GS2018-7

Geology and bedrock mapping of the Wekusko Lake pegmatite field (northeastern block), central Manitoba (part of NTS 63J13)

by D. Benn[1], R.L. Linnen[1] and T. Martins

In Brief:
- Defining zonation and mineralogy of Li bearing pegmatite dikes aids identification of high concentrations of spodumene
- Detailed geological mapping provides a better understanding of morphology, regional deformation and rheology context of pegmatite emplacement
- Future studies will include measuring Li content of micas and geochronology of columbite group minerals

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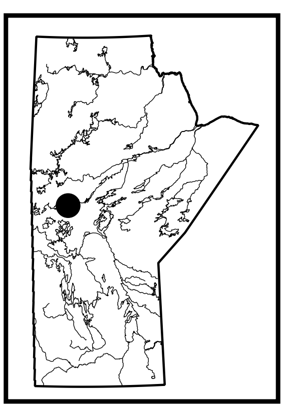

Summary

Pegmatite dikes from the Green Bay group of the Wekusko Lake pegmatite field were examined in summer 2018 through geological mapping and relogging drillcore from several diamond drill holes. The pegmatite dikes exhibit five zones: the border zone, the wall zone, the intermediate zone, the central zone and the core zone. The dikes vary in size and not all zones are present in all dikes. The zones vary in mineralogy and crystal size. An abundance of alkali feldspars is characteristic of the wall zone and the intermediate zone, whereas the abundances of albite and spodumene are key for identifying the central zone. The central zone also hosts rare-metal–bearing minerals such as those found in the columbite group. Field mapping reveals that the pegmatites are folded and that the width of the pegmatite affects the degree to which it was folded during regional deformation. Future work will involve mineralogical studies (particularly of muscovite) as vectors for exploration. Uranium-Pb geochronological studies of the columbite-group minerals will also be carried out.

Introduction

With the rise of interest in renewable energy and electric cars, batteries have become significantly more important. Many new battery technologies use Li as a main component. For this reason, Li has become a widely sought-after element. Lithium is typically obtained either through mining pegmatites, where spodumene is the most common Li ore mineral (e.g., Greenbushes, Australia), or extraction from brines (e.g., Salar de Atacama, Chile).

In Manitoba, Li is predominantly associated with Li-Cs-Ta (LCT) pegmatites, the best-known example being the world-class Archean Tanco deposit in southeast Manitoba (Černý, 2005). Trans-Hudson–aged LCT pegmatites are present in the Wekusko Lake pegmatite field (Černý et al., 1981; Martins et al., 2017), approximately 25 km east of Snow Lake in central Manitoba. This pegmatite field is currently the target of exploration work focusing on the Li mineralization of the pegmatite dikes (e.g., FAR Resources Ltd., 2018).

Bedrock mapping at a scale of 1:4 000 (Benn et al., 2018) was undertaken to investigate and document the zoning, morphology and structural controls of the emplacement of the pegmatite dikes. In addition, drillcore from several diamond drill holes was relogged and sampled to provide a better understanding of the mineralogy and zonation of the pegmatite dikes. Mineral studies, particularly focusing on using muscovite as a vector for mineralization, will be one of the next steps of this project. Columbite-group minerals were also sampled for U-Pb geochronology studies to help determine the timing of deformation and emplacement of the pegmatite dikes.

Regional geology

The Wekusko Lake pegmatite field (Černý et al., 1981) is located within the ca. 1.91–1.83 Ga Flin Flon–Glennie complex (Connors et al., 2002) of the Paleoproterozoic Trans-Hudson orogen (Figure GS2018-7-1; modified from the NATMAP Shield Margin Working Group, 1998; Bailes and Galley, 1999), an easterly trending belt approximately 140 km wide and 240 km long. Peak thermal metamorphism is interpreted to have occurred at

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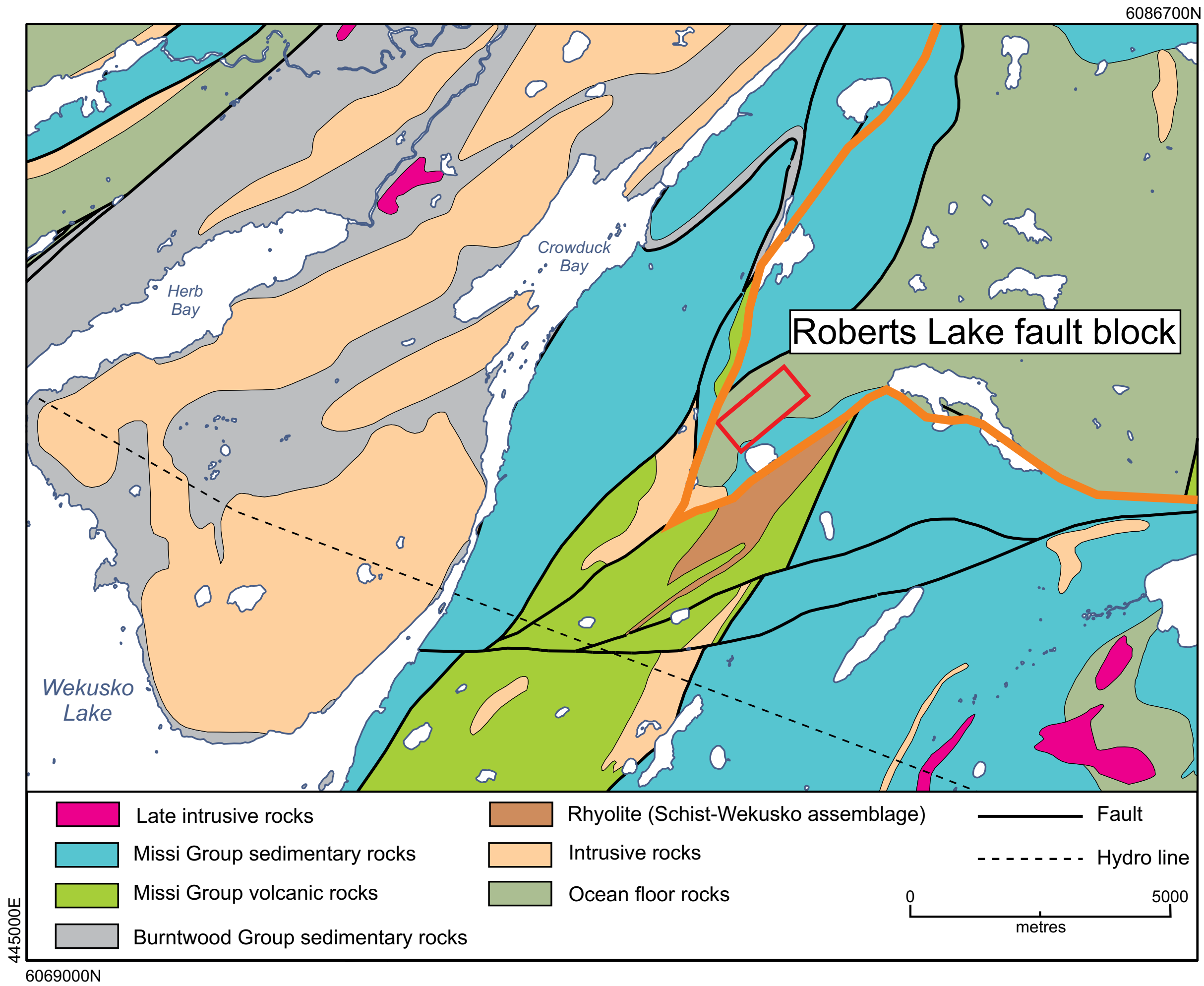


Figure GS2018-7-1: *Regional geology of the east side of Wekusko Lake, central Manitoba. The red square outlines the Green Bay group pegmatite mapping area, and the orange line outlines the Roberts Lake fault block (modified and simplified from NATMAP Shield Margin Working Group, 1998).*

ca. 1.81 Ga, and a sillimanite+garnet-in isograd is mapped in the vicinity of the Wekusko Lake pegmatite field (Connors et al., 2002). The region has undergone five deformation and folding events (D_1 to D_5; Kraus and Williams, 1999; Connors et al., 2002). The first three are linked to the thrusting of the Kisseynew basin over the Flin Flon belt (Kraus and Williams, 1999). This resulted in isoclinal folding and low-angle shear zones. Deformation phase D_4 is associated with east-west shortening during the underthrusting of the Superior plate, which resulted in north-northeast folds. Deformation event D_5 is associated with the renewal of the north-south convergence (Kraus and Williams, 1999).

The pegmatites that are the focus of this report are part of the Green Bay group within the Wekusko Lake pegmatite field (Černý et al., 1981). The studied pegmatites are hosted primarily by a mafic volcanic assemblage. The mafic volcanic assemblage is unconformably overlain by Missi group metasedimentary rocks (Connors et al., 1999). These units make up the Roberts Lake fault block (Figure GS2018-7-1; Connors et al., 1999, 2002). This block is bound to the west by a north-northeast-trending fault and to the south by an east-northeast-trending fault. The two faults meet at the southwestern corner of the Roberts Lake fault block.

Multiple mafic and felsic intrusive events, both syn- and late tectonic, occurred in the Flin Flon belt (Černý et al., 1981; Kraus and Williams, 1999). These events ranged from large granite plutons to smaller dikes, sills and stocks. The emplacement of the granitic pegmatites is thought to be the last intrusive event (Černý et al., 1981; Kraus and Williams, 1999), although folding in the pegmatites may indicate that these dikes could have been emplaced prior to some less or undeformed granitoid bodies. The genetic relationship between the various granitic bodies and the pegmatites in the area remains unclear (Černý et al., 1981).

Unit descriptions

Mafic volcanic rocks (unit 1)

Amphibolite, likely derived from mafic volcanic rock, (Figure GS2018-7-2a) is the predominant map unit in the study area. The amphibolite is host to the pegmatite dikes, is fine grained (<1 mm), foliated and folded, and consists mostly of hornblende, lesser plagioclase and local garnet. Fresh surfaces are dark green and weather to dark grey. Quartz veins occur locally and range in width from veinlets that are less than 1 cm wide to veins up to 30 cm wide. Observed folding is consistent with the regional folding events, with both tight and gentle folds. Foliation in the amphibolite is commonly deflected at the boundary with pegmatite dikes. Aphyric pillow basalt was observed at two outcrops (Figure GS2018-7-2b; Benn et al., 2018), suggesting a subaqueous depositional environment. Pillows are slightly flattened with recessive selvages of darker grey colour. Vesicles are visible at the edges of the pillows. Younging directions could not be determined with certainty but limited observations at one outcrop suggested younging to the east.

The major- and trace-element compositions of mafic volcanic rock samples from outcrop and drillcore are given in Table GS2018-7-1. The SiO_2 content of samples ranges from 45.98 to 51.78 wt. %, MgO from 4.61 to 7.93 wt. % and the average Mg# is 43.73. Samples plotted in the basalt and basaltic andesite sections of a total alkali silica diagram (Figure GS2018-7-3a). The chondrite-normalized rare-earth-element (REE) profiles are relatively flat (Figure GS2018-7-3b), typical of normal mid-ocean-ridge basalt (N-MORB). This supports the previous interpretation (NATMAP Shield Margin Working Group, 1998; Syme et al., 1999) that the amphibolite host unit in the Wekusko Lake pegmatite field is similar to modern ocean-floor basalt.

Quartzofeldspathic gneiss

Quartzofeldspathic gneiss is present in the southern and western parts of the map area (Figure GS2018-7-2c; Benn et al., 2018); it is interpreted as part of the Missi group. It is a feldspar-quartz-biotite metasedimentary gneiss with medium grey fresh surfaces and pink weathered surfaces. It is fine grained (1–2 mm) and strongly foliated. The foliation is dipping greater than 50° and strikes to both the northeast and southwest. Dike 1 intruded into this unit at the southernmost end of the dike, where it quickly thins from 2 m to 30 cm. Quartzofeldspathic gneiss may act as a rheologic control on the pegmatite dikes. Very few pegmatite dikes, other than Dike 1, are hosted by the quartzofeldspathic gneiss unit. These dikes are typically less than 10 cm wide and are barren of Li mineralization.

Garnet-biotite gneiss

Garnet-biotite gneiss, only locally present in the southwestern corner of the map area, is interpreted as part of the Burntwood Group. It is fine grained, mainly composed of feldspar, biotite and garnet with dark grey fresh surfaces. Locally, fine-grained (<2 mm) pink feldspar augens are present and weather to a brown colour. No pegmatite dikes were found intruding this unit.

Granitic pegmatite

Most pegmatite dikes in the map area consist of quartz, K-feldspar, albite, muscovite, spodumene and tourmaline with accessory beryl, Fe-Mn phosphate minerals, apatite, garnet and columbite-group minerals. The spodumene-bearing dikes can be classified as part of the rare-element (REL) class, REL-Li subclass, complex type, spodumene subtype, as per the classification scheme of Černý and Ercit (2005). The pegmatite dikes range in colour from red to white depending on the K-feldspar to albite ratio, with albite-rich zones being white. The pegmatite dikes are very coarse grained with crystals of up to 30 cm in length. The pegmatite contact with the host mafic volcanic rocks shows no observable chilled margin. Tourmaline and local muscovite formed comb structures that are perpendicular to the contacts and are interpreted as growth from the border zones into the wall zones (Figure GS2018-7-2c). Locally, an aplitic phase is present throughout the pegmatite dikes and ranges in size from 5 to 30 cm. The patches contain a similar mineralogy to the surrounding pegmatite. At the north tip of Dike 1, elongation and stretching of minerals was observed (Figure GS2018-7-2d). Deformation in Dike 1 was previously reported by Martins et al. (2017) in feldspar and muscovite (e.g., kink bands in muscovite), which suggests that pegmatite emplacement was prior to the latest stages of regional deformation.

There are at least eight large (>1 m wide) dikes exposed in the map area, all oriented to the southeast. The dikes are folded and undulating over several metres (Figure GS2018-7-2e). The largest dike known (Dike 1) varies from 1 to 15 m wide and is 300 m long at surface. It is hosted by the mafic volcanic rocks except for at its southern tip, where it thins and disappears over a few metres in quartzofeldspathic gneiss (as described above). The thicker dikes show less folding at the surface. As a result, Dike 1 is relatively planar throughout most of its length and is folded only near its northern tip.

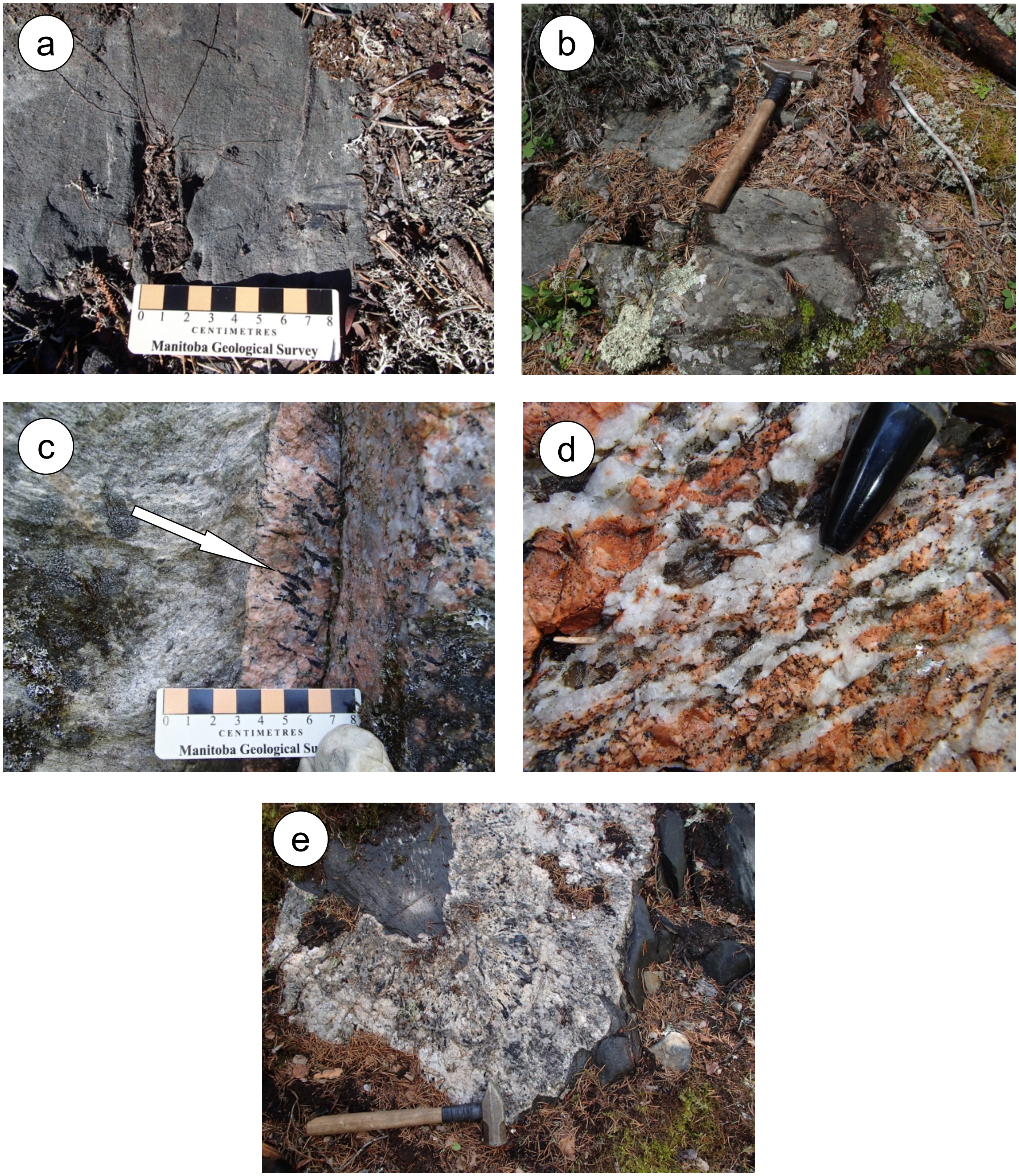


Figure GS2018-7-2: *Outcrop photographs of the map units in the northeastern block of the Wekusko Lake pegmatite field:* ***a)*** *amphibolite, likely derived from massive mafic volcanic rock;* ***b)*** *pillow basalt (hammer for scale, hammer head points north);* ***c)*** *pegmatite dike hosted in quartzofeldspathic gneiss showing tourmaline comb texture perpendicular to the margins of the pegmatite dike (arrow points to tourmaline);* ***d)*** *stretched feldspars from the north edge of Dike 1 (pen tip for scale is 1.5 cm long);* ***e)*** *folded pegmatite dike hosted by amphibolite likely derived from massive mafic volcanic rock (hammer for scale).*

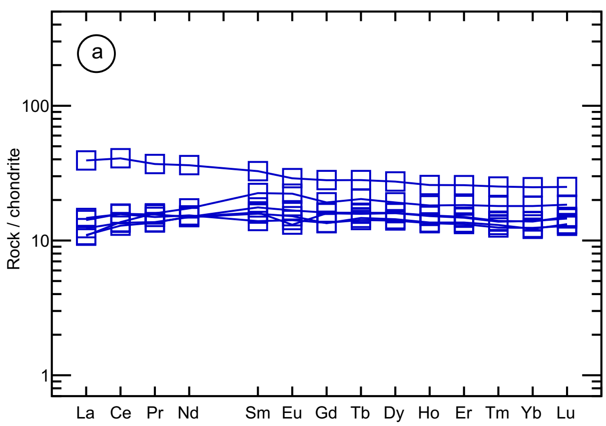
Table GS2018-7-1: Whole-rock geochemical results of the massive and pillow basalt.

Sample	113-18-D007	113-18-16-004-7.5 m	113-18-18-23-325 m	113-18-18-23-33 m	113-18-18-23-182 m	113-18-D088
Rock type	Massive basalt	Massive basalt	Massive basalt	Massive basalt	Massive basalt	Pillow basalt
SiO_2	51.78	45.98	51.14	50.6	48.02	49.01
Al_2O_3	11.84	14.5	14.05	13.5	14.7	13.55
Fe_2O_3	18.95	19.82	13.18	13.44	14.48	13.18
MnO	0.237	0.185	0.184	0.188	0.204	0.199
MgO	4.61	7.44	7.29	7.45	7.93	7.03
CaO	7.84	7.68	10.24	10.33	10.67	9.65
Na_2O	2.79	2.38	2.51	2.54	2.36	2.66
K_2O	0.27	0.13	0.23	0.17	0.19	0.53
TiO_2	2.174	1.729	1.058	1.141	1.141	1.184
P_2O_5	0.15	0.12	0.08	0.08	0.09	0.09
LOI	0.17	0.53	0.76	0.66	0.78	3.44
Total	100.8	100.5	100.7	100.1	100.6	100.5
Sc	47	41	44	46	48	45
Be	<1	<1	<1	<1	<1	<1
V	601	476	345	362	377	365
Cr	<20	50	180	170	190	230
Co	51	75	44	46	50	44
Ni	30	200	90	80	110	100
Cu	170	100	150	140	210	60
Zn	150	130	90	90	100	80
Ga	20	19	17	14	18	17
Ge	1.2	1.4	1.4	1.3	1.4	1.2
As	<5	6	10	<5	25	18
Rb	<1	<1	<1	<1	<1	1
Sr	114	108	137	131	162	161
Y	40.8	29.4	21.5	22.2	23	23.6
Zr	135	95	61	63	67	68
Nb	5.3	4.6	2.2	2.6	1.8	2.3
Mo	<2	<2	<2	<2	<2	<2
Ag	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
In	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sn	<1	<1	<1	<1	<1	<1
Sb	0.2	0.3	0.6	0.4	0.9	0.4
Cs	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
Ba	30	16	35	44	22	63
La	9.3	2.57	3.48	2.92	2.6	3.36
Ce	24.9	8.37	9.6	8.28	7.88	9.67
Pr	3.51	1.51	1.42	1.3	1.29	1.48
Nd	16.9	8.08	7.17	6.95	7.03	6.99
Sm	5	3.44	2.13	2.42	2.47	2.69
Eu	1.68	1.29	0.821	0.878	0.76	0.97
Gd	5.76	3.94	2.78	2.76	3.27	3.31
Tb	1.05	0.76	0.53	0.55	0.59	0.6
Dy	6.95	4.87	3.57	3.65	4.05	4.07
Ho	1.46	1.03	0.76	0.77	0.86	0.87

Table GS2018-7-1 (continued): Whole-rock geochemical results of the massive and pillow basalt.

Sample	113-18-D007	113-18-16-004-7.5 m	113-18-18-23-325 m	113-18-18-23-33 m	113-18-18-23-182 m	113-18-D088
Rock type	Massive basalt	Massive basalt	Massive basalt	Massive basalt	Massive basalt	Pillow basalt
Er	4.26	3.03	2.19	2.25	2.44	2.48
Tm	0.641	0.46	0.318	0.332	0.352	0.357
Yb	4.22	3.06	2.11	2.07	2.37	2.35
Lu	0.634	0.468	0.326	0.336	0.37	0.38
Hf	3.1	2.1	1.4	1.4	1.5	1.6
Ta	0.43	0.33	0.2	0.17	0.22	0.24
W	1.9	1.6	2.5	1.4	1.7	2.7
Tl	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Pb	<5	<5	<5	<5	<5	<5
Bi	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Th	0.58	0.39	0.27	0.22	0.19	0.23
U	0.17	0.13	0.14	0.1	0.07	0.09

Samples were submitted to Actlabs (Ancaster, ON) for major- and trace-element analyses using research-grade lithogeochemistry package (4Litho-research)



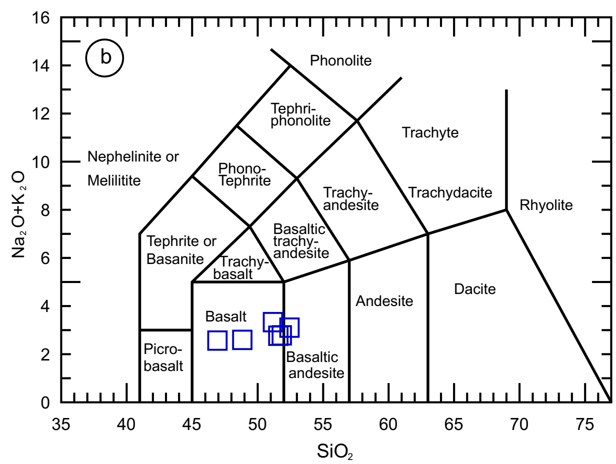


***Figure GS2018-7-3:** Major- and trace-element diagrams for mafic volcanic rocks (unit 1): **a)** total alkalis versus silica (TAS) diagram (after Le Maître et al., 2002); **b)** chondrite-normalized rare-earth-element spider profile. Normalizing values for chondrite are from Sun and McDonough (1989).*

Other dikes such as Dike 7 and 8, which are 5–10 m thick, show much more folding and undulation. Dike thicknesses change locally as they pinch and swell. Thin, granitic dikes (<30 cm) and dikelets (<1 cm) are also present in the study area. Pegmatites locally exhibit tight folding, and at some locations the pegmatite has folded over on itself causing ballooning (Figure GS2018-7-4). No known Li mineralization is associated with the thin dikes and dikelets.

Mineralogy of the Li-bearing pegmatites

Spodumene is present in three phases in pegmatites at the Wekusko Lake pegmatite field (Martins et al., 2017). The first and most common phase (Figure GS2018-7-5) is euhedral to subhedral and very coarse grained (crystals up to 30 cm in diameter occurring locally). The spodumene is a pale green colour, likely due to Fe impurities (London, 2017). The second phase is fine grained (<2 mm), has a grey-green colour and is intergrown with quartz. The third phase is interstitial spodumene. It is very fine grained and forms small masses between larger, well-developed crystals, suggesting a late crystallization.

There are at least two phases of muscovite as observed by Martins et al. (2017). The first is coarse-grained (<5 cm) subhedral books that are interpreted as primary. Muscovite is present locally as comb structures in the wall zone where it is intergrown with tourmaline, which suggests that these two minerals crystalized at the same time. The second phase of muscovite is secondary

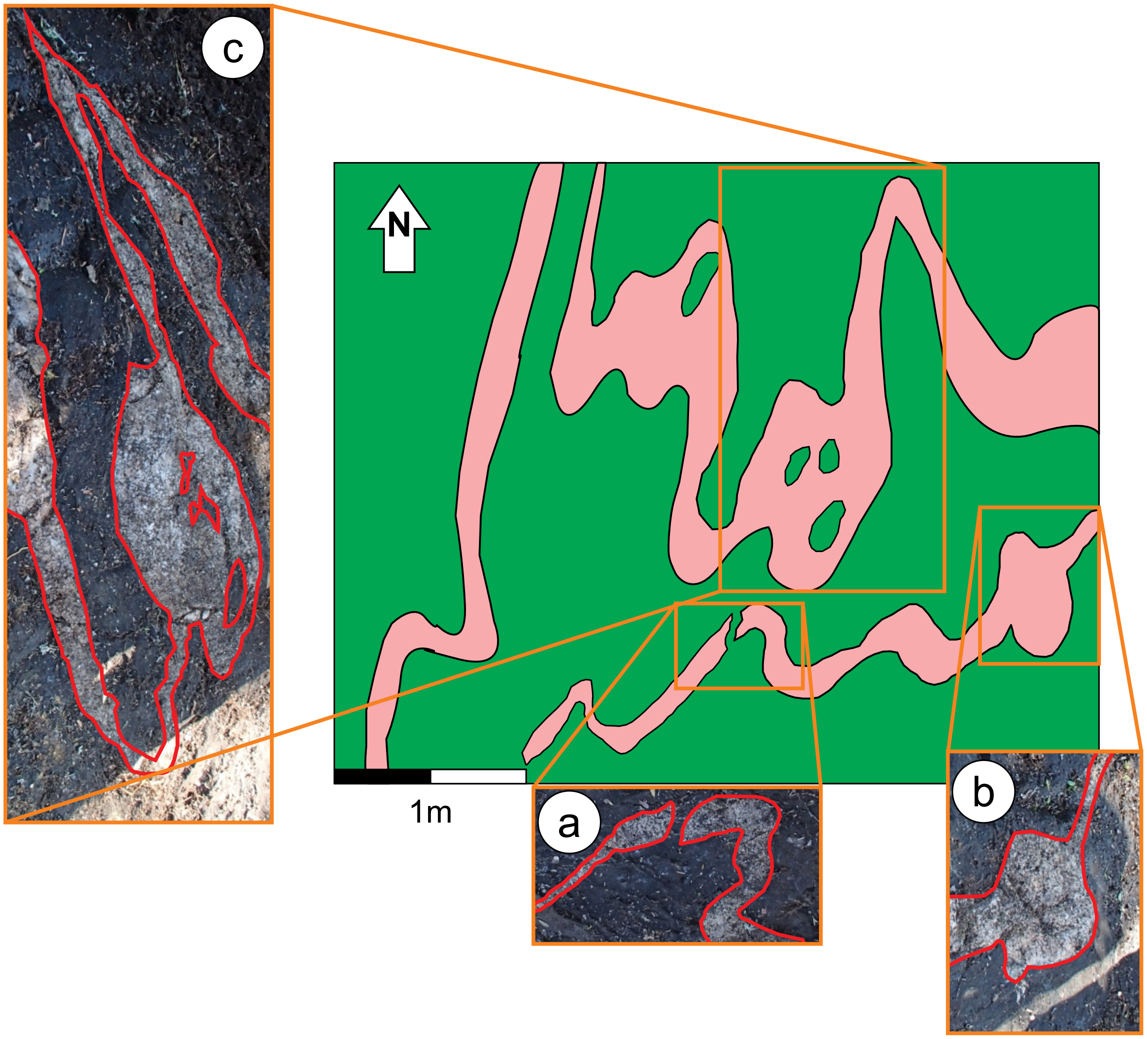


Figure GS2018-7-4: *Sketch and outcrop photos showing folding in pegmatite near Dike 7:* ***a)*** *break in folded pegmatite;* ***b)*** *ballooning in pegmatite;* ***c)*** *ballooning in pegmatite with mafic volcanic xenoliths.*

and is present as fine-grained masses. The secondary muscovite is most commonly found in the wall zone and decreases in abundance toward the centre of the dike.

At least two varieties of feldspar are present. The first occurs as creamy white, very coarse grained crystals (<20 cm) that are likely albite, although perthitic and graphic textures indicate that at least some of the white crystals are K-feldspar. The second is a brick red K-feldspar that occurs as interstitial masses.

Trace amounts of apatite, Fe-Mn phosphate minerals, columbite-group minerals and beryl are present. The apatite is fine grained (<1 mm), has a dark blue colour and is present primarily in the central zone. The phosphate minerals are dark red to brown, medium grained (<1 cm) and present in the central zone of the pegmatite. These phosphates are thought to be part of the triphylite (Fe^{2+}) to lithiophilite (Mn^{2+}) series. Columbite-group minerals are present as black, fine-grained needles (<1 mm) and likely explain the elevated Ta and Nb assay values; identification of the Nb-Ta phases will be undertaken by future petrography. Dikes 1, 5 and 8 all have Ta assay values above 100 ppm (FAR Resources Ltd., 2017, 2018). Columbite-group minerals most commonly occur in the central zone. Beryl forms stubby, white, opaque, euhedral to subhedral, medium-grained (<2 cm) crystals. Beryl potentially explains the Cs anomalies in the pegmatites (Černý and Simpson, 1977), although Cs also substitutes into K-feldspar and mica. Beryl occurs in all zones within the pegmatite, but it is most commonly observed in the wall zone. It is difficult, however, to identify in the central zone because it is easily confused for albite.

Zoning of the Li-bearing pegmatites

Based on observations from drillcore from 29 drillholes, 5 zones for the Li-bearing pegmatite dikes were recognized: the border zone, the wall zone, the inter-

Figure GS2018-7-5: *Primary, phase one spodumene crystal from halved drillcore; coin for scale (arrow points to the spodumene crystal).*

mediate zone, the central zone and the core zone. This builds on the work of Martins et al. (2017), although the border zone was not identified in that study. These zones are not apparent in all eight dikes or at all depths within the dikes. Thin dikes, in particular, tend to lack the central or core zones, and the width of the different zones greatly varies between the dikes. The zones vary in grain size and mineralogy, but grain sizes generally increase toward the centre of the dike. There is a colour variation from red to salmon pink to white from the wall zone to the intermediate zone to the central zone. This may be due to variations in the contents of K-feldspar and albite although the red colour (due to hematization) may also be the result of greater external fluid interaction near pegmatite contacts (Gysi et al., 2016). Detailed feldspar mineralogy will be investigated in the future using petrography and Raman spectroscopy.

Border zone

The border zone is the outermost, smallest zone and is not always present. It is up to 1 cm wide along the outer edge of the pegmatite. The border zone is composed primarily of quartz, muscovite, feldspar and tourmaline. Grain sizes are between 0.5 and 2 mm.

Wall zone

The wall zone (Figure GS2018-7-6a) is composed of K-feldspar, quartz, muscovite, albite and tourmaline with accessory beryl, spodumene and apatite and has a brick red colour. Muscovite is present as both primary and secondary phases. Tourmaline commonly forms comb structures perpendicular to the pegmatite contact. Grain sizes are typically between 0.25 and 2 cm; however, it is not uncommon for larger crystals to be present in the wall zone.

Intermediate zone

The intermediate zone (Figure GS2018-7-6b, c) is composed of albite, K-feldspar, quartz, muscovite and spodumene (5%). Grain sizes range from 0.5 to 5 cm with rare crystals up to 10 cm in length. All three phases of spodumene can be present in this zone. The albite to K-feldspar ratio is approximately 1:1, which gives the zone a salmon pink colour. The K-feldspar forms fine-grained (<0.5 cm) masses, whereas albite occurs as larger subhedral crystals (3–5 cm).

Central zone

The central zone (Figure GS2018-7-6d) is composed of albite, spodumene, quartz and muscovite with accessory apatite, columbite-group minerals and Fe-Mn phosphate minerals, but the central zone is not always present. The central zone contains the highest concentrations of spodumene varying from 10 to 30 modal percent and locally up to 50 modal percent. The average grain size ranges from 3 to 10 cm, with some crystals up to 15 cm long. The central zone has a greyish white colour due to the presence of albite and quartz. Spodumene is mostly seen as euhedral to subhedral crystals between 3 and 6 cm long. Muscovite is present in euhedral to subhedral coarse-grained books.

Core zone

The core zone is the innermost zone of the dike and is composed predominantly of quartz and albite, with minor spodumene (<5%). The grain sizes range from 3 to 10 cm, locally with crystals up to 20 cm long. Spodumene is typically present as large euhedral to subhedral crystals up to 15 cm long. The core zone replaced the central zone in some thinner sections of the dike, but this zone is not always present.

Future work

During this study, samples were collected from all zones and pegmatites at varying depths. Sampling focused on obtaining both primary and secondary muscovite crystals to determine their Li content and to evaluate whether muscovite chemistry is related to the proximity of spodumene or the spodumene grade of a pegmatite zone. Samples of drillcore with high Nb and Ta values were also targeted for geochronology studies.

Lithium substitutions mostly occur in the octahedrally coordinated sites and minor Li^+–K^+ substitution may also occur in the interlayer (Brigatti et al., 2001); therefore, the Li content of the muscovite may reflect the Li content in the melt. Thus, muscovite has the potential

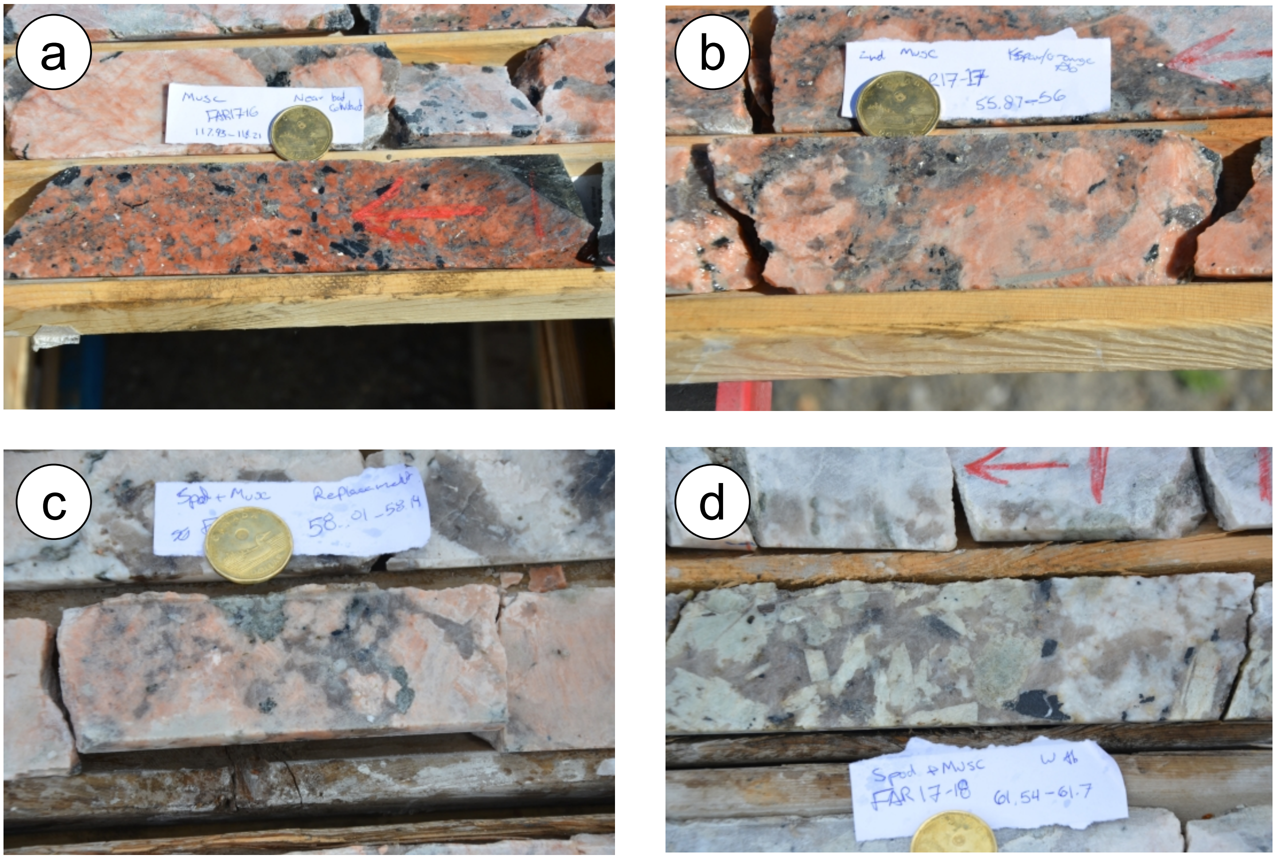


Figure GS2018-7-6*: Drillcore displaying the transition from* ***a)*** *the brick red wall zone to* ***b), c)*** *the salmon pink intermediate zone to* ***d)*** *the white central zone. Coins for scale.*

to be an indicator mineral for Li exploration in pegmatites; i.e. the Li content of muscovite could indicate the potential for Li mineralization where spodumene is not present in a sample. Lithium content will be determined by laser-ablation inductively coupled plasma–mass spectroscopy (LA-ICP-MS). Peak shifts related to the muscovite molecular structure (muscovite to polylithionite) will be measured by portable Raman spectroscopy and calibrated by LA-ICP-MS to evaluate the utility of portable Raman spectroscopy in Li pegmatite exploration. The portable Raman spectrometer will also be used to determine feldspar compositions (albite versus K-feldspar) and this instrument will be evaluated as a more general tool for use in pegmatite exploration.

Geochronology studies on columbite-group minerals will help determine the timing of the pegmatite emplacement in relation to the peak metamorphism and deformation history of the region.

Economic considerations

Manitoba is highly prospective for Li pegmatites. This includes the Green Bay group of the Wekusko Lake pegmatite field, which contains at least eight large Li-bearing pegmatite dikes. Of those, two contain central zones with more than 2 wt. % Li_2O (FAR Resources Ltd., 2017; FAR Resources Ltd., 2018 lists additional assay results). The Li content within mica grains will be tested to identify the proximity to high spodumene concentrations and to identify the central zone (where spodumene is most abundant) within pegmatite. It is anticipated that variations of Li between mica grains within pegmatite can act as a vector to identify the central zone.

The largest dikes in the Green Bay group of the Wekusko Lake pegmatite field contain central zones with increased abundances of Ta and Nb, hosted by columbite-group minerals. The white colour and stubby crystal habit of the beryl is thought to be related to high Cs values within the mineral structure. The origin of these concentrations is currently under investigation.

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