

# LITHIUM GEOCHEMISTRY AND THE SOURCE OF THE SPODUMENE PEGMATITES OF THE PREISSAC- LAMOTTE-LACORNE REGION OF WESTERN QUEBEC

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## ABSTRACT

Sixty-seven separated minerals and 45 rocks from the Preissac-Lamotte-Lacorne batholiths in western Quebec have been analyzed for Li by a spectrochemical method. The batholithic rocks include amphibolite, hornblende monzonite, biotite granodiorite, biotite-muscovite granite, aplite and pegmatite. The granites are unusually rich in Li which is mainly contained in biotite and muscovite. The region thus constitutes a Li-rich geochemical province, which is also demonstrated by the presence of spodumene pegmatites of economic value.

The source of the spodumene pegmatites has been attributed to fractional crystallization of the batholith magmas on the basis of previous field investigations. The present data substantiate this theory and attempt to explain why the Li-pegmatites are mainly associated with the Lacorne mass.

## INTRODUCTION

The Rouyn-Val D'Or-Amos region of northern Quebec has been a major producing area of gold and base metals for many years. More recently, numerous spodumene pegmatites have been discovered in the north-eastern part of the area, associated with a batholithic complex of quartzo-feldspathic plutonic rocks: spodumene is currently being mined from some of these pegmatites by the Quebec Lithium Corporation. In view of the economic interest of these pegmatites much geological work has been done in the region and it has been concluded that the pegmatites are genetically related to the batholithic rocks. The latter occur in three main masses, known as the Lacorne, Lamotte and Preissac complexes, from the townships in which they are principally exposed.

L. B. Halferdahl (1954) made a survey of minor element distribution in rocks of the region, using spectrochemical methods of analysis. His work included some Li determinations but, owing to the low sensitivity of the spectral line used, there were insufficient data to study in detail the distribution of Li or to investigate directly the source of lithium mineralization.

During the summer of 1955 the first author carried out mapping in Lamotte township in a Quebec Department of Mines field-party directed

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by R. E. Jones. A subsequent programme of spectrochemical analysis for Li in rocks and minerals of the batholithic masses was carried out in collaboration with the second author, to study the geochemistry of lithium in an area of economic importance and investigate the source of the spodumene deposits. The present paper summarizes a thesis completed by the first author (Siroonian, 1957).

The authors wish to acknowledge the generous assistance of research funds by the Geological Survey of Canada and the National Research Council. In addition to specimens collected by the first author numerous samples collected by L. B. Halferdahl were made available by the kindness of Dr. J. E. Hawley, Department of Geological Sciences, Queen's University. The Quebec Department of Mines kindly gave permission to use material from unpublished reports.

#### GENERAL GEOLOGY

Much reconnaissance and detailed geological mapping has been carried out in the Preissac-Lacorne area. The following paragraphs give a general account of the areal geology pertinent to the present paper. Further details are available in works by Wilson (1913), Cooke, James and Mawdsley (1931), Gerrie (1927), Gussow (1937), Norman (1944), Tremblay (1950), Ingham (1949), Latulippe (1953), Rowe (1953), Dawson (1954), Halferdahl (1954), and Jones (1955, 1956).

The rocks of the Preissac-Lamotte-Lacorne batholiths occur in a belt of Precambrian sedimentary and volcanic rocks which trends roughly east-west and includes the Kinojevis, Malartic, and Kewagama Groups. The Kinojevis and Malartic Groups are dominantly flows and pyroclastics (now schists) of silicic, intermediate, basic, and ultrabasic composition. The Kewagama Group consists of schists of mainly sedimentary origin derived from greywacke, sandstone, and conglomerate. Into these rocks were intruded minor bodies of basic to silicic igneous rocks, following which the batholithic rocks were emplaced. Diabase dykes of presumed late Precambrian age are the youngest consolidated rocks in the area.

The Lacorne batholith outcrops in the eastern part of the area, occurring in parts of Lacorne, Fiedmont, Senneville, Vassan, and Lamotte townships. The Lamotte mass occurs to the north-west in Lamotte, Preissac, Figuery, and Villemontel townships, while the Preissac batholith occurs in the townships of Preissac and Lamotte, being located south of the Lamotte mass. Similar rock-types occur in all three batholiths, which are believed to be magmatic bodies of common parentage (see Tremblay, 1950), probably derived by crystal fractionation. Only the

Lacorne mass is strictly large enough to be classed as a batholith, but the three bodies outcrop over an area exceeding 250 square miles.

The rock-types constituting and derived from the batholiths include amphibolite, hornblende monzonite, biotite-hornblende granodiorite, biotite granodiorite, biotite-muscovite granite, aplite, and pegmatite. The following petrographic descriptions are taken from the reports of Tremblay and Jones.

Amphibolite occurs as irregular masses up to a half square mile in area and has been found only in the Lacorne batholith. Hornblende forms grains up to 1 inch across: it constitutes 65–95% of the rock and usually exceeds 80%. Plagioclase (An 28) is the other principal constituent, but small amounts of augite, microcline and quartz are present. Jones (1956) also recognizes a diorite, which resembles the amphibolite but contains less hornblende (50–70%) and a more sodic plagioclase (An 20).

Hornblende monzonite mainly consists of hornblende, zoned plagioclase (An 10–26), and microcline. The proportions are as follows: hornblende, 34%; plagioclase, 40%; microcline, 22%; accessory quartz. In the margins of the Lacorne mass the monzonite has undergone hydrothermal alteration (Tremblay, *op. cit.*) to form a biotite-hornblende granodiorite with the following mode: biotite, 3.5%; hornblende, 15%; plagioclase, 52%; microcline, 10%; quartz, 15%. Further alteration at the eastern contact in Fiedmont Township has given rise to biotite granodiorite with no hornblende (Jones, 1955). Magnetite, titanite, apatite, and zircon are accessories in all of the hornblende rocks whereas sericite, epidote, chlorite, and biotite are secondary.

The main bodies of biotite granodiorite contain zoned plagioclase; An 18–23 in the Lacorne mass according to Tremblay (1950), and, in the Lamotte mass, core An 25–40, rim An 10–25 (Jones, 1956). The mineral proportions are as follows: biotite, 10%; plagioclase, 54–70%; microcline, 5%; quartz, 15–27%; accessory epidote, chlorite, muscovite, sphene, and magnetite.

The biotite-muscovite rocks contain about 40% plagioclase, 24% microcline, 30% quartz, some myrmekite, and about 5% mafic minerals: the latter include muscovite, biotite, garnet, and the usual accessories. In the Lacorne mass Tremblay (1950) found the plagioclase to be albite (An 4–7) and calls the rock granite: in the Lamotte mass Jones (1956) found a more calcic feldspar (An 11–13) along with interstitial albite, and calls the rock quartz-monzonite. The difference is slight, and, for convenience, both can be considered to be granite.

Jones (1956) found the plagioclase of both the biotite granodiorite and the biotite-muscovite granite (quartz-monzonite) to be more calcic in the Lamotte than in the Lacorne mass.

The areal distribution of these rock-types is important to the later discussion and is shown in Figure 1. The Lacorne mass is the only one which shows all the rock-types described above, but at the current level of erosion about 75% of the batholith consists of monzonite and hornblende is, therefore, the dominant mafic mineral. The Lamotte and Preissac masses mainly consist of granite (95% of the former and 45% of the latter), the remainder being biotite granodiorite, and micas are the principal dark minerals.

Aplite and pegmatite bodies are abundant, both in the batholithic rocks and in nearby schists. They commonly occur together, showing gradational contacts. The aplites usually consist of quartz and two feldspars, with minor muscovite and garnet. Most of the pegmatites are similar in composition to the aplites, but those of economic interest also contain spodumene, beryl, lepidolite, columbite-tantalite: numerous other rare minerals have been identified. An account of the pegmatites has been given by Rowe (1953), who states that no complex pegmatites have been located in or near the Preissac complex. Most of the complex pegmatites occur in a roughly east-west zone near the northern margins of the Lamotte and Lacorne masses, and Halferdahl (1954) states that the Lacorne batholith contains three times as many lithium-bearing pegmatites as the Lamotte mass. Derry (1946), Tremblay (1950), Rowe (1953), and Halferdahl (1954) all adduce field and laboratory evidence that the lithium pegmatites crystallized from a residual melt from the biotite-muscovite granite: the evidence need not be summarized here.

The genetic aspects of the series have been studied by Tremblay (1950 pp. 49-58), who finds an hypothesis of magmatic differentiation of a basic magma adequate to explain the observed facts: details of the differentiation mechanism are not explained in Tremblay's report.

#### ANALYSIS

At each outcrop to be sampled several pounds of fresh rock chips were taken. These were crushed and quartered. The samples obtained from Queen's University had been treated in a similar manner. About 100 grams of the pulp was split into two portions, one of which was ground to a fine powder for rock analysis; the other portion was crushed and screened, saving the 100-200 mesh fraction for mineral separation. Minerals were isolated using a Frantz Isodynamic Separator, heavy liquids, rolling on coarse paper (for micas), and hand-picking. Clean separations (less than 2% impurities) were obtained for most minerals, but the feldspars were difficult to separate from each other. The resulting fractions were then ground to a fine powder.

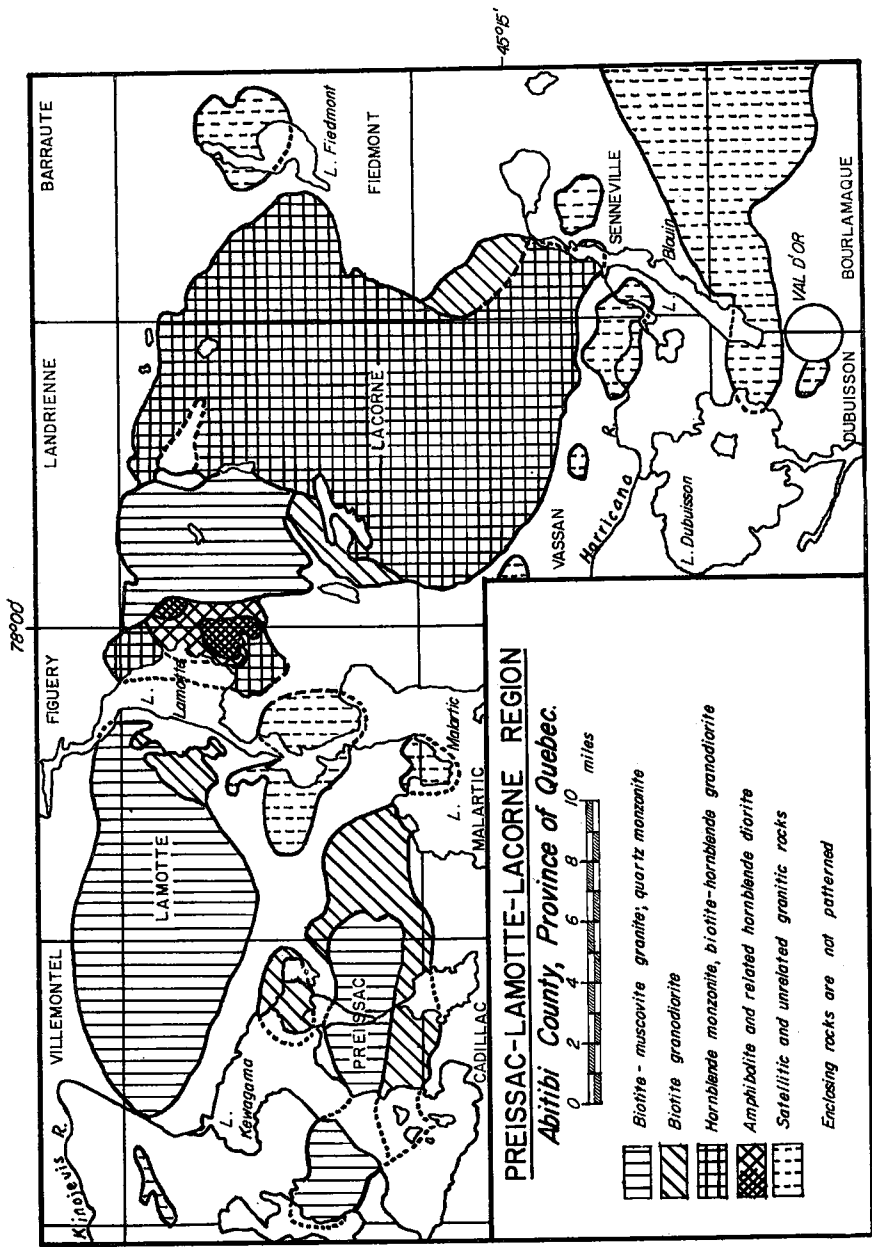


FIG. 1. Generalized geological sketch-map of Preissac-Lamotte-Lacorne Region.

Samples were analyzed by spectrochemical methods. Two techniques were developed, the first for minerals (excluding feldspars) using the lines Li 6707.844 Å and 6103.642 Å, with Na 6160.760 Å as internal standard: details are given in Table 1. The second, for rocks, used the lines Li 3232.61 Å and In 3258.56 Å (internal standard): details differing from Table 1 are given in Table 2. Working curves were constructed by arcing synthetic standards containing Li in the range 3.16–3160 ppm (first method) and 25–500 ppm (second method), plotting the log intensity ratio analysis line/internal standard line *vs.* log concentration (background corrections were unnecessary). An Applied Research Laboratories

TABLE 1. SPECTROCHEMICAL ANALYSIS PROCEDURE FOR MINERALS EXCLUDING FELDSPARS

Instrument	21 foot Jarrell-Ash grating spectrograph (1st order dispersion 5.2 Å/mm)
Condensing optics	Arc focused on an adjustable diaphragm by a 10 cm. spherical lens. Diaphragm focused on the slit by a 6.7 cm. cylindrical lens with axis vertical and focused on spectrograph mirror by a 45 cm. cylindrical lens placed at the slit with axis horizontal
Anode	1/8" crater graphite electrode (National Carbon Co. Special Grade)
Cathode	1/8" graphite electrode (National Carbon Co. Special Grade)
Electrode gap	10 mm
Wave length range	5600–6900 Å
Current	7 amperes D.C.
Exposure time	40 seconds
Step sector	8 steps (intensity ratio $\log I_0/I = 0.2$ )
Density filter	Metal screen, mesh #150
Slit width	30 microns
Slit length	5 mm
Optical filter	Yellow, Corning #3486, cut-off about 5000 Å
Photographic plates	Eastman Kodak, Type III-F
Buffer	1 part NaCl to 9 parts SiO <sub>2</sub> (Na as internal standard)
Sample	9 parts buffer to 1 part mineral, mixed for 2 minutes in a Wigglebug
Sintering	Filled electrodes were dried and sintered to a red heat for 10 to 15 seconds in a blow-pipe flame
Plate calibration	Iron electrodes, 10-second exposure at 3.5 amperes, the other parameters as above
Processing	3 minutes in Kodak D-19 developer at 20°C (constant manual agitation), 10 seconds in 2.5% acetic acid stopbath, 10 minutes in acid fix, 20–30-minute continuous-flow water bath; plates were dried at room temperature in a dust-free enclosure

TABLE 2. SPECTROCHEMICAL ANALYSIS PROCEDURE FOR ROCKS AND FELDSPARS

Wave length range	2200–3500 Å
Current	4 amperes D.C.
Exposure time	90 seconds
Filter	None
Photographic plates	Eastman Kodak, Type S.A.I
Buffer	NaCl containing 0.25% In as In <sub>2</sub> O <sub>3</sub> (internal standard)
Sample	1 part buffer to 9 parts rock
Processing	4 minutes at 22°C in Kodak D19 (constant manual agitation): other details as before

photo-densitometer was used to measure line blackness, and plate calibration curves were constructed using the 2-step method (Harvey, 1950) with an iron-arc spectrum. Initially each plate was calibrated, but this was later found to be unnecessary. The matrices of the synthetic standards had the compositions given below and were made using materials free of detectable Li: lithium was added as the carbonate.

Standard Matrix for First Method		Standard Matrix for Second Method	
SiO <sub>2</sub>	36	SiO <sub>2</sub>	74.4
Al <sub>2</sub> O <sub>3</sub>	18	Al <sub>2</sub> O <sub>3</sub>	14.4
MgO	14	KCl	5.6
CaCO <sub>3</sub>	18	Pyroxene	5.6
Fe <sub>2</sub> O <sub>3</sub>	14		
	100		100.0

In the first method, using Na as internal standard, some of the minerals analyzed might be expected to contain Na as a constituent. Constancy of the absolute intensity of the Na line used (within experimental error) indicated negligible contamination, however, and this source of error was consequently ignored.

Reproducibility error was found from replicate analyses to be about 10%. To check on systematic error (bias) three standards were analyzed. These were the well-known granite and diabase samples G1 and W1, and a synthetic standard prepared by Spex Industries Inc. to contain 1000 ppm of 43 elements in a graphite base. The granite G1 has a recommended Li content of 22 ppm (Ahrens, 1954), and four analyses gave 32, 29, 29 and 26 ppm, averaging 29 ppm: W1 has a recommended value of 9 ppm, and three analyses gave 11, 8.5 and 9.5, averaging 9.7 ppm: two analyses of the Spex Industries standard both gave 985 ppm.

#### LITHIUM IN THE MINERALS

The analysis results for individual minerals are presented in Tables 3, 4 and 5, and the data are summarized in Table 6. In considering the significance of these results it must be borne in mind that minor elements in minerals cannot be assumed to be bound at atomic sites in the structure without first considering other possibilities. Elements may occur in minerals in one or more of the following ways:

- (a) in mechanically admixed impurities,
- (b) in inclusions and alteration products,
- (c) in lattice voids or cavities,
- (d) in an adsorbed phase located at surfaces and in structure imperfections.
- (e) in isomorphous replacement, bonded at regular atomic sites.

TABLE 3. LI CONTENT OF HORNBLLENDE FROM THE LACORNE COMPLEX

Rock No.	Rock	Li ppm
La3	Amphibolite	105
D412	Hornblende monzonite	442
D67	" "	193
D413	" "	257
D71	" "	88
B5	" "	170

TABLE 4. LI CONTENT OF MICAS

Rock No.	Rock	Li ppm	
		Biotite	Muscovite
<u>LACORNE COMPLEX</u>			
Da496	Biotite granodiorite	1640	—
Da499	" "	x	—
H1	Biotite muscovite granite	x	2930
H2	" "	3120	2740
H3	" "	1580	—
H4	" "	x	x
H5	" "	x	x
H6	" "	x	x
H7	" "	—	2430
H8	" "	x	x
J2	" "	x	x
J3	" "	—	x
J4	" "	—	x
ApH1	Aplite	—	680
<u>LAMOTTE COMPLEX</u>			
Da228	Biotite granodiorite	660	—
Da546	" "	490	—
K1	Biotite muscovite granite	x	x
K2	" "	—	x
K3	" "	x	2260
K4	" "	x	—
K5	" "	2080	1480
K6	" "	—	2830
K7	" "	2510	—
K8	" "	3070	—
N1	" "	—	3130
N2	" "	2370	—
N3	" "	x	—
N4	" "	x	—
N5	" "	3000	—
N6	" "	1630	1050
N7	" "	x	960
N8	" "	520	—
<u>PREISSAC COMPLEX</u>			
D559	Biotite granodiorite	270	—
D363	Biotite muscovite granite	1530	2040
D572	" "	—	660
D2	" "	—	630

— Mineral not present or not available.

x Li content in excess of 3200 ppm.



TABLE 5. LI CONTENT OF MINERALS OF THE LACORNE ROCKS

		Li ppm							
		Hornblende	Epidote	Biotite	Muscovite	Quartz	Total Feldspar	Microcline	Garnet
La3	Amphibolite	105	—	—	—	—	—	—	—
B5	Hornblende monzonite	170	23	—	—	—	22	*	—
F5	Biotite granodiorite	—	36	390	—	52	22	—	—
J2	Biotite muscovite granite	—	—	x	x	89	220	—	—
ApH1	Aplite	—	—	—	680	17	27	—	140
L10	Simple pegmatite	—	—	—	970	22	—	*	—
L11	Spodumene pegmatite	—	—	—	1190	—	—	*	—

\*not detected.

— mineral not present or not available.

x Li in excess of 3200 ppm.

TABLE 6. SUMMARY OF LI CONTENT OF MINERALS

Mineral	Number of samples	Li ppm	
		Range	Average
Quartz	4	17- 89	45
Microcline	3	*	*
Total Feldspar	4	22-220	73
Hornblende	6	88-442	209
Epidote	2	23- 36	30
Garnet	1		140
Biotite	25	270- > 3200	>2500
Muscovite	22	630- > 3200	>2500

Symbols as in Table 5.

These varied possibilities have seldom been given much attention in past literature, but Jedwab (1953) and Kutina (1957) have recently given interesting discussions, and DeVore (1955) has considered the possible effects of absorption in some detail.

Contamination by foreign grains, microscopic inclusions, and alteration products may be largely ignored in the light of earlier remarks on sample preparation. However, the influence of small inclusions (solid or fluid) not revealed by the microscopic examination cannot be assessed. With regard to possibilities (c) and (d), it seems best to consider these as alternatives in cases where isomorphous replacement appears unlikely in the light of crystal, chemical and bonding theory.

The geochemistry of lithium was first studied in detail by Strock (1936) and has been summarized by Rankama & Sahama (1950) and Goldschmidt (1954). In magmatic rocks and minerals lithium accumulates in

ferromagnesian silicates as a result of its geometric preference for 6-fold co-ordination. The ionic radii (Å) of some octahedrally co-ordinated ions follow (Ahrens, 1952):

Al <sup>+3</sup>	.51	Li <sup>+1</sup>	.68
Fe <sup>+3</sup>	.64	Ti <sup>+4</sup>	.68
Mg <sup>+2</sup>	.66	Fe <sup>+2</sup>	.74

Li is within  $\pm 15\%$  of the radii of both the major cations (Mg<sup>+2</sup> and Fe<sup>+2</sup>) and is therefore eligible for camouflage or lattice substitution, but, owing to its lower charge, the coupled replacement of a trivalent ion would be necessary. Li<sup>+1</sup> would, therefore, enter suitable structures by "admission", providing a mechanism for concentration of Li in late magmatic fractions (Strock, 1936).

The data of Table 6 show a clear tendency for Li to concentrate in micas and hornblende, with lower figures for epidote, feldspar, and quartz. This agrees with the view that Li is admitted to minerals with octahedral positions, and this is further substantiated by the analyses of co-existing minerals from individual rocks, given in Table 5. Where two micas occur in the same rock it is seen (Table 5) that the Li concentration is about the same in each: (there might be a tendency for biotite to contain a little more than muscovite, but this cannot be fully substantiated because of the experimental error in the determination). Moreover, the mica analyses in Table 4 show that biotite in granodiorite generally has less Li than biotite in the associated but later granite: this supports the admission hypothesis, whereby Li would tend to be stored up in later magmatic fractions.

The analyses for Li in the minerals show quite definitely that the Li content of the micas in the granites are not the same for each of the masses. This is best demonstrated by calculating the average for each mica in the granite of each complex, taking the conservative estimate that an "x" in Table 4 signifies only 3200 ppm. The averages are as follows:

	Biotite	Muscovite
Lacorne	3010 ppm	3050 ppm
Lamotte	2640	2260
Preissac	1530	1110

In spite of the small number of samples from the Preissac mass, it is clear that the micas of the Lacorne granite contain more Li than the micas of the Lamotte granite, whereas the Preissac granite has the least Li in the micas.

Table 4 further shows that in the granodiorites the order of decreasing Li enrichment in biotite is also in the order Lacorne-Lamotte-Preissac. These relations are summarized in Figure 2.

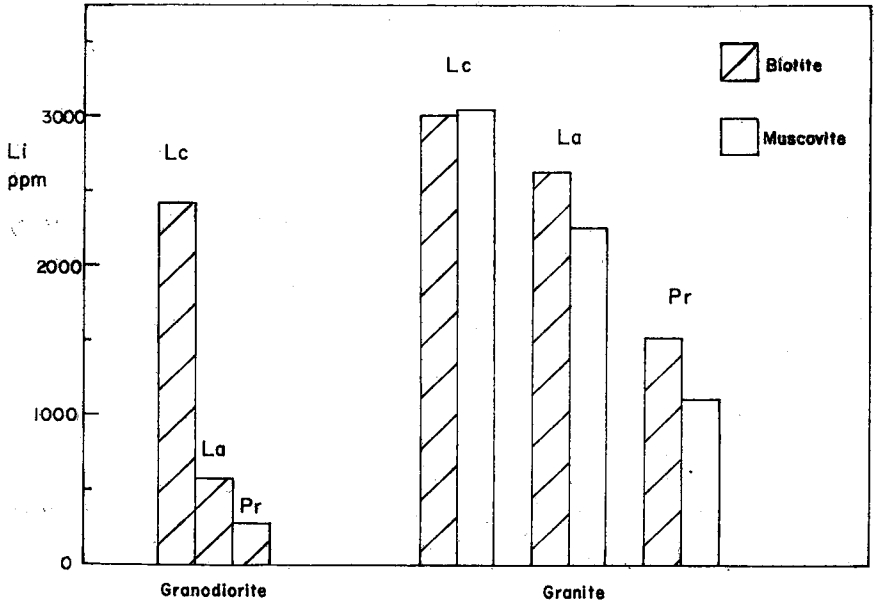


FIG. 2. Li content of the average biotite and muscovite in the granodiorites and granites of the Lacorne (Lc), Lamotte (La) and Preissac (Pr) complexes.

#### LITHIUM IN THE ROCKS

The results for the 45 batholithic rocks analysed are given in Table 7, and are summarized in Table 8.

It may be seen that the Li content of the rocks increases in the sequence amphibolite–monzonite–granodiorite–granite, decreasing again to low values in aplite. The increase is to be expected from the previous discussion of minerals, whereby Li is concentrated into the later magmatic fractions. The aplite will be discussed later with the pegmatites. The averages in Table 8 also clearly show that the Lacorne granite is the richest in Li of all the rocks analysed, although the associated biotite granodiorite for some reason has less Li than the granodiorite of both Lamotte and Preissac masses.

The last line in Table 8 shows the average composition of each mass, obtained by weighting each average rock-type by the percentage surface area (obtained from the Figure 1). The lower average for the Lacorne mass reflects the predominance of monzonite over granite and granodiorite.

It is of interest at this point to consider the Li content of the granites in relation to analyses from other massifs. Some figures from the literature

TABLE 7. LI CONTENT OF THE ROCKS

Sample No.	Rock	(Twp.)	Location (Range)	(Lot)	Li ppm
<b>LACORNE COMPLEX</b>					
La1	Amphibolite	Lac.	VII	3	*
La2	"	"	VII	3	*
La3	"	"	IX	34	*
B4	Hornblende monzonite	Fig.	VII	1	23
B5	"	"	VI	6	20
B7	"	"	V	12	20
C5	"	Vas.	IX	26	*
C10	"	"	X	53	*
E3	"	Lac.	I	41	*
E5	"	Vas.	IX	40	*
E6	"	"	IX	54	*
P4	"	Lam.	IV	41	*
Da496	Biotite granodiorite	Lac.	III	11	35
F5	"	Sen.	VII	5	20
F6	"	"	VI	6	20
H1	Biotite-muscovite granite	Lac.	IX	14	140
H3	"	"	VIII	16	89
H5	"	"	VI	13	390
H8	"	"	V	11	310
J2	"	"	VIII	21	290
J4	"	"	VII	30	270
ApH1	Aplite	"	IX	14	49
<b>LAMOTTE COMPLEX</b>					
J1715	Biotite granodiorite	Lam.	IX	36	27
R2826	"	"	VIII	26	140
K2	Biotite-muscovite granite	Prei.	IX	26	93
K4	"	"	IX	37	95
K6	"	"	IX	48	120
K8	"	Lam.	IX	7	66
L1	"	Vill.	I	37	120
L3	"	Fig.	I	1	160
L5	"	"	I	19	330
L10	"	Lam.	X	45	40
M2	"	"	IX	1	120
M4	"	"	VII	2	160
N1	"	Fig.	I	28	150
N3	"	"	I	27	240
N5	"	Lam.	IX	28	74
N8	"	"	VIII	26	23
ApL2	Aplite	Prei.	X	44	8
<b>PREISSAC COMPLEX</b>					
Q4	Biotite granodiorite	Prei.	V	10	32
R1	"	Lam.	IV	22	69
O1	Biotite-muscovite granite	Prei.	III	29	25
O7	"	"	II	44	110
R3	"	Lam.	II	4	32
U4	"	Prei.	IV	13	180

\*Signifies not detected.

Each analysis is the average of three.

Township names abbreviated as follows: Lacorne, Lac.; Fiedmont, Fig.; Vassan, Vas.; Lamotte, Lam.; Senneville, Sen.; Preissac, Prei.; Villemonteil, Vill.; Figury, Fig.

TABLE 8. SUMMARY OF LI CONTENT OF THE ROCKS

Rock	Lacorne			Lamotte			Preissac			Grand Average
	Number of samples	Li		Number of samples	Li		Number of samples	Li		
		Range	Average		Range	Average		Range	Average	
Amphibolite	3	*	*	-	-	-	-	-	*	
Monzonite	9	*- 23	7	-	-	-	-	-	7	
Granodiorite	3	20- 35	25	2	27-140	83	2	32- 69	50	
Granite	6	89-390	248	14	23-325	127	4	25-180	87	
Aplite	1		49	1		8	-		29	
Weighted average (see text)			40			125			67	62

Symbols as in Table 5.

TABLE 9. THE LI CONTENT OF VARIOUS GRANITES

Rock type	Analyst	Li ppm	Age
Transgressive Granophyre	Wager & Mitchell (1951)	20	Tertiary
Acid Granite	Wager & Mitchell (1951)	13	Tertiary
Acid Rocks (Av.)	Nockolds & Mitchell (1948)	20	Caledonian
Ademellite	Nockolds & Mitchell (1948)	40	Caledonian
White Mtn. Granite (U.S.A.)	Webber (1952)	48	Mississippian
Finnish Granites (Av.)	Webber (1952)	44	Precambrian
German Granites (Av.)	Strock (1936)	179	Precambrian
Irish Lavas (rhyolitic)	Patterson (1951)	80	Tertiary
Swedish Granites	Lundegardh (1946)	70	Precambrian
North American Granites	Deleon & Ahrens (1957)	44	
Yugoslavian Granites	Deleon & Ahrens (1957)	34	
Lacorne Granite	This paper	248	Precambrian
Lamotte Granite	This paper	127	Precambrian
Preissac Granite	This paper	87	Precambrian
Average Granite (World)	Strock (1936)	150	
Average Granite (World)	Horstmann (1957)	40	
Av. Granite (Preissac-Lacorne)	This paper	151	Precambrian

have been assembled in Table 9, along with the results from the present study. With the exception of Strock's analyses the Preissac-Lacorne granites are considerably richer in Li than most other granites. It is clear that the area is a geochemical province marked by a high Li abundance, quite apart from the evidence of the economic deposits. This would also be true if the Preissac-Lacorne granodiorites were included in the comparison; that is, the meaning of "granite" is irrelevant to the present argument (some of the rocks referred to in Table 9 may well be granodiorite or tonalite).

#### ORIGIN OF THE PEGMATITES

It should be stressed at once that the following argument is concerned only with geochemistry, although it deals with the hypothesis based on

field geology and petrography that the spodumene pegmatites represent products of residual magmatic solutions derived from fractional crystallization of the batholithic rocks. This hypothesis is confirmed and extended, for the association of the spodumene pegmatites with the Lacorne mass can be partially explained.

The main features brought out by the field studies are as follows:

(i) Differentiation at depth of a magma more basic than any of the exposed rocks gave rise successively, to a hornblende monzonite magma, then to the magma from which biotite granodiorite, muscovite granite, pegmatite, aplitite, and quartz veins crystallized.

(ii) Both Tremblay (1950) and Jones (1955, 1956) suggest that the hornblende monzonite magma was largely crystalline when it came into place. Microcline and albite formed interstitially as the result of local differentiation, some fractionation being achieved by zoning of plagioclase crystals.

(iii) Granite magma was injected later, to cut hornblende monzonite in the Lacorne mass, and to form the Lamotte and Preissac masses. This magma continued to differentiate in place, the different fractions giving rise to biotite granodiorite on the one hand, and muscovite granite, pegmatite, aplitite, and quartz veins, on the other.

Tremblay (1950) has shown well-marked geochemical trends for the major oxide components in each of the three principal rocks of the Lacorne mass, the percentage of the oxides being shown as a function of  $\text{SiO}_2$  percentage. Comparison of these trends with those found for an average andesite, dacite, and rhyolite suggested to Tremblay (1950) that the rocks of the Lacorne complex might have formed as the results of differentiation by fractional crystallization of a basaltic magma at depth: (there is no evidence to indicate whether this primary magma was basaltic or dioritic). Progressive decrease of  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ , and particularly  $\text{MgO}$  in the more silicic members, and concomitant increase of  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ , are in accord with an hypothesis of fractional crystallization. Tremblay suggested this hypothesis in the light of field geology and petrography.

A marked increase of  $\text{Li}$ , parallel to that of  $\text{SiO}_2$ , and contrary to that of  $\text{MgO}$ , in each of these three rocks of the Lacorne mass is brought out in Figure 3. The  $\text{Li}$  trend can be extended to the amphibolite: a similar (but restricted) trend can be followed for each of the other two masses of the complex. The trend for the Lacorne mass can be followed, not only in the rock analyses, but also in each mineral, as shown in Table 5. The increase becomes very marked in the muscovite granite, which is consistent with hypotheses of differentiation by fractional crystallization and concentration of  $\text{Li}$  by failure of admission to early-formed crystals,

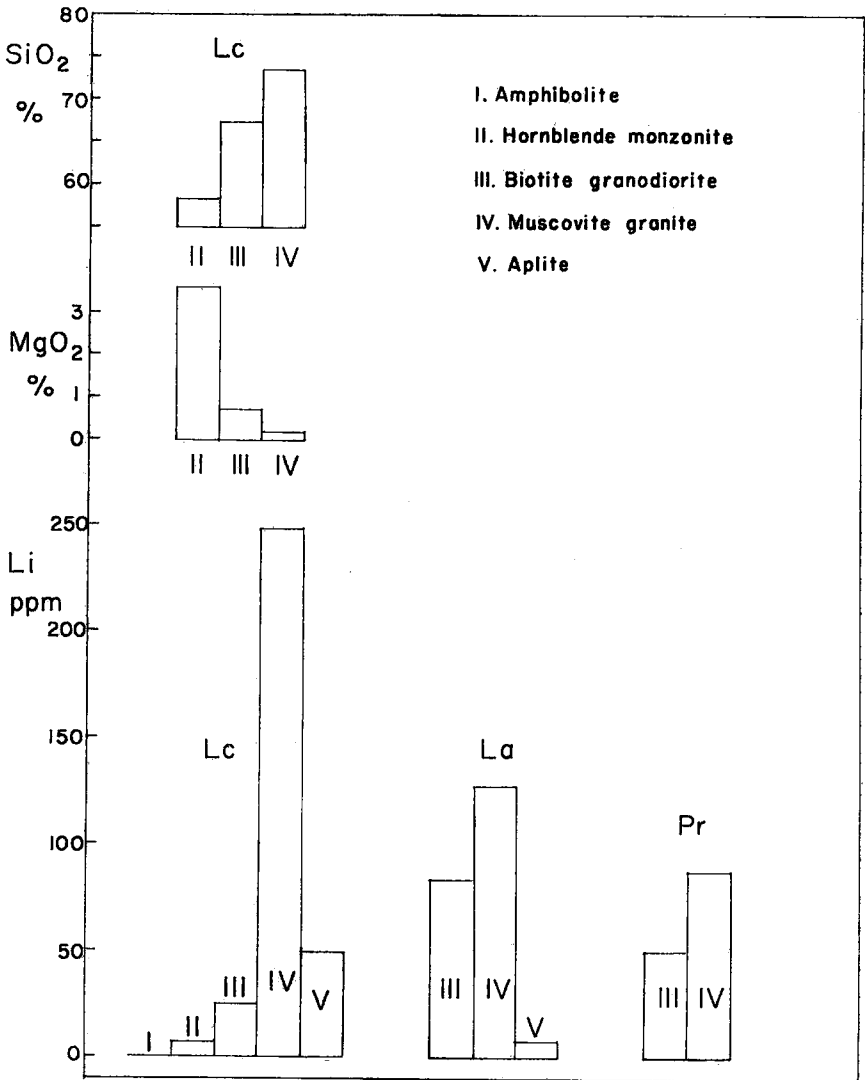


FIG. 3. Some geochemical trends in rocks of the Lacorne (Lc), Lamotte (La), and Preissac (Pr) masses (values for SiO<sub>2</sub> and MgO from Gussow, 1937).

enrichment in this case following a hyperbolic curve (Neumann, 1948). For comparison of the muscovite and biotite bearing rocks, the content of Li in the micas can probably be taken as proportional to that in the residual fluids in equilibrium with the micas, although rock analyses of biotite granodiorite and aplite of the Lacorne mass (Table 8) indicate anomalous low values, to be explained later.

Analyses of both minerals and rocks (Tables 5 and 8) clearly indicate that the greatest enrichment in Li is in the muscovite granite of the Lacorne mass, granites of the Lamotte and Preissac masses having, respectively, less Li. Micas from the three masses indicate a parallel trend, as shown in Figure 2, in spite of the anomalous low value for biotite granodiorite rock of the Lacorne mass (Table 8).

Among the granites, the Lacorne mass represents the product of the most advanced differentiation of the parent magma up to the time of its injection. This is supported, not only by the geochemical culmination of Li, but also by the higher content of pegmatitic material indicating concentration of volatiles, and, further, by the more sodic plagioclase feldspar when compared, at least, with the Lamotte mass.

In all three masses the residual magmas crystallized to form pegmatites, aplites, and quartz veins, which were emplaced in suitable structural loci, as described by Rowe (1953) and Tremblay (1950). That the Lacorne granite magma was somewhat richer in Li than the Lamotte, and considerably richer than the Preissac, explains the spatial distribution of the spodumene pegmatites, that is, in close association with the Lacorne, to a less degree with the Lamotte, and not at all with the Preissac mass.

All the geochemical features of the distribution of Li in the minerals and rocks so far discussed agree with the hypothesis of enrichment by differentiation, with the exception of two anomalies mentioned above. The first of these is the low Li content of the biotite granodiorite of the Lacorne mass. The second is the low Li content of aplite and its contained muscovite (Tables 4, 5, and 8).

The low content of Li in the biotite granodiorite might be the result of a low mica content, since modes of the specimens are not known. But the biotite from the rock (F5) shown in Table 5 is also low in Li, this specimen coming from the body lying southeast of the hornblende monzonite in Senneville township, and far removed from muscovite granite. The two results for biotite from the rocks given in Table 4 (Da 496, 499) are from a body in Lacorne township which is associated with muscovite granite. These both show high Li content, and the average of these two values is used for Figure 2. The average value in Table 8 is made up of two specimens from the Senneville body and only one from the Lamotte body. The possibility that the Senneville body is an altered contact phase of the hornblende monzonite should be considered; and even some of the biotite granodiorite of the Lamotte body might also be this altered contact phase.

The low content of Li in both aplite and its contained muscovite seems at variance with the hypothesis of concentration of Li with progressive differentiation. However, the rock analysis is not significant because of the low content of micas in the aplite. On the other hand, micas in the



aplite (and pegmatites as well) associated with the Lacorne mass, show lower concentrations of Li than micas of the muscovite granite, as shown in Table 5. This is possibly the result of preferential partition of Li into an aqueous fluid separating as an immiscible phase from the magma at the pegmatitic stage as suggested by Smith (1948) and Neumann (1948), this fluid going on to deposit spodumene and lepidolite at suitable loci in some of the pegmatites. Tremblay (1950) suggested that the aplites were left to crystallize rapidly after withdrawal of the volatiles consequent on sudden reduction of pressure. Unfortunately so little is known of the relationship of pegmatite and aplite crystallization that it is difficult to gauge the validity of these speculations. In any case, the hyperbolic increase of Li up to the muscovite granite would not be expected to continue, because the assumption of negligible partition of Li between the crystal phase and magma no longer holds, the micas removing large quantities of Li.

Reasons for the more advanced differentiation of the granite of the Lacorne mass are not easy to find. Possibly this granite is structurally highest in the sequence, lying at the top of the batholithic complex as a cupola into which the more fluid late solutions have risen. But association with the earlier differentiated hornblende monzonite does not support this. Besides, the regional plunge of the anticline into which the masses are intruded is westwards into Lapause and Clericy townships (Dugas & Gilbert, 1953). If this plunge developed after intrusion, the Lacorne mass would be lowest in the sequence.

The chief condition for differentiation under conditions of fractional crystallization is that early crystals be removed as soon as they are formed, and prevented from reaction with the remaining magma. Tremblay (1950) suggests that the hornblende monzonite represents a segregated early crystal fraction, which has been injected into its present situation, together with some lubricating fluid, from a magma chamber at depth.

The injection of hornblende monzonite from the eastern part of the magma chamber may have left hornblende monzonite crystals in the western part of the chamber to react with the residual magma. Reaction of this kind could lead to the formation of larger amounts of biotite granodiorite in the western masses (as observed in the field), and the abundant crystallization of biotite in this rock could draw off the bulk of lithium in the residual magma in this part of the chamber. Accordingly, the only lithium-rich residual magma would be at the eastern end of the chamber from whence it was injected to form the Lacorne complex and adjacent parts of the Lamotte body. Such a hypothesis would of course demand some kind of isolation of the western and eastern ends, at least as far as diffusion is concerned.

Not enough is known at present of the structure and petrology of the region to assess these speculations.

It might be asked why monzonites, granodiorites and granites are not always associated with spodumene pegmatites, if the present interpretation be correct. The answer to this criticism is not known. It may be that a few ppm more Li in the parent magma are enough to give rise to a Li rich end-product, but there is no evidence that this was the case in the Preissac-Lacorne region. Assimilation of country-rock and the innumerable opportunities for slight changes in the type and proportion of the phases forming during the evolution of a magma are factors which would be important, but which can seldom be completely assessed. It is clear, however, that Li pegmatites should always be sought in the vicinity of granites known to be Li rich.

Nevertheless, the authors are satisfied that the present case has afforded an opportunity to trace a real genetic relation between economic deposits (spodumene pegmatites) and their parent rock (Lacorne muscovite granite). In most cases the source of an ore-deposit (even some sedimentary ones) is vague in the extreme, relying only on uncertain field-relations (however see Montgomery, 1950, who uses a similar argument to the one in this paper). The application of spectrochemical analysis for traces of economically valuable metals in common rocks associated with ore-deposits may shed light on many aspects of ore genesis in the future.

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