

Geological setting of the Lonnie niobium deposit, British Columbia, Canada

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Abstract

The Lonnie Nb deposit lies along the Wolverine fault, which is related to the Manson Creek fault system. It is the third-most developed Nb prospect in British Columbia. Unlike the larger Aley Carbonatite and Upper Fir deposits, where the Nb and Nb+Ta zones are carbonatite-hosted, historical work suggests that the highest Nb grades at the Lonnie complex are in quartz-free feldspathic rocks. The carbonatite (metacarbonatite) zones also contain significant concentrations of Nb. Limited sampling carried out in 2012, including 12 samples from the Lonnie deposit, agrees with the historical findings: the highest Nb value (>2500 ppm) is from one of three quartz-free feldspathic samples; the next highest values (1670 and 1210 ppm) are from two of five carbonatite samples. The 2012 sampling indicates that the metacarbonatites have chondrite-normalized REE patterns that are similar to the quartz-free feldspathic rocks, fenites, and nearby limestone; however, they have the highest REE concentrations. Feniitization extends for more than 30 metres southwestward into the host rock, perpendicular to the strike of the Lonnie mineralization and projection of the Wolverine fault. Carbonatite emplacement predates 4 periods of tectonic activity and the metamorphic peak. Pyrochlore is the main Nb-bearing mineral within the aegirine carbonatite. However, its paucity in quartz-free feldspathic rocks, suggests the presence of minerals of the columbite series or fersmite, a possibility that remains to be tested by microprobe analysis. Projection of the Wolverine fault zone, probably the main Nb metallogene in the area, was shifted northeast to reflect results of a recent magnetic survey. Geochemical anomalies identified by Rara Terra Minerals Corp. at the Vergil carbonatite, less than 5 km northwest of the Lonnie complex, lie along the reinterpreted projection of the Wolverine fault.

Keywords: Niobium, quartz-free feldspathic rocks, carbonatite, fenite, pyrochlore, columbite series minerals

1. Introduction

Niobium (Nb) is a strategic metal that is mainly used for the production of steel and superalloys (e.g., Simandl et al., 2012). The global Nb supply for 2011 is estimated at 63 000 tonnes of contained Nb. Brazil (58 000 tonnes) and Canada (4400 tonnes) are the main producing countries (Papp, 2012). Carbonatites and their weathered equivalents are the main sources of Nb (Mariano, 1989a, b; Birket and Simandl, 1999; Simandl et al., 2012). Most carbonatites are found in stable cratonic settings, commonly along ancient rift zones (Wolley and Kjarsgaard, 2008; see Gwalani et al., 2010 and references therein for summaries of recent research on carbonatites and alkaline rocks). British Columbia carbonatite-related deposits straddle the western margin of ancestral North America, in the British Columbia alkaline province (Fig. 1, inset; Pell, 1994), which also hosts numerous other potential specialty metals deposits (Birkett and Simandl, 1999). In British Columbia, carbonatites and their host rocks have been affected by several periods of tectonic activity and overprinted by medium- to high-grade metamorphism.

Niobium mineralization associated with the Lonnie metacarbonatite (MINFILE 093N 012) represents the

third-most developed Nb prospect in British Columbia (after the Aley and Upper Fir deposits). The Lonnie deposit, the smallest of the three, lies 220 kilometres northwest of Prince George and approximately 7 kilometres east of the Manson Creek settlement (Fig. 1, inset). Discovered in 1953, Lonnie was stripped and drilled by Northwest Exploration Limited (Thompson, 1955; Hankinson, 1958). Since then it has been intermittently investigated by a number of individuals and companies (Vaillancourt and Payne, 1979). Currently, the deposit is being investigated by Rara Terra Minerals Corp, which recently conducted airborne geophysical and soil surveys (Helmel, 2012).

This deposit was chosen as part of the specialty metals component of the 2012 Targeted Geoscience Initiative 4 (TGI4) because: 1) the paragenesis, mineralogy, and mineral chemistry of this complex has not been investigated by modern laboratory methods; and 2) much of the mineralization is considered to be in feldspar-rich lithologies, which contrasts with the Aley and Upper Fir deposits. The main objective of this component of TGI4 is to reduce the knowledge gaps currently hampering the exploration for, and development of, specialty metal deposits. This study describes the

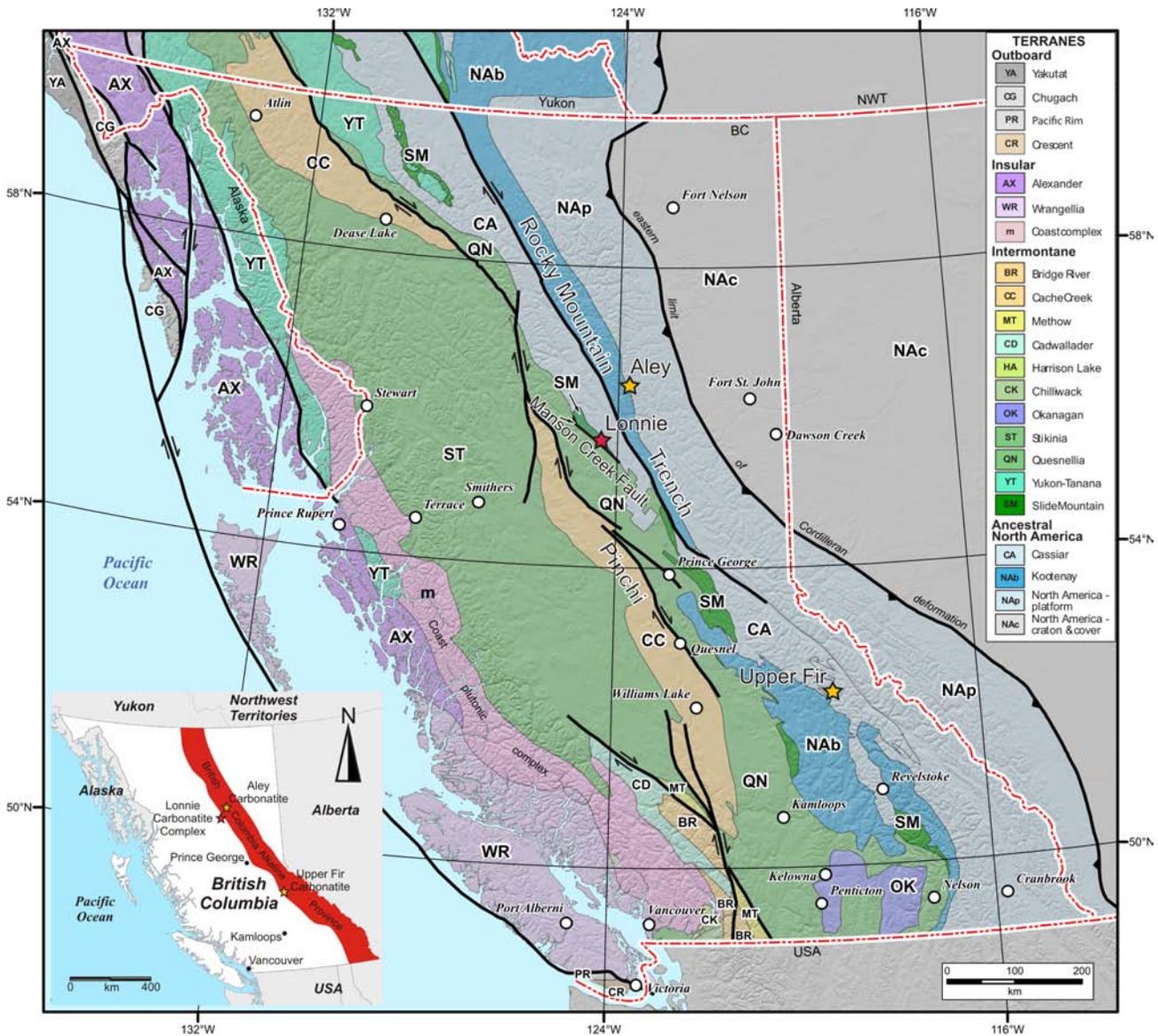


Fig. 1. Location and tectonic setting of the Lonnie carbonatite complex. Towns and major settlements are represented by white circles. Modified from Colpron and Nelson (2011).

regional tectonic setting of the Lonnie deposit and presents the preliminary results of detailed sampling in 2012.

2. Geological setting

The Lonnie carbonatite belongs to a series of metacarbonatites, syenite complexes, and other alkaline rocks of the British Columbia alkaline province, which follows the Rocky Mountain Trench (e.g., Pell, 1994; Simandl et al., 2012). It is in the southern Omineca Mountains, which straddle the boundary between the Intermontane and Omineca Belts. The Lonnie metacarbonatite outcrops along the projection of the Wolverine fault (Fig. 2), an extensional structure that is sub-parallel to the nearby dextral, transcurrent Manson

Creek fault zone (Fig. 1). The Manson Creek fault zone is a 1-5 km wide, near-vertical system of anastomosing transcurrent faults considered to be part of the Rocky Mountain Trench system, separating the Quesnel Terrane from the Slide Mountain and Cassiar terranes (Ferri and Melville, 1994). We modified the projection of the Wolverine fault zone, shifting it an average of 700 m to the northeast, to fit both previously available geological constraints and results from a recent magnetic survey conducted by Rara Terra (Helmel, 2012). Following this modification, it appears that the Vergil carbonatite occurrence (MINFILE 093N 174), less than 5 km northwest of the Lonnie complex, and a number of geochemical soil anomalies located by Rara Terra, also align along the reinterpreted projection of the Wolverine

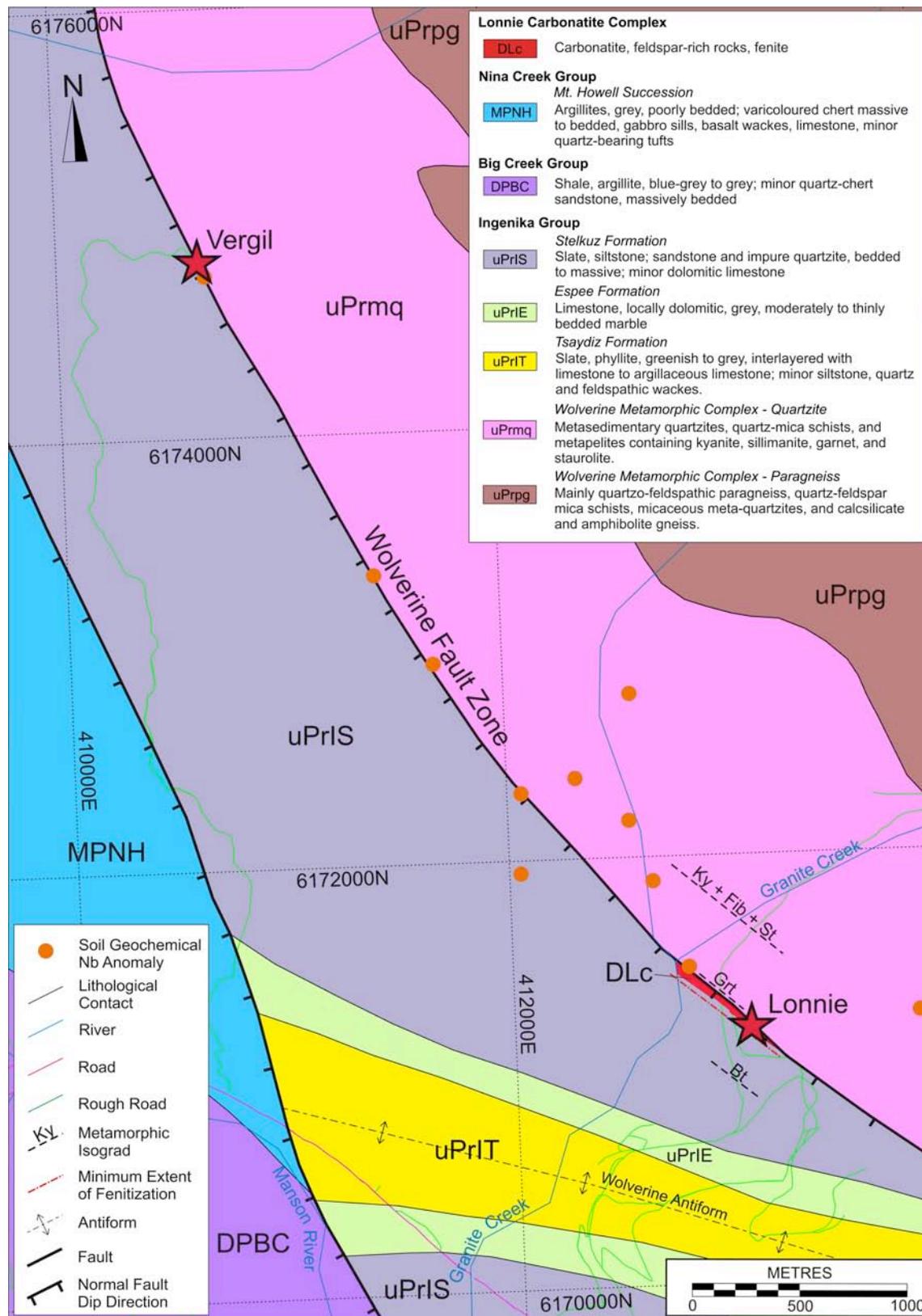


Fig. 2. Regional map of the Lonnie carbonatite complex. Abbreviations of metamorphic index minerals are placed on the high-grade side of the isograd; Bt = biotite, Grt = garnet, Ky = kyanite, St = staurolite, and Fib = fibrolite. Most geochemical soil anomalies (Nb and Total REE) and a strong magnetic signature (Helmel, 2012) coincide with the most likely projection of the Wolverine fault zone. Modified from Ferri and Melville (1994).

fault (Fig. 2).

The Wolverine fault zone represents the boundary between polydeformed, amphibolite grade (garnet, staurolite, kyanite, and fibrolite-bearing) rocks of the Wolverine metamorphic complex to the northeast, and less metamorphosed strata of the upper Proterozoic Ingenika Group and the Paleozoic Nina Creek and Big Creek groups to the southwest (Fig. 2; Ferri and Melville 1994). In the Lonnie Creek area, the fault is probably manifested as multiple splays rather than a single strand as shown on Figure 2. For example, fault gouge more than 1 metre thick is exposed less than 40 m northeast of the projection of the Wolverine fault. The northeastern contact of the Lonnie carbonatite complex is not exposed. However, southwest of the fault, carbonatite-related fenitization was observed to have survived metamorphic overprint.

The Wolverine metamorphic complex is composed of amphibolite facies rocks of the Ingenika Group. Metasedimentary rocks outcropping less than 540 metres north of the Wolverine fault contain white mica, biotite, garnet, staurolite, fibrolite, and kyanite (Figs. 3-5).

Near the Lonnie deposit, southwest of the Wolverine fault zone, are Upper Proterozoic siliciclastic and carbonate rocks of the Stelkuz Formation, a lower to middle Paleozoic continental succession (Big Creek Group), and upper Paleozoic oceanic rocks of the Nina Creek Group. In addition, a series of excellent marker units, such as the upper Proterozoic Espee Formation, outline megascopic geological structures (Fig. 2). All of these rocks were affected by lower grade metamorphism, indicated by: phyllitic and slaty textures; the appearance of sericite, chlorite, and biotite; and an absence of garnet in gneiss (Fig. 6).

2.1. Age relationship between carbonatite emplacement and deformation

The Lonnie complex is considered to have been emplaced during the Late Devonian to Early Mississippian, before regional deformation. This timing is based on U-Pb zircon data from carbonatite samples at both the Lonnie and Vergil occurrences, including a discordant U-Pb age of ~340 Ma, and Pb-Pb ages of 351-365 Ma (Pell, 1987; 1994). Rukhlov and Bell (2010) reported a similar U-Pb zircon crystallization age (~360 Ma) from a composite sample of British Columbia alkaline province rocks that included Vergil carbonatite material.

Four penetrative phases of deformation (D1, Early to Middle Jurassic; D2, Middle to Late Jurassic; D3, Early to Middle Cretaceous; and D4, Late Cretaceous to Early Tertiary) have been identified in metamorphic rocks of the area based on interference, crosscutting relationships, structural styles, and relationships to metamorphism (Ferri and Melville, 1994). The metamorphic peak appears to postdate D1 and predate D2, the Wolverine antiform was created during D3, and development of the Wolverine and Manson Creek fault systems and

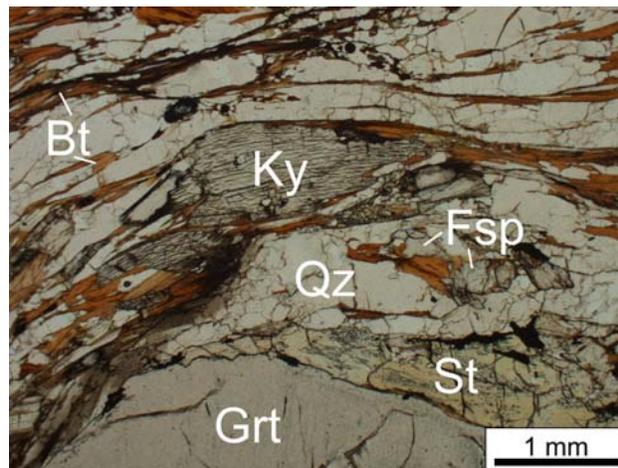


Fig. 3. Garnet (Grt), staurolite (St), and kyanite (Ky) metapelite from the Wolverine complex. Quartz (Qz), biotite (Bt) and feldspar (Fsp) are also present. (Plane-polarized light).

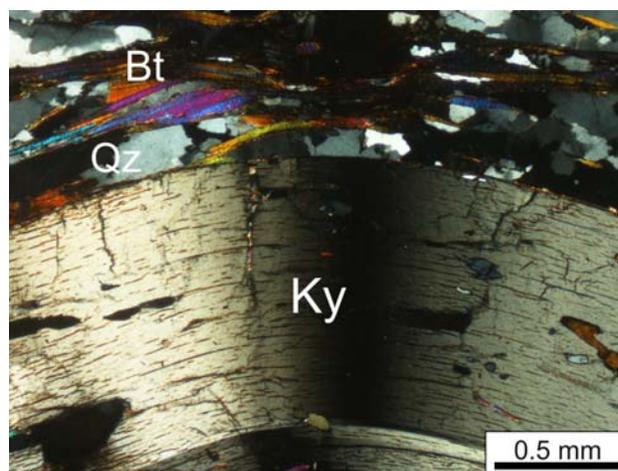


Fig. 4. Bent kyanite (Ky) crystal from the Wolverine complex showing wavy extinction, indicating that kyanite predates at least the last deformation (D4). Groundmass consists mainly of biotite (Bt) and quartz (Qz). (Cross-polarized light).

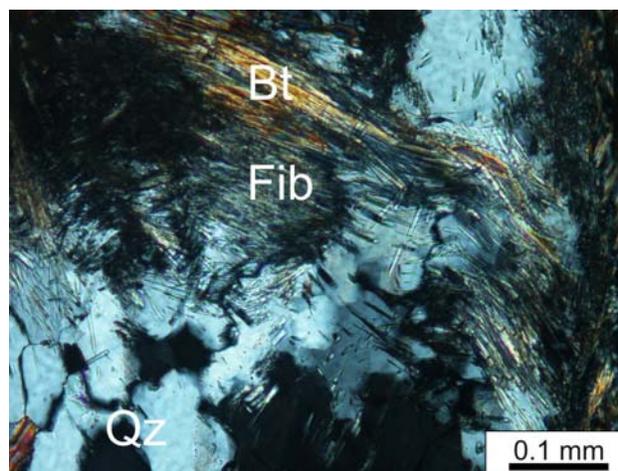


Fig. 5. Fibrolite (Fib) growing on biotite (Bt) in quartz (Qz) groundmass. This mineral is common in rocks approaching the sillimanite stability field. (Cross-polarized light).

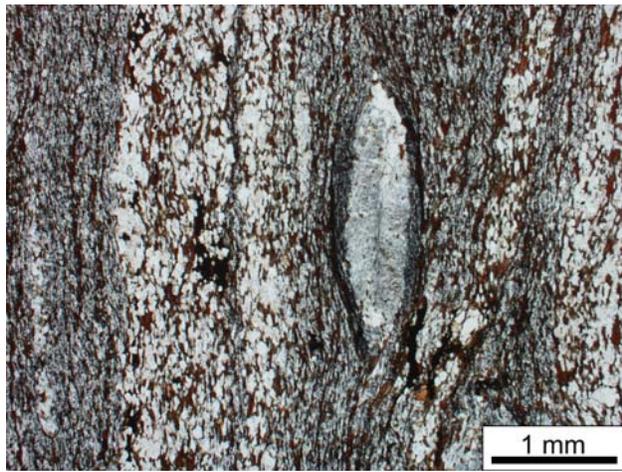


Fig. 6. Biotite-quartz-feldspar gneiss in the hanging wall, 25 metres from the Lonnie complex. Pale grey minerals are quartz and feldspar; biotite is reddish-brown. Darker grey bands are finer-grained, and contain micron-scale opaque minerals. (Plane-polarized light).

emplacement of most of the intrusions in the Wolverine complex was during D4 (Ferri and Melville, 1994). K-Ar geochronological studies, described in detail by Ferri and Melville (1994), indicate that the Wolverine metamorphic complex remained hot until early Tertiary times, when it was rapidly uplifted. Unless the zircon that was dated was inherited by the ascending carbonatite from continental crustal rocks or underlying subducting oceanic crust, the Lonnie carbonatite complex pre-dates all four phases of deformation. The alignment of the Vergil and Lonnie complexes along the projection of the Wolverine fault suggests that this fault may have been a plane of weakness for at least 350 million years (since the emplacement of carbonatites in an extensional regime) and could have been reactivated several times, with most of the displacement along this plane occurring during the Late Cretaceous to Early Tertiary D4 deformation event.

The steep metamorphic gradient, in agreement with primary sedimentary features partly preserved in the limestones and phyllites southwest of the Wolverine fault, in contact with the Wolverine metamorphic complex, is explained by inferred lateral or vertical step-like offsets parallel to the Manson Creek/Wolverine fault system. Fluid movement along this fault zone cannot explain this steep, asymmetric metamorphic gradient. Southwest of the Lonnie carbonatite complex and Wolverine fault, carbonatite-related fenitization has survived metamorphic overprint; however, the northeastern contact of the Lonnie complex is not exposed, is absent, or has been rendered unrecognizable due to metamorphism.

3. Deposit geology

The Lonnie carbonatite complex has been traced by trenching over a length of approximately 650 metres, with widths of up to 50 metres. It strikes 120E/60SW (Hankinson, 1958; Rowe, 1958). It consists of biotite-bearing sövite, aegerine-amphibole sövite, and a variety of quartz-free feldspathic rocks. These feldspathic rocks

have Na-plagioclase contents corresponding to syenite monzonite or monzodiorite, according to the IUGS classification of Streikenson (1978) and Le Maitre (2002). The geochemical classification scheme of Wilson (1989) categorizes these rocks as syenites.

The map produced by K.C. Campbell on behalf of Northwestern Exploration Ltd. in 1955 has been reproduced many times (e.g., Hankinson, 1958; Rowe, 1958; Halleran, 1980; Pell, 1987) and will not be shown here. Instead, our examination and sampling concentrates on a single, relatively well exposed vertical section over 40 metres long and approximately 5 metres high, oriented nearly perpendicular to the strike of the Lonnie complex (Fig. 7).

Host rocks of the Lonnie complex are strongly fenitized on the southwest side of the Wolverine fault (see section 3.4). In general, the degree of fenitization decreases with increasing distance from the complex. The 1955 trenching program (pre- NI-43-101) outlined a zone 530 metres long and approximately 17 metres wide grading 0.21% Nb₂O₅ (Rowe, 1958; Chisholm, E.O., 1960). In this zone, the Na-amphibole-bearing carbonatite assayed 0.16% Nb₂O₅ over 6 metres. Feldspathic rocks averaged 0.23% Nb₂O₅ over nearly 10 metres.

Furthermore, the central portion of this zone averaged 0.3% Nb₂O₅ across 8.3 metres over a length of 283 metres (Rowe, 1958). In summary, assuming that the laboratory digestion (see section 4) of both pyrochlore and columbite series minerals was complete, the feldspathic rocks have higher Nb content than the carbonatites.

3.1. Biotite-rich calcite carbonatite

Biotite-bearing calcite carbonatite (biotite sövite, Fig. 8) is beige on weathered surfaces and pale gray on fresh surfaces. It reacts strongly with HCl, and is locally moderately magnetic. Most of this unit is sheared and highly friable (Fig. 9). Where the carbonatite is intact, it is mottled and displays well-developed planar fabrics. It consists of calcite (>75%, 25 mm) with deformed twin planes, biotite (~20%, 1-6 mm) which is locally crenulated, potassium and plagioclase feldspar (2-15%, ~1 mm), subhedral to anhedral apatite (2-10%, 1-3 mm), pyrochlore (0-0.5%, <2 mm), pyrite in form of cubes (<0.5%, <2 mm) or as anhedral grains (<0.5 mm) with hematite rims, and other opaque minerals (<2%, <1 mm) consisting mainly of magnetite. Columbite series minerals [(Fe,Mn)(Nb,Ta)2O6] or fersmite may also be present. Vestiges of small aegirine grains (<0.1%, <0.2 mm) were observed in thin section. Biotite near the carbonatite-syenite contact locally forms platy crystals up to 15 cm in the largest dimension and approaching 1 cm in thickness. Pyrochlore has been identified, and is found locally in biotite (Fig. 10). Where carbonatite forms enclaves in feldspathic rocks, the biotite appears strongly chloritized, and laths of opaque minerals are abundant. Chemical analyses of representative biotite-rich calcite carbonatite are provided in Table 1.

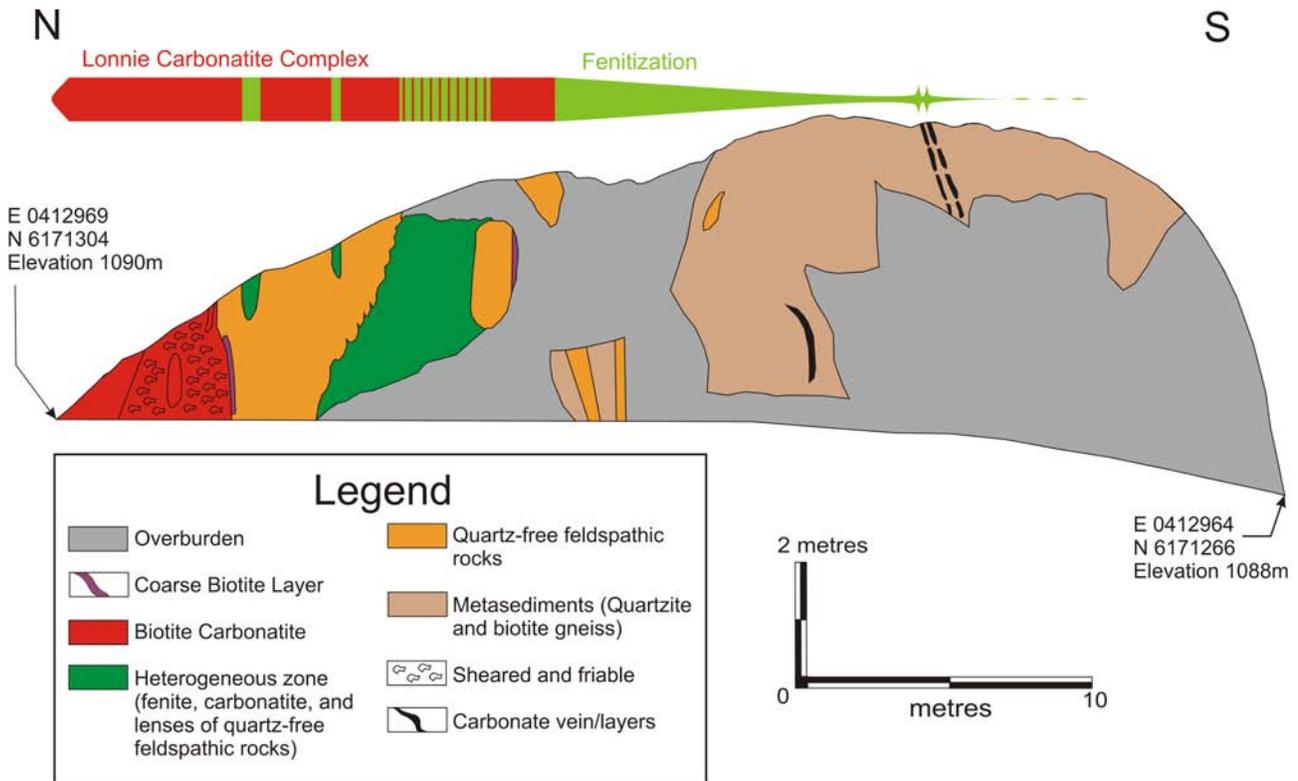


Fig. 7. Vertical section of the Lonnie complex, looking east. Fenitization and the modal ratio of aegirine to Na-amphibole decreases with increasing distance from the complex.

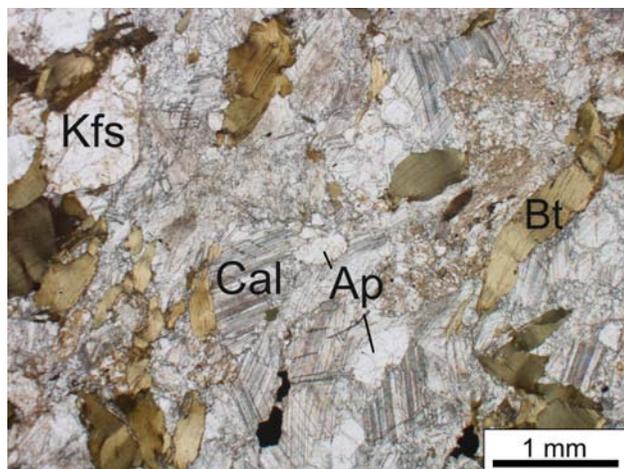


Fig. 8. Biotite-rich calcite carbonatite, containing potassic feldspar (Kfs), calcite (Cal), apatite (Ap), and biotite (Bt). (Plane-polarized light).



Fig. 9. Friable biotite-rich calcite carbonatite. Marker for scale.

3.2. Aegirine ± Na amphibole-bearing carbonatite

Aegirine ± Na amphibole-bearing carbonatite is mostly pale beige to grey on the weathered surfaces and white to pale-gray on fresh surfaces. It is typically massive; local macroscopic fabrics are weakly developed. This carbonatite also reacts strongly with HCl. It is interlayered with fenite rocks approximately 5 metres from the main biotite carbonatite exposure. It consists

predominantly of calcite (>75%, <5 mm) and aegirine (2-20%, 0.5-6 mm), with accessory pyrochlore (<3%, <1 mm), apatite (<5%, <2 mm), and feldspars (<3%, <2 mm); it may also contain Na-amphiboles (<0.5-5%, <5 mm) displaying strong blue-green pleochroism in thin section. Pyrochlore appears to be the main niobium-bearing mineral. It is subhedral, commonly containing carbonate inclusions. Zoning is caused by preferential concentrations of small (<0.003 mm) dark inclusions and separate colour variations are probably caused by

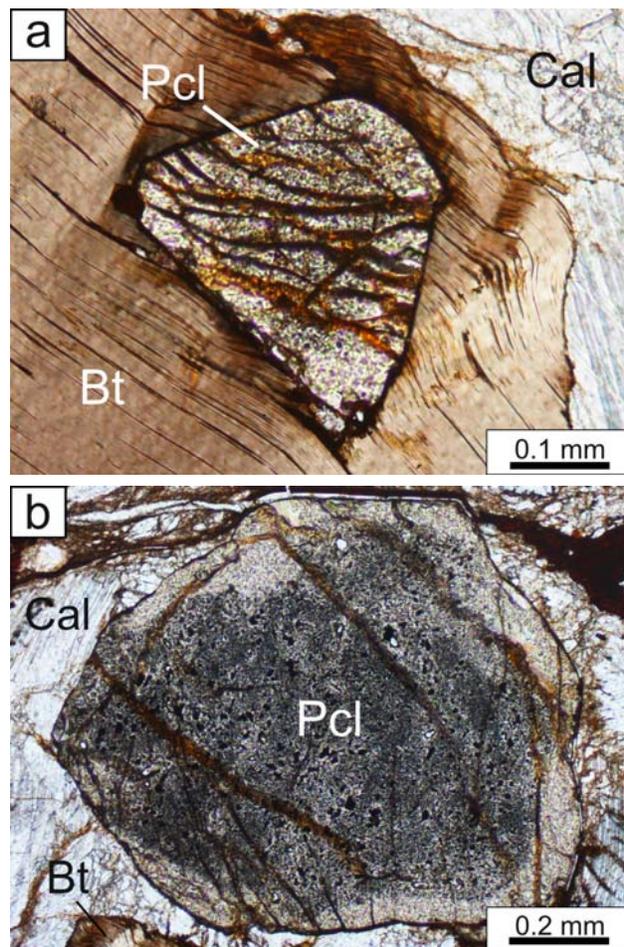


Fig. 10. Biotite-rich calcite carbonatite. **a)** Pyrochlore (Pcl) growing in biotite (Bt). **b)** Pyrochlore growing in calcite (Cal). (Plane-polarized light).

variations in chemical composition (Fig. 11). Opaque minerals, mostly anhedral (<0.5%, <2 mm) are also present. Electron microprobe analysis is needed to confirm the presence of columbite series minerals or fersmite. Pyrite accounts for a small proportion of opaques (<0.05%, 0.05 mm). Chemical analyses of representative samples are in Table 1.

3.3. Quartz-free feldspathic rocks

Leucocratic, quartz-free feldspathic rocks are brown on weathered surfaces and pale gray on fresh surfaces (Fig. 12). They are massive, but locally display layering, and are cut by fractures and micro-fractures filled by brown Fe oxides or carbonate. They consist mainly of feldspar displaying deformed twin planes (>80%, <1 cm), biotite – commonly showing a kinked texture – (<5%, <6 mm), calcite (<5%, <2 mm), and opaques (probably hematite and/or columbite filling fractures and interstitial spaces). Sparse grains of pyrite (<0.01%, <0.05 mm) have been largely converted to Fe oxides. Some of these rocks are characterized by small, untwinned feldspars (<0.3 mm) along the interstitial boundaries of large feldspar crystals (1.5-2.5 mm). Locally, carbonates fill interstitial spaces. Where carbonate invades along

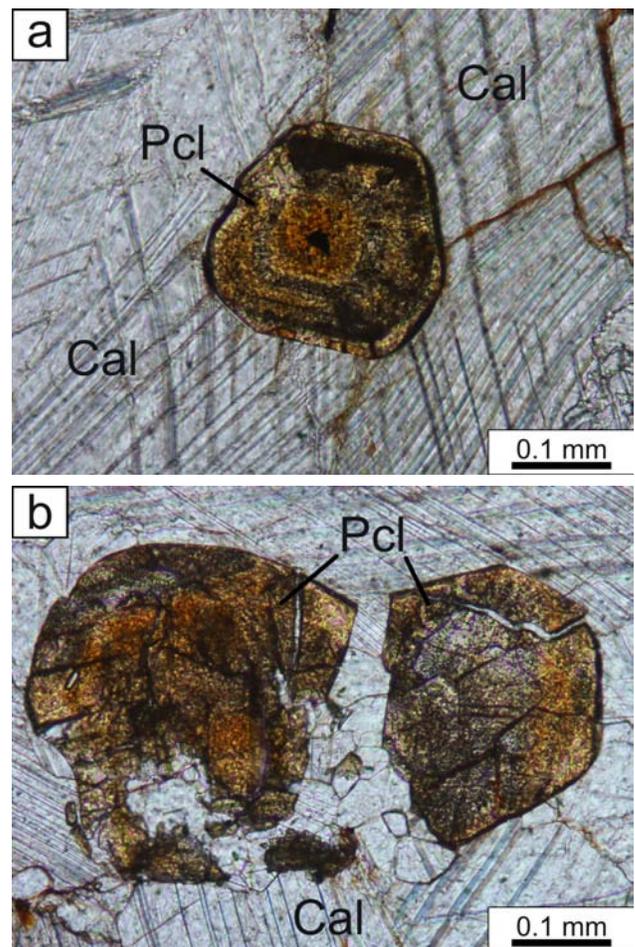


Fig. 11. Zoned pyrochlores (brown) in aegerine-dominated sövite carbonatite. **a)** Shows zoning parallel to the nearly euhedral outline of the crystal. **b)** Pyrochlore, fractured and partially resorbed. (Plane-polarized light).

fractures, biotites are strongly altered. Samples collected in 2012 contain trace microscopic pyrochlore (<0.01%, <0.1 mm). High Nb values suggest that Nb is concentrated in opaque minerals, probably belonging to the columbite series or fersmite. Zircons can be observed in some hand specimens and in all thin sections. One sample, consisting predominantly of plagioclase (>85%), also contains white mica (<1%, <4 mm). These rocks are probably, at least in part, the result of fenitization.

3.4. Fenites

The zone of fenitization associated with the Lonnie meta-carbonatite extends for at least 33 metres southwestward into the host rock, and the degree of fenitization decreases with increasing distance from the complex. Within or immediately adjacent to the complex or related carbonatite dikes, the fenite is brown or green on weathered surfaces, medium green on fresh surfaces (Fig. 13), and massive to crudely layered. In thin section, fenites display distinct layering and typically contain alkali feldspar (40-80%, <2 mm) and aegerine (10%-50%, <4 mm), with Na-amphibole (<10%, <4 mm) and accessory quartz and calcite. Fenitization within or

Table 1. Major and trace element analyses of samples from the Lonnie carbonatite complex and surrounding area (see section 4 for description of analytical methods).

Rock Type:	Biotite Carbonatite			Aegirine Carbonatite		Quartz-free Feldspathic Rocks			Fenites		Fenitized Metasediments*		Limestone
Sample:	LO-12-09	LO-12-10	LO-12-10A	LO-12-14C	LO-12-14E	LO-12-12	LO-12-13	LO-12-15 ¹	LO-12-14B	LO-12-14D	LO-12-16	LO-12-17 ²	LO-12-19
<i>wt%</i>													
SiO ₂	21.5	6.38	1.72	22.4	35	61.4	62.9	62.6	53.2	50.4	77.4	49.7	2.39
Al ₂ O ₃	9.83	1.78	0.5	1.58	3.58	17.15	17.45	17.55	7.84	7.68	7.29	9.59	0.47
Fe ₂ O ₃	5.53	5.39	1.82	10.45	12.9	0.32	0.5	0.83	13.15	12.05	4.72	6.73	0.18
CaO	33.2	47.2	54.5	34.9	21.5	2.99	1.21	4.52	9.12	11.35	1.43	16.25	60.6
MgO	1.96	2.1	0.95	0.78	1.27	0.06	0.05	0.06	1.75	1.64	1.09	1.18	0.66
Na ₂ O	1.5	0.21	0.11	4.49	6.84	5.79	5.52	11	7.89	8.37	5.02	5.98	0.03
K ₂ O	2.88	0.54	0.28	0.84	1.29	6.88	7.44	0.25	2.62	1.45	1.73	1.46	0.11
TiO ₂	0.65	0.36	0.1	0.45	0.43	0.01	0.05	0.04	0.78	0.75	0.57	0.54	0.02
MnO	0.28	0.69	0.69	0.57	0.48	0.05	0.04	0.07	0.37	0.39	0.14	0.5	0.01
P ₂ O ₅	2.28	2.02	0.68	3.23	0.54	0.07	0.37	1.18	1.75	2.14	0.1	0.47	0.01
SrO	0.81	1.6	1.88	0.98	0.72	0.12	0.07	0.2	0.18	0.29	0.04	0.55	0.46
LOI	17.5	33.3	38.1	18.45	17.2	2.87	1.13	-0.11	2.04	2.97	0.35	8.63	36.3
Total	97.92	101.57	101.33	99.12	101.75	97.71	96.73	98.19	100.69	99.48	99.88	101.58	101.24
S	0.24	0.04	0.07	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.02	0.05	0.08	<0.01
C	6.29	9.35	11.25	6.38	4.37	0.64	0.23	0.65	1.34	1.82	0.24	3.35	11.7
<i>ppm</i>													
V	105	51	18	704	533	<5	12	5	404	354	114	135	<5
Cr	<10	<10	<10	10	30	<10	<10	10	70	70	90	70	10
Co	7	7.7	1.2	1.7	2.5	<0.5	<0.5	<0.5	8.8	7.1	8.6	8.7	0.5
Ni	<5	<5	<5	5	7	<5	<5	<5	29	26	23	31	<5
Cu	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	11	9	<5
Zn	94	91	32	63	81	5	8	6	188	144	94	70	16
Ga	18.4	18.5	8.1	21.2	21.4	33	33.3	75.4	45.1	48.5	14.5	20.9	0.8
Rb	110	69.2	18.9	20.5	26.3	98.6	132.5	4.7	73.1	35.7	56.8	32	2.2
Zr	130	30	<20	280	350	330	5000	3370	150	110	360	220	<20
Nb	312	1210	131.5	1670	291	617	>2500	939	236	140	369	193	1.3
Mo	<2	<2	<2	<2	<2	<2	4	<2	<2	<2	169	25	<2
Ag	<1	<1	<1	<1	<1	<1	<1	<1	<1	1	<1	<1	<1
Sn	1	1	<1	10	12	<1	5	1	7	8	2	6	<1
Cs	1.97	1.68	0.39	0.13	0.12	0.21	0.82	0.1	0.24	0.16	0.27	0.28	0.07
Ba	2300	1250	1260	607	709	3120	4200	135	243	272	380	439	316
Hf	1.5	0.5	<0.2	3.9	5.4	3.5	48	39.7	1.4	1.4	8.4	4.9	<0.2
Ta	3.2	1	0.1	7.4	1.2	12.8	63.4	6	1.6	1.1	1.1	0.9	<0.1
W	<1	1	<1	1	1	1	12	1	1	1	<1	1	<1
Tl	1.1	1	0.8	<0.5	1.3	0.8	0.9	1.5	0.6	<0.5	2.4	3.5	1.3
Pb	20	26	22	103	33	11	14	43	38	128	54	40	19
Th	8.56	12.9	3.24	21.7	28	14.75	69	47	436	230	50.1	33.9	0.93
U	3.03	2.21	0.18	46.7	7.91	51	39.6	8.41	3.14	2.26	3.55	4.72	1.38
F	1900	2530	730	2420	940	90	360	840	1820	2070	1320	1340	110
La	328	570	489	506	354	69	147.50	383	172.50	205	54.30	176	3.70
Ce	580	1000	889	809	537	113.50	265	662	283	335	95.50	332	6.90
Pr	58.50	103	90.60	77.80	49.20	10.95	24.60	65	28.10	33.50	10.15	35.60	0.75
Nd	188	320	289	239	142.50	31.80	71.10	194.50	85.20	104.50	32.90	118	2.50
Sm	30.20	52.20	48.40	36.20	20.20	4.31	9.02	26	12.90	16.05	5.75	22.80	0.44
Eu	9.05	15.60	14.70	10.65	5.81	1.22	2.41	6.73	3.58	4.81	1.61	6.50	0.13
Gd	25.50	43.60	38.90	29.30	15.90	3.32	6.51	17.85	9.78	13.65	5.61	21.50	0.40
Tb	3.18	5.46	5.17	3.65	2.05	0.41	0.76	1.97	1.17	1.64	0.74	3.08	0.05
Dy	13.90	25.10	23.90	16.35	9.37	1.82	3.18	8.11	5.10	7.11	3.63	15.85	0.28
Ho	2.42	4.46	4.24	2.87	1.68	0.32	0.58	1.34	0.85	1.20	0.67	3.10	0.05
Er	6.09	11.35	11.15	7.37	4.47	0.85	1.60	3.46	2.09	2.98	1.87	8.84	0.15
Tm	0.83	1.62	1.59	1.05	0.66	0.14	0.27	0.51	0.31	0.45	0.31	1.38	0.02
Yb	4.37	9.11	9.03	5.85	3.98	0.74	1.60	3.01	2.07	2.74	1.92	8.03	0.13
Lu	0.68	1.49	1.49	0.98	0.72	0.13	0.29	0.53	0.45	0.56	0.36	1.33	0.02
Y	59.10	113.50	122.50	70.10	44.20	8.50	12.7	33.50	21.50	27.40	16.40	86	1.50
ΣREE	1250.72	2162.99	1916.17	1746.07	1147.54	238.51	534.42	1374.01	607.10	729.19	215.32	754.01	15.52
ΣREY	1309.82	2276.49	2038.67	1816.17	1191.74	247.01	547.12	1407.51	628.60	756.59	231.72	840.01	17.02
Ce/Yb	132.72	109.76	98.44	138.29	134.92	153.37	165.62	219.93	136.71	122.26	49.73	41.34	53.07
Nb/Ta	97.50	1210.00	1315.00	225.67	242.50	48.20	39.43	156.50	147.50	127.27	335.45	214.44	26.00

Lower detection limit for major elements and LOI is 0.01%. Lower detection for REE: (0.5 ppm), Ce (0.5 ppm), Pr (0.03 ppm), Nd (0.1 ppm), Sm (0.03 ppm), Eu (0.03 ppm), Gd (0.05 ppm), Tb (0.01 ppm), Dy (0.05 ppm), Ho (0.01 ppm), Er (0.03 ppm), Tm (ppm), Yb (0.03 ppm), Lu (0.01 ppm) and Y (0.5 ppm).

*Fine-grained biotite quartz feldspar gneiss and quartzites

¹Primarily composed of albite

²Quartzite with carbonate veins



Fig. 12. Quartz-free, Nb-bearing feldspathic rocks. Marker for scale.



Fig. 13. Aegirine carbonatite–fenite contact. Carbonatite is grey, fenite is rusty brown.

immediately adjacent to the complex is characterized by aegirine, with subordinate Na-amphibole (Fig. 14). In one sample, where carbonatite layers are in contact with feldspar, aegirine is particularly coarse (>5 mm). In addition, within fine, feldspar-rich layers, aegirine creates a net-like texture. Carbonatite forms the northern extremity of the rock exposure. As distance from the complex increases, aegirine becomes confined to minor distinct bands, commonly adjacent to carbonatite veinlets, and Na-amphibole becomes the main indicator of fenitization (Fig. 7). Trace amounts of interstitial opaque minerals (including pyrite) are present.

The first outcrops northeast of the biotite carbonatite are quartz-rich schists characterized by white mica and, at least locally, garnet. It is possible that the fenitization zone was truncated by faulting, is simply narrower than 34 metres, or, less likely, that the alkalis were incorporated into white micas (muscovite), potentially forming phengite ($\text{KA}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$) or paragonite ($\text{NaAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$). Electron microprobe analyses are required to determine the chemical composition of these micas.

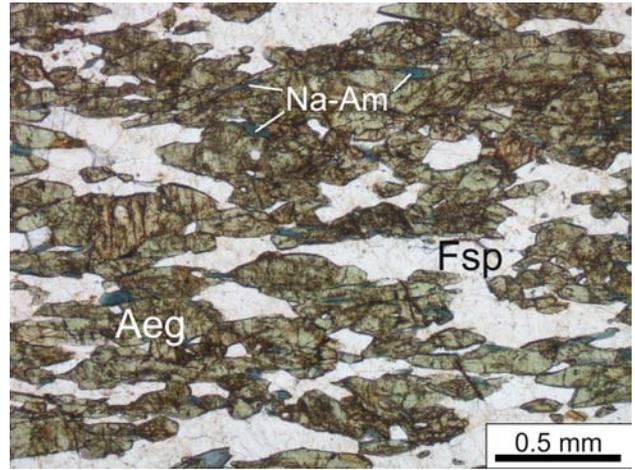


Fig. 14. Aegirine fenite consisting of green aegirine (Aeg), white feldspar (Fsp), blue Na-amphiboles (Na-Am). (Plane-polarized light).

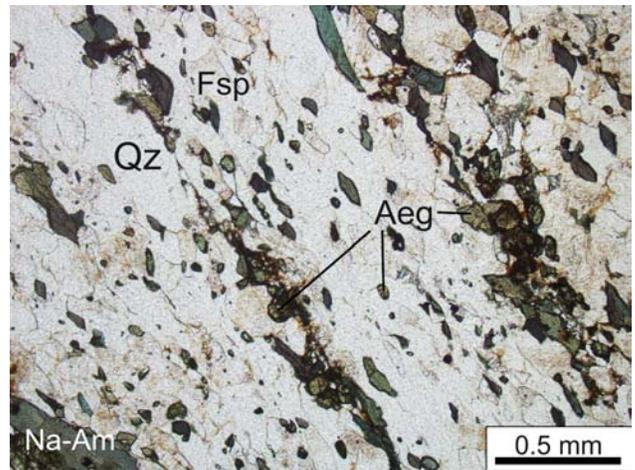


Fig. 15. Fenitized quartzite, 8 metres from the Lonnie complex. Contains quartz (Qz), feldspar (Fsp), small aegirines (Aeg), and strongly pleochroic Na-amphiboles (Na-Am). (Plane-polarized light).

3.5. Fine-grained biotite-quartz-feldspar gneiss and quartzite (metasedimentary rocks)

Fine-grained biotite gneiss is exposed near the southern end of the outcrop. This rock is medium to dark brown on weathered surfaces and medium grey on fresh surfaces. It is difficult to break, tending to separate along planes of weakness 2-20 centimetres apart. Grain size varies within individual gneiss layers. The main leucocratic constituents are quartz ($\approx 25\%$, 0.03-1.4 mm), potassium feldspar ($\approx 20\%$, 0.03-1 mm), and plagioclase ($\approx 25\%$, <1 mm). The proportions of these minerals are difficult to estimate, but collectively they account for more than 60% of the rock. The main ferromagnesian mineral is biotite (<10-30%, <0.4 mm in longest dimension). White mica (<2%, <0.5 cm) is also present along some of the planes coexisting with biotite. Pyrite is present as irregular, oriented, coplanar grains concentrated along the fine-grained layers (<2%, <1 mm). Some of the pyrite grains are fresh; others are partly or entirely converted to hematite. Chalcopyrite is present as

a trace mineral (<0.05%, <0.2 mm), mainly within pyrite. The layers with the finest grains appear to contain dust-like particles of an opaque mineral, probably pyrite and iron oxides. No pyrochlore or minerals belonging to columbite series were observed in this rock. Chemical analyses of these rocks are provided in Table 1, and supports the absence of Nb-bearing ore minerals.

With increasing quartz content, fine-grained biotite gneiss grades into quartzofeldspathic gneiss and quartzite (Fig. 15). The quartzofeldspathic gneiss has a similar appearance and physical properties to the biotite gneiss. However, closer to the carbonatite than the biotite gneiss, it is fenitized. This quartzofeldspathic gneiss is brown on weathered surfaces, gray on fresh surfaces and displays layering and fissility similar to the biotite gneiss. It contains mainly quartz (>40%, <1.4 mm) and alkali feldspar (~40%, <1 mm). Na-amphibole (~5-15%, <0.9 mm) and aegirine (~5-15%, <0.6 mm) are other major constituents. Aegirine tends to be confined to a few bands associated with trace plagioclase and calcite, particularly on the boundaries of calcite veins. Interstitial opaques comprising <1% of the quartzite are locally poikilitic, enclosing small feldspar grains.

4. Lithogeochemistry

Five carbonatite, three quartz-free feldspathic rocks, two fenites, two fenitized metasediments, and a limestone sample (collected nearby to provide background for carbonatite analyses) were analysed (Table 1). The chemical analyses were done by ALS Laboratories in Vancouver. All samples were ground using a steel mill. Major element chemistry was determined using lithium metaborate fusion followed by Inductively Coupled Plasma Emission Spectrometry (ICPES). Loss on ignition (LOI) was determined during the sample fusion (at 1000°C). Total carbon and sulphur were determined using the LECO combustion method. Most of the trace elements were analyzed by lithium metaborate fusion followed by Inductively Coupled Plasma Mass Spectrometry (ICPMS).

These samples show a significant variation in the concentrations of specialty metals (Table 1). The REE content of carbonatites is much higher than in nearby limestone (Fig. 16). The chondrite-normalized REE element pattern of metacarbonatites, quartz-free feldspathic rocks, amphibole (±pyroxene)-bearing fenites, and other rocks are similar. None of the samples that were analysed have pronounced Eu anomalies and, as expected, Lonnie carbonatites have higher REE concentrations than associated quartz-free feldspathic rocks and fenites. Based on the geochemical classification diagram of Wilson (1989), the quartz-free feldspathic rock can be geochemically classified as syenites (Fig. 17). These observations suggest that all rock types close to the Lonnie complex were affected by carbonatite-related fluids.

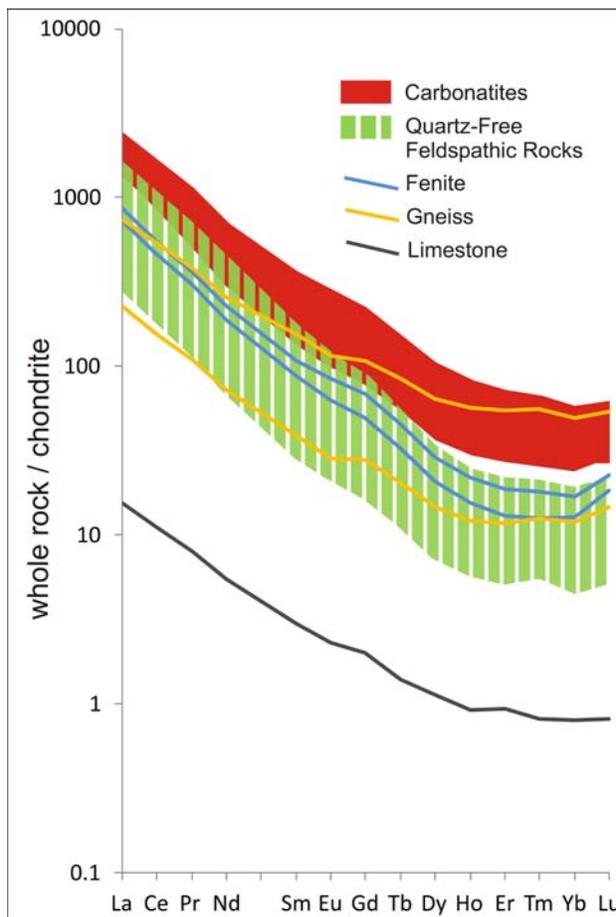


Fig. 16. REE spider plot for samples from the complex and surrounding rocks. Chondrite normalized using values from McDonough and Sun (1995).

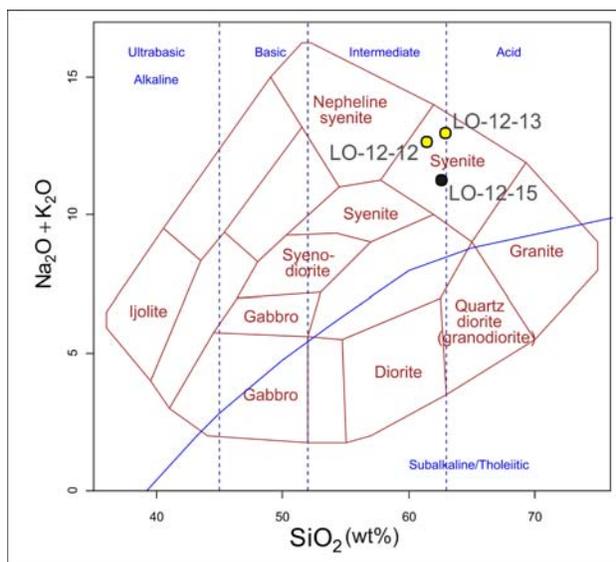


Fig. 17. Quartz-free feldspathic rocks plotted on the TAS diagram for plutonic rocks of Wilson (1989). Samples represented by yellow circles are composed primarily of potassium feldspar. The sample represented by the black circle consists primarily of plagioclase.

4.1. Soil Geochemistry

A cursory examination of geochemical soil survey results conducted in the area by Rara Terra indicates that several Nb and total REE (including Y) anomalies coincide with the projection of Wolverine fault system (Fig. 2). This observation further confirms the importance of the Wolverine fault system as a potential metallotect.

5. Summary

Unlike the larger Aley Carbonatite and Upper Fir deposits, where the Nb and Nb+Ta zones are carbonatite-hosted, historical work at the Lonnie deposit, which lies along the Wolverine fault zone, suggests that, although the carbonatite zones contain significant concentrations of Nb, the highest Nb grades are associated with quartz-free feldspathic rocks. Fenitization extends for more than 30 metres southwestward into the host rock, perpendicular to the strike of the Lonnie mineralization and the Wolverine fault zone. Niobium is probably contained mostly in pyrochlore and unidentified opaque minerals (probably columbite series minerals or fersmite). Electron microprobe analyses are required to positively identify Nb-bearing minerals, and determine the composition of potential indicator minerals. Carbonatites of the Lonnie complex have similar chondrite-normalized REE patterns to related quartz-free feldspathic rocks and fenites; however, they have the highest REE concentrations.

Based on the combination of new aeromagnetic data of Rara Terra Minerals Inc., and previously recognized geological controls, we have moved the projection of the Wolverine fault zone northeastward. The revised projection now connects the Lonnie and Vergil Nb-bearing complexes. The Wolverine Fault Zone probably reflects movement along an old zone of weakness that provided structural control for the emplacement of Nb mineralization in the Lonnie–Vergil area.

Detailed ore and gangue mineralogy, mineral chemistry, and paragenesis based on samples collected during 2012, are currently unavailable. These samples will be examined in a future study using electron microprobe and laser ablation ICP-MS technologies, and the results will be merged with data from other specialty metals-bearing deposits. The results of this research, together with ongoing studies on the tectonic, regional, and deposit-scale controls of other specialty metal deposits, will be used to define parameters permitting vectoring towards high-grade mineralization on regional and deposit scales.

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