The Canadian Mineralogist
Vol. 33, pp. 817-833 (1995)

THE RARE-ELEMENT-ENRICHED MONZOGRANITE – PEGMATITE – QUARTZ VEIN SYSTEMS IN THE PREISSAC–LACORNE BATHOLITH, QUEBEC.
II. GEOCHEMISTRY AND PETROGENESIS

THOMAS MULJA, ANTHONY E. WILLIAMS-JONES, SCOTT A. WOOD[1] AND MICHEL BOILY[2]

Department of Earth and Planetary Sciences, McGill University, 3450 University Street, Montreal, Quebec H3A 2A7

ABSTRACT

The Archean Preissac–Lacorne batholith in northwestern Québec includes four felsic plutons (Preissac, Moly Hill, Lamotte, Lacorne), which are zoned from biotite to muscovite monzogranite. The Lamotte and Lacorne plutons are associated spatially with rare-element pegmatites, whereas pegmatites are absent from the Moly Hill pluton and do not contain rare-element minerals in the Preissac pluton. The rare-element pegmatites are zonally distributed from beryl-bearing in the plutons to spodumene-bearing in the country rocks. Molybenite-bearing quartz veins are associated with all four plutons, and in the case of the Lamotte and Lacorne plutons, occur beyond the spodumene pegmatites. Dikes of molybdenite-bearing albitite occur north of the Lacorne pluton. All the plutons are weakly to moderately peraluminous (A/CNK: 1.0–1.3) and exhibit a compositional continuum in major- and trace-element contents from biotite to muscovite monzogranite. This compositional continuum extends to the rare-element pegmatites, indicating that the monzogranites and pegmatites are comagmatic. The chemistry of the pegmatites suggests that they underwent further evolution from beryl-bearing to spodumene-bearing varieties. The monzogranites and pegmatites have $\delta^{18}O_{(SMOW)}$ values (8.6 ± 0.3‰). The zonation of the plutons, the geochemical trends, and the oxygen isotopic compositions indicate that the various types of monzogranite were mainly the products of fractional crystallization. Trace element (Rb, Ba, Sr) modeling of the Lamotte and Lacorne plutons suggests that the most fractionated monzogranite could have been formed by 80–90% crystallization of the magma that formed the biotite monzogranite. A model is proposed for the evolution of the Lamotte and Lacorne plutons, in which side-wall crystallization produced their observed quasi-concentric zonation, and created volatile-rich residual melts. These melts were subsequently injected sequentially into the overlying parental monzogranite and later the country rocks, producing zonally distributed beryl and spodumene pegmatites, respectively. Fluids exsolved from the most evolved pegmatites back-reacted with earlier-crystallized spodumene-bearing aplite to form albitite, or separated from the melts, filling fractures as molybdenite-bearing quartz veins. The smaller Preissac and Moly Hill plutons, which host molybdenite-bearing quartz veins, did not evolve sufficiently to form rare-element pegmatites. Vapor saturation occurred during late crystallization of the muscovite monzogranite, and culminated in the formation of molybdenite-bearing quartz veins, which filled fractures in the overlying crust of previously solidified magma.

Keywords: rare-element monzogranite, granitic pegmatite, beryl pegmatite, spodumene pegmatite, molybdenite-bearing albitite, quartz veins, geochemistry, fractional crystallization, Preissac–Lacorne batholith, Archean, Québec.

SOMMAIRE

Le batholite archéen de Preissac–Lacorne, dans le nord–ouest du Québec, comprend quatre plutons monzogranitiques (Preissac, Moly Hill, Lamotte, Lacorne) présentant une zonation pétrologique depuis un faciès à biotite jusqu'à un faciès à muscovite. Les plutons de Lamotte et de Lacorne renferment de plus des massifs pegmatitiques à éléments rares, tandis que le pluton de Moly Hill n'a pas de cortège de pegmatites, et celles qui sont associées avec le pluton de Preissac ne montrent pas d'enrichissement en éléments rares. Les pegmatites à éléments rares définissent une zonation à partir d'un faciès à béryl dans les plutons à un faciès à spodumène dans les roches encaissantes. Les veines de quartz à molybdénite sont associées aux quatre plutons, et dans le cas des plutons de Lamotte et de Lacorne, se trouvent au delà des pegmatites à spodumène. Des filons d'albitite à molybdénite sont disposés le long du flanc nord du pluton de Lacorne. Tous les plutons sont faiblement à modérément hyperalumineux (A/CNK: 1.0–1.3), et contiennent un spectre continu de compositions (éléments majeurs et traces), de monzogranite à biotite à monzogranite à muscovite. Ce spectre se poursuit jusqu'aux pegmatites à éléments rares, indication que ces deux groupes de roches seraient comagmatiques. D'après la composition des pegmatites, il y aurait eu évolution progressive du faciès à béryl vers le faciès à spodumène. Les monzogranites et les pegmatites partagent des valeurs du rapport $\delta^{18}O_{(SMOW)}$ (8.6 ± 0.3‰). La zonation des plutons, les tendances géochimiques, et la composition isotopique de l'oxygène montrent que les divers types de monzogranite ont été produits par processus de cristallisation fractionnée surtout. D'après un modèle de

---

[1] Present address: Department of Geology and Geological Engineering, University of Idaho, Moscow, Idaho 83843, U.S.A.

[2] Present address: Géon, 10785, rue St-Urbain, Montréal, Québec H3L 2V4.

fractionnement fondé sur la distribution des éléments traces Rb, Ba et Sr dans les plutons de Lamotte et de Lacorne, le magma monzogranitique le plus évolué aurait bien pu résulter par cristallisation à 80–90% du magma responsable pour le monzogranite à biotite. Une cristallisation le long des parois aurait produit une cristallisation quasi-concentrique, et un enrichissement d'une phase aqueuse dans les volumes de magma résiduel. Ces venues de magmas ont par la suite été injectées dans le monzogranite susjacent, et ensuite dans les roches encaissantes, pour produire un essaim de filons de pegmatite à béryl et à spodumène, respectivement. Une phase fluide exsolvée des pegmatites les plus évoluées a ensuite réagi avec une aplite précoce à spodumène pour produire les filons d'albitite, ou bien a rempli des fractures avec quartz + molybdénite. Les plutons plus petits de Preissac et de Moly Hill, qui renferment des veines de quartz + molybdénite, n'ont pas évolué suffisamment pour produire des pegmatites enrichies en éléments rares. Dans ces cas, la saturation en phase aqueuse dans le magma monzogranitique à muscovite était tardive, et mena éventuellement à la formation de veines de quartz dans les fractures de la coquille supérieure de la chambre magmatique solidifiée.

(Traduit par la Rédaction)

Mots-clés: monzogranite à éléments rares, pegmatite granitique, pegmatite à béryl, pegmatite à spodumène, albitite à molybdénite, veines de quartz, géochimie, cristallisation fractionnée, batholite de Preissac–Lacorne, archéen, Québec.

INTRODUCTION

Recent investigations of rare-element-enriched granites and granitic pegmatites have been concerned mainly with the very late stages of the evolution of the magma, particularly the transition to subsolidus processes (*e.g.*, Černý *et al.* 1986, London 1986, Trumbull 1993, Linnen & Williams-Jones 1994). However, comparatively few studies have focused on the early history of magmatic crystallization (*e.g.*, Goad & Černý 1981, Černý & Meintzer 1988, Breaks & Moore 1992, Shearer *et al.* 1992), which controls the pattern of subsequent enrichment of the residual melt in the rare elements (Burnham & Ohmoto 1980). Another feature that is poorly documented is the zonal distribution of bodies of granitic pegmatite with respect to their predominant rare-element-bearing minerals, *e.g.*, the occurrence of beryl-bearing granitic pegmatite within and close to the parental pluton, and of spodumene-bearing granitic pegmatite further away, in the country rocks.

The Preissac–Lacorne batholith in Québec (Fig. 1) contains several excellent examples of zoned monzogranitic intrusions and associated bodies of rare-element-enriched granitic pegmatite and Mo-bearing quartz veins. The monzogranites vary from biotite- to muscovite-bearing varieties, and show continuous variations in the composition of plagioclase, biotite and muscovite, suggesting that the various subtypes of monzogranite are comagmatic (Mulja *et al.* 1995b). This compositional continuity extends to the bodies of rare-element pegmatite, thereby linking the evolution of the monzogranite to the formation of the Be-, Li-, Nb- and Ta-enriched pegmatites. The distribution of pegmatite bodies is zoned, from beryl-bearing varieties within the monzogranitic plutons to spodumene-bearing varieties in the country rocks (Figs. 1A–D). Previous investigators (Dawson 1966, Bourne & Danis 1987, Feng & Kerrich 1992) have presented some geochemical data on the Preissac–Lacorne monzogranites, but have not distinguished between types of monzogranite (*cf.* Mulja *et al.* 1995b) nor analyzed the associated pegmatites. In this study, results of 85 chemical analyses of samples representing the various subtypes of monzogranite and pegmatite are used to decipher the geochemical evolution of the plutons. These data are integrated with geological and mineralogical data (Mulja *et al.* 1995b) to develop a model that explains the processes responsible for the development of zoned rare-element-enriched granitic systems in and around the Preissac–Lacorne batholith.

GEOLOGICAL SETTING AND MINERALOGY OF THE MONZOGRANITE

The Preissac–Lacorne batholith crops out over an area of approximately 600 km^2 in the southern Abitibi subprovince of the Superior province, and was emplaced in mafic to felsic volcanic rocks of the Kinojevis and Malartic groups, and biotite schist of the Kewagama Group (Fig. 1; Dawson 1966). Intrusive activity took place in two stages; the first stage at 2671–2675 Ma (Feng & Kerrich 1991) was marked by the emplacement of syntectonic gabbro to granodiorite, and the second stage at 2630–2655 Ma (Gariépy & Allègre 1985, Feng & Kerrich 1991, Feng *et al.* 1993), by the emplacement of post-tectonic monzogranite and pegmatite. This plutonism is believed to have occurred late in the development of the Abitibi Greenstone belt, and to have involved collision of continents in a convergent-plate setting (Dimroth *et al.* 1983). The early Preissac–Lacorne intrusions are interpreted to result from partial melting of a mantle wedge above a subduction zone; the later intrusions are considered to be products of the melting of Pontiac Subprovince sedimentary rocks, which were part of a continental crust thickened by collision (Feng & Kerrich 1992).

The monzogranite forms four plutons, two of which, Lamotte and Lacorne, host and are surrounded by numerous rare-element-enriched pegmatite bodies. The other plutons, Preissac and Moly Hill, are associated with fewer bodies of pegmatite, most of which do not

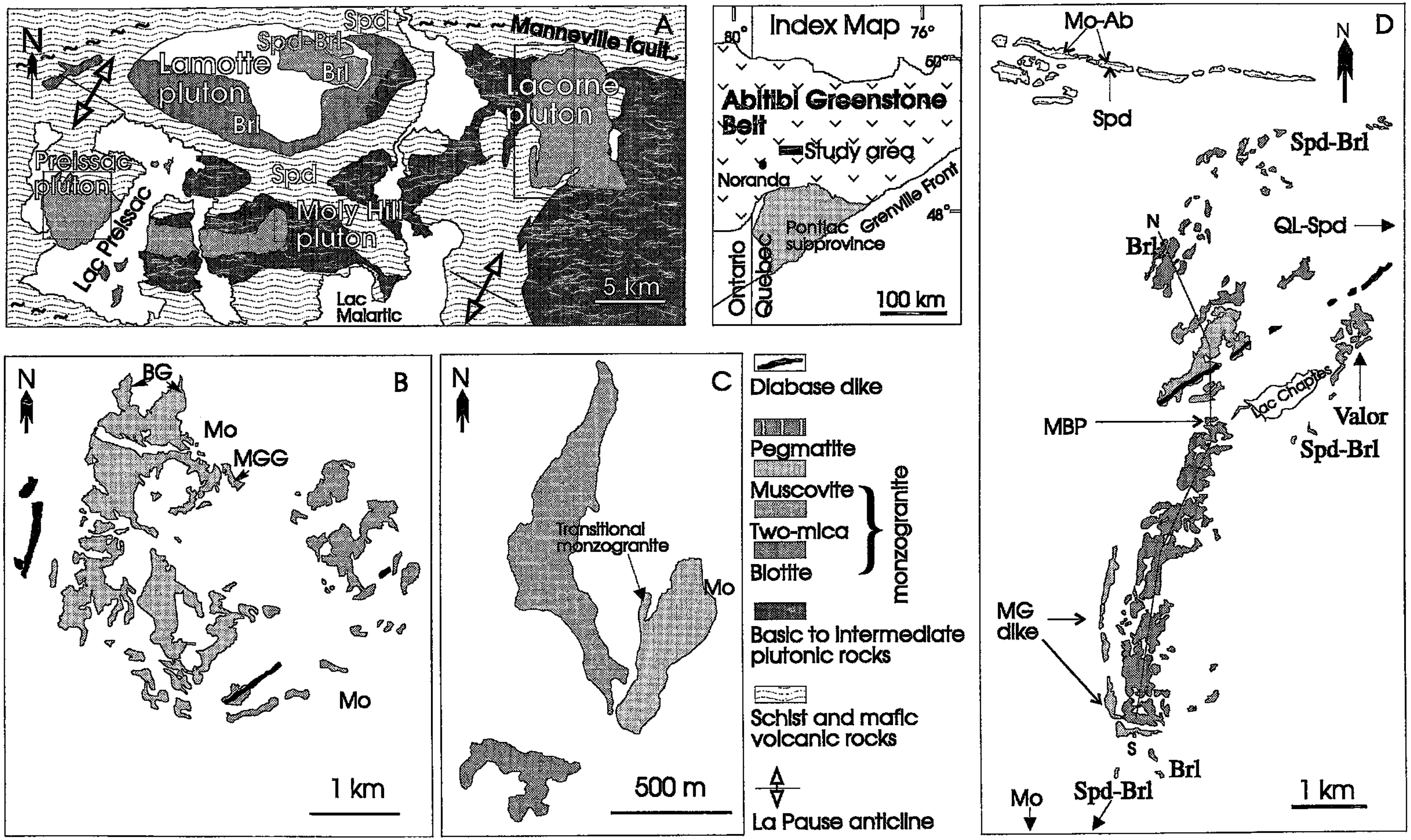

FIG. 1. Geological map of the Preissac–Lacorne batholith in northwestern Quebec, showing the locations of four monzogranitic plutons (after Dawson 1966) and the various subtypes of monzogranite and pegmatite (after Mulja *et al.* 1995b). The boxes around the Preissac, Moly Hill and part of the Lacorne plutons in Figure 1A correspond to Figures 1B, 1C and 1D, respectively. The exposure of biotite monzogranite (BG) and muscovite–garnet (MGG) monzogranites in the Preissac pluton (B) are too small to be shown as separate units; the biotite monzogranite occurs as a narrow marginal facies of the muscovite monzogranite (MG), and the muscovite–garnet monzogranite occurs as dikes cutting the muscovite monzogranite in the northeast. The Moly Hill pluton (Fig. 1C) is small, and its three subtypes of monzogranite are separated by faults. A north–south (N–S) traverse along the length of the Lacorne pluton (D) is a reference for Figure 4. The boundaries of the plutons are based on the locations of the outermost occurrences of granitic rocks (Dawson 1966). Abbreviations used in Fig. 1D are: Ab, Albitite; Brl, beryl pegmatite; Mo, molybdenite-bearing quartz veins; Spd, spodumene pegmatite; MBP, Mass Beryl Pegmatite (name of a prospect); QL–Spd, former Québec Lithium mine, about 7 km from the margin of the map.

contain rare-element-bearing minerals. Molybdenite-bearing quartz veins and stockworks occur in or near all of the plutons.

Detailed mapping by Mulja *et al.* (1995b) has shown that each of the monzogranite plutons comprises biotite, two-mica and muscovite subtypes. The most westerly pluton, Preissac, is dominated by two-mica and muscovite monzogranites; biotite monzogranite occurs only as a narrow marginal facies adjacent to muscovite monzogranite in the northern part of the pluton. In addition to the principal subtypes of monzogranite, there are also fine-grained dikes of muscovite–garnet monzogranite (Fig. 1A). Contacts between the principal subtypes of monzogranite are not exposed, except for that between biotite and muscovite monzogranite, which is marked by narrow, anastomosing veins (< 20 cm wide) containing quartz and K-feldspar. The three subtypes of monzogranite in the Moly Hill pluton form discrete bodies, which are separated by screens of mafic volcanic rocks and biotite schists. The contact relationships among the monzogranite subtypes are hidden, except at one locality, near the edge of the muscovite monzogranite, where there is a gradual transition from two-mica to muscovite monzogranite (Fig. 1B). Both the Lamotte and Lacorne plutons are quasi-concentrically zoned, with the outer unit of biotite monzogranite giving way inward to two-mica and muscovite monzogranites. A separate intrusion of muscovite monzogranite forms an L-shaped dike in the southern part of the Lacorne pluton. Contacts between subtypes of monzogranite are not exposed, except in the northern part of the Lacorne pluton, where the biotite monzogranite grades imperceptibly into two-mica monzogranite.

All subtypes of monzogranite vary from fine to coarse grained (crystals up to 0.5 cm across) and consist essentially of quartz (25–35 vol.%), plagioclase (30–45%) and perthitic microcline (25–45%), approximately 5% biotite + muscovite, up to 3% garnet, and minor epidote. Biotite monzogranite is distinguished from the other types of monzogranite by the presence of biotite and a lack of primary muscovite; the two-mica monzogranite contains muscovite and biotite roughly in the proportion 2:1, and muscovite monzogranite contains little or no biotite. Biotite and garnet show an antithetic relationship in the transition from biotite to muscovite monzogranite. In the compositional range from biotite to muscovite monzogranite, the plagioclase composition varies from $An_{17.5}$ to An_5, the Fe/(Fe+Mg) value of biotite increases from 0.69 to 0.85, and the Fe/(Fe+Mg) value and ^{IV}Al of muscovite increase from 0.65 to 0.85 and from 1.55 to 1.72 atoms per formula unit, respectively. The garnet is a spessartine–almandine solid solution (Sps_{30-60} Alm_{59-37}) and does not show systematic compositional variations with monzogranite subtypes. The accessory minerals are xenotime, apatite, zircon, monazite, titanite, magnetite and ilmenite. In the muscovite and muscovite–garnet monzogranite subtypes, columbite–tantalite and molybdenite also are present as accessory minerals. With the exceptions of xenotime and ilmenite, which are present in similar amounts ($\leq$ 0.1 vol.%) in the main subtypes of monzogranite (xenotime is not present in the muscovite–garnet monzogranite dike), the abundances of all accessory minerals decrease systematically from biotite to muscovite monzogranite.

The bodies of rare-element-enriched pegmatite occurs as vertical to subhorizontal dikes (up to 8 meters wide and about 200 meters long), which generally strike east–west and randomly in the Lacorne and Lamotte plutons, respectively. On the basis of the predominant rare-element-hosting minerals, the pegmatite is subdivided into beryl-bearing, spodumene–beryl-bearing and spodumene-bearing types. In the text that follows, these types of pegmatite are referred to as beryl, spodumene–beryl and spodumene pegmatites. These bodies of pegmatite are zonally distributed, from beryl pegmatite in the monzogranite through spodumene–beryl pegmatite at and near the margins of the monzogranite, to spodumene pegmatite in the country rocks (Figs. 1A–D). Beyond the spodumene pegmatite to the north of the Lacorne pluton is a set of east–west-trending dikes of molybdenite-bearing albitite, which occupy fractures in the intercalated schist and basalt. The albitite dikes vary from 20 cm to 1 m wide and dip steeply 75° to the south.

The beryl pegmatite and muscovite monzogranite are mineralogically similar, except that the pegmatite contains beryl, more garnet (up to 10 vol.%), considerably more columbite–tantalite (up to 1 vol.%), and traces of gahnite. Spodumene–beryl pegmatite in the Lamotte pluton is distinguished from beryl pegmatite only by the presence of spodumene in the center of the body of pegmatite. In contrast, spodumene–beryl pegmatite associated with the Lacorne pluton has spodumene throughout, variable amounts of lepidolite (up to 5 vol.%), and traces of schorl and pyrophanite. The spodumene pegmatite differs mineralogically from the spodumene–beryl pegmatite in containing much more spodumene (up to 30 vol.%), much less microcline (<10 vol.%), less garnet, and generally no beryl or lepidolite. Both beryl and spodumene–beryl pegmatites are zoned from a garnet-rich aplite border through an albite – perthite – quartz – muscovite zone to a core of massive quartz. In contrast, bodies of spodumene pegmatite are not zoned, or subtly zoned where large crystals of perthite occur in the inner part of the pegmatite. The albitite is an almost monomineralic rock, composed mainly of euhedral to subhedral albite, variable amounts of molybdenite, and traces of zircon, Ta-enriched ilmenite and garnet.

The plagioclase composition in the pegmatite is An_{1-5}, and the Fe/(Fe+Mg) and ^{IV}Al of muscovite are similar to those of muscovite monzogranite. The Cs content of muscovite in the muscovite monzogranite and rare-element pegmatites correlates positively with the contents of Ta and Rb, and negatively with those of Sc and K/Rb. The composition of columbite–tantalite ranges from ferrocolumbite in beryl pegmatite to manganotantalite in spodumene pegmatite (Mulja *et al.* 1995a).

GEOCHEMISTRY OF THE MONZOGRANITE

Analytical methods

Concentrations of the major and trace elements were determined with X-ray fluorescence spectrometry at McGill University, the Université de Montréal, and the Centre de Recherches Minérales du Québec. The concentrations of rare-earth elements (*REE*) in selected samples were determined by instrumental neutron-activation analyses at the Université de Montréal, and by inductively coupled plasma – mass spectrometry (ICP–MS) at Memorial University of Newfoundland. Twelve whole-rock compositions from Bourne & Danis (1987) and Feng (1992) were included in this study.

Major and trace elements

The Preissac–Lacorne monzogranites are siliceous (72.4–76.5 wt.% SiO_2, Tables 1A, B), and weakly to moderately peraluminous [molar ratio Al_2O_3/($CaO + Na_2O + K_2O$): 1.1–1.3; 1.2–2.8% normative corundum]. Although there is considerable scatter in

TABLE 1A. BULK COMPOSITION OF THE PREISSAC AND MOLY HILL PLUTONS

	Preissac monzogranite							Moly Hill monzogranite				
Rock	Biotite	Two-mica		Muscovite		MG		Biotite	Two-mica		Muscovite	
		x	n	x	n	x	n		x	n	x	n
Major-element oxides (wt. %)												
SiO_2	72.4	74.8	7	75.5	10	76.1	3	73.8	74.2	2	75.4	7
TiO_2	0.16	0.10	7	0.04	10	0.02	3	0.16	0.09	2	0.03	7
Al_2O_3	15.4	14.4	7	14.4	10	14.2	3	14.6	14.6	2	14.5	7
Fe_2O_3	1.75	0.86	7	0.40	10	0.44	3	1.33	1.60	2	0.41	7
MnO	0.06	0.04	7	0.02	10	0.26	2	n.a	0.05	2	n.a	7
MgO	0.03	0.19	7	0.10	10	0.06	3	0.31	0.14	2	0.05	7
CaO	0.5	0.73	7	0.50	10	0.29	3	1.26	1.10	2	0.61	7
Na_2O	4.21	4.16	7	4.27	10	4.70	3	3.73	4.33	2	4.2	7
K_2O	5.63	4.20	7	4.10	10	3.63	3	4.37	4.47	2	4.24	7
P_2O_5	0.03	0.03	7	0.04	10	0.04	3	0.07	0.03	2	0.03	7
Trace-elements (ppm)												
Ba	6.76	419	5	10	6	4.62		788	236	3	9.5	
Rb	450	365	7	496	13	476	2	350	348	3	465	4
Sr	10.5	98	7	9.5	13	7.81	2	165	57	3	19	4
Zr	33	69	7	58	13	16	2	80	53	2	40	4
Nb	28	22	7	37	13	73	2	15	23	2	22.5	4
Y	24	12	7	26	13	24	2	8.7	11	3	33	4
Ta	4.82	6.3	2	5.6	2	9.6	2	4	3.8	3	5.6	
Hf	2.76	2.9	2	1.75	2	2.6	2	4.5	2.3	3	1.43	
Th	10.4	13	2	7.89	2	1.2	2	19.5	14	3	12	
Li	91	92	3	30	3	44		134	118		18	
Be	n.d	5	3	3		2.25		2.6	3.8	2	3	
Rare-earth elements (ppm)												
La	5.22	21.2	2	4.69	2	0.64		50.32	9.4	2	7.46	
Ce	15.7	36	2	11.7	2	1.67		91.5	17.7	2	15.6	
Pr	1.51			1.69	2	0.23		9.72	2	2	1.92	
Nd	6.23	13.3	2	6.27	2	0.9		31.7	7.1	2	7.44	
Sm	2.47	2.3	2	2.1	2	0.88		4.57	1.8	2	2.38	
Eu	0.09	0.2	2	0.12	2	0.02		0.67	0.31	2	0.14	
Gd	3.05			1.97	2	2.08		3.1	1.8	2	2.61	
Tb	0.49	0.35	2	0.35	2	0.62		0.34	0.26	2	0.4	
Dy	3.14			2.1	2	4.22		1.84	1.53	2	2.53	
Ho	0.6	0.9	2	0.36	2	0.7		0.31	0.27	2	0.43	
Er	1.51			0.97	2	1.87		0.74	0.77	2	1.18	
Tm	0.23	0.8	2	0.15	2	0.35		0.12	0.12	2	0.17	
Yb	1.55	1.05	2	0.91	2			0.64	0.76	2	1	
Lu	0.2	0.15	2	0.12	2	0.36		0.1	0.11	2	0.14	
Σ REE	42	76.3		33.5		14.5		196	43.9		43.4	
Eu/Eu*	0.03	0.08		0.06		0.01		0.17 #	0.17	#	0.06	
$\delta^{18}O$		8.50		8.50	9							

*Including two samples, LC-5 and 6, from Feng (1992), with the exception of the REE

MG: muscovite-garnet monzogranite

E* = (Sm + Gd)/2. Where no data for Gd are reported, its value is approximated by the intersection of a straight line interpolated values for Sm and Tb.

X: mean; n: number of analyses (blank: one analysis)

Complete REE analyses (14 elements) were determined with the ICP-MS methods, partial REE analyses were determined with the NAA methods.

TABLE 1B. BULK COMPOSITION OF THE LAMOTTE AND LACORNE PLUTONS

	Lamotte monzogranite						Lacorne monzogranite							
	Biotite		Two-mica		Muscovite		Biotite		Two-mica		MG 1		MG 2	
	x	n	x	n	x	n	x	n	x	n	x	n	x	n
Major-element oxides (wt. %)														
SiO_2	74.4	6	75.1	4	76.05	2	74.5	10	75.4	8	76.5	2	75.2	3
TiO_2	0.08	6	0.04	4	0.03	2	0.09	10	0.06	8	0.03	2	0.06	3
Al_2O_3	14.2	6	14.37	4	14.6	2	14.1	10	13.8	8	14.0	2	14.8	3
Fe_2O_3	0.74	6	0.68	4	0.6	2	1.37	10	0.82	8	0.4	2	0.6	3
MnO	0.05	6	0.01	4	0.16	2	0.04	10	0.04	8	0.07	2	0.06	3
MgO	0.07	6	0.11	4	0.09	2	0.16	10	0.10	8	0.08	2	0.04	3
CaO	0.92	6	0.78	4	0.33	2	0.91	10	0.67	8	0.55	2	0.55	3
Na_2O	3.82	6	4.0	4	4.69	2	3.95	10	4.17	8	4.21	2	4.56	3
K_2O	4.36	6	4.43	4	3.39	2	4.63	10	4.28	8	4.3	2	4.16	3
P_2O_5	0.03	6	0.04	4	0.02	2	0.03	10	0.02	8	0.01	2	0.03	3
Trace-elements (ppm)														
Ba	502	6	145	5	12.5	2	550	11	154	8	69	2	28	3
Rb	284	6	367	8	455	2	391	11	641	8	488	2	703	3
Sr	110	6	46.1	8	10.5	2	118	11	59	8	36.5	2	18.3	3
Zr	88	6	52.9	7	18.5	2	79	10	61	8	60	2	40	3
Nb	16	6	17.9	7	42	2	16	10	22.7	8	24.5	2	48.5	3
Y	17	6	19.2	8	42.5	2	17.2	11	29	8	30.5	2	33	3
Ta	6.13	4	6	4	12	2	5	8	5.5	4	4.5	2	6.7	3
Hf	2.93	4	2.1	4	2.15	2	3.35	8	1.8	3	2		2.4	2
Th	16	5	16.2	5	4.55	2	22	8	21	5	15.5	2	8.3	3
Li	232	5	340	3	78	2	247	8	150	6	165	2	179	3
Be	3.6	5	5.75	4	4.5	2	4.22	8	5.8	5	6.5	2	8	3
U	4.13	4	8	5	7.3	2	3.21	8	5.5	5	4.6	2	11.3	3
Ga	21	5	24	3	34		20	3	23	3	26.5	2	26	
Rare-earth elements (ppm)														
La	19.5	5	11.7	6	5.1		24.3	3	12.8	2	9.35		5.54	
Ce	37.5	5	21	6	16		41.7	3	27.4	2	19.2		11.7	
Pr							4.62	3	3.15	2	2.4		1.34	
Nd	14	5	8.12	6	8		12.7	3	11.6	2	8.93		4.73	
Sm	2.1	5	2.33	6	2.6		2.4	3	3.23	2	2.62		1.63	
Eu	0.36	5	0.23	6	0.1		0.38	3	0.24	2	0.19		0.14	
Gd							2.22	3	3.28	2	2.9		1.93	
Tb	0.36	5	0.4	6	0.9		0.25	3	0.55	2	0.51		0.35	
Dy							1.5	3	3.85	2	3.7		2.4	
Ho	0.7	5	0.85	6	1.5		0.31	3	0.73	2	0.7		0.46	
Er							0.7	3	2.17	2	2.1		1.36	
Tm	0.65	5	0.13	6	1.3		0.11	3	0.35	2	0.34		0.2	
Yb	0.86	5	1.85	6	2.2		0.76	3	2.44	2	2.42		1.32	
Lu	0.3	5	0.25	6	0.3		0.12	3	0.36	2	0.35		0.16	
Σ REE	76.3		46.9		38		92.1		72.2		55.7		33.3	
Al/Ga	3639		3150		2272		3852		3196		2796		3012	
Th/U	4.15		2.23		0.55		7		3.75		3.4		1.45	
Eu/Eu*	0.23		0.13		0.03		0.16		0.07		0.07		0.08	
$\delta^{18}O$	8.6		8.5	2	9.3		8.60	3	8.40	2	8.30		9.60	

*Including three samples, BD-3060, 3061 and 3062, from Danis (1985), and one sample, LC-30, from Feng (1992), with the exception of the REE

MG 1: main muscovite monzogranite; MG 2: muscovite monzogranite dike (see Figure 1D)

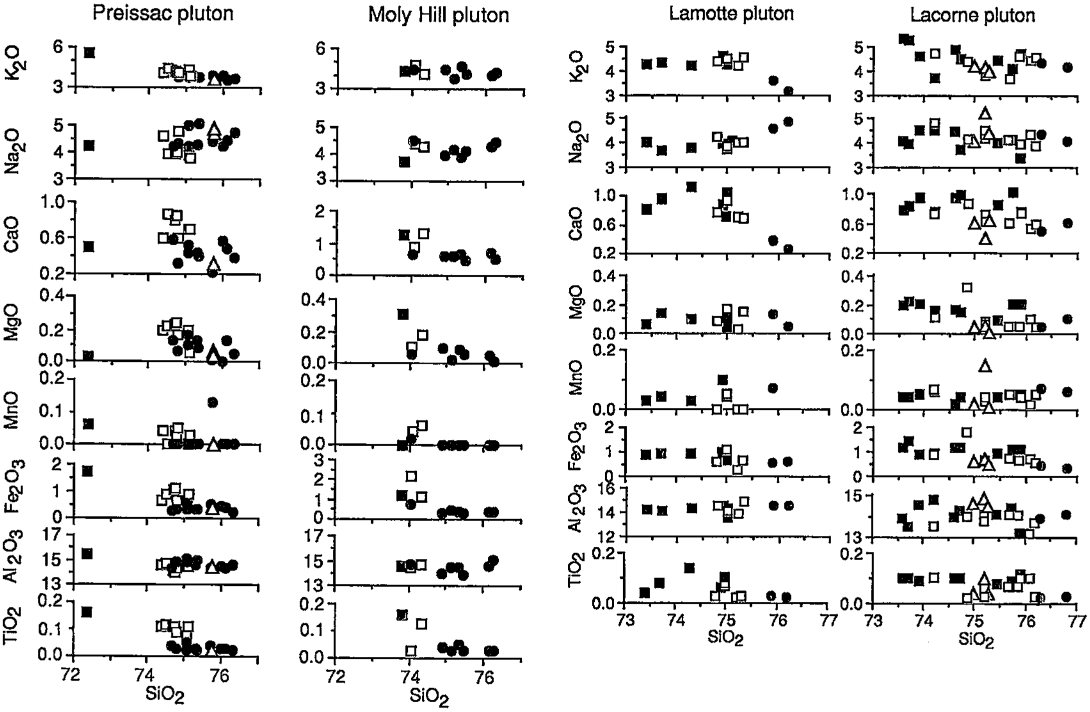

Fig. 2. Plot of major element oxides (wt.%) *versus* SiO_2 for all types of monzogranite in the Preissac, Moly Hill, Lamotte and Lacorne plutons. In this and subsequent diagrams, the symbols of the monzogranite, unless otherwise indicated, are: ■, biotite monzogranite; □, two-mica monzogranite; ●, muscovite monzogranite; ▲, dikes of muscovite–garnet monzogranite (Preissac pluton) and muscovite monzogranite (Lacorne pluton). There is only one data point for biotite monzogranite of the Preissac pluton owing to the small exposure of the rock (Fig. 1, and Mulja *et al.* 1985b).

the data, generally, the SiO_2 content increases from biotite to muscovite monzogranite (to muscovite–garnet monzogranite in the Preissac pluton), whereas the K_2O, CaO, MgO, Fe_2O_3 and TiO_2 contents decrease (Fig. 2); the Na_2O, MnO and Al_2O_3 contents do not vary. Two exceptions to these generalizations are the trend of decreasing CaO content with monzogranite evolution in the Lamotte pluton, and the low SiO_2 content of the highly evolved muscovite monzogranite dike in the Lacorne pluton.

The concentration of Ba, Sr and Th decreases from biotite to muscovite monzogranite (Fig. 3). The Zr content also decreases, but only in the Lamotte and Lacorne plutons. In contrast, the Rb content increases from biotite to muscovite monzogranite, and the content of Nb is highest in muscovite monzogranite. The concentration of trace elements other than those mentioned above, and of Li, Be, U, Ga, F and *REE*, which are discussed below, do not exhibit systematic trends with monzogranite type.

Besides varying with monzogranite type, the contents of Ba and Sr also vary spatially within the Lacorne pluton. In the northern part of the pluton, their contents decrease toward the two-mica monzogranite (Fig. 4). On the other hand, in the southern biotite monzogranite, Ba and Sr contents decrease inward from the margins of the intrusion.

The distribution of bodies of spodumene pegmatite, *i.e.*, their restriction to the Lamotte and Lacorne plutons, is reflected in the relative contents of Li in the monzogranites of the four plutons. The content of this element in each of the monzogranite types in the Preissac and Moly Hill plutons is low relative to that in the corresponding monzogranites in the Lamotte and Lacorne plutons. Moreover, the content of Li in the muscovite monzogranite of each pluton is markedly lower than that of the other types of monzogranite. In the Preissac and Moly Hill plutons, the contents of Li averaged over biotite and two-mica monzogranites are 92 ± 12 ppm and 126 ± 11 ppm, respectively. In contrast, the corresponding values in the Lamotte and Lacorne plutons are 265 ± 107 and 202 ± 124 ppm. The amount of Li in the muscovite monzogranite of the four plutons (ppm) are 30 ± 2 (Preissac), 18 (Moly Hill), 78 ± 32 (Lamotte) and 173 ± 70 (Lacorne, including the muscovite monzogranite dike). The

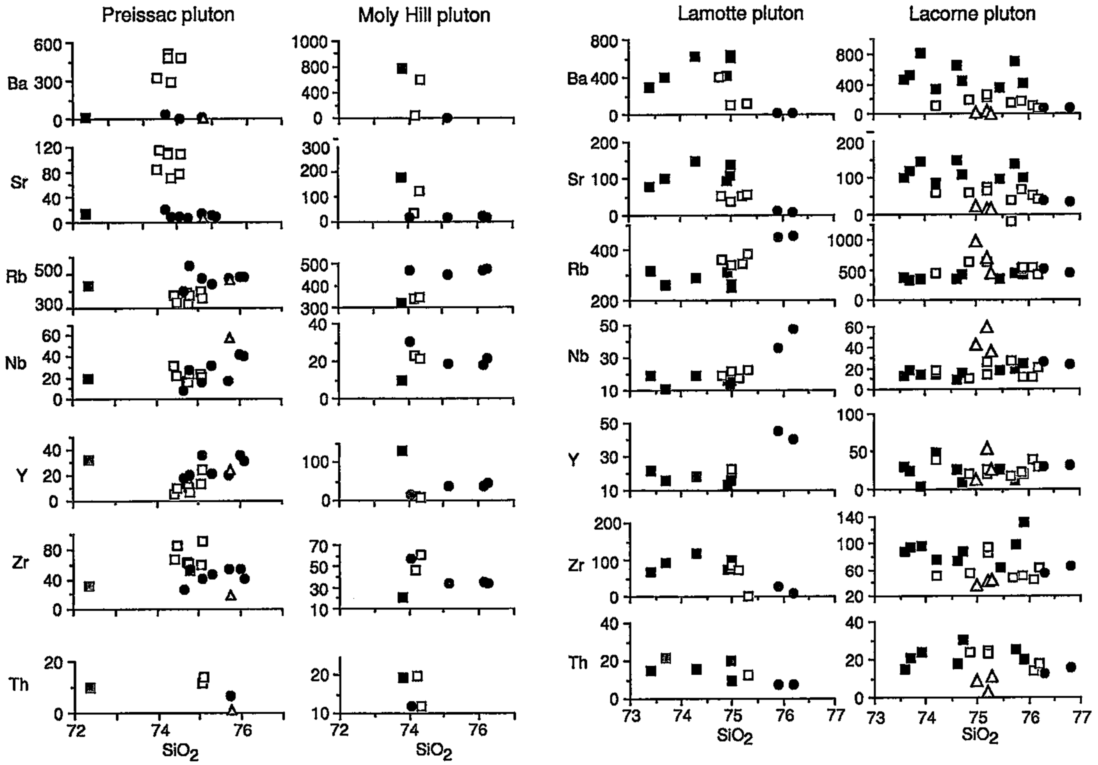

FIG. 3. Plot of trace-element contents (ppm) *versus* SiO_2 for all types of monzogranite in the Preissac, Moly Hill, Lamotte and Lacorne plutons.

distribution of Be is much more uniform among the four plutons, and does not vary appreciably with monzogranite type. However, it may be significant that the Be content is lowest in the Moly Hill pluton (3 ± 0.6 ppm *versus* 4 ± 1.4, 4.5 ± 1.8 and 5.5 ± 1.8 ppm in the Preissac, Lamotte and Lacorne plutons, respectively); the Moly Hill pluton is the only one that does not contain beryl.

Concentrations of U and Ga were determined only for the Lamotte and Lacorne monzogranites, and were found to increase systematically from biotite to muscovite monzogranite (Table 1B). The average Th/U values in the Lamotte and Lacorne plutons decrease from 5.4 and 7 in biotite monzogranite, through 2.2 and 3.9 in two-mica monzogranite, to 0.55 and 0.4 in muscovite monzogranite, respectively. In the same order of types of monzogranite, the mean values of Al/Ga decrease: 3639 $\rightarrow$ 3150 $\rightarrow$ 2272 in the Lamotte pluton, and 3852 $\rightarrow$ 3196 $\rightarrow$ 2796 in the Lacorne pluton.

The fluorine content was established in only three samples of two-mica monzogranite and two samples of muscovite monzogranite, all from the Lacorne pluton. The average F content is 0.03 wt.%, and does not vary with rock type.

The sum of the rare-earth elements is low, less than 100 ppm, in all subtypes of monzogranite, except for the Moly Hill biotite monzogranite, where it is approximately 200 ppm (Tables 1A, B). Chondrite-normalized profiles display light rare-earth enrichment and negative Eu anomalies, and there is a general tendency for the profiles to flatten and the Eu anomaly to become increasingly negative from biotite to muscovite monzogranite (Fig. 5).

GEOCHEMISTRY OF THE PEGMATITES AND ALBITITES

Major and trace elements

Only a small number of the occurrences of spodumene pegmatite in the Lamotte pluton, and of beryl and spodumene pegmatites in the Lacorne pluton, could be analyzed (rare-element pegmatites do not occur in the Preissac and Moly Hill plutons), owing to the difficulty of obtaining representative bulk-

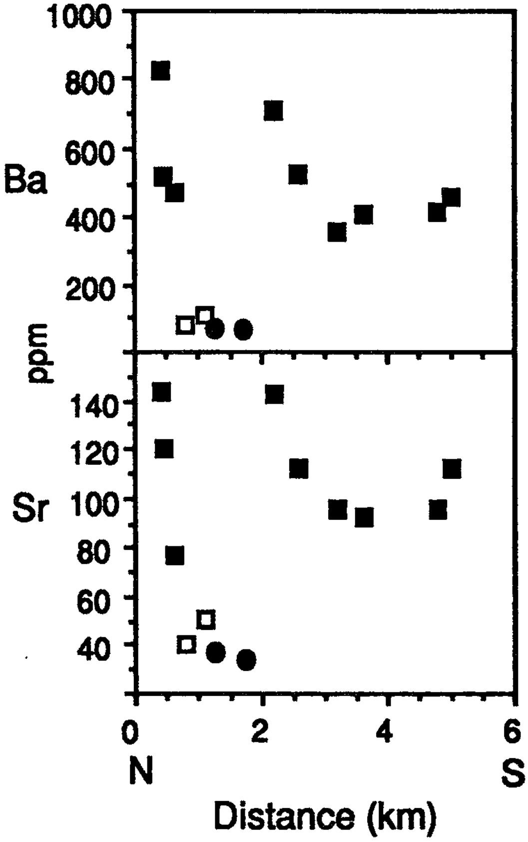

FIG. 4. Bulk-rock contents of Ba and Sr along a north–south traverse (N–S) in the Lacorne pluton (Fig. 1D), showing chemical trends from biotite to muscovite monzogranite in the northern part of the pluton, and from the margins to the center of the southern biotite monzogranite.

samples of these very coarse-grained rocks. In order to minimize the problem of sample heterogeneity, approximately 4 kg of material were collected from channels cut across small bodies of pegmatite (<1 m wide).

The beryl pegmatite in the Lacorne pluton contains 73.5 to 77 wt.% SiO_2 (most samples contain between 76 and 77 wt.% SiO_2), and thus is indistinguishable in terms of SiO_2 content from the muscovite monzogranite (Tables 1B, 2). The spodumene pegmatite in the Lacorne and Lamotte plutons contains 73–74 wt.% and 74 wt.% SiO_2, respectively.

Harker diagrams of major-element oxides against SiO_2 for the muscovite monzogranite and the pegmatites do not show any significant variations except for Na/K, which is slightly higher in beryl pegmatite. The contents of Ba, Y and Th decrease, whereas those of Rb and Ga increase, from muscovite monzogranite to spodumene pegmatite in both plutons (Fig. 6). The contents of Zr and Hf decrease in the

TABLE 2. BULK COMPOSITION OF PEGMATITE AND ALBITITE

	Lamotte pluton		Lacorne pluton						
Rock	Spd		Brl		Spd	Ab 1		Ab 2	
	x	n	x	n		x	n	x	n
Major-element oxides (wt. %)									
SiO_2	74.4	2	75.9	4	73.6	69	4	68	2
TiO_2	0.01	2	0.02	4	0.01	0.01	4	0.02	2
Al_2O_3	16	2	14.6	4	16	19.4	4	20.1	2
Fe_2O_3	0.97	2	0.51	4	0.16	0.16	4	0.11	2
MnO	0.16	2	0.3	4	0.13	0.07	4	0.2	2
MgO	0.24	2	0.03	4	0.01	0.01	4	0.01	2
CaO	0.27	2	0.3	4	0.06	0.53	4	0.13	2
Na_2O	3.91	2	5.13	4	4.31	10.1	4	10.8	2
K_2O	2.02	2	3.12	4	4	0.09	4	0.3	2
P_2O_5	0.01	2	0.02	4	0.04	0.03	4	0.05	2
Trace-elements (ppm)									
Ba	10	2	26.3	4	3.2	48	4	67	2
Rb	1104	2	853	4	4875	13.6	4	2.25	2
Sr	22	2	31.3	4	53	72	4	511	2
Zr	26	2	42	4	7	31	4	55	2
Nb	60	2	95	4	50	45.7	4	44	2
Y	14.5	2	15	4	0.6	2.55	4	2.25	2
Ta	43		60	4	67	225	2	122	2
Th	2.4		9.5	4	2	4		5	
U	1.7		18	4		5.5		12	
Ga	46	2	43	4		57	2	60	2
Li	6735	2	257	4		6.5	2	6	2
								Aplite	
Rare-earth elements (ppm)									
La	0.8	2	5.72		0.2	1.86		0.96	
Ce	1.75	2	18		0.52	3.35		3.22	
Pr			2.71		0.06	0.37		0.51	
Nd	3.5	2	10.5		0.24	1.63		2	
Sm	0.65	2	8.68		0.34	1.18		1.81	
Eu	0.1	2	0.03		0.01	0.06		0.05	
Gd			5.63		0.33	1.02		1.43	
Tb	0.15	2	0.63		0.06	0.19		0.16	
Dy			1.62		0.18	0.68		0.47	
Ho	0.35	2	0.13		0.02	0.06		0.05	
Er			0.19		0.02	0.11		0.1	
Tm			0.02		0.01	0.02		0.01	
Yb	0.2		0.12		0.06	0.16		0.05	
Lu	0.1	2	0.02		0.01	0.03		0.02	
Σ REE	7.6		54		2.06	10.7		10.8	
Al/Ga	1806		1826						
Th/U	1.4		0.58						
Eu/Eu*	0.21		0.004		0.03	0.055		0.031	
$\delta^{18}O$	8.8		8.7-9.5		7.6-10.3	8.8	2		

Brl: beryl pegmatite; Spd: spodumene pegmatite; Ab: albitite

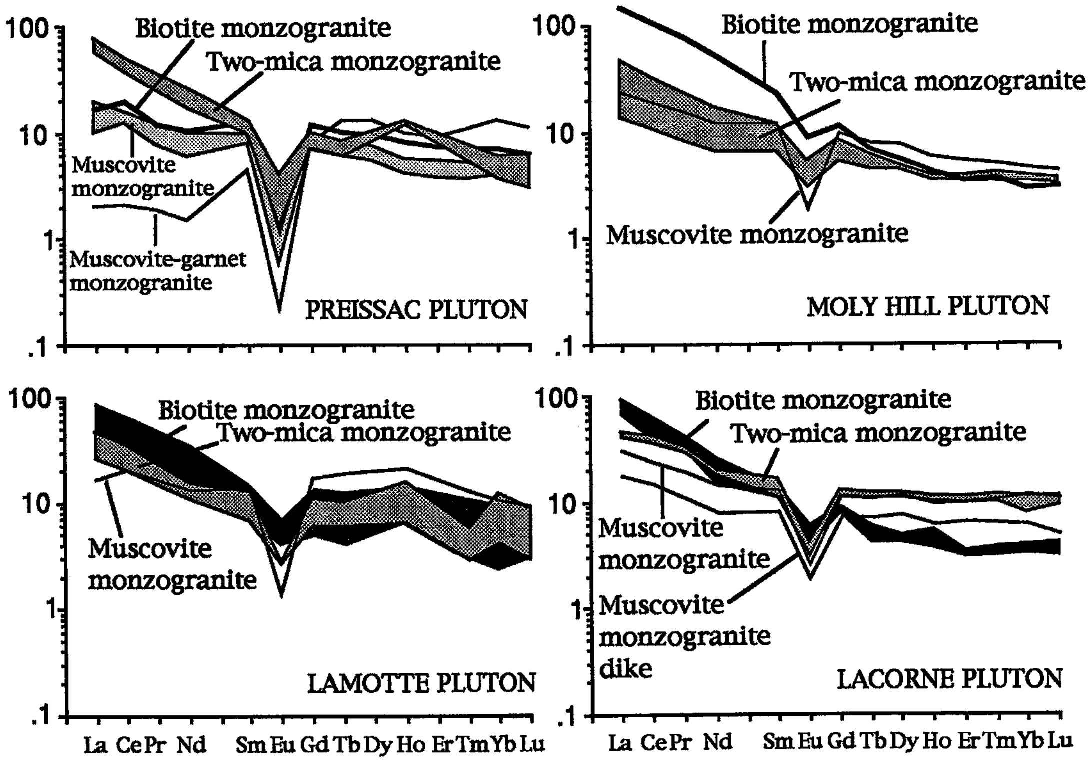

FIG. 5. Chondrite-normalized *REE* profiles for the subtypes of monzogranite in all four plutons. The chondrite values are those recommended by Boynton (1984).

Lacorne pluton but increase in the Lamotte pluton from muscovite monzogranite to spodumene pegmatite. The content of Sr decreases initially from the monzogranite to the beryl pegmatite, but then increases in the spodumene pegmatite, in the Lacorne pluton. A possible explanation for the high Sr content of the spodumene pegmatite is the breakdown of radiogenic Rb (*cf.* Clark & Černý 1987). In the Lamotte pluton, the Sr content is higher in the spodumene pegmatite than in the muscovite monzogranite. The content of Nb increases from the monzogranite to the beryl pegmatite, and then drops in the spodumene pegmatite. This sharp decrease is reflected by the presence of tantalite as opposed to columbite in the latter pegmatite (Mulja *et al.* 1995b). In the Lamotte pluton, the Nb content is higher in the spodumene pegmatite than in the muscovite monzogranite.

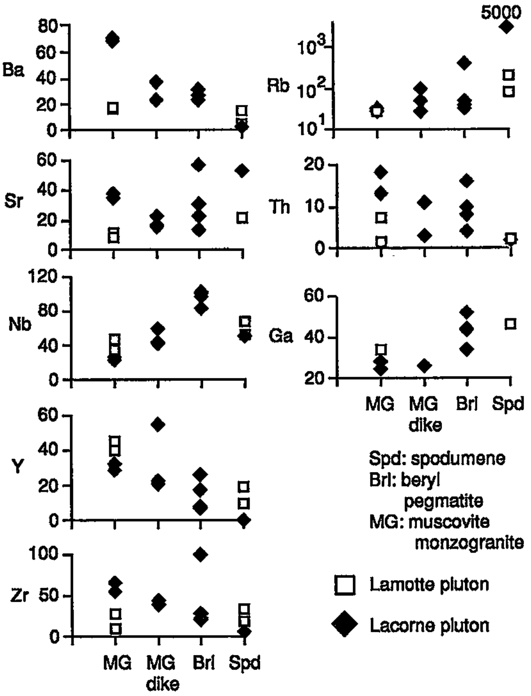

FIG. 6. Selected trace-element (ppm) concentrations in the muscovite monzogranite and types of pegmatite in the Lamotte and Lacorne plutons. The elevated Sr contents of beryl and spodumene pegmatites in the Lacorne pluton could be due to the decay of ^{87}Rb (see text).

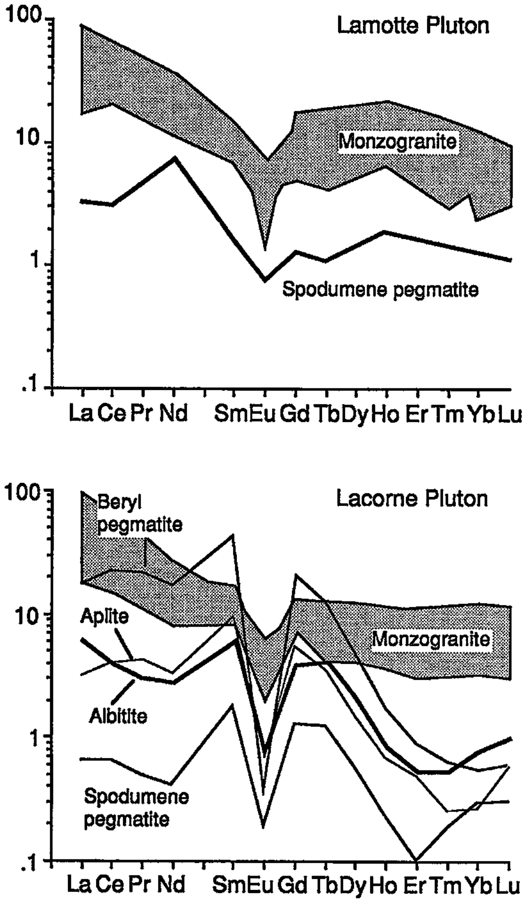

FIG. 7. REE_N profiles of rare-element pegmatites in the Lamotte and Lacorne plutons. Also shown are the REE_N profiles for dikes of aplite and albitite. The stippled area indicates the range of REE_N in the monzogranite.

The ΣREE content of beryl pegmatite (Lacorne pluton) is similar to that of the muscovite monzogranite (54 *versus* 56 ppm). However, the ΣREE content of spodumene pegmatite in both plutons is sharply lower at 2.06 ppm (Lacorne) and 7.6 ppm (Lamotte). Both beryl and spodumene pegmatites display chondrite-normalized gull-wing profiles as a result of depletions of *LREE* and *HREE* (Fig. 7). An aplite dike, which cuts the L-shaped muscovite monzogranite dike in the Lacorne pluton, has a chondrite-normalized *REE* pattern similar to that of the pegmatites (Fig. 7).

The albitite dikes, which occur only in association with the Lacorne pluton, have a uniform major-element composition, but form two distinct populations with respect to their trace-element concentrations (Table 2). Group-1 albitite has much higher Rb and Ta contents, and Group-2 albitite has a much higher content of Sr. The ΣREE content of the albitite (Group 1) is 10.7 ppm, intermediate in value between the beryl and spodumene pegmatites in the Lacorne pluton. It is worth noting that the REE_N profile of such albitite is almost identical to that of aplite (Fig. 7).

Oxygen Isotope Analyses

Oxygen isotope analyses (whole rock) of representative samples of monzogranite, pegmatite, and albitite were performed at the Université de Montréal and the University of Saskatchewan. Details of the analytical technique are given in Hoy (1993). All $\delta^{18}O$ values are reported relative to Standard Mean Ocean Water (SMOW).

The whole-rock $\delta^{18}O$ values of the Preissac, Lamotte and Lacorne monzogranites range from 8.1 to 9.8‰, with most values lying between 8.1 and 8.8‰ (Tables 1, 2, Fig. 8); the Moly Hill monzogranite was not analyzed. As a group, the types of monzogranite are isotopically indistinguishable within each of the plutons, or from one pluton to another, *i.e.*, they have not undergone significant interaction with meteoric water. A similar range of $\delta^{18}O$ values is also displayed by the four samples of beryl pegmatite, whereas the spodumene pegmatites show a somewhat wider range of $\delta^{18}O$ values (7.4 to 10.3‰). Interestingly, the mean $\delta^{18}O$ values of monzogranite, beryl and spodumene pegmatites are almost identical (Tables 1, 2), and similar to the $\delta^{18}O$ values of the two samples of albitite analyzed.

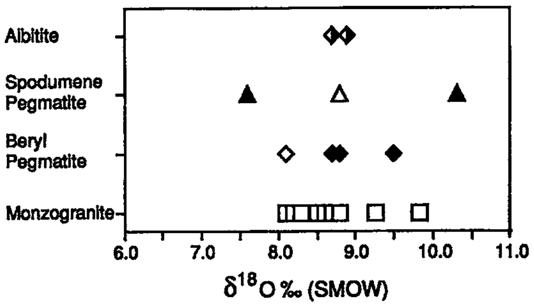

FIG. 8. Results of oxygen isotope analyses of monzogranite, pegmatite (white and black symbols are for Lamotte and Lacorne plutons, respectively), and albitite in the Preissac–Lacorne batholith. The values are quoted with respect to SMOW.

DISCUSSION

Nature of source rocks

The chemical composition of the Preissac–Lacorne plutons, in terms of major and trace elements, and notably the high level of K, Rb, Th, Ta and Nb, and the low level of Ca, Zr, Hf, Y and Sr, is typical of syncollisional granites (Harris *et al.* 1986), and has been noted by previous authors (*e.g.*, Feng & Kerrich 1992). It has also been shown from Pb isotopic data (Gariépy & Allègre 1985) and Nd isotopic data (Ducharme *et al.* 1995) that the magmas forming the plutons represent mixtures of juvenile, mantle-derived and older, crust-derived sources. As previously proposed by Gariépy & Allègre (1985), Feng & Kerrich (1992) and Boily (1995), we believe that the most plausible source for the magmas is the Pontiac suite of clastic metasedimentary rocks exposed to the south. This sequence is interpreted to have been thrust under the Abitibi Southern Volcanic Zone during an arc–continent collision between 2670 and 2630 Ma (Feng & Kerrich 1992). According to this model, the mixing could indicate anatexis of the Pontiac metasedimentary sequence and input of magma from the underlying mantle, or the melting of sedimentary rocks containing both crustal and mantle components. Although it is difficult to decide between the two alternatives, we favor the latter because of evidence for two populations of zircon in the metasedimentary rocks (Feng *et al.* 1993), one with an age of up to 3050 Ma, representing an older basement component, and the other with an age of 2700 Ma, possibly representing arc-related felsic igneous rocks.

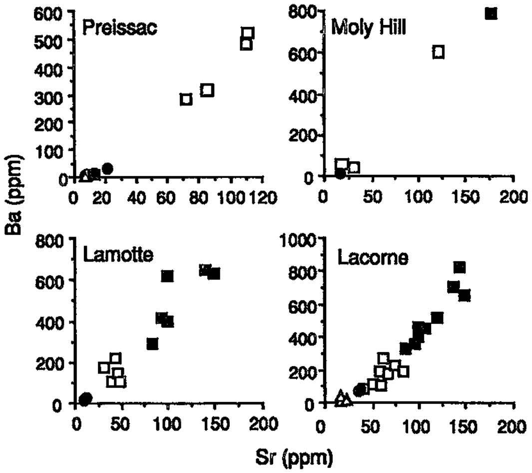

FIG. 9. Plots illustrating Ba *versus* Sr concentrations in the four monzogranite plutons of the Preissac–Lacorne batholith. All values are in ppm.

Geochemical evolution

The systematic chemical trends described above and the geological relationships discussed earlier, and in Mulja *et al.* (1995b), provide strong evidence of the evolution of the Preissac–Lacorne plutons from early biotite through two-mica and muscovite monzogranite to beryl and spodumene pegmatites. The most plausible explanation for this evolution is fractional crystallization of a parental monzogranitic magma.

Depletion of Ti, Fe, Ca, Ba, Sr, Zr and Th, and concomitant enrichment of Rb, Nb and U from biotite to muscovite monzogranite (Figs. 2, 3, 5) are consistent with early fractionation of plagioclase, biotite, zircon, monazite and apatite, and late crystallization of albite, muscovite, garnet, and columbite–tantalite. Similarly, the systematic increase in the negative Eu anomaly with magma evolution is consistent with fractionation of early, more calcic plagioclase (*cf.* Cullers & Graf 1984); the corresponding decrease in total *REE*, particularly in the *LREE*, can be explained by early fractionation of monazite and apatite (Fig. 5). Finally, the linear relationship between Ba and Sr, and the marked decrease in Ba content from biotite to muscovite monzogranite (Fig. 9), are strong evidence for fractional crystallization of plagioclase and K-feldspar.

Other processes that have been proposed to explain compositional evolution in monzogranitic plutons similar in extent of zonation to that observed in the Preissac–Lacorne plutons are restite unmixing (Chappell *et al.* 1987), source-rock heterogeneity (Nabelek *et al.* 1992), and sequential partial melting (Holtz 1989). We can rule out restite unmixing as the cause of the monzogranite zonation, because of the conspicuous absence of xenoliths or xenocrysts that could represent restite, and the requirement that the contents of *all* elements vary linearly with SiO_2 contents (Chappell *et al.* 1987). Although the concentrations of many of the major and trace elements do show such linear variations (Figs. 2, 3), a significant number shows trends that are clearly nonlinear, *e.g.*, Nb, Y, and Rb. Source-rock heterogeneity also can be ruled out because of the remarkable consistency of $\delta^{18}O$ values from biotite (8.6 ± 0.1‰) through two-mica (8.5 ± 0.1‰) to muscovite (8.6 ± 0.4‰) monzogranite. Finally, sequential partial melting can be eliminated because this process tends to produce relatively constant concentrations of compatible elements (Hanson 1978). In the Preissac–Lacorne plutons, several of the compatible elements display wide variations in concentrations, *e.g.*, Ba and Sr. The relatively high contents of Ba and Sr in the biotite monzogranite and their extreme depletion in the muscovite monzogranite simply cannot be explained by partial melting (*cf.* Mittlefehldt & Miller 1983).

TABLE 3. MINERAL/MELT DISTRIBUTION COEFFICIENTS (KD) USED IN TRACE-ELEMENT MODELING, AND VOLUME % OF PHASES FRACTIONATED FROM BIOTITE TO MUSCOVITE MONZOGRANITE

Mineral	Ba	Sr	Rb	Vol. %
Plagioclase	1.3	2.8	0.09	31
K-feldspar	6.12	3.6	1.6	32
Biotite	6.4	0.12	4.3	5
Muscovite	12	0.4	1.5	1
C^o: Lamotte	635	131	265	
C^o: Lacorne	822	144	360	

Source of K_D data:Hanson (1978), Nash & Crecraft (1985), Mahood & Hildreth (1983)

C^o: original concentration of element in "parent" melt (see text)

Trace-element modeling

In order to test the hypothesis that fractional crystallization was the principal process responsible for the compositional diversity of the Preissac–Lacorne monzogranites, we applied Rayleigh fractionation calculations to simulate the behavior of Ba, Sr and Rb, which are generally considered to be petrogenetic indicators in granitic rocks (*e.g.*, McCarthy & Hasty 1976, Tindle & Pearce 1981). This modeling was restricted to the Lamotte and Lacorne plutons because the data for the Preissac and Moly Hill plutons are considered inadequate. The following equation was used to describe fractional crystallization (after Hanson 1978):

$$C^l/C^o = F^{(D-1)},$$

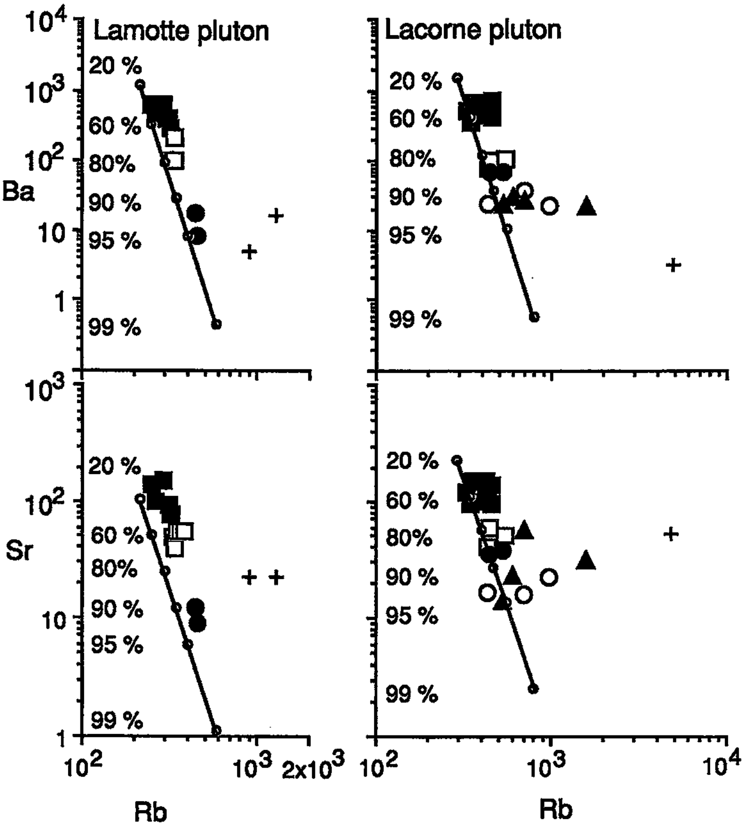

FIG. 10. Comparisons of the Rayleigh fractionation model (solid line) and observed data of all subtypes of monzogranite and pegmatites in the Lamotte and Lacorne plutons. The agreement between the theoretically calculated and measured compositions strongly supports the conclusion that fractional crystallization was the main process responsible for the compositional diversity of the monzogranite. Deviation of some measured values for some of the pegmatites suggest that the distribution coefficients used for the monzogranite are not applicable to volatile-rich batches of pegmatite-forming liquid. Symbols: ■ biotite monzogranite, □ two-mica monzogranite, ● muscovite monzogranite (main body), ○ muscovite monzogranite (dike), ▲ beryl pegmatite, + spodumene pegmatite.

where C^l and C^o are weight concentrations of a trace element in the derived melt, and in the parental melt, respectively; F is the fraction of melt, and D is the bulk distribution-coefficient. The concentration of a trace element in the residual mineral phases, C^s, relative to the parent, C^o, was calculated from the relationship $C^s = C^l * D$. Barium, Sr, and Rb were used in the modeling; among the trace elements whose concentration was established, these are the elements for which the mineral/melt distribution coefficients (K_D) are best known (Table 3). The values of K_D used in the calculations were selected from the literature because the rocks from which they were estimated have compositions similar to those of the Preissac–Lacorne monzogranites. Initial values of Ba, Sr and Rb concentrations were those of the least evolved biotite monzogranite, *i.e.*, that with the smallest negative Eu anomaly. The results of the modeling suggest that the various subtypes of monzogranite in the Lamotte and Lacorne plutons can be produced by moderate to high degrees of fractional crystallization (60–95%) from such a biotite monzogranite parent (Fig. 10). Such high degrees of fractionation are consistent with the relatively small volumes of the more evolved monzogranites relative to those of biotite monzogranite. Although the calculations also produce good correspondence between the model and observed compositions of most of the occurrences of beryl pegmatite in the Lacorne pluton (over 90% fractional crystallization, Fig. 10), spodumene pegmatites have substantially higher Rb, Ba and Sr contents than predicted. The reason for this is unclear. However, one possible explanation (at least for Rb) is that the magmas that produced the spodumene pegmatites had higher contents of volatile constituents such as F and B, which are known to increase the solubility of Group-1 elements in the melt (London 1987, Manning & Pichavant 1988). This explanation is consistent with the presence of tourmaline and a higher content of fluorine in the muscovite (Mulja *et al.* 1995b) in the spodumene pegmatite.

These arguments, the coherent relationships among trace elements between the monzogranite and pegmatites (Figs. 6, 7), and the evidence from the trace-element data for muscovite (Fig. 8; Mulja *et al.* 1995b) illustrating a linear relationship of Sc, Rb and Ta *versus* Cs, demonstrate the genetic link of the monzogranite to the rare-element pegmatites.

Behavior of REE during pegmatite evolution

The concentrations of Eu, and of the light and heavy *REE*, decrease progressively from beryl to spodumene pegmatite in the Lacorne pluton (Fig. 7). The large negative Eu anomaly is most reasonably interpreted by fractionation of plagioclase, as discussed previously. Given the relative abundance of xenotime in the muscovite monzogranite (Mulja *et al.* 1995b) and the absence of this mineral in the beryl pegmatite, we interpret the strong depletion of *HREE* in the latter rock to be a result of xenotime fractionation (in view of its well-established tendency to concentrate the *HREE*). The depletion in *HREE* may also be due in part to fractionation of garnet in the muscovite-monzogranite-forming magmas. The depletion of *LREE* in the beryl pegmatite can be interpreted to reflect fractionation of monazite; monazite is considerably more abundant in the muscovite monzogranite than in the beryl pegmatite (Mulja *et al.* 1995b). The extreme depletion of both *LREE* and *HREE* in the spodumene pegmatite can be explained by the continued fractionation of monazite and garnet in the beryl–pegmatite-forming magma, and the absence of these minerals in the spodumene pegmatite. Other explanations that have been proposed for extreme depletion of *REE* in pegmatites are F–*REE* complexing (Flynn & Burnham 1978) and subsolidus mobilization of *REE* by hydrothermal processes (*e.g.*, Sverjensky 1984). Although we do not have a test of the former hypothesis, replacement of amphibolite by biotite near the spodumene pegmatite and replacement of hornblende by holmquistite $[Li_2(Fe,Mg)_3Al_2Si_8O_{22}(OH,F)_2]$ indicate there was significant transfer of materials from the spodumene pegmatite to the country rocks. Moreover, altered amphibolite within a centimeter of the contact commonly contains abundant apatite. It is thus possible that some *REE* may have been hydrothermally transported out of the pegmatite and concentrated in apatite in the country rocks.

Formation of albitite dikes

The almost monomineralic nature of the albitite dikes (97% albite and minor molybdenite) rules out their formation by equilibrium magmatic crystallization. A purely metasomatic replacement of the host basalt or biotite schist is unlikely because of the sharp contact between the albitite and the country rocks. Moreover, the REE_N pattern of the albitite does not resemble that of the biotite schist (*cf.* Feng 1992). On the other hand, the bodies of albitite could represent felsic dikes that have been metasomatically altered. This interpretation is supported by the similarity of the REE_N profile of the albitite to that of aplite (Fig. 7). We therefore propose that the dikes are the products of a complete replacement of highly evolved granitic rocks by residual aqueous fluids, which evolved during the late-stage crystallization of the magma, *i.e.*, the precursor magmatic rock stewed in its own residual fluids. A question that needs to be addressed, however, is why quartz was removed completely from the rock, given that the residual fluids would have been quartz-saturated. The precursor may have been a spodumene-rich aplite, in which spodumene and quartz reacted with the fluid phase to form albite. This process has been predicted thermodynamically by Wood &

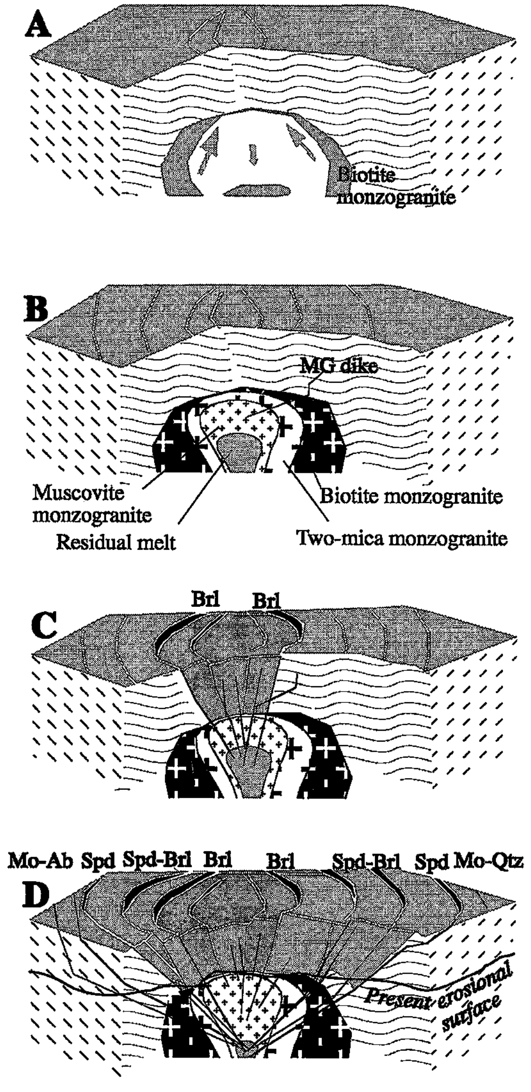

FIG. 11. Sketches depicting the proposed history of crystallization of the rare-element-enriched granitic magma of the Lamotte and Lacorne plutons. Note that if drawn to scale, the roof would appear several times thicker to represent its pre-intrusion thickness of about 10 km. A) Early side-wall crystallization produces marginal biotite monzogranite and less dense boundary-layer melts, which ascend to the roof of the magma chamber. These melts displace downward the denser crystal-mushes that formed earlier. B) Continued fractional crystallization forms successive two-mica and muscovite monzogranite layers and more differentiated melts. Late-stage crystallization moves toward the center of the chamber, where the residual magma continues to differentiate. A small portion of the more differentiated muscovite-bearing monzogranitic melt breaches the chamber and intrudes the country rocks as a dike (MG) in the Lacorne pluton. C) Expulsion of pegmatite-forming volatile-rich magma from the chamber owing fluid overpressure results in the emplacement of the beryl (Brl) pegmatite in the overlying monzogranite. D) Later contraction of the pluton, partly due to its advanced stage of crystallization, and to the cooling of magma, reactivates fractures in the country rocks and produces new fractures, into which the more evolved melts are intruded. This gives rise to the spodumene–beryl (Spd–Brl) and spodumene (Spd) pegmatites. Aqueous fluids exsolve from the spodumene pegmatites; some back-react with earlier-formed aplite and pegmatite to form Mo-bearing albitite (Mo–Ab), and some precipitate quartz and molybdenite as veins (Mo–qtz), in the country rocks.

Williams-Jones (1993) to be an inevitable consequence of the cooling of a fluid initially in equilibrium with spodumene-bearing pegmatite.

THE MAGMA CHAMBER

The (quasi-) concentric zonation displayed by the Lamotte and Lacorne plutons, *i.e.*, less evolved biotite monzogranite along the margin of the intrusions and the most evolved muscovite monzogranite in the center, suggests that the magma underwent side-wall crystallization, in which the earliest solidification occurred at the contact between the liquid and the intruded country-rocks. In the Lacorne pluton, the geochemical (Fig. 4) and mineral-chemical (Fig. 6, Mulja *et al.* 1995b) trends corroborate strongly the process of side-wall crystallization. The Lamotte pluton, which lacks observable systematic chemical variations across the monzogranites, could have been formed in a regime of slow solidification, as is the case for homogeneous plutonic rocks (Sawka *et al.* 1990). Furthermore, the comagmatic beryl and spodumene pegmatites, which represent the more and most evolved felsic liquids, respectively, cut all types of monzogranite, indicating that the liquids must have evolved toward the interior of the body of magma. On the basis of these geological and geochemical observations, we envisage an initial stage of side-wall crystallization that produced a crystal mush (biotite monzogranite) and a less dense boundary-layer liquid (Fig. 11A) [see McBirney *et al.* (1985) for a discussion of the dynamics of magma chambers]. According to this model, boundary-layer liquid rises buoyantly to the top of the chamber, displacing earlier-formed, denser crystal-mush layers from the roof. Convection and high density eventually drive these layers into the lower part of the chamber, where they undergo further upward crystallization. This stage of continued crystallization along the walls produced the more evolved two-mica monzogranite, which led to the ascent of an even more differentiated boundary-layer (Fig. 11B). In the Lacorne pluton, a portion of the biotite monzogranitic crystal-mush layer (southern biotite monzogranite) must have separated from the other layers prior to its complete consolidation, and must have begun its own pattern of side-wall crystallization. The separation and independent crystallization were necessary to produce the observed geochemical and mineral–chemical trends mentioned above. One cause for the separation of the southern biotite monzogranite was perhaps the emplacement of the magma along reactivated pre-existing fractures or along new ones. This tectonically induced emplacement of magma seems applicable also to the emplacement of the L-shaped muscovite monzogranite dike (labeled MG-dike, Fig. 1D), which suggests that a batch of somewhat evolved felsic liquid breached the walls of the magma chamber through fractures.

A consequence of the inward crystallization was the accumulation of more differentiated and volatile-rich batches of residual liquid, which were below an already lithified carapace. Fractures in the roof rocks, produced tectonically or by overpressures, provided the conduits for the early, beryl-pegmatite-producing liquid (Fig. 11C). At an advanced stage of crystallization, corresponding to the onset of withdrawal of the above liquid from the chamber, the pluton underwent contraction, producing conical fractures, analogous to those associated with the main events of caldera formation, and reactivated pre-existing east–west-trending fractures in the country rocks. These fractures tapped deep pockets of more evolved liquid, which was drawn upward and outward, solidifying as spodumene–beryl pegmatite along the margins of the plutons, and eventually as spodumene pegmatite in the country rocks (Fig. 11D). Crystallization of the spodumene pegmatite terminated with the exsolution of aqueous fluids from the melt, which formed systems of quartz veins or, in some cases, caused the albitization of the associated aplites. Molybdenum, which has a fluid/melt distribution coefficient greater than 1 (Candela & Holland 1984), partitioned into the residual fluid and concentrated as molybdenite in the veins and albitite. The proposed evolution of granite-related mineralization is consistent with the spatial distribution of pegmatites, and the proximity of the most evolved spodumene pegmatites to the dikes of albitite and the veins of quartz.

ORIGIN OF MOLYBDENITE-BEARING QUARTZ VEINS IN THE PREISSAC AND MOLY HILL PLUTONS

In contrast to the Lamotte and Lacorne plutons, where molybdenite is concentrated in albitite dikes and quartz veins that are spatially associated with spodumene pegmatite in the country rocks, molybdenite in the Preissac and Moly Hill plutons occurs almost exclusively in quartz veins in the muscovite monzogranite. Pegmatite bodies are relatively uncommon in these two plutons; they rarely contain beryl, never contain spodumene, and show no obvious spatial association with molybdenite-bearing quartz veins. The small size of the plutons and the fact that they did not undergo differentiation to the same extent as the Lamotte and Lacorne plutons are considered responsible for these characteristics. Consequently, vapor saturation occurred during crystallization of the muscovite monzogranite under a relatively thin crust of solidified magma, which was readily fractured. The exsolved fluid phase escaped through these fractures and formed molybdenite-bearing quartz veins in the muscovite monzogranite. This exsolution is reflected in the finer-grained nature of the monzogranite around the veins (Mulja *et al.* 1995b), which developed as a result of compositional quenching of the melt. Support for the above interpretation is provided by the fine-grained muscovite–garnet monzogranite dike, which contains small molybdenite-bearing vugs that probably represent the site of vapor-phase exsolution. Significantly, this dike crystallized late in the history of the pluton, and in fact cuts molybdenite-bearing quartz veins.

CONCLUSIONS

Field, petrochemical and oxygen isotope data for four peraluminous monzogranitic plutons that make up the Preissac–Lacorne batholith, taken in conjunction with geological and mineralogical indicators (Mulja *et al.* 1995b), have distinguished suites of comagmatic monzogranite and pegmatite subtypes, and shown that their compositional diversity was mainly the result of fractional crystallization. Magma in the Lamotte and Lacorne bodies underwent the most extensive differentiation, and evolved to the stage of producing rare-element-bearing pegmatites. The mechanism of fractionation in these plutons was side-wall crystallization, which developed quasi-concentrically zoned intrusive bodies. The rare-element-enriched pegmatites were derived from batches of residual melt trapped in the interior of the cooling plutons. Beryl and spodumene pegmatites were emplaced sequentially, the former filling pressure-induced fractures in the overlying parental monzogranites, and the latter filling extension fractures in the country rocks, reactivated and produced by contraction of the adjacent solidified plutons. The terminal stage of pegmatite evolution was marked by exsolution of an aqueous fluid, which in some places back-reacted with earlier-formed spodumene-bearing aplite to form albitite, and in other places separated from the parental bodies of pegmatite to precipitate quartz, muscovite and molybdenite in veins.

The Preissac and Moly Hill plutons underwent much less extensive differentiation than the Lamotte and Lacorne plutons, probably owing to their small size. Consequently, they did not evolve magmas capable of crystallizing rare-element-enriched pegmatite. Vapor saturation occurred during crystallization of the muscovite monzogranite under a relatively thin crust of solidified magma. The latter was readily fractured, allowing the exsolved fluid to escape into the overlying muscovite monzogranite, and there to form molybdenite-bearing quartz veins.

Acknowledgements

This study was supported financially by NSERC operating grants to AEW-J and SAW, a FCAR team grant to AEW-J, SAW and MB, and an MERQ contract to MB. Reviews by D. Kontak, R.F. Martin, D.B. Clarke, P. Černý and an anonymous referee helped improve the presentation of this manuscript.

References

Boily, M. (1995): Pétrogenèse du batholite de Preissac–Lacorne: implications pour la métallogénie des gisements de métaux rares. *Ministère des Ressources naturelles de Québec, rapp.* **ET93-05**.

Bourne, J. & Danis, D. (1987): A proposed model for the formation of reversely zoned plutons based on a study of the Lacorne complex, Superior Province, Québec. *Can. J. Earth Sci.* **24**, 2506-2520.

Boynton, W.C. (1984): Cosmochemistry of the rare earth elements: meteorite studies. *In* Geochemistry of Rare-Earth Elements (P. Henderson, ed.). Elsevier, Amsterdam, The Netherlands (63-107).

Breaks, F.E. & Moore, J.M., Jr. (1992): The Ghost Lake Batholith, Superior Province of northwestern Ontario: a fertile, S-type, peraluminous granite – rare-element pegmatite system. *Can. Mineral.* **30**, 835-875.

Burnham, C.W. & Ohmoto, H. (1980): Late-stage processes in felsic magmatism. *Mining Geol., Spec. Issue* **8**, 1-11.

Candela, P.A. & Holland, H.D. (1984): The partitioning of copper and molybdenum between silicate melts and aqueous fluids. *Geochim. Cosmochim. Acta* **48**, 373-380.

Černý, P., Goad, B.E., Hawthorne, F.C. & Chapman, R. (1986): Fractionation trends of the Nb- and Ta-bearing oxide minerals in the Greer Lake pegmatitic granite and its pegmatite aureole, southeastern Manitoba. *Am. Mineral.* **71**, 501-517.

________ & Meintzer, R.E. (1988): Fertile granites in the Archean and Proterozoic fields of rare-element pegmatites: crustal environment, geochemistry and petrogenetic relationships. *In* Recent Advances in the Geology of Granite-Related Mineral Deposits (R.P. Taylor & D.F. Strong, eds.). *Can. Inst. Mining Metall., Spec. Publ.* **39**, 170-206.

Chappell, B.W., White, A.J.R. & Wyborn, D. (1987): The importance of residual source material (restite) in granite petrogenesis. *J. Petrol.* **28**, 1111-1138.

Clark, G.S. & Černý, P. (1987): Radiogenic ^{87}Sr, its mobility, and the interpretation of Rb–Sr fractionation trends in rare-element granitic pegmatites. *Geochim. Cosmochim. Acta* **51**, 1011-1018.

Cullers, R.L. & Graf, J.L. (1984): Rare earth elements in igneous rocks of the continental crust: intermediate and silicic rocks, ore petrogenesis. *In* Rare Earth Element Geochemistry (P. Henderson, ed.). Elsevier, Amsterdam, The Netherlands (275-308).

Danis, D. (1985): *Pétrologie et géochimie du batholite de Lacorne.* Thèse de maîtrise, Univ. du Québec, Montréal, Québec.

Dawson, K.R. (1966): A comprehensive study of the Preissac–Lacorne batholith, Abitibi County, Québec. *Geol. Surv. Can., Bull.* **142**.

Dimroth, E., Imreh, L., Goulet, N. & Rocheleau, M. (1983): Evolution of the south-central segment of the Archean Abitibi belt, Quebec. III. Plutonic and metamorphic evolution and geotectonic model. *Can. J. Earth Sci.* **20**, 1374-1388.

Ducharme, Y., Stevenson, R.K. & Machado, N. (1995): Isotopic evolution of the La Motte and Preissac plutons, Abitibi. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **20**, A-26.

Feng, Rui (1992): *Tectonic Juxtaposition of the Archean Abitibi Greenstone Belt and Pontiac Subprovince: Evidence from Geobarometry, Geochemistry, and Ar–Ar Geochronology of Metasedimentary Rocks and Granitoids.* Ph.D. thesis, Univ. of Saskachewan, Saskatoon, Saskachewan.

________ & Kerrich, R. (1991): Single zircon age constraints on the tectonic juxtaposition of the Archean Abitibi greenstone belt and Pontiac Subprovince, Québec, Canada. *Geochim. Cosmochim. Acta* **55**, 3437-3441.

________ & ________ (1992): Geochemical evolution of granitoids from the Archean Abitibi Southern Volcanic Zone and the Pontiac subprovince, Superior Province, Canada: implications for tectonic history and source regions. *Chem. Geol.* **98**, 23-70.

________, Fan, J. & Kerrich, R. (1993): Noble metal abundances and characteristics of granitic magma series, Archean Abitibi belt, Pontiac subprovince: relationships to metallogeny and overprinting of mesothermal gold deposits. *Econ. Geol.* **88**, 1376-1401.

________, Kerrich, R. & Maas, B. (1993): Geochemical, oxygen and neodymium isotope compositions of metasediments from the Abitibi greenstone belt and Pontiac

Subprovince, Canada: evidence for ancient crust and Archean terrane juxtaposition. *Geochim. Cosmochim. Acta* **57**, 641-658.

FLYNN, R.T. & BURNHAM, C.W. (1978): An experimental determination of rare-earth partition coefficients between a chloride containing vapor phase and silicate melts. *Geochim. Cosmochim. Acta* **42**, 685-701.

GARIÉPY, C. & ALLÈGRE, C.J. (1985): The lead isotope geochemistry and geochronology of late kinematic intrusives from the Abitibi Greenstone Belt and the implications for late Archean crustal evolution. *Geochim. Cosmochim. Acta* **49**, 2371-2383.

GOAD, B.E. & ČERNÝ, P. (1981): Peraluminous pegmatitic granites and their pegmatite aureoles in the Winnipeg River district, southeastern Manitoba. *Can. Mineral.* **19**, 177-194.

HANSON, G.N. (1978): The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth Planet. Sci. Lett.* **38**, 26-43.

HARRIS, N.B.W., PEARCE, J.A. & TINDLE, A.G. (1986): Geochemical characteristics of collision-zone magmatism. *In* Collision Tectonics (M.P. Coward & A.C. Ries, eds.). *Geol. Soc., Spec. Publ.* **19**, 67-81.

HOLTZ, F. (1989): Importance of melt fraction and source rock composition in crustal granitoid genesis. The example of two granitic suites of northern Portugal. *Lithos* **24**, 21-35.

HOY, L.D. (1993): Regional evolution of hydrothermal fluids in the Noranda district, Quebec: evidence from $\delta^{18}O$ values from volcanogenic massive sulfide deposits. *Econ. Geol.* **88**, 1526-1541.

LONDON, D. (1986): Magmatic-hydrothermal evolution in the Tanco rare element pegmatite: evidence from fluid inclusions and phase equilibrium experiments. *Am. Mineral.* **71**, 376-395.

________ (1987): Internal differentiation of rare-element pegmatites: effects of boron, phosphorus and fluorine. *Geochim. Cosmochim. Acta* **51**, 403-420.

MAHOOD, G. & HILDRETH, W. (1983): Large partition coefficients for trace elements in high-silica rhyolites. *Geochim. Cosmochim. Acta* **47**, 11-30.

MANNING, D.A.C. & PICHAVANT, M. (1988): Volatiles and their bearing on the behavior of metals in granitic systems. *In* Recent Advances in the Geology of Granite-Related Mineral Deposits (R.P Taylor & D.F. Strong, eds.). *Can. Inst. Mining Metal., Spec. Pap.* **39**, 13-24.

MCBIRNEY, A.R., BAKER, B.H. & NILSON, R.H. (1985): Liquid fractionation. I. Basic principles and experimental simulation. *J. Volcanol. Geotherm. Res.* **24**, 1-24.

MCCARTHY, T.S. & HASTY, R.A. (1976): Trace element distribution patterns and their relationship to the crystallization of granitic melts. *Geochim. Cosmochim. Acta* **40**, 1351-1358.

MITTLEFEHLDT, D.W. & MILLER, C.F. (1983): Geochemistry of the Sweetwater Wash pluton, California: implications for anomalous trace element behaviour during differentiation of felsic magmas. *Geochim. Cosmochim. Acta* **47**, 109-124.

MULJA, T., WILLIAMS-JONES, A.E., MARTIN, R.F. & WOOD, S.A. (1995a): Compositional variation and structural state of Nb–Ta oxide minerals in rare-element granitic pegmatites from the Preissac–Lacorne batholith, Quebec. *Am. Mineral.* (in press).

________, ________, WOOD, S.A. & BOILY, M. (1995b): The rare-element-enriched monzogranite – pegmatite – quartz vein systems in the Preissac–Lacorne batholith, Quebec. I. Geology and mineralogy. *Can. Mineral.* **33**, 793-815.

NABELEK, P.I., RUSS-NABELEK, C. & DENISON, J.R. (1992b): The generation and crystallization conditions of the Proterozoic Harney Peak leucogranite, Black Hills, South Dakota, USA: petrologic and geochemical constraints. *Contrib. Mineral. Petrol.* **110**, 173-191.

________, ________ & HAEUSSLER, G.T. (1992a): Stable isotope evidence for the petrogenesis and fluid evolution in the Proterozoic Harney Peak leucogranite, Black Hills, South Dakota. *Geochim. Cosmochim. Acta* **56**, 403-417.

NASH, W.P. & CRECRAFT, H.R. (1985): Partition coefficients for trace elements in silicic magmas. *Geochim. Cosmochim. Acta* **49**, 2309-2322.

SAWKA, W.N., CHAPPELL, B.W. & KISTLER, R.W. (1990): Granitoid compositional zoning by side-wall boundary layer differentiation: evidence from the Palisade Crest Intrusive Suite, central Sierra Nevada, California. *J. Petrol.* **31**, 519-553.

SHEARER, C.K., PAPIKE, J.J. & JOLLIFF, B.L. (1992): Petrogenetic links among granites and pegmatites in the Harney Peak rare-element granite-pegmatite system, Black Hills, South Dakota. *Can. Mineral.* **30**, 785-809.

SVERJENSKY, D.A. (1984): Europium redox equilibria in aqueous solution. *Earth Planet. Sci. Lett.* **67**, 70-78.

TINDLE, A.G. & PEARCE, J.A. (1981): Petrogenetic modelling of in situ fractional crystallization in the zoned Loch Doon Pluton, Scotland. *Contrib. Mineral. Petrol.* **78**, 196-207.

TRUMBULL, R.B. (1993): A petrological and Rb–Sr isotopic study of an early Archean fertile granite–pegmatite system: the Sinceni pluton in Swaziland. *Precamb. Res.* **61**, 89-116.

WOOD, S.A. & WILLIAMS-JONES, A.E. (1993): Theoretical studies of the alteration of spodumene, petalite, eucryptite and pollucite in granitic pegmatites: exchange reactions with alkali feldspars. *Contrib. Mineral. Petrol.* **114**, 255-263.

Received June 13, 1994, revised manuscript accepted January 11, 1995.