic biotite granite), in addition to a molybdenite-mineralized leucogranitic variety. The Moly May leucogranites (MML) and the CPC granite–granodiorite host rocks are chemically distinguished by strikingly different geochemical trends, which indicate that the two granitic suites are not genetically related. The MML is exclusively peraluminous (molar A/CNK in the range 1.00 to 1.78), whereas the CPC rocks are metaluminous to weakly peraluminous (molar A/CNK in the range 0.84 to 1.06). The MML is significantly enriched in K, Rb, Nb, Y, and depleted in Mg, Ca, Na, Ba, Sr, and Zr compared to the CPC. The *REE* patterns of the MML are fractionated [$(La/Yb)_N$ = 23] and show a minor negative Eu anomaly, but those of the garnet-bearing leucogranitic variety lack the *REE* fractionation [$(La/Yb)_N$ = 2], and have a significant negative Eu anomaly. The mineralized leucogranite is strongly depleted in the *LREE*, K, Rb, and Nb; these elements are interpreted to have been leached out at subsolidus temperatures by mineralizing hydrothermal solutions, which led to deposition of molybdenite. Compared to the *REE* patterns of the MML, those of the CPC are slightly more fractionated [$(La/Yb)_N$ = 27], and lack a Eu anomaly. The MML was developed in association with an Eocene transtensional tectonic regime. Chemical features suggest that the MML is of a sedimentary origin. Results of geochemical modeling show that the leucogranitic magma was produced by a large degree (65%) of batch partial melting of a metasedimentary protolith.

Keywords: Moly May leucogranite, Coast Plutonic Complex, peraluminous, garnet, geochemistry, molybdenite, rare-earth elements, petrogenetic model, British Columbia.

Sommaire

Le pluton de Moly May, dans le secteur nord-ouest de la Colombie-Britannique, fait partie d'un groupe de petits complexes intrusifs (dits de Alice Arm) d'âge cénozoïque et minéralisés en molybdénite. Ils ont été mis en place dans la bordure orientale du Complexe Plutonique Côtier et dans les roches métasédimentaires du Groupe de Bowser Lake (faciès schistes verts). Le pluton contient trois unités distinctes (leucogranite aplitique à grenat + muscovite, leucogranite à grains moyens, et granite à biotite à grains grossiers, voire pegmatitique), ainsi que la variété de leucogranite à molybdénite. Les leucogranites du pluton de Moly May (MML) et l'encaissant granitique et granodioritique du Complexe Plutonique Côtier (CPC) sont chimiquement distincts, ce qui laisse supposer qu'ils ne sont pas génétiquement liés. La suite MML est exclusivement hyperalumineuse (rapport A/CNK molaire entre 1.00 et 1.78), tandis que la suite CPC est métalumineuse à légèrement hyperalumineuse (rapport A/CNK entre 0.84 et 1.06). La suite MML est enrichie en K, Rb, Nb, Y, et appauvrie en Mg, Ca, Na, Ba, Sr, et Zr comparée à la suite CPC. Les spectres de terres rares de la suite MML sont fractionnés [$(La/Yb)_N$ = 23] et font preuve d'une légère anomalie négative en Eu, tandis que les leucogranites à grenat ne sont pas fractionnés [$(La/Yb)_N$ = 2] et n'ont pas d'anomalie négative importante en Eu. Les échantillons minéralisés sont fortement appauvris en terres rares légères, K, Rb, et Nb; ces éléments auraient été lessivés lors de la minéralisation hydrothermale à une température subsolidus. En comparaison des spectres de terres rares dans les leucogranites, ceux des roches-hôtes (suite CPC) sont légèrement plus fractionnés [$(La/Yb)_N$ = 27] et dépourvus d'une anomalie en Eu. La suite MML s'est développée en association avec un régime tectonique de transtension à l'époque éocène. Elle aurait un antécédant sédimentaire. Un modèle géochimique fondé sur les terres rares montre que le magma leucogranitique est issu d'une fusion partielle massive (65%) d'un protolithe métasédimentaire.

(Traduit par la Rédaction)

Mots-clés: leucogranite de Moly May, Complexe Plutonique Côtier, hyperalumineux, grenat, géochimie, molybdénite, terres rares, modèle pétrogénétique, Colombie-Britannique.

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Introduction

Numerous investigations have been carried out to document the nature, petrological and geochemical characteristics, tectonic regimes, style of associated mineralization, and origin of peraluminous (molar A/CNK > 1.0; Shand 1947), or S-type (molar A/CNK > 1.1; Chappell & White 1974) granites (*e.g.*, Barker *et al.* 1992, Clarke *et al.* 1993, Maas *et al.* 1997). An example of such peraluminous granite type is afforded by the Moly May pluton (latitude 55º 21' N, longitude 129º 48' W), located some 130 km north of Prince Rupert in northwestern British Columbia (Fig. 1). It is one of several molybdenite-mineralized, locally peraluminous granitic complexes known as the Alice Arm intrusions (Woodcock & Carter 1976). The general geology and style of mineralization of these intrusions, including the Moly May leucogranite (MML), have been studied in a general way; the aim of this first detailed investigation of the MML is to delineate its main petrological and geochemical features, to investigate the interrelations between it and the host granitic suite of the Coast Plutonic Complex (CPC), and to discuss the source and origin of the magma.

The Geological Context

The Eocene Moly May felsic pluton, along with the other Alice Arm intrusions (48–53 Ma, K–Ar ages; Woodcock & Carter 1976), were forcefully intruded into the eastern margin of the CPC, and Jurassic metasedimentary rocks. These units are described in turn.

The Moly May pluton

The Moly May pluton (48 Ma; K–Ar age, Woodcock & Carter 1976) is mineralogically and texturally

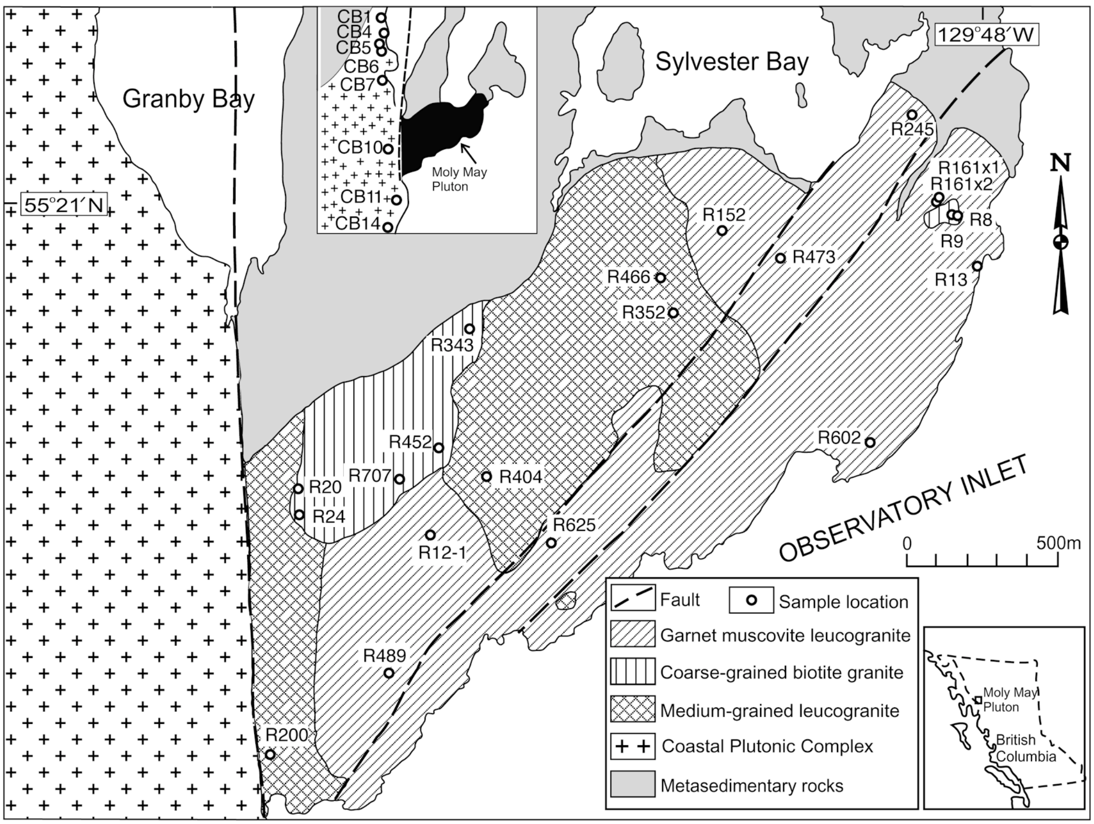

FIG. 1. Simplified geological map of the Moly May pluton and its host rocks (based on maps of Carter & Grove 1972, Woodcock & Carter 1976, and Evenchick & Holm 1997). Location of the MML samples are given on the main map, the mineralized zones occur at the location of the mineralized samples (sample R8 and R12–1), and location of the CPC samples are shown in the upper inset map. Lower inset is a location map for the area of study.

distinct from the proximal CPC rocks. A fault contact along the N–S-oriented Big Dam fault occurs between the two granitic bodies (Fig. 1). In addition to a molybdenite-mineralized leucogranitic variety, three mappable units of white, mostly leucogranitic rocks (Fig. 1) are recognized within the Moly May pluton: 1) aplitic garnet–muscovite leucogranite, the most abundant variety, 2) medium-grained leucogranite, containing muscovite but with very little or no garnet, and 3) coarse-grained to pegmatitic biotite granite facies, containing randomly oriented, large flakes of biotite. Localized pegmatitic pods are characterized by biotite enrichment. The presence of abundant miarolitic cavities and vugs, along with the pegmatitic pods, are taken to represent local saturation in H_2O near the exposed roof of the Moly May pluton, and a high level of emplacement. Rocks of the Moly May pluton vary in texture from fine-grained, equigranular, aplitic leucogranite, to inequigranular, medium- to coarse-grained, and occasionally pegmatitic varieties. Highly localized molybdenite-mineralized showings (1 to 15 m across), with up to 12.7% MoS_2, are present. Gossans and highly stained rocks occur in various parts of the pluton. Mineralization occurs in the form of disseminated molybdenite grains and rosettes (1–5 mm across). Molybdenite and gold-bearing pyrite (unpubl. data) are rarely present in some late-stage biotite-rich pegmatitic masses. Molybdenite also lines miarolitic cavities, and thus presumably deposited from the fluid phase.

The northeastern part of the Moly May pluton contains metasedimentary xenoliths and roof pendants; the xenoliths are highly deformed, folded, and contain quartzofeldspathic ptygmatic veins. The pluton is bordered to the west by the Big Dam fault (Evenchick & Holm 1997), cross-cut by two main NE-trending faults, and some peripheral parts of the pluton are densely fractured. Quartz stockworks occur locally along NE- and NW-trending fracture systems, but mineralization is only rarely associated with the stockwork zones. Stockwork quartz veinlets are commonly 0.5 to 1 cm wide, but reach widths of 0.5 m. Although most of the pluton is relatively fresh, hydrothermal alteration is common near areas of mineralization. The latter may include small gossans (0.5 – 3 m across) that are rarely rimmed by a thin layer of greisen (mostly sericitized rocks) formed by hydrothermal alteration. Some gossans are located along fault planes.

The Coast Plutonic Complex (CPC)

The CPC occurs as an elongate (1760 km) belt, and extends from the British Columbia – Washington border to southeastern Alaska and Yukon Territory (Roddick & Hutchison 1974). It is made up of numerous plutons, and represents the largest continental-margin batholith in the world (Barker *et al.* 1986). Several studies have been carried out on the CPC, including its exposures in the Prince Rupert region, and in southeastern Alaska (Hudson *et al.* 1979, Monger *et al.* 1982, Barker *et al.* 1986). The CPC is dominated by plutonic rocks that border a core consisting of high-grade granitic gneisses and migmatites of the Central Gneiss Complex. The plutonic rocks range in composition from gabbro, quartz monzonite, quartz diorite, to granodiorite and granite, with the more felsic varieties more abundant at the eastern part of the CPC (Roddick & Hutchison 1974, Hutchison 1982, Douglas 1986, Woodsworth *et al.* 1991). In the vicinity of the Moly May pluton, emplacement of the granodioritic complexes of the eastern margin of the CPC have produced a hornfels aureole in the metasedimentary rocks, up to 1.5 km outward from the contact (Steininger 1985). In the study area, the CPC host rocks are generally medium- to very coarse-grained, pink to gray, locally weakly foliated, mostly porphyritic granitic to granodioritic rocks. Abundant biotite, and minor chloritized amphibole are the main ferromagnesian minerals present; the CPC rocks contain no muscovite or garnet.

The metasedimentary rocks

The metasedimentary rocks of the region were described by Tipper & Richards (1976) as a thick and widespread assemblage including quartzofeldspathic greywacke, argillite, and siltstone of the Hazelton Group, deposited in Early and Middle Jurassic. Evenchick *et al.* (1997) showed that the metasedimentary rocks that host the MML belong to the Middle and Upper Jurassic Bowser Lake Group, and were regionally metamorphosed to the greenschist facies (Steininger 1985). As a result of the intrusion of the Moly May pluton, the metasedimentary rocks were arched and domed around it, and an andalusite–cordierite contact-metamorphic aureole was developed.

PETROGRAPHY

The modal proportion and size of the mineral constituents in the textural varieties of the MML, the CPC, and the metasedimentary rocks are summarized in Table 1. Rocks of the MML consist essentially of subequal proportions of quartz, K-feldspar, and albite, with variable contents of muscovite, garnet, and biotite. Quartz is generally strained, as indicated by the common presence of undulatory extinction. The K-feldspar is typically perthitic. Muscovite is a common mineral in most of the MML varieties. Biotite is also present in most samples, but is only common in the coarse-grained biotite granite, where it occurs as large, well-developed, euhedral, strongly pleochroic reddish brown flakes, typical of biotite in peraluminous rocks (Lalonde 1986, Abdel-Rahman 1994). Pale pinkish garnet is ubiquitous in most samples, and occurs either as minute, subhedral to euhedral grains (Fig. 2a) in aplitic varieties, or as large, mostly euhedral grains in medium-grained and in molybdenite-mineralized leucogranites, commonly oc-

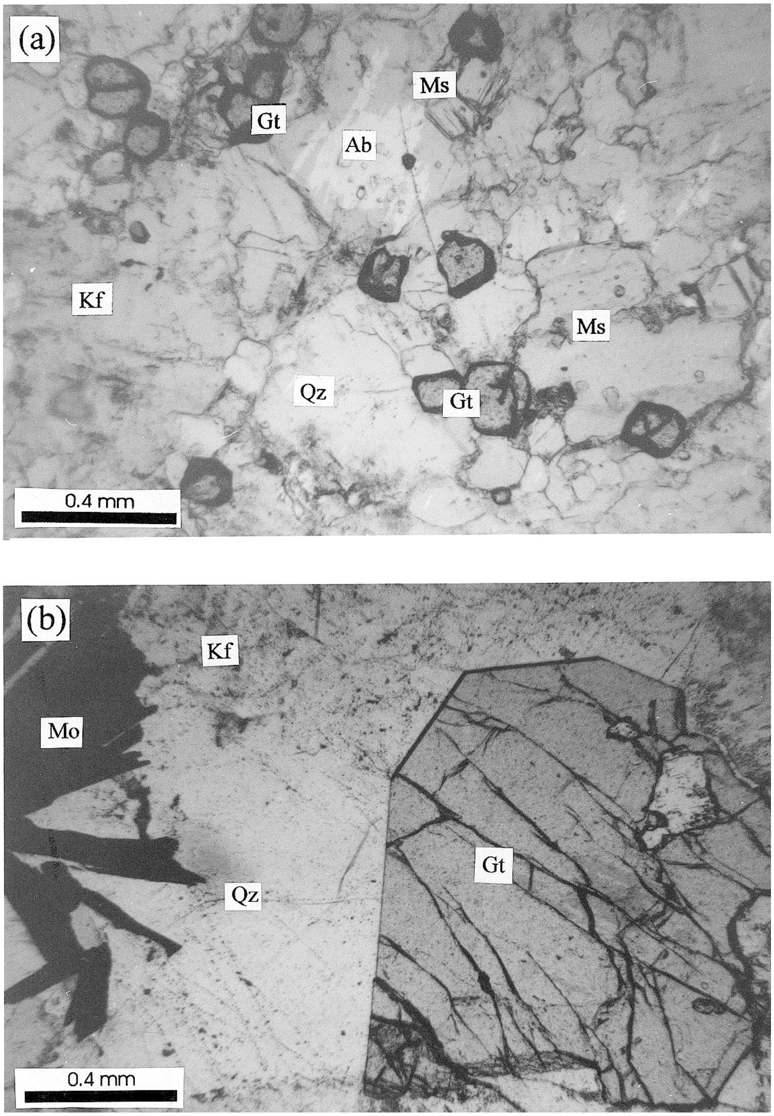

FIG. 2. Photomicrographs showing (a) subhedral to euhedral, small (0.15–0.2 mm across) garnet (Gt) crystals occurring within fine-grained, aplitic, garnet–muscovite leucogranite: Ab, albite; Kf, K-feldspar; Ms, muscovite; Qz, quartz. (b) A large, euhedral, fractured crystal of garnet (Gt) and rosettes of molybdenite (Mo) in molybdenite-mineralized Moly May leucogranite; other mineral abbreviations as in (a). The length of the scale bar on each of the two photomicrographs is 0.4 mm.

curring in association with flakes and rosettes of molybdenite (Fig. 2b). Yellowish monazite, metamict zircon, and rare apatite, as well as Fe–Ti oxides and pyrite, occur as accessory and opaque phases.

The CPC granite and granodiorite are texturally medium- to coarse-grained, inequigranular, hypidiomorphic rocks, consisting essentially of variable contents of quartz, plagioclase, K-feldspar, biotite and chloritized amphibole (Table 1). These rocks are largely porphyritic, and some contain a graphic texture. Quartz occurs as individual grains, as large masses consisting of anhedral subgrains, or as elongate aligned masses defining a weakly developed fabric. Plagioclase ($An_{12–35}$) is mostly strongly zoned, and is rarely weakly

TABLE 1. PETROGRAPHIC DATA FOR THE MOLY MAY PLUTON, NORTHWESTERN BRITISH COLUMBIA, AND ITS HOST ROCKS

Rock unit	Moly May granitic rocks				CPC granitic rocks		Sed. rocks
Type	GML	ML	CBG	MMG	GR	GD	SED
Quartz	30, 0.1–0.3	29, 0.5–2.0	30, 1.5–3.2	32, 0.2–2.0	29, 1.0–3.0	26, 1.0–3.0	30, 0.2–1.0
K-feldspar	30, 0.1–0.3	32, 0.5–2.0	30, 1.5–3.2	20, 0.2–2.0	28, 1.0–4.0	24, 1.0–4.0	20, 0.2–2.0
Plagioclase	29, 0.1–0.3	29, 0.5–2.0	30, 1.5–3.2	28, 0.2–2.0	32, 1.0–4.0	36, 1.0–4.0	25, 0.2–2.0
Muscovite	6, 0.1–0.4	4, 0.6–2.0	1, 1.0–3.0	4, 0.1–1.5	–	–	10, 0.2–1.2
Garnet	3, 0.1–0.2	2, 0.2–0.5	–	4, 0.2–2.0	–	–	–
Biotite	1, 0.1–0.2	3, 0.2–0.5	8, 2.0–5.0	1, 0.2–0.8	8, 2.0–4.0	5.5, 2.0–4.0	15, 0.2–1.2
Hornblende	–	–	–	–	2, 1.0–3.0	6, 2.0–4.0	–
Molybdenite	–	–	–	8, 0.4–5.0	–	–	–
Monazite	0.3	0.3	0.3	0.3	–	–	–
Zircon	0.1	0.1	0.1	0.1	0.5	0.5	–
Apatite	–	–	0.1	–	0.5	0.5	–
Fe–Ti oxides	0.1	0.1	0.5	0.5	1.0	1.5	–
Pyrite	0.2	0.2	0.5	1.0	–	–	–

Note that the first number represents the volume percent of the mineral phase (determined by visual inspection); listed second is the range in size of the grains in millimeters. Petrographic types recognized in the Moly May pluton are garnet–muscovite leucogranite (GML), medium-grained leucogranite (ML), coarse-grained biotite granite (CBG), and Mo-mineralized leucogranite (MMG). Granite (GR), and granodiorite (GD) are the two petrographic types of the Coast Plutonic Complex (CPC). SED: metasedimentary rocks.

altered. K-feldspar shows well-developed perthite, and represents a phenocryst phase in the porphyritic varieties. In some samples, biotite is weakly chloritized. Moderately to strongly chloritized greenish hornblende is present in most samples.

The metasedimentary rocks consist of fine-grained biotite – muscovite – quartz – feldspar schist, containing large euhedral muscovite porphyroblasts occurring within moderately to strongly foliated matrix. The feldspars, quartz, and muscovite occur both as groundmass materials and as porphyroblasts. Abundant felted brownish biotite defines a crude foliation.

Analytical Techniques

The rocks were ground using a tungsten carbide crusher and pulverizer. Concentrations of the major elements were determined on fused lithium metaborate discs by X-ray-fluorescence spectrometry (Philips PW1400 spectrometer, McGill University) using a Rh tube operated at 40 kV and 70 mA. Loss on ignition (LOI) was determined by heating powdered samples for 50 minutes at 1000°C. Concentrations of Ba, Rb, Sr, Zr, Y, Nb, U, Th, Pb and V were determined on pressed pellets by X-ray fluorescence (operating conditions: Rh radiation, 70 kV, 40 mA). The analytical precision, as calculated from 20 replicate analyses of one sample, is better than 1% for most major elements and better than 5% for most trace elements. Concentrations of the rare-earth elements, as well as of Hf and Ta, were determined by induced coupled plasma – mass spectrometry (ICP–MS) at Memorial University of Newfoundland. Full details of the procedure are given in Longerich *et al.* (1990). Detection limits and reagent blanks are generally about 10% of chondrite values.

Geochemistry

Bulk composition of the rocks

The chemical composition of 17 representative samples of the Moly May granite, two samples of the Moly May molybdenite-mineralized granite, eight samples representing the CPC host rocks, and two samples of the metasedimentary rocks, is presented in Table 2. The Moly May rocks exhibit a wide range of silica (67.2 to 79.2 wt.% SiO_2). The average composition of the MML, compared to that of the CPC rocks, indicates a significant enrichment in K, Rb, Nb, Y, and depletion in Mg, Ca, Na, Ba, Sr, and Zr. As illustrated in Figure 3, the two granitic suites exhibit two sets of strikingly different major- and trace-element trends. In the MML, the concentrations of CaO, Sr, Al_2O_3 and FeO (both not shown) decrease gradually with increasing silica, whereas those of (Na_2O + K_2O) and Y (both not shown) increase, and those of Rb and Nb do not show much variation (Fig. 3). In the CPC granite, the concentrations of CaO, Sr, Al_2O_3 and FeO (both not shown) decrease gradually with increasing silica, whereas those of (Na_2O + K_2O; not shown) increase with increasing silica, and those of Y (not shown), Rb, and Nb do not show much variation. The data suggest that the two granitic suites are chemically distinct, and are probably not genetically related.

TABLE 2. MAJOR- AND TRACE-ELEMENT COMPOSITION OF THE MOLY MAY LEUCOGRANITE, HIGHLY MINERALIZED SAMPLES, AND THE HOST ROCKS, REPRESENTED BY THE COAST PLUTONIC COMPLEX AND METASEDIMENTARY ROCKS

Rock unit	Moly May leucogranite															
Sample	R9	R13	R20	R24	R152	R200	R245	R343	R352	R404	R452	R466	R473	R489	R602	R625
Type	CBG	GML	CBG	CBG	GML	ML	GML	CBG	ML	ML	CBG	ML	GML	GML	GML	GML
SiO_2 wt.%	72.79	79.22	75.83	69.24	76.41	76.81	67.23	72.41	77.16	76.74	72.22	76.68	69.51	76.03	76.08	75.74
TiO_2	0.33	0.03	0.04	0.65	0.04	0.05	0.51	0.33	0.05	0.05	0.38	0.05	0.44	0.05	0.05	0.04
Al_2O_3	13.81	11.83	13.88	13.99	13.93	13.30	16.87	13.91	13.26	13.44	14.10	13.29	15.72	13.69	13.78	13.86
Fe_2O_3	3.23	0.29	0.37	6.70	0.40	0.40	3.47	3.00	0.18	0.23	3.07	0.34	2.42	0.45	0.44	0.64
MnO	0.12	0.24	0.19	0.17	0.26	0.06	0.11	0.08	0.20	0.12	0.12	0.01	0.08	0.06	0.14	0.10
MgO	0.19	<0.01	<0.01	0.58	<0.01	<0.01	1.27	0.36	<0.01	<0.01	0.36	<0.01	0.78	<0.01	<0.01	<0.01
CaO	0.60	0.38	0.40	0.78	0.37	0.43	1.53	0.67	0.48	0.51	0.62	0.43	2.05	0.39	0.51	0.49
Na_2O	3.29	3.55	4.62	3.16	4.29	4.08	3.11	3.57	3.80	4.13	3.56	3.98	4.18	4.05	4.22	4.40
K_2O	4.77	4.05	4.26	4.25	4.22	4.18	3.75	4.49	4.26	4.15	4.68	4.31	3.34	4.29	4.13	4.34
P_2O_5	0.07	0.01	0.02	0.08	0.02	0.02	0.12	0.06	0.02	0.02	0.07	0.02	0.15	0.01	0.02	0.02
LOI	1.00	0.31	0.32	0.99	0.42	0.72	2.43	0.91	0.83	0.68	0.77	0.80	1.38	0.49	0.78	0.41
Total	100.20	99.92	99.94	100.59	100.37	100.06	100.40	99.79	100.20	100.08	99.96	99.92	100.05	99.52	100.16	100.06
V ppm	21	10	10	38	18	20	93	29	17	18	27	13	52	<10	<10	22
Pb	16	18	19	6	23	16	<4	9	15	12	14	16	6	15	18	20
Ba	519	185	90	1197	99	150	416	1663	49	33	964	182	1133	81	35	82
Rb	153	136	143	103	159	145	217	133	146	137	173	128	123	183	162	150
Sr	98	46	20	175	31	44	55	227	32	33	156	49	539	34	32	34
Nb	19	14	28	20	28	14	91	12	15	17	19	13	7	21	18	18
Y	10	21	26	17	24	11	91	8	15	16	6	9	9	17	18	19
Zr	105	51	41	196	37	37	85	117	34	35	114	46	139	40	37	43
Hf		2.7		3.4			2.6				2.8				2.9	
Ta		3.5		1.3			8.6				1.8				3.2	
Th	21	24	18	35	15	21	17	19	4	13	20	15	19	22	19	25
U	5	16	8	9	6	2	8	7	2	3	5	4	4	6	6	7

Rock unit	Moly May leucogranites					Coast Plutonic Complex granites									Metasedim. rocks		
Sample	R707	Ave.	R12-1	R8	Ave.	CB1	CB4	CB5	CB6	CB7	CB10	CB11	CB14	Ave.	161x1	161x2	Ave.
Type	CBG		MMG	MMG		GR	GR	GD	GD	GD	GR	GD	GD		SED	SED	
SiO_2 wt.%	73.54	74.34	71.98	72.74	72.36	74.32	73.99	72.14	67.27	71.50	77.02	72.30	72.06	72.58	69.30	69.54	69.42
TiO_2	0.27	0.20	0.01	0.23	0.12	0.16	0.10	0.28	0.36	0.38	0.11	0.39	0.38	0.27	0.51	0.55	0.53
Al_2O_3	13.69	13.90	8.83	14.27	11.55	14.23	14.72	14.95	17.76	14.73	12.87	14.73	14.48	14.80	14.37	14.51	14.44
Fe_2O_3	2.32	1.64	0.29	2.40	1.35	1.15	0.54	1.72	2.16	2.28	0.82	2.53	2.36	1.70	4.57	4.88	4.73
MnO	0.06	0.13	0.25	0.06	0.16	0.04	0.02	0.05	0.05	0.06	0.03	0.06	0.06	0.05	0.07	0.06	0.07
MgO	0.19	0.23	<.01	0.19	0.10	0.21	0.14	0.45	0.60	0.69	0.03	0.65	0.66	0.43	2.26	2.15	2.21
CaO	0.78	0.67	0.58	1.13	0.85	1.35	1.25	1.42	3.24	1.26	0.83	2.01	1.81	1.65	0.69	0.50	0.59
Na_2O	3.63	3.86	3.97	3.97	3.97	3.75	3.82	4.22	5.00	4.42	3.54	4.10	4.19	4.13	4.13	3.06	3.59
K_2O	4.61	4.24	0.34	3.83	2.08	4.19	4.56	3.94	2.53	2.95	4.15	2.91	2.83	3.42	2.64	2.03	2.33
P_2O_5	0.04	0.05	0.13	0.04	0.09	0.06	0.02	0.10	0.14	0.12	0.03	0.12	0.14	0.09	0.10	0.10	0.10
LOI	0.93	0.83	2.96	0.94	1.95	0.33	0.32	0.55	0.40	1.45	0.33	0.53	0.64	0.57	1.43	2.68	2.06
Total	100.12	100.08	89.35	99.80	94.58	99.97	99.61	100.01	99.69	100.01	99.91	100.53	99.79	99.94	100.19	100.18	100.19
V ppm	27	26	13	23	18	38	27	36	40	46	15	53	51	38	100	108	104
Pb	17	14	15	13	14	20	25	15	11	6	10	10	10	13	5	6	6
Ba	585	439	<9	900	455	1615	1211	1757	1645	1413	1365	1603	1462	1509	652	768	793
Rb	134	149	21	95	58	102	86	78	80	84	87	64	66	81	153	76	115
Sr	121	102	57	206	132	377	269	391	732	455	202	446	450	415	158	163	161
Nb	16	22	<2	<2	<2	8	7	14	7	11	8	12	11	10	8	8	8
Y	9	19	61	9	35	8	5	12	8	11	5	7	7	8	12	14	13
Zr	279	85	130	87	109	89	63	118	162	154	55	143	142	116	99	114	107
Hf	6.9	3.6	3.8		3.8	3.5			5.1		2.2		4.4	3.9	2.6	2.8	2.7
Ta	2.5	3.5	2.7		2.7	2.1			1.8		1.9		1.4	1.7	1.6	1.5	1.5
Th	31	20	368	23	196	17	13	20	10	12	15	16	15	15	8	9	9
U	12	7	122	6	64	7	7	4	6	9	2	6	4	6	2	3	3

Rock types of the Moly May pluton are garnet–muscovite leucogranite (GML), medium-grained leucogranite (ML), coarse-grained biotite granite (CBG), represented by samples R9 to R707, and Mo-mineralized leucogranite (MMG), represented by samples R12-1 and R8. The CPC rocks include granite (GR) and granodiorite (GD), represented by samples CB1 to CB14. SED: metasedimentary rocks (samples 161x1 and 161x2). Total iron is expressed as Fe_2O_3.

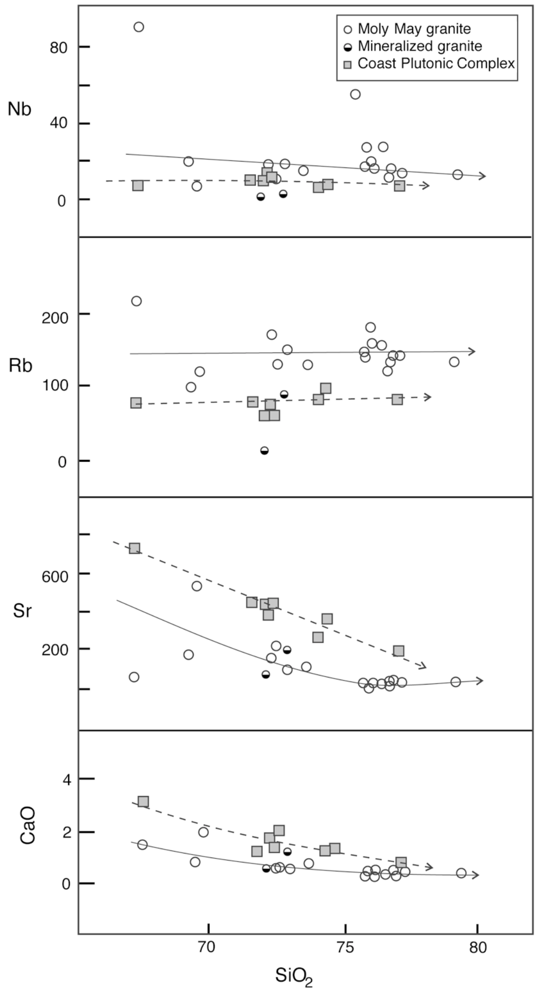

FIG. 3. Variations of selected major and trace elements *versus* silica for the MML and its CPC host rocks. The MML exhibits distinct trends, and is relatively depleted in Ca and Sr, but enriched in Rb and Nb compared to the CPC rocks. Arrows depict differentiation trends, and were derived visually.

Rocks of the MML exhibit molar A/CNK values ranging from 1.00 to 1.78, and are peraluminous (Fig. 4). Five of the seventeen leucogranitic samples exhibit values typical of S-type granites (A/CNK > 1.1; average weight ratio K_2O/Na_2O = 1.1), which suggest metasedimentary or supracrustal source-rocks (*e.g.*, White & Chappell 1988; see Discussion). The CPC rocks have an average K_2O/Na_2O value of 0.85, and have A/CNK values ranging between 0.84 and 1.06, indicating that they are metaluminous to weakly peraluminous (Fig. 4). The fractionation vectors shown in Figure 4 suggest that the crystallization of K-feldspar (with some albite), and of plagioclase (with some biotite) played a significant role in defining the geochemical trends during the evolution of the MML and the CPC, respectively. Based on the proportions of normative quartz, K-feldspar, and plagioclase, the Moly May rocks are classified as granites, whereas the CPC rocks are classified as granodiorites and granites.

Trace elements

In general, the MML rocks vary widely in their trace-element proportions, but the CPC rocks exhibit a relatively narrower compositional range (Table 2). For example, the Ba *versus* Sr diagram (Fig. 5) shows that in the MML rocks, Ba content decreases significantly (from 1663 to 33 ppm) with decreasing Sr, compared with the CPC samples, which show a marked decrease in Sr (from 732 to 202 ppm), but with a minor decrease in Ba. A marked depletion in Ba, and in Sr, in granitic melts has been explained by significant crystallization of K-feldspar and of plagioclase, respectively (*e.g.*, Černý *et al.* 1985). The fractionation vectors generated by single mineral phases, assuming Rayleigh fractionation (Fig. 5), confirm that the crystallization of K-feldspar controlled the evolutionary trend of the MML, whereas that of plagioclase played a significant role during the fractionation of the more calcic CPC rocks.

In terms of variations of Rb *versus* Zr (Fig. 6a), and of Rb/Zr *versus* Rb/Sr (Fig. 6b), the two granitic suites define distinct trends; the MML rocks are significantly enriched in Rb, and have a relatively wide range of Rb/Zr (0.48–4.57) and Rb/Sr values (0.23–7.15), but show a much wider scatter of data points, compared to the CPC rocks (0.45 < Rb/Zr < 1.58, 0.11 < Rb/Sr < 0.43). The MML rocks are significantly enriched in both Y and Nb compared to the CPC rocks (*cf.* Table 2).

Rare-earth elements (*REE*)

The abundances of the *REE* are given in Table 3, and the chondrite-normalized *REE* patterns (using the chondrite values of Taylor & McLennan 1985) are presented in Figure 7. Overall, the Moly May granites (total *REE* = 105 ppm, on average) are slightly more enriched in *REE* compared to the CPC granitic host-rocks (total *REE* = 97 ppm, on average). The Moly May mineralized leucogranite, however, is significantly depleted in the *REE* (total *REE* = 27 ppm).

REE patterns of the MML (Fig. 7a) distinguish the leucogranites from the garnet-bearing varieties. The *REE* patterns of the two groups show no overlap, but cross over at Eu. The *REE* patterns of the Moly May leucogranites are parallel to subparallel, show enrichment in the light rare-earth elements (*LREE*) compared to the heavy *REE* (*HREE*) [with $(La/Sm)_N$ = 4.7, and $(Gd/Yb)_N$ = 2.3, on average], are generally fractionated [$(La/Yb)_N$ = 23], and exhibit a very small negative Eu

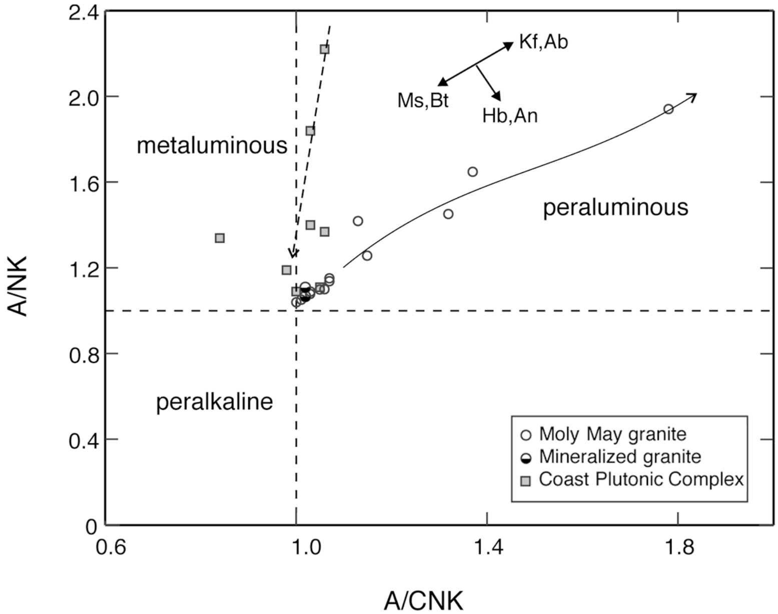

FIG. 4. Molar A/CNK *versus* A/NK variation diagram. Compositions for the MML are exclusively peraluminous, whereas those of the CPC rocks are metaluminous to weakly peraluminous. Short arrows represent fractionation vectors for mineral phases that may control these ratios in granitic rocks, and are after Zen (1986) and Brandon & Lambert (1994): mineral symbols; Ab, albite; An, anorthite; Bt, biotite; Hb, hornblende; Kf, K-feldspar; Ms, muscovite. Long arrows depict differentiation trends, and were derived visually.

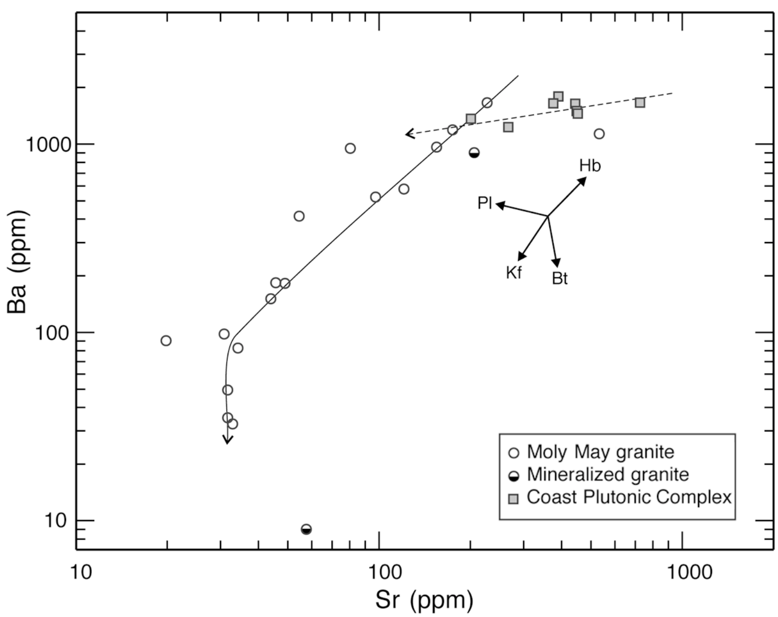

TABLE 3. CONCENTRATION OF THE RARE-EARTH ELEMENTS IN THE MOLY MAY LEUCOGRANITE, MINERALIZED LEUCOGRANITE, AND THE HOST ROCKS (THE COAST PLUTONIC COMPLEX AND METASEDIMENTARY ROCKS)

Rock unit	Moly May leucogranite								Coast Plutonic Complex granites					Metased. rocks		
Sample Type	R13 GML	R24 CBG	R245 GML	R452 CBG	R602 GML	R707 CBG	Ave.	R12-1 MMG	CB1 GR	CB6 GD	CB10 GR	CB14 GD	Ave.	161x1 SED	161x2 SED	Ave.
La ppm	5.29	38.21	15.21	22.21	6.23	39.46	21.10	2.92	19.92	23.45	17.86	40.31	25.38	14.41	14.67	14.54
Ce	10.96	67.67	31.39	43.17	13.63	78.31	40.86	5.93	36.06	40.95	33.74	69.02	44.94	28.02	28.66	28.34
Pr	1.42	7.78	4.21	4.92	1.84	9.28	4.91	0.75	3.97	4.37	3.91	6.94	4.79	3.37	3.49	3.43
Nd	5.75	27.29	18.53	17.07	7.46	33.48	18.26	3.15	14.29	15.93	14.59	22.78	16.89	13.41	13.39	13.40
Sm	2.17	4.56	6.87	2.91	2.59	6.00	4.18	1.36	2.96	2.45	2.83	2.96	2.80	2.75	2.78	2.77
Eu	0.22	0.61	0.72	0.58	0.26	0.87	0.54	0.12	0.68	0.94	0.69	0.83	0.78	0.69	0.68	0.69
Gd	3.03	2.95	10.98	1.98	2.69	3.58	4.20	2.47	2.28	1.90	1.85	2.10	2.03	2.48	2.58	2.53
Tb	0.53	0.35	2.10	0.23	0.45	0.39	0.68	0.56	0.32	0.22	0.23	0.23	0.24	0.37	0.35	0.36
Dy	3.58	1.97	14.60	1.16	3.21	2.12	4.44	4.06	1.91	1.33	1.43	1.14	1.45	2.34	2.32	2.33
Ho	0.67	0.35	2.63	0.23	0.60	0.40	0.81	0.76	0.33	0.25	0.29	0.19	0.26	0.47	0.49	0.48
Er	1.95	0.94	7.23	0.69	1.74	1.27	2.30	2.11	0.91	0.66	0.76	0.52	0.71	1.46	1.47	1.47
Tm	0.28	0.14	1.02	0.08	0.25	0.21	0.33	0.28	0.11	0.12	0.12	0.08	0.10	0.23	0.22	0.23
Yb	1.80	0.89	6.84	0.67	1.55	1.54	2.22	1.84	0.78	0.65	0.71	0.55	0.67	1.50	1.53	1.52
Lu	0.25	0.12	0.87	0.09	0.22	0.24	0.30	0.25	0.13	0.10	0.12	0.09	0.11	0.23	0.25	0.24
Σ *REE*	37.90	153.83	123.33	95.99	42.72	177.15	105.13	26.56	84.65	93.32	79.13	147.74	101.15	71.73	72.88	72.33

Rock types of the Moly May pluton are garnet–muscovite leucogranite (GML), coarse-grained biotite granite (CBG), and Mo-mineralized leucogranite (MMG). The CPC rocks include granite (GR) and granodiorite (GD). SED: metasedimentary rocks. Samples: R13 to R707: Moly May leucogranite, R12-1: highly mineralized Moly May leucogranite, CB1 to CB14: Coast Plutonic Complex, 161x1 and 161x2: metasedimentary rocks.

anomaly. The *REE* patterns for the garnet-bearing leucogranites indicate that these rocks are relatively depleted in *LREE*, but are enriched in the *HREE* compared with the leucogranites, as indicated by virtually horizontal patterns, or are non-fractionated [$(La/Sm)_N$ = 1.5, $(Gd/Yb)_N$ = 1.4, and $(La/Yb)_N$ = 2, on average], and exhibit a larger negative Eu anomaly (Fig. 7a). The mineralized Moly May leucogranite is significantly depleted in *LREE* and Eu, moderately enriched in *HREE*, and shows a larger negative Eu anomaly (Fig. 7a). The *REE* patterns of the CPC rocks (Fig. 7b) are generally uniform, *LREE*-enriched compared to *HREE* [with $(La/Sm)_N$ = 5.7, $(Gd/Yb)_N$ = 2.5], show no Eu anomaly, and are generally more strongly fractionated [$(La/Yb)_N$ = 27], compared to those of the MML.

FIG. 5. Ba *versus* Sr diagram. The fractionation vectors (marked by short arrows) show the theoretical effects on the composition of a liquid crystallizing single mineral phases. The vectors were calculated assuming Rayleigh fractionation ($C^l/C^0 = F^{D-1}$), for F = 0.5; the mineral–liquid partition coefficients used are from Arth (1976). Pl = plagioclase, and the other mineral symbols as in Figure 4. Long arrows depict differentiation trends, and were derived visually.

Normalized multi-element profiles

The chondrite-normalized multi-element profiles of the MML (Fig. 8a) exhibit negative Sr and Eu anomalies. The profile of the mineralized leucogranite indicates that this rock is significantly depleted in K, Rb, Nb, *LREE* and Eu compared to the non-mineralized varieties. These elements are interpreted to have been selectively leached out at subsolidus temperatures by the sulfur-rich hydrothermal (mineralizing) fluids that deposited molybdenite (see Discussion). The multi-element profiles of the CPC rocks (Fig. 8b) show that these rocks are markedly depleted in K, Rb, and Nb, slightly depleted in Y and *HREE*, but significantly enriched in Sr compared to the MML. In general, negative Nb anomalies in normalized multi-element plots are probably inherited from the source region, and are interpreted to characterize subduction-related magmas (*e.g.*, McCulloch & Gamble 1991).

DISCUSSION

Tectonic regime of emplacement

Peraluminous granitic rocks occur as large batholiths (McKenzie & Clarke 1975, Le Fort 1981, White &

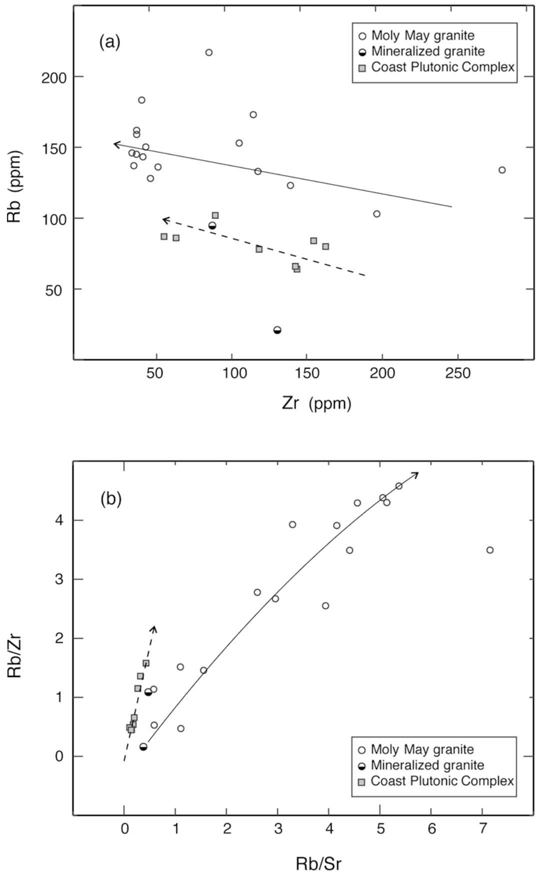

FIG. 6. (a) Rb *versus* Zr diagram, and (b) Rb/Zr *versus* Rb/Sr diagram for the MML and its CPC host rocks. Arrows depict differentiation trends, and were derived visually. See text for details.

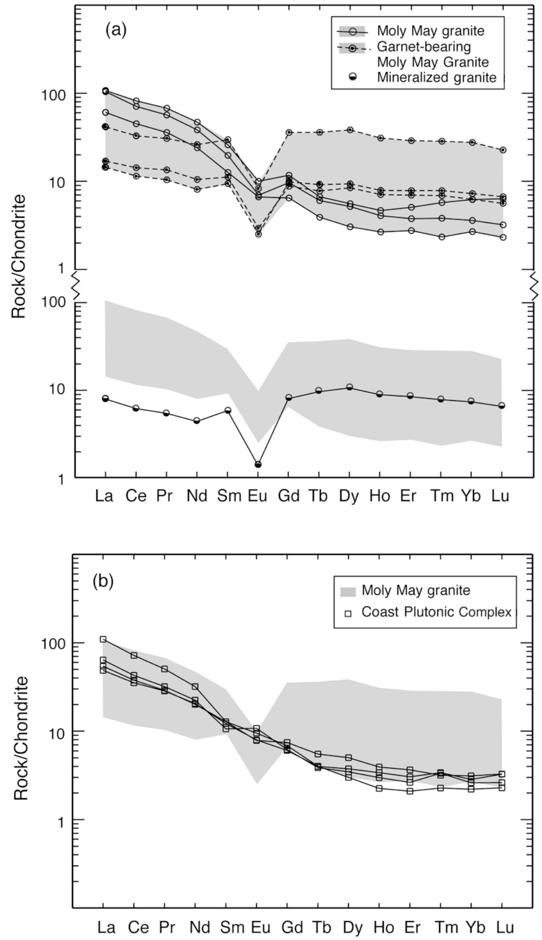

FIG. 7. (a) Chondrite-normalized *REE* patterns of representative samples of the Moly May rocks (muscovite leucogranite: open circle; garnet–muscovite leucogranite: open circle marked by a point in its center). The *REE* profiles of the garnet-bearing variety are *LREE*-depleted, but *HREE*-enriched, and are thus flat or non-fractionated compared to those of the leucogranite. The *REE* pattern of the molybdenite-mineralized variety is shown superimposed on a shaded envelope representing the *REE* patterns of the MML. (b) *REE* patterns of the CPC rocks superimposed on a shaded envelope representing the *REE* patterns of the MML. The chondrite values used for normalization are those of Taylor & McLennan (1985).

Chappell 1983), and as small plutons (Rottura *et al.* 1993, and this study), in a wide variety of tectonic environments, including: active accretionary prisms, continental belts inboard of active arcs, closing back-arc basin environments, continent–continent collisions, large-scale shear zones associated with continental collisions, and in association with anorogenic rift systems (Lalonde 1989, Barker *et al.* 1992, and references therein).

According to Monger *et al.* (1982), the CPC formed mainly in Cretaceous to Early Tertiary time during and following the convergence of Late Jurassic Terrane II, which was accreted to western North America (Late Triassic Terrane I) in about mid-Cretaceous time, forming a magmatic arc. The convergence took place within the overall setting of the North American plate moving relatively westward into various Pacific plates, and was accompanied by subduction of Pacific oceanic lithosphere. Barker *et al.* (1986) further interpreted the CPC as a continental-margin batholith developed in an Andean-type magmatic arc system. The more recent studies of Woodsworth *et al.* (1991) and van der Heyden (1992) show that only the older components of the CPC (Middle Jurassic to Early Tertiary) were developed in

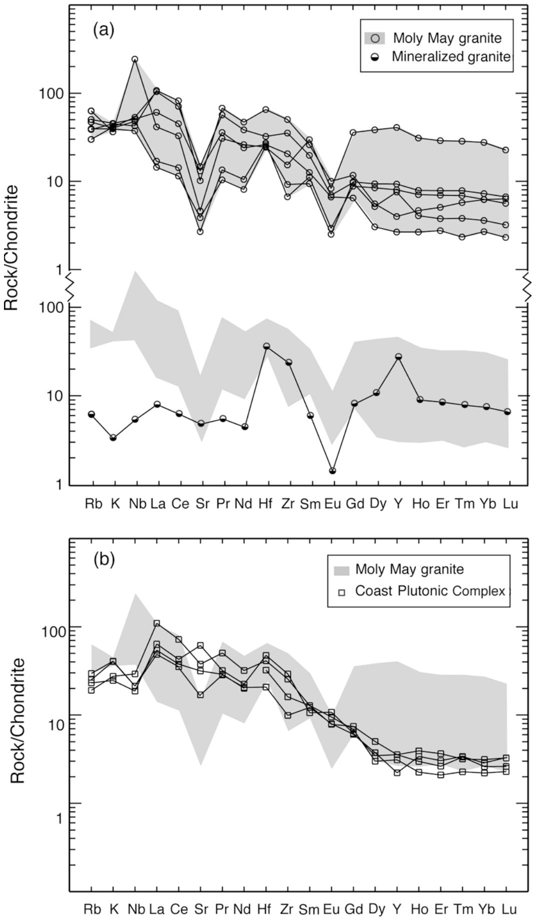

FIG. 8. (a) Chondrite-normalized multi-element profiles for the Moly May rocks; they are depleted in Sr and Eu. The spidergram of the molybdenite-mineralized variety is shown superimposed on a shaded envelope representing the profiles of the MML; this variety is significantly depleted in K, Rb, Nb, *LREE*, and Eu. (b) Multi-element profiles of the CPC rocks superimposed on a shaded envelope representing the profiles of the MML. The chondrite values used for normalization are those of Taylor & McLennan (1985).

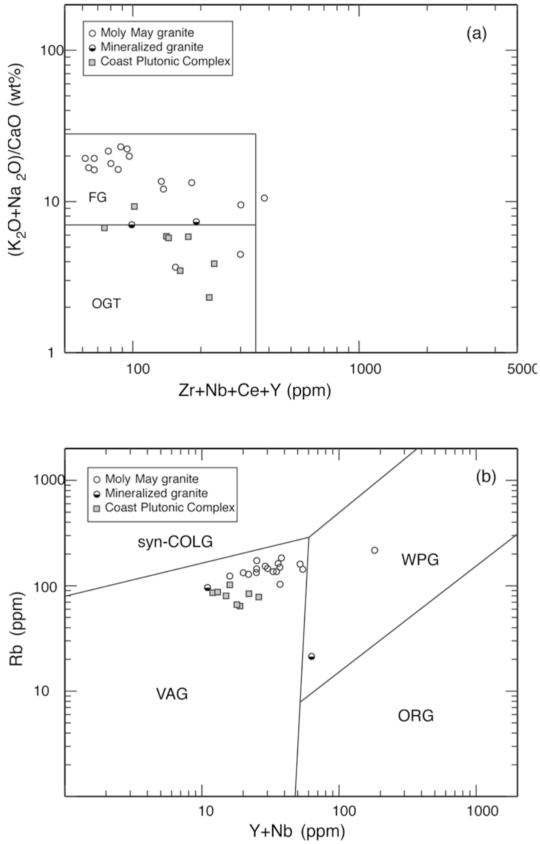

FIG. 9. (a) Discrimination diagram (after Whalen *et al.* 1987), showing that the MML compositions are typical of the fractionated, I- and S-type, felsic granite group (FG field), whereas those of the CPC rocks plot in the field of unfractionated granites (OGT field). (b) Rb *versus* (Y + Nb) tectonic discrimination diagram (after Pearce *et al.* 1984), showing that most compositions for the MML and the CPC rocks plot in the field of volcanic arc granites (VAG). Other fields are: syn-COLG: syn-collisional granite, ORG: ocean-ridge granite, and WPG: within-plate granite.

an Andean-type arc setting. Monger *et al.* (1982) emphasized that late modifications took place along major Eocene strike-slip faulting.

Using the discrimination diagram of Whalen *et al.* (1987), data points of the CPC rocks plot in the unfractionated M- or I-type granite field, whereas those of the MML plot in the fractionated I- and S-type granite field (Fig. 9a). The CPC and most of the MML compositional data plot in the field of volcanic arc granites in the Y + Nb *versus* Rb tectonic discrimination diagram of Pearce *et al.* (1984; Fig. 9b), suggestive of a subduction-related formation, which is inconsistent with the Eocene transtensional tectonic setting. Irving *et al.* (1980) demonstrated that during Late Cretaceous to Early Tertiary, the amalgamated terranes (now containing the CPC) moved northward (as observed paleomagnetically), owing to major dextral strike-slip faults occurring along the continental margin; they considered these faults to represent Early Tertiary analogues of the present-day San Andreas transform fault system. Also, Monger *et al*. (1982), Gabrielse (1985), and Struik (1993) showed that by Early Tertiary time, the tectonic regime in western British Columbia was dominated by major Eocene dextral strike-slip faulting and related tensional strain. The presence of large-scale faults and dyke swarms (such as the Larcom Island and the Portland Canal dyke swarms occurring in the vicinity of the study area), were shown to be Eocene in age and intruded dilationally (Grove 1986, Green *et al.* 1995, Evenchick & Holm 1997, Evenchick *et al.* 1997, 1999). Therefore, local and regional structural – tectonic data suggest that the Moly May pluton and the Eocene components of its CPC host rocks formed in association with an Eocene transtensional tectonic regime.

Petrogenesis

Peraluminous leucogranitic magmas may form by partial melting of metasedimentary rocks, or of metaluminous granitic rocks, by extensive fractional crystallization of a tonalitic – granodioritic – monzogranitic parental magma, or by late magmatic and postmagmatic hydrothermal alteration (Strong & Hanmer 1981, Monier *et al.* 1984, Clarke *et al.* 1993). Peraluminous granites of the Monashee Mountains in the southeastern Canadian Cordillera were interpreted to have been produced by partial melting of metapelites of the Horsethief Creek Group (Sevigny *et al.* 1989). Melting of crustal material of variable compositions to produce granitic melts of orogenic and of anorogenic characters have been documented for a number of granitic complexes (*e.g.*, Abdel-Rahman & Martin 1990, Barker *et al.* 1992, Brandon & Lambert 1994, Maas *et al.* 1997, King *et al.* 1997). Inherent in models of partial melting is the character of the parental material, which includes rocks of tonalitic–granodioritic composition, basalt or eclogite, and greywacke or other metasedimentary units.

The Moly May and CPC granitic suites do exhibit strikingly different geochemical trends (*cf.* Figs. 3 to 6), as they are chemically distinct, and not genetically related. The highly evolved nature of the MML, its exclusively peraluminous character, with mineral phases containing A/CNK > 1, and the presence of highly deformed metasedimentary xenoliths (containing folded quartzofeldspathic ptygmatic veins) within the Moly May rocks, support a sedimentary source. Modeling of partial melting processes was performed using the batch melting equations of Shaw (1970), and the mineral/melt partition coefficients of Arth (1976) and Irving (1978). The composition of the metasedimentary xenoliths occurring within the Moly May pluton is here assumed to approximate the composition of a metasedimentary protolith. The *REE* concentrations in the assumed metasedimentary source-material, its modal proportions, and the calculated compositions of melt at different degrees of partial melting are given in Table 4. The results of the partial melting modeling indicate that the *REE* pattern of the liquid expected by 65% batch partial melting coincides with the *REE* patterns of the analyzed MML samples (Fig. 10). Melting experiments of Conrad *et al.* (1988) indicate that peraluminous granitic magmas are produced by large fractions (65–85%) of melting of

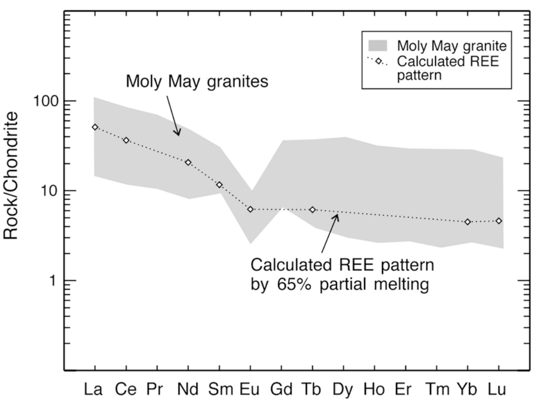

FIG. 10. Chondrite-normalized plot showing the calculated *REE* concentrations in a melt produced by 65% batch partial melting of metasedimentary xenoliths occurring within the MML pluton (an analogue to the composition of a metasedimentary protolith), compared with the range of *REE* concentrations of the MML. The chondrite values used for normalization are those of Taylor & McLennan (1985).

TABLE 4. MODEL PARAMETERS AND RESULTS OF BATCH PARTIAL MELTING CALCULATIONS, BASED ON RARE-EARTH ABUNDANCES

Phase	Starting mode	Melt mode
Quartz vol.%	0.270	0.0000
K-feldspar	0.300	0.4220
Plagioclase	0.250	0.3510
Biotite	0.100	0.1130
Amphibole	0.050	0.0550
Zircon	0.015	0.0295
Apatite	0.015	0.0295

Source composition and inferred composition of melts

REE	1	2	3	4	5
La ppm	14.41	18.62	18.64	18.67	18.70
Ce	28.02	32.74	33.39	34.07	34.78
Nd	13.41	12.45	13.12	13.87	14.71
Sm	2.75	2.22	2.36	2.51	2.69
Eu	0.69	0.46	0.48	0.51	0.54
Tb	0.37	0.25	0.28	0.31	0.36
Yb	1.50	0.58	0.69	0.85	1.11
Lu	0.23	0.08	0.10	0.13	0.18

Source composition 1 is that of a metasedimentary xenolith, taken to approximate the composition of a metasedimentary protolith. Melt compositions 2, 3, 4, and 5 are produced by partial melting of the assumed metasedimentary source at degrees of partial melting F of 0.50, 0.55, 0.60, and 0.65, respectively. Note that in terms of the rare-earth elements, the calculated composition of melt 5 coincides with that of the Moly May granites (see text for details).

crustal rocks. Thus, the modeled proportions are considered to be realistic.

The relatively high degree of partial melting (F = 0.65) that produced a granitic liquid similar to that of the MML exceeds the critical melt-fraction required for granitic melts to separate from their source region(s) and to accumulate into discrete bodies of magma (minimum 30%; Wickham 1987). Chemical data and modeling of Barker *et al.* (1992) showed that granodioritic rocks from Alaska formed by a very high degree of melting (80%) of sedimentary (graywacke and argillite) host rocks. High degrees of melting (50%) of crustal rocks to produce the White Creek granitic batholith in the Canadian Cordillera has been proposed by Brandon & Lambert (1994). Thus, as inferred from the chemical data and results of modeling, the Moly May granitic magma is interpreted to have been formed by approximately 65% partial melting of metasedimentary rocks.

Possible source of heat

In his investigation on deformational history of metasedimentary rocks hosting the CPC in a large area that includes the Moly May pluton, Douglas (1986) identified a major thermal pulse between 51 and 44 Ma (which also caused the area to be uplifted). The peak of that thermal pulse, at 48 Ma, coincides with the age of emplacement of the Moly May leucogranite, suggesting a causal relationship. The temperature necessary for anatexis to produce such a melt could have been produced as a result of shear-induced heating associated with the change from dominantly compressional to dominantly transtensional regimes (as indicated by the presence of major faults and dyke swarms in that region: Evenchick *et al.* 1997, 1999) during the Eocene. The role of shear-induced heating along strike-slip fault systems in the generation and emplacement of granitic magmas has also been emphasized by a number of authors including Gabrielse (1985), Brown (1994), and Abdel-Rahman & El-Kibbi (2001). Late Carboniferous plutonism associated with a similar transtensional environment led to the formation of the small peraluminous plutons of Hercynian age in Calabria, southern Italy (Rottura *et al.* 1993, and references therein).

Mineralization

Geochemical evidence for the fractionation of the Moly May suite is described above (*cf.* Figs. 4, 5). Fractional crystallization of significant amounts of K-feldspar has played a major role in the development of a hydrothermal fluid phase, and in concentrating Mo (and rare Au) during late stages of evolution of the MML magma. The presence of miarolitic cavities and pegmatitic pods, and the development of a pegmatitic biotite-rich unit in the Moly May pluton, are considered to represent field evidence for vapor saturation, formed as a result of such a fractionation process. Under these conditions, a supercritical fluid phase may have separated as cooling and fractionation proceeded. Owing to the accompanying resurgent boiling and an increase in fluid pressures compared to confining pressures, hydrofracturing at the roof of the pluton may have occurred (*e.g.*, Mutschler *et al.* 1981). Such hydrofracturing may have facilitated the passage of the mineralizing fluids. The presence of hydrothermally altered and stained rocks in association with localized highly mineralized zones, and the development of a thin rim of greisen around gossans and at some of these mineralized zones, along with the development of stockworks and quartz veins, presumably all represent field evidence for hydrothermal activity.

The partitioning of Mo between silicate melts and aqueous fluids has been determined by Candela & Holland (1984), who concluded that F and Cl contents of magmas have little or no effect on Mo partitioning, and that Mo is probably present in the aqueous phase as one or more molybdate species. The deposition of porphyry molybdenite in the form of disseminated grains, rosettes, or flakes, occasionally found intergrown with muscovite, and lining miarolitic cavities in leucogranites and pegmatitic varieties, was the result. Chemical features of the mineralized MML indicate that the fluids may have resulted in a quantitative removal of K, Rb, Nb, *LREE*, and Eu (*cf.* Fig. 8), and an addition of Mo, S, and rarely Au. Rare Au-bearing pyrite (unpubl. data) occurs in some late-stage quartz veins, and in association with some high-grade molybdenite showings.

CONCLUSIONS

1. In addition to quartz, perthitic K-feldspar, and albite, the Moly May leucogranites consist of variable contents of muscovite, garnet, biotite, and accessory monazite, zircon, and apatite, along with molybdenite in the mineralized facies. The CPC host rocks are made up of biotite-bearing granodiorite and granite, with minor chloritized amphibole, and accessory zircon and apatite.
2. The MML is exclusively peraluminous, whereas the CPC host rocks are metaluminous to weakly peraluminous. The MML is significantly enriched in K, Rb, Nb, Y, and depleted in Mg, Ca, Na, Ba, Sr, and Zr compared to the CPC host rocks. The two granitic suites are chemically distinct, exhibit strikingly different geochemical trends, and are thus considered genetically unrelated.
3. Chondrite-normalized *REE* patterns of the MML are characterized by *LREE* enrichment over *HREE* and a minor negative Eu anomaly, whereas the garnet-bearing variety shows a nearly flat *REE* pattern, with a significant negative Eu anomaly. The mineralized MML shows strong depletion in *LREE*, which parallels an overall depletion in K, Rb, and Nb; these elements are interpreted to have been leached out at subsolidus temperatures by mineralizing hydrothermal solutions. The

latter have led to localized deposition of molybdenite (and rare Au-bearing pyrite). Compared to *REE* patterns of the MML, those of the CPC are slightly more fractionated, and lack a Eu anomaly.

4. The peraluminous nature and S-type characteristics of the MML suggest that it is derived from melting of a protolith of former sedimentary origin. Based on petrological–geochemical data and results of modeling, the MML magma is interpreted to have been formed by a large degree (65%) of batch partial melting of a metasedimentary protolith. The heat necessary for anatexis was likely the result of shear-induced heating developed in response to the change from a dominantly compressional to dominantly transtensional tectonic regime during the Eocene.

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