GS2017-5

Whole-rock and mineral geochemistry as exploration tools for rare-element pegmatite in Manitoba: examples from the Cat Lake–Winnipeg River and Wekusko Lake pegmatite fields (parts of NTS 52L6, 63J13)

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In Brief:

- Elevated Li, Rb and Cs in mafic metavolcanic country rocks is a useful exploration guide for rare-element pegmatite
- Li-rich amphibole (holmquistite) in country rocks indicates proximity to Li-bearing pegmatite
- Mineral chemistry of feldspar and muscovite provide measures of pegmatite fractionation
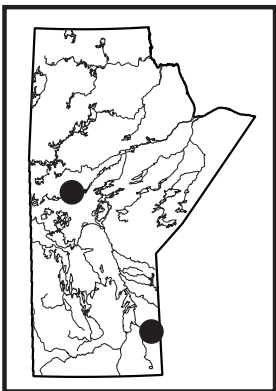
Summary

This report summarizes fieldwork conducted in the Cat Lake–Winnipeg River pegmatite field in southeastern Manitoba and the Wekusko Lake field in west-central Manitoba. Both of these pegmatite fields are endowed with Li mineralization, but their geological settings and ages are different. Country rocks surrounding Li-bearing pegmatite in both fields were analyzed for major and trace elements, revealing anomalous values of highly mobile elements such as Li, Rb and Cs. This study indicates that whole-rock geochemistry can be a very useful tool in exploration programs for rare-element pegmatite. Holmsquistite-bearing assemblages, identified in the country rock to 'Dike 1' in the Wekusko Lake field, can also be used as an exploration tool for Li-bearing pegmatite. In addition, results from mineral-chemistry studies of muscovite and K-feldspar from Dike 1 indicate that it is possible to track pegmatite fractionation using these minerals.

Introduction

Alteration haloes resulting from metasomatism have been documented around many pegmatites, with Cabot Corporation's Tanco mine in the Bird River greenstone belt of southeastern Manitoba being the most studied example in the province (e.g., Trueman, 1978; Morgan and London, 1987; Halden et al., 1989). At Tanco, this type of country-rock metasomatism has been utilized for exploration (Trueman, 1978), and this methodology has since been applied throughout the Bird River greenstone belt (Galeschuk and Vanstone, 2005, 2007; Linnen et al., 2015). Lithium anomalies define the widest haloes adjacent to Li-Cs-Ta (LCT) pegmatites (Linnen et al., 2012) and, in the case of Tanco, Li haloes have been recognized to extend more than 100 m away from the pegmatite body (Černý, 1989). However, dispersion of other elements such as Rb and Cs seems to be more restricted (e.g., Černý, 1989; London, 2008).

This type of country-rock alteration is caused by the influx of pegmatite magma and coexisting fluids rich in incompatible elements. The composition of the fluid phase is related to the magma composition; therefore, the diagnostic elements of the alteration aureoles are related to element enrichments and mineralogy of the associated pegmatite intrusion (Beaus, 1960). In the case of evolved LCT pegmatites, the adjacent country rock is altered by an influx of alkali rare elements (e.g., Li, Rb and Cs) and subsequent interaction between the fluid phase and the country rock, forming a dispersion halo. This interaction results in a change of the composition of pre-existing mineral assemblages in the country rock and stabilization of exotic mineral assemblages. Metasomatism by Li-enriched fluids can produce holmsquistite-bearing assemblages in amphibolitic country rock, as has been documented at several locations, including the Edison pegmatite in the Black Hills of South Dakota (Shearer et al., 1986; Shearer and Papike, 1988) and the Tanco pegmatite in Manitoba (Morgan and London, 1987; Selway et al., 2000). These alteration assemblages can be a good exploration tool and have been used in many pegmatite districts (e.g., Beus, 1960; Truman and Černý, 1982; Norton, 1984; London, 1986).

This study focuses on alteration haloes caused by 1) the Dibs LCT pegmatite from the Cat Lake–Winnipeg River pegmatite field in the Archean Bird River greenstone belt, and 2) the Dike 1 LCT pegmatite from the Wekusko Lake pegmatite field in the Paleoproterozoic Flin Flon–Snow Lake greenstone belt. Although the ages differ, both bodies intrude metamorphosed volcanic rocks and the premise for this study is that both would be associated with above-normal background values for elements that are enriched in the pegmatite. There are a number of factors that could influence the metasomatic halo around Li-bearing pegmatites, including 1) the relationship between

dike thickness and the size of the metasomatic halo; 2) the shape of the halo related to the location of the Li mineralization within the pegmatite; 3) fluid pressures at time of emplacement; 4) structural permeability; 5) country-rock composition; 6) emplacement history; and 7) overprinting by later structural, metamorphic or hydrothermal events. All these variables could influence the sampling methodology and the interpretation of the results; one of the goals of this study is to better understand the metasomatic haloes in the context of these various factors.

Regional geology

Cat Lake–Winnipeg River pegmatite field

The Dibs pegmatite is part of the Bernic Lake pegmatite group (Galeschuk and Vanstone, 2005), which includes the Tanco pegmatite, of the Cat Lake–Winnipeg River pegmatite field (Černý et al., 1981) in the Bird River greenstone belt of the Archean Superior province (Figure GS2017-5-1). Most of the supracrustal units of the Bird River greenstone belt range in age from 2.85 to 2.64 Ga (Gilbert et al., 2008) and represent a transitional oceanic–continental margin setting (Gilbert et al., 2008) between the North Caribou terrane to the north and the Winnipeg River terrane to the south (nomenclature of Stott et al., 2010).

The Bird River greenstone belt has been historically described as a large synclinal keel (Trueman, 1980; Černý et al., 1981); however, recent mapping by the Manitoba Geological Survey has led to a reinterpretation of the stratigraphic framework of the belt, summarized by Gilbert et al. (2008). The Bird River belt has been subdivided into two distinct panels (North and South), both of which are composed of ca. 2.75–2.72 Ga, juvenile, arc-type metavolcanic and associated metasedimentary rocks. These two panels are separated by turbidites of the Booster Lake Formation (<2712 ±17 Ma; Gilbert, 2006).

The hostrock for both the Dibs and the Tanco pegmatites is a gabbroic to dioritic body (known as the Tanco gabbro) that is approximately 1.5 km by 3 km in size. It is a relatively homogeneous, equigranular, medium- to coarse-grained intrusion that contains rare pegmatitic phases and intrudes volcanic rocks of the Bernic Lake formation, part of the South panel of the belt (Gilbert et al., 2008; Kremer, 2010). Its margins are characterized by a well-defined, east-trending, steeply dipping foliation and local, narrow, high-strain zones. A sample of pegmatitic gabbro yielded a U-Pb age of 2723.1 ±0.8 Ma, contemporaneous with the age of volcanic rocks in the Bernic Lake Formation (2724.6 ±1.1 Ma) and with the Birse Lake granodiorite (2723.2 ±0.7 Ma), suggesting that these represent components of a single subvolcanic to volcanic system (Gilbert et al., 2008; Kremer, 2010).
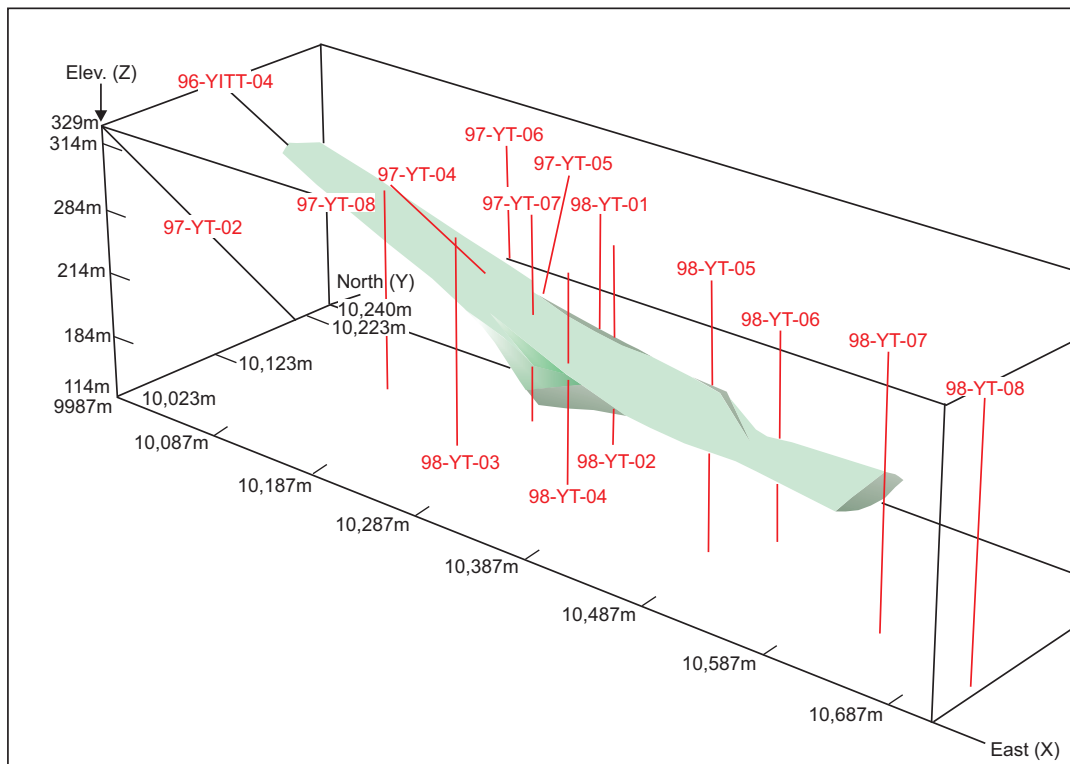
Dibs pegmatite

The Dibs pegmatite, which does not outcrop, was discovered during an exploration program carried out by Cabot Corporation (Tanco) during the 1990s and early 2000s (Assessment Files 73144, 74409, Manitoba Growth, Enterprise and Trade, Winnipeg). Galeschuk and Vanstone (2005) described the Dibs pegmatite as a horizontal body at least 500 m in length and up to 100 m in width, with a maximum thickness of approximately 65 m (Figure GS2017-5-2). Five different zones were identified in the Dibs pegmatite (Galeschuk and Vanstone, 2005):

1) the border zone, consisting predominantly of quartz, albite and local black tourmaline;
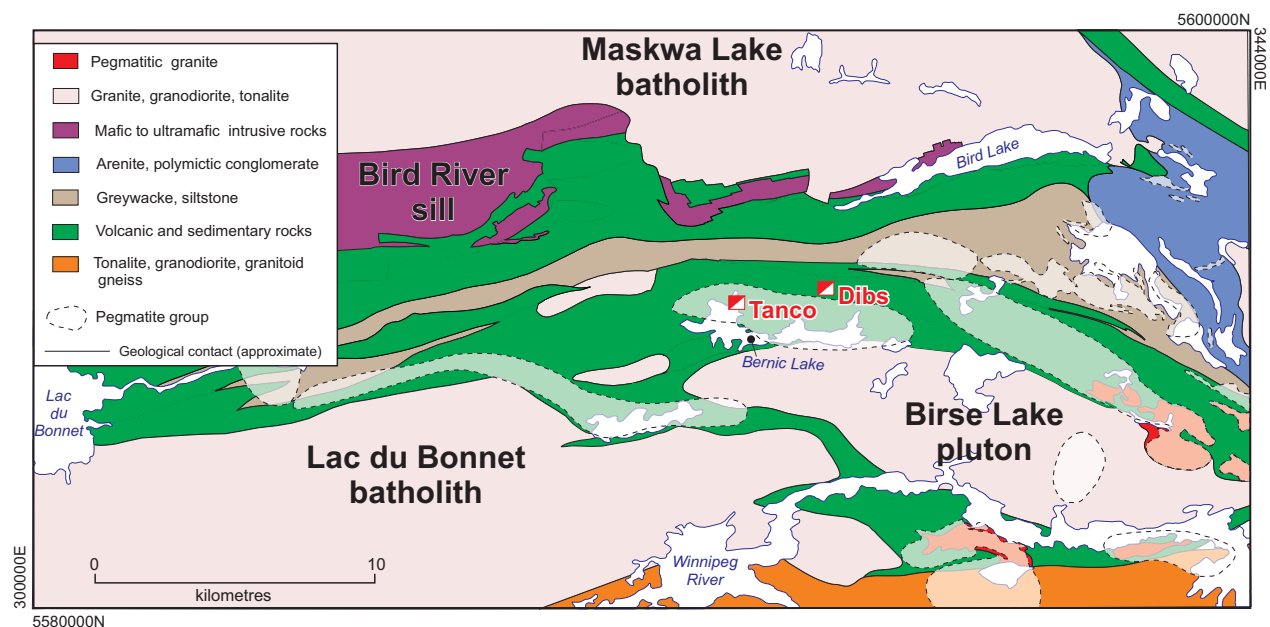
Figure GS2017-5-1: Simplified regional geology of the Bird River greenstone belt (after Gilbert et al., 2008), showing the locations of the Tanco mine and the Dibs pegmatite.

Figure GS2017-5-2: *Three-dimensional block model of the Dibs pegmatite, looking northwest (modified after Galeschuk and Vanstone, 2005).*

2) the wall zone, consisting of K-feldspar, quartz, albite (cleavelandite habit), mica, petalite, tourmaline and minor amblygonite, triphylite, spodumene, lepidolite and smoky quartz;

3) the central intermediate zone, consisting of K-feldspar, quartz-rich sections with masses of muscovite, minerals of the columbite group, and cassiterite;

4) the lower intermediate zone, consisting mainly of K-feldspar, albite (cleavelandite habit), quartz, muscovite, accessory beryl, 'ball peen' mica, petalite, cookeite, amblygonite and smoky cleavable quartz;

5) the quartz±K-feldspar zone or core, composed mainly of massive quartz, K-feldspar and minor petalite, amblygonite and muscovite.
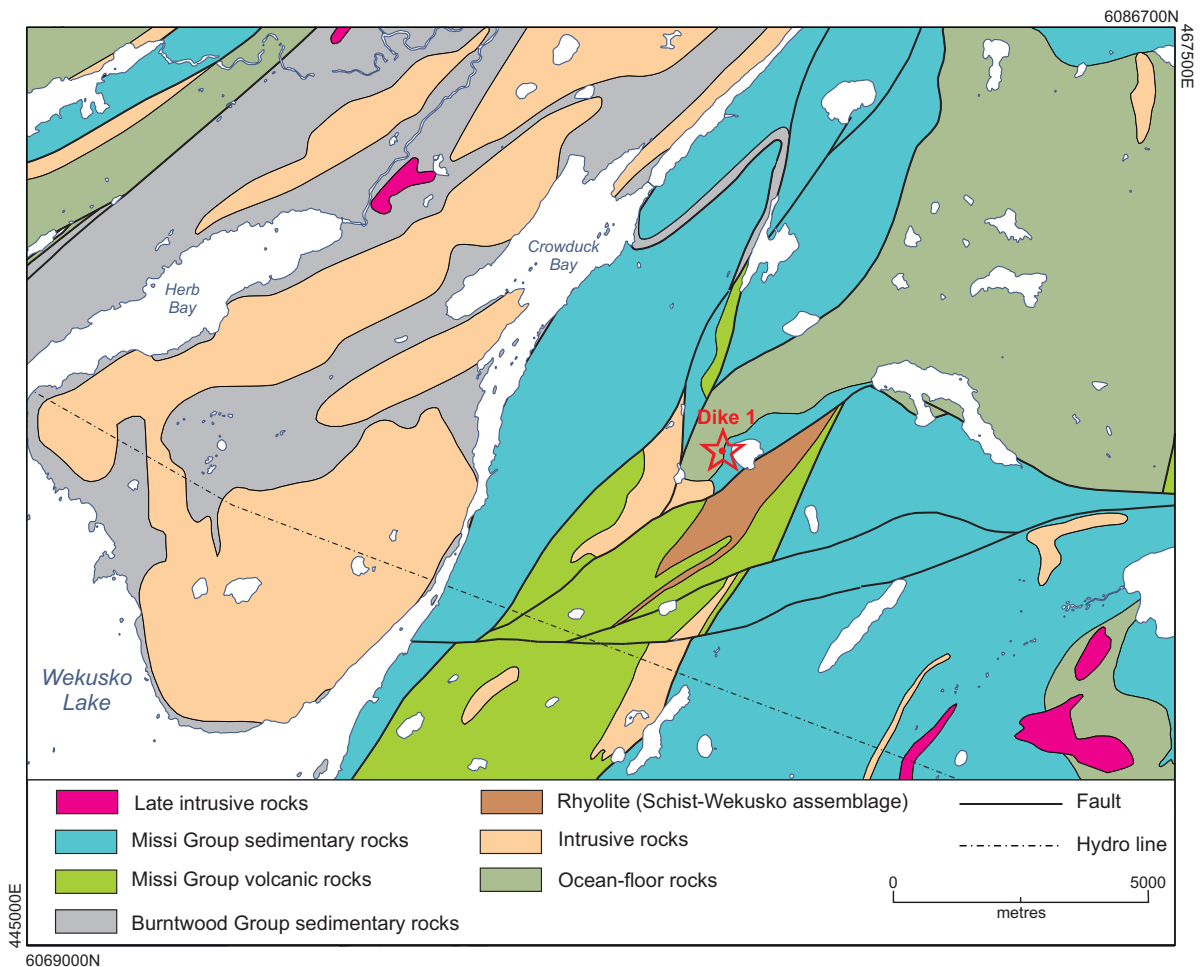
Wekusko Lake pegmatite field

The Dike 1 pegmatite is part of a swarm of at least seven pegmatite dikes that make up the Green Bay group of the Wekusko Lake pegmatite field (Černý et al., 1981). This pegmatite field is located east of Wekusko Lake within the Flin Flon–Glennie complex of the Paleoproterozoic Trans-Hudson orogen (Figure GS2017-5-3; NATMAP Shield Margin Working Group, 1998; Bailes and Galley, 1999). Bedrock exposures east of Wekusko Lake are dominantly Paleoproterozoic metavolcanic and metasedimentary rocks of the Missi group intruded by granitoid rocks (NATMAP Shield Margin Working Group, 1998; Gilbert and Bailes, 2005a). Surface exposures and drillcore

indicate that the hostrocks for the Dike 1 pegmatite are ocean-floor mafic volcanic rocks likely deposited between 1.92 and 1.87 Ga (NATMAP Shield Margin Working Group, 1998). Locally in drillcore, the country rock to the Dike 1 pegmatite can also be metasedimentary biotite-garnet-muscovite schist, possibly belonging to the Missi group (NATMAP Shield Margin Working Group, 1998).

Dike 1 pegmatite

The Dike 1 pegmatite is the largest and best known dike of the Green Bay group. It is a north-trending, near-vertical body that extends for at least 280 m along strike, with a maximum thickness of approximately 35 m (Figure GS2017-5-4). The apparent absence of country-rock alteration was commonly noted in historical drill logs (Assessment File 93562). Results from this study however, identified holmquistite in the mafic-volcanic country rock, indicating metasomatic alteration associated with pegmatite intrusion, and lithogeochemical analyses (see below) demonstrate that a broad metasomatic halo is present. The development of holmquistite-bearing assemblages is controlled by the activity of Li introduced into the country rock during pegmatite emplacement. These assemblages reflect greenschist-facies metamorphic conditions and are only found in amphibolitic wallrock, usually replacing hornblende, pyroxene or biotite (Heinrich, 1965; London, 1986). Based on historical (Assessment File 93562) and recent drill-log descriptions, the zonation in the Dike 1 pegmatite can be defined as follows:

Figure GS2017-5-3: *Regional geology of the east side of Wekusko Lake, with the location of the Dike 1 pegmatite (modified and simplified from NATMAP Shield Margin Working Group, 1998).*

1) the wall zone, composed predominantly of quartz, microcline and muscovite, with accessory tourmaline, hornblende, biotite and rare beryl and spodumene;

2) the intermediate zone, with medium-sized crystals of microcline, albite, quartz, muscovite and spodumene (<5%);

3) the central zone, with abundant spodumene (locally up to 50% but more commonly varying between 10% and 30%), albite, quartz and locally pollucite, and accessory apatite, tourmaline, pyrrhotite, lepidolite, columbite-group minerals and Fe-Mn–phosphate minerals;

4) the core zone, composed mainly of quartz with small- to medium-grained spodumene crystals (although locally 15–20 cm crystals of spodumene are observed) in a quartz matrix, with minor tourmaline and muscovite.

From historical descriptions and recent preliminary petrographic work, it is possible to distinguish at least three different stages of spodumene growth: greenish spodumene with characteristics typical of a primary phase; spodumene-quartz intergrowths, possibly after petalite breakdown (Černý and Ferguson, 1972); and late bands of very fine grained spodumene

that crosscut other mineral phases or surround feldspar and muscovite grains. Locally, spodumene crystals are surrounded by fine-grained mica, possibly Li-mica or lepidolite. This could be indicative of a late Li-enriched fluid episode (possibly autometasomatism) that could have produced late Li-enriched mica. Acicular opaque minerals of the columbite group are present, and late bands of fluorite occur locally in fractures (Assessment File 93562). The latest event, identified in thin section, produced late, Fe-rich, quartz-calcite stringers with no preferred orientation crosscutting the pegmatite, which could be similar to the quartz–Fe-carbonate–albite–sericite assemblage described by Galley et al. (1989) in association with Au occurrences east of Wekusko Lake. In thin section, feldspar and muscovite show evidence of deformation (for example, kink bands in muscovite), suggesting that pegmatite emplacement occurred prior to the latest stages of regional deformation.

Methodology

Samples of country rock to the Dibs pegmatite were collected from Tanco's drillcore library to complement and expand on the work carried out by Linnen et al. (2009). Fifty-six
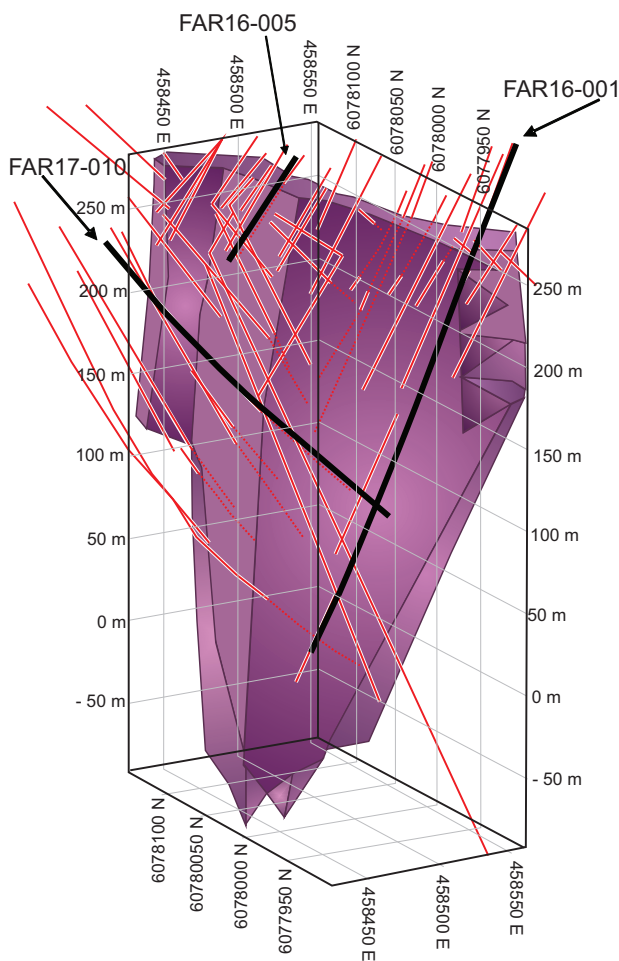
Figure GS2017-5-4: *Three-dimensional block model of the Dike 1 pegmatite, including locations of historical and recent drillholes. Drillholes selected for this study are indicated by arrows.*

samples were selected from drillholes 98-YT-01, 98-YT-03, 98-YT-04, 98-YT-05, 98-YT-08, 06-YT-01, 06-YT-03 and 06-YT-04. Samples were collected from both the hangingwall and footwall at 5–10 m intervals in proximity to the pegmatite contacts, and at 10–20 m intervals distal from the contacts; zones of visible alteration were not sampled. Samples, each consisting of about a 20–30 cm length of drillcore, were crushed at the Midland Sample and Core Library in Winnipeg and the rock powders were sent to Activation Laboratories Ltd. (Ancaster, Ontario) for lithogeochemical analysis. The samples were analyzed using a Li metaborate/tetraborate fusion technique, followed by nitric-acid digestion and analysis by inductively coupled plasma–emission spectrometry (ICP-ES) and inductively coupled plasma–mass spectrometry (ICP-MS). Added element Li was analyzed using total digestion–inductively coupled plasma (TD-ICP). Fluorine was converted to a fuseate and then analyzed by an automated fluoride analyzer.

Three drillholes from the Dike 1 pegmatite were selected for this study: FAR16-001, FAR16-005 and FAR17-010. Sixty-nine samples of mafic-volcanic country rock and one sample of biotite-garnet-muscovite schist were collected from the hangingwall and footwall of the pegmatite dike. Sample spacing was 5 m close to the contact with the pegmatite, and 10 m and 20 m apart farther away from the contact. The samples consisted of about 20 cm of split drillcore. Analyses were performed by Activation Laboratories (Ancaster, Ontario) using a sodium-pyrophosphate fusion technique, followed by ICP-MS. Selected samples of muscovite and K-feldspar from Dike 1 were analyzed using a JEOL JXA-8530F field-emission electron microprobe at Western University. Analytical details are provided in DRI2017004 (Martins and Linnen, 2017)[4].

Results

Whole-rock geochemistry

According to Černý (1989), background values for geochemical anomalies of a certain element can be defined for concentrations that are greater than two standard deviations. Values for Li in the country rock of Dike 1 are generally not available in the literature because this element is not routinely analyzed. Lithium is a moderately incompatible trace element in magmatic systems and its abundance in the mantle is estimated to be about 1.9 ppm (Ryan and Langmuir, 1987). The same authors reported that the world-wide range in Li content for mid-ocean ridge basalt (MORB) is 3–17 ppm (only evolved Fe-Ti basalts have >8 ppm Li), and andesites and dacites from the East Pacific Rise contain up to 30 ppm Li, indicating that Li increases with differentiation. Given that Dike 1 country rock has flat rare-earth element (REE) profiles characteristic of MORB (not plotted; data from Gilbert and Bailes, 2005b), the assumption for this study is that the background concentrations of Li should be low (<8 ppm) in nonmetasomatized country rock to Dike 1. Values for Rb and Cs are more readily available in the literature. Samples from an equivalent unit to the Dike 1 country rock at south Wekusko Lake contain <7 ppm Rb and <0.03 ppm Cs (Gilbert and Bailes, 2005b). Thus, based on available data, values >6 ppm Rb and >0.02 ppm Cs are considered anomalous (twice the values of the standard deviation of data from Gilbert and Bailes, 2005b). For Li background, values are considered to be anomalous at >16 ppm (double the maximum value for non-evolved MORB defined by Ryan and Langmuir, 1987).

At the time of writing, the full dataset of whole-rock geochemistry for the country rocks to the Dibs pegmatite was not available. Therefore, previous work conducted on this dike by Linnen et al. (2009, 2015) will be used for comparison with results obtained during this study for the country rocks to Dike 1. For the country rock to the Dike 1 pegmatite, some of the highest values attained are 1900 ppm Li, 196 ppm Rb and 225 ppm Cs adjacent to the upper contact of the pegmatite,

indicating the rare-element character of this dike. The Rb and Cs values are well above what is reported for nonmetasomatized ocean-floor mafic volcanic rocks from the same area (Gilbert and Bailes, 2005b). They are comparable to values obtained by Linnen et al. (2009) in country rock at the upper contact of the Dibs pegmatite: up to 2256 ppm Li, 184.5 ppm and 72.4 ppm Cs.

For the Dibs pegmatite, values of Li, Rb and Cs in the country rock increase substantially toward the contact of the pegmatite (Linnen et al., 2009, 2015). For Dike 1, the maximum concentrations for each element occur mostly in the country rock adjacent to the pegmatite contacts (Figure GS2017-5-5a–f). However, the increase in concentration approaching the contact might not always be a steady one. Within the same drillhole (FAR17-010), values at 11 m for Li, Rb and Cs are 48, 39.1 and 1.1 ppm, respectively (all values above background; Figure GS2017-5-5d–f). These values close to surface are higher than at roughly 70 m downhole (14 ppm Li, 1 ppm Rb, 0.2 ppm

Cs). Deeper than 70 m there is a steady increase of Li, Rb and Cs until the pegmatite intrusion at 163 m (922 ppm Li, 51 ppm Rb, 23.9 ppm Cs; Figure GS2017-5-5d–f). This downhole variation in concentration of Li, Rb and Cs could be related to the presence of fractures, the size or shape of the pegmatite (and consequently the metasomatic halo), and the zonation of the pegmatite itself (i.e., location of the Li or Cs mineralization and Rb enrichment within the pegmatite). The data also indicate that above-background concentrations of Li, Rb and Cs in the country rock of Dike 1 can be measured up to 150 m away from the pegmatite contact.

Elements such as Nb and Ta are low and do not show any particular enrichment at the contacts with the pegmatite (Nb <5 ppm; Ta <2 ppm, with only one analysis as high as 8 ppm), indicating low mobility of these elements and a weak enrichment in Dike 1. This is corroborated by mineralogical studies in the Wekusko Lake pegmatite field, in which no minerals of the
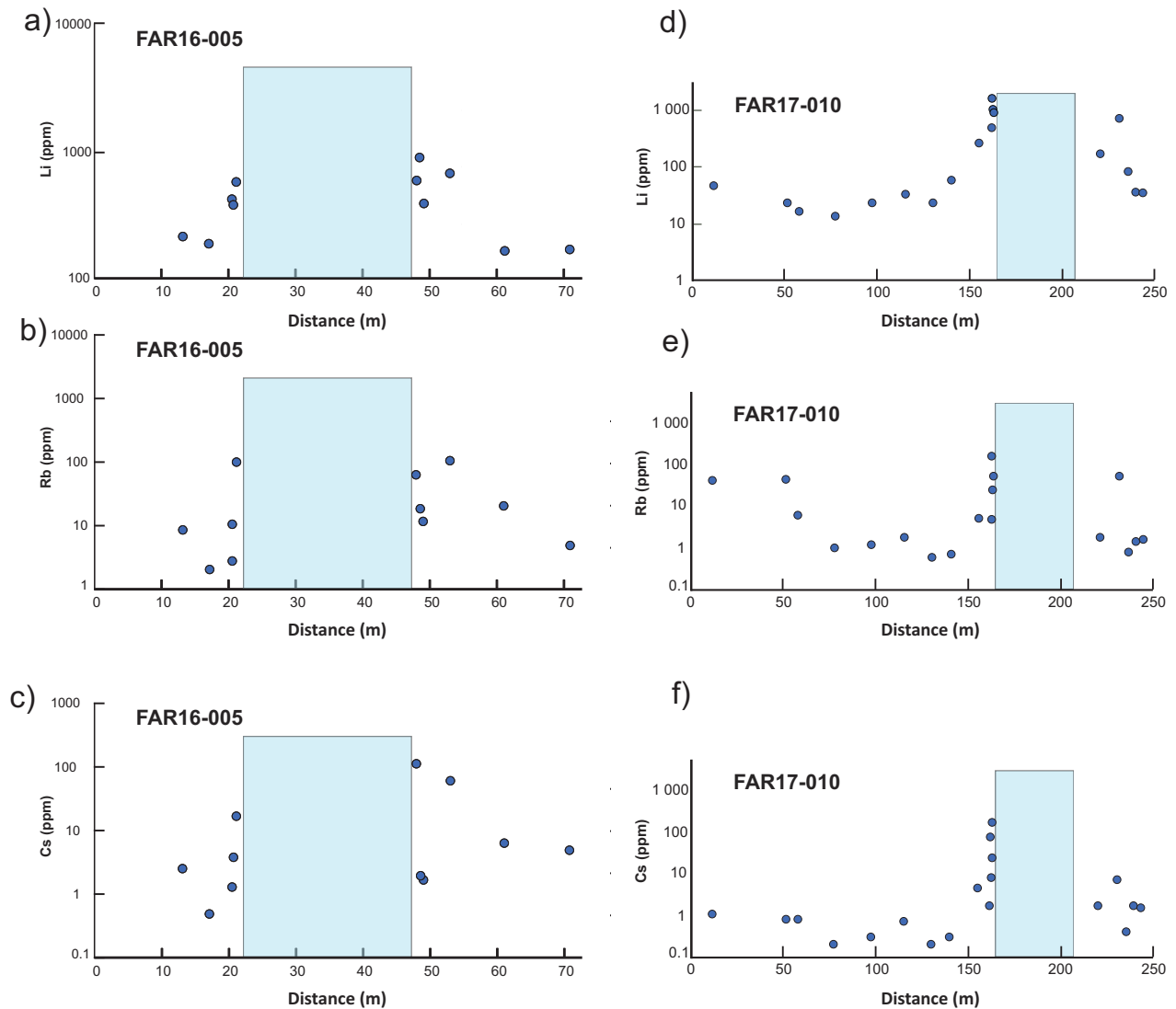
Figure GS2017-5-5: *Element distribution diagrams showing variations along the length of the studied drillholes from Dike 1:* ***a)*** *Li for drillhole FAR16-005;* ***b)*** *Rb for drillhole FAR16-005;* ***c)*** *Cs for drillhole FAR16-005;* ***d)*** *Li for drillhole FAR17-010;* ***e)*** *Rb for drillhole FAR17-010;* ***f)*** *Cs for drillhole FAR17-010. Shaded areas mark the location of the pegmatite.*

columbite group were reported (Černý et al., 1981). However, petrographic work during this study (see above) reveals trace amounts of minerals of the columbite group. Values for Sn are usually <4 ppm, with a few higher values (up to 91 ppm) close to the contact with the pegmatite. Other pegmatite fields show a correlation between Li and Sn mineralization (for example, the Barroso-Alvão pegmatite field in northern Portugal; Martins et al., 2011), but mineralogy studies (Černý et al., 1981) did not identify cassiterite or any other Sn-bearing minerals, suggesting that such a relationship does not occur in the Wekusko Lake pegmatite field. Tellurium and As show dispersion patterns with weak anomalies around the Dibs pegmatite, but this does not seem to be the case for the Dike 1 pegmatite. Values for Tl are usually below detection limit and vary up to 6 ppm. Values for As in the country rock of Dike 1 are elevated (up to 6450 ppm) but could be associated with the Au mineralization known to occur in this area (Galley et al., 1989).

Mineral chemistry of Dike 1 pegmatite

Mineral-chemistry data for both muscovite and K-feldspar obtained during this study are similar to results reported by Černý et al. (1981) for pegmatites from the Green Bay group of the Wekusko Lake pegmatite group. Only ranges will be mentioned in this section. The full dataset of electron microprobe results can be found in DRI2017004 (Martins and Linnen, 2017).

Muscovite

At least two generations of mica were found in Dike 1, but this study focuses on primary muscovite, identified on the basis of the following criteria (Fleet et al., 2003): sharp boundaries, subhedral to euhedral shape, grain size comparable to that of other magmatic minerals, absence of reactions with other minerals, absence of alteration in surrounding minerals,

and relative abundance. The mica compositions are all close to the stoichiometric dioctahedral muscovite end-member within the expected values for spodumene-subtype pegmatite (e.g., Selway et al., 2005; Martins et al., 2012). In the diagram for mica classification proposed by Tischendorf et al. (1997) in which $(Fe_{tot} + Mn + Ti) - {}^{VI}Al$ is plotted against $Mg - Li$, the analyzed micas have compositions close to end-member muscovite (Figure GS2017-5-6) and show a trend toward the Li-enriched muscovite end-member. Most of the analyses reveal interlayer occupancies, with $\Sigma(Na + K + Rb + Cs)$ values varying around the ideal 2.00 atoms per formula unit (apfu; most values ranging from 1.86 to 2.09 apfu, with only a few ranging as high as 2.26 apfu). The octahedral site-occupancy ^{VI}R is higher than the ideal 4.0 apfu, ranging from 4.24 to 4.68 apfu. This is not uncommon for muscovite in pegmatitic environments, as reported by other authors (e.g., Černý et al., 1995; Vieira et al., 2011; Martins et al., 2012). Foord et al. (1995) and du Bray (1994) suggested that the high occupancy of the octahedral site might be indicative of a mixed-layer form, involving both dioctahedral and trioctahedral structures, and could be a sign of disequilibrium crystallization. It is also possible that part of the Li might be an interlayer occupant, or part of the measured FeO is actually Fe^{3+} occupying the tetrahedral site. Note that all Fe is here considered Fe^{2+}. According to Černý and Burt (1984), the existence of FeO is favoured because micas seem to grow under rather reducing conditions, so that Fe^{3+} contents are minor.

With respect to the major-elements, the muscovite samples analyzed show minor variation in their Si and Al content, and Fe contents vary between 0.60 and 4.70 wt. % FeO. Regarding the trace-element concentrations, F varies from below detection limit to 1.53 wt. % F, Rb ranges from 0.18 to 0.81 wt. % Rb_2O, and Cs varies from below detection limit to 0.36 wt. % Cs_2O. The K/Rb ratio values of muscovite in Dike 1
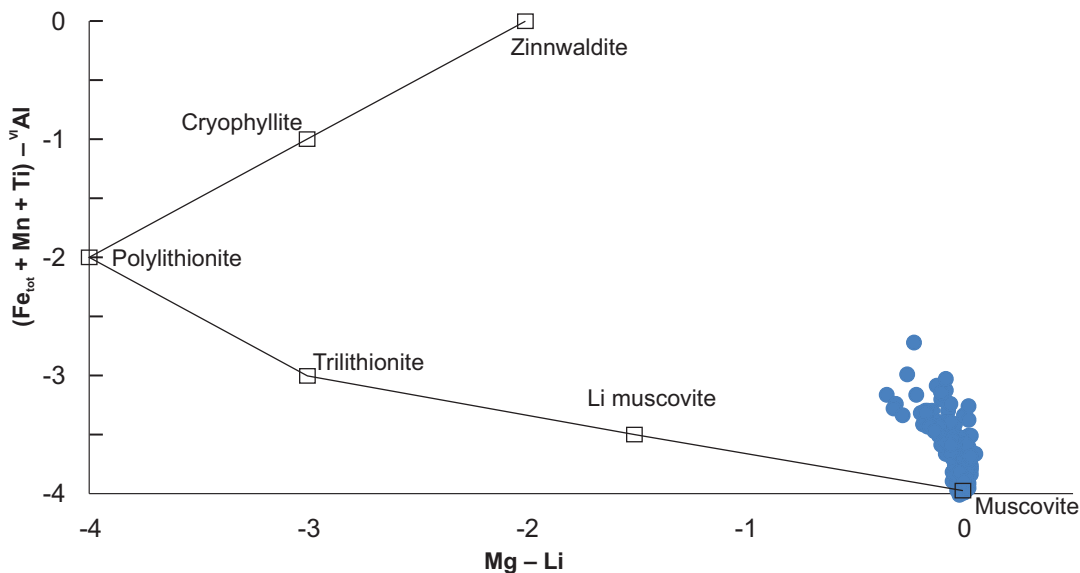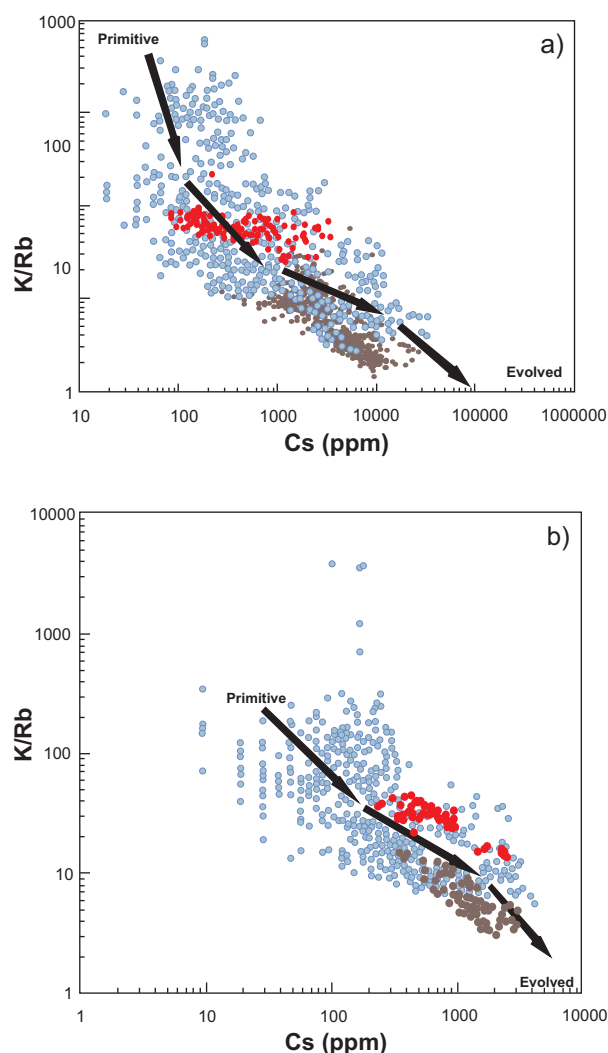

Figure GS2017-5-6: *Muscovite from Dike 1 (blue dots) plotted on the $Mg - Li$ versus $(Fe_{tot} + Mn + Ti) - {}^{VI}Al$ diagram for mica classification (values in apfu; modified after Tischendorf et al., 1997). Squares indicate the ideal locations for mica end-members of this section of the diagram.*

vary between 10.99 and 28.73, comparable to moderately evolved pegmatites from Ontario (Figure GS2017-5-7a; Tindle et al., 2002; Selway et al., 2005) but higher than the highly evolved Tanco pegmatite, in which mica has ratio values varying from 2.9 to 10.6 (Černý, 2005); these results indicate that the Dike 1 pegmatite is less fractionated than the Tanco pegmatite. The K/Cs ratio values of muscovite in Dike 1 vary from 27.89 to 871.48, corroborating the lower level of fractionation of this pegmatite compared to Tanco, in which mica ratio values vary from 14 to 93 (Černý, 2005). (Higher K/Cs ratio values of 1002.59, 1032.18 and 1045.34 are reported in DRI2017004, but they were calculated using Cs results too close to the detection limit of 80 ppm and were not considered for the variation interval.)

Figure GS2017-5-7: *Mineral-chemistry results for muscovite and K-feldspar from Dike 1:* **a)** *general fractionation trend (arrows) for micas from Ontario pegmatites (blue dots; data from Selway et al., 2005) and those from the Tanco pegmatite (brown dots; S. Margison, unpublished data) and Dike 1 (red dots);* **b)** *general fractionation trend (arrows) for K-feldspar from Ontario pegmatites (blue dots; Selway et al., 2005), Tanco pegmatite (brown dots; data from Brown, 2001) and Dike 1 (red dots).*

K-feldspar

Selected K-feldspar grains were initially considered primary when sampled, but petrography and backscattered imagery indicate albitization. This suggests that the analyzed grains might not be good indicators of high-temperature primary-crystallization processes. The stoichiometry of the analyzed K-feldspar is slightly non-ideal, which is typical for K-feldspar in granitic pegmatites (Černý et al., 2012; Brown et al., 2017). Major elements do not vary significantly throughout the several analyses. Regarding trace elements, Rb varies from below detection limit to 0.70 wt. % Rb_2O and Cs varies from below detection limit to 0.27 wt. % Cs_2O. The values obtained indicate a moderate level of fractionation relative to pegmatites from Ontario (Figure GS2017-5-7b; Tindle et al., 2002; Selway et al., 2005). The K/Rb ratio values vary from 13.45 to 43.92, higher than the values listed for Tanco feldspar (4.0 to 14.2; Černý, 2005) but typical for spodumene-type pegmatites in Ontario (Tindle et al., 2002). The K/Cs ratio values of K-feldspar from Dike 1 vary from 48.26 to 584.62, well above the values reported for the Tanco pegmatite (6 to 26; Černý, 2005), corroborating the lower degree of fractionation of Dike 1.

Economic considerations

The results from this report corroborate the conclusion from other studies (e.g., Halden et al., 1989; Linnen et al., 2009, 2015) that using lithogeochemistry of country rocks is a viable and relatively inexpensive tool to explore for rare-element pegmatites. This is valid for metavolcanic rocks, the country rocks in both of the study areas presented herein, but has not been sufficiently tested for other types of wallrock and should therefore be used with caution. Work by Linnen et al. (2009, 2015) found that a major drawback of using lithogeochemistry of country rocks is the occurrence of Li-Rb-Cs–bearing minerals along fractures, which complicates the interpretation of results. Linnen et al. (2009) suggested that indicator minerals (such as biotite) are potentially more reliable than lithogeochemistry in pegmatite exploration. Despite the potential complication associated with fractures, additional lenses of the Dibs pegmatite were found at depth by following up on Li anomalies occurring below the main body (Linnen et al., 2009).

The presence of holmquistite-bearing assemblages in the amphibolitic country rock to the Dike 1 pegmatite indicates interaction of Li-enriched fluid sourced from the Li-bearing pegmatite. Hence, identification of these assemblages could also be a very useful and inexpensive tool in exploration for Li-bearing pegmatite because they can occur up to 20 m away from pegmatite contacts (Černý et al., 1981). The formation of holmquistite is not restricted to early episodes of interaction between pegmatite fluid and the amphibolite country rock, but can occur at any time from pegmatite injection to final consolidation (London, 1986).

Mineral-chemistry results for muscovite and K-feldspar indicate that Dike 1 is a moderately fractionated pegmatite (Figure GS2017-5-7a, b; Martins and Linnen, 2017). This kind of information could be a useful tool for understanding fractionation

trends within a pegmatite field. According to Selway et al. (2005), compositions of K-feldspar and muscovite are excellent exploration tools because these minerals are common in barren and fertile granites as well as rare-element pegmatites, allowing for an understanding of fractionation trends. Research shows that Rb and Cs contents increase in K-feldspar and muscovite with increasing fractionation of a granitic melt (e.g., Selway et al., 2005; Černý et al., 2012; Martins et al, 2012; Brown et al., 2017). Similarly, pegmatites with the highest degree of fractionation (and thus the most economic potential for Li-Cs-Ta) usually contain K-feldspar with >3 000 ppm Rb, K/Rb <30, and >100 ppm Cs (Tindle et al., 2002; Selway et al., 2005). Pegmatites with the most economic potential contain muscovite with >2 000 ppm Li, >10 000 ppm Rb, >500 ppm Cs and >65 ppm Ta (Tindle et al., 2002; Selway et al., 2005).

Expanding the mineral-chemistry study to other pegmatite dikes in the area might help in understanding fractionation paths in the Wekusko Lake pegmatite field and establishing areas of higher probability of finding pegmatite dikes with higher degrees of fractionation. Further petrographic studies of mineralogy and zonation would also give a better idea of the degree of fractionation of the Dike 1 pegmatite and a better understanding of the Li mineralization and its associations. Future work in the area around the Dike 1 pegmatite could also include rock, vegetation or soil geochemical surveys and selective-extraction analytical techniques, which have been widely used in other areas with LCT potential (Galeschuk and Vanstone, 2005). Collectively, the techniques presented in this report can provide effective exploration tools for identifying and characterizing Li-bearing pegmatite dikes.

Acknowledgments

References

Bailes, A.H. and Galley, A.G. 1999: Evolution of the Paleoproterozoic Snow Lake arc assemblage and geodynamic setting for associated volcanic-hosted massive sulphide deposits, Flin Flon Belt, Manitoba, Canada; Canadian Journal of Earth Sciences, v. 36, p. 1789–1805.

Beus, A.A. 1960: Geochemistry of beryllium and genetic types of beryllium deposits; Academy of Science, USSR, Moscow (in Russian; translation, Freeman & Co, San Francisco, 1966), 329 p.

Brown, J.A. 2001: Mineralogy and geochemistry of alkali feldspars from the Tanco pegmatite, southeastern Manitoba; M.Sc. thesis, University of Manitoba, Winnipeg, Manitoba, 238 p.

Brown, J.A., Martins, T. and Černý, P. 2017: The Tanco pegmatite at Bernic Lake, Manitoba, XVII: mineralogy and geochemistry of alkali feldspars; Canadian Mineralogist, v. 55, p. 483–500.

Černý, P. 1989: Exploration strategy and methods for pegmatite deposits of tantalum; in Lanthanides, Tantalum and Niobium, P. Möller, P. Černý and F. Saupé (ed.), Springer-Verlag, Heidelberg, p. 274–310.

Černý, 2005: The Tanco rare element pegmatite deposit, Manitoba: regional context, internal anatomy and global comparisons; in Rare Element Geochemistry and Ore Deposits, R.L. Linnen and I.M. Samson (ed.), Geological Association of Canada, Short Course Notes, v. 17, p. 127–158.

Černý, P. and Burt, D.M. 1984: Paragenesis, crystallochemical characteristics, and geochemical evolution of micas in granite pegmatites; in Micas, S.W. Bailey (ed.), Reviews in Mineralogy, v. 13, p. 257–297.

Černý, P. and Ferguson, R.B. 1972: The Tanco pegmatite at Bernic Lake, Manitoba. IV. Petalite and spodumene relations; The Canadian Mineralogist, v. 11, pt. 3, p. 660–678.

Černý, P., Trueman, D.L., Ziehlke, D.V., Goad, B.E. and Paul, B.J. 1981: The Cat Lake–Winnipeg River and the Wekusko Lake pegmatite fields, Manitoba; Manitoba Department of Energy and Mines, Mineral Resources Division, Economic Geology Report ER80-1, 215 p.

Černý, P., Staněk, J., Novák, M., Baadsgaard, H., Rieder, M., Ottolini, L., Kavalová, M. and Chapman, R. 1995: Geochemical and structural evolution of micas in the Rožná and Dobrá Voda pegmatites, Czech Republic; Mineralogy and Petrology, v. 55, p. 177–201.

Černý, P., Teertstra, D.K., Chapman, R., Selway, J.B., Hawthorne, F.C., Ferreira, K., Chackowsky, L.E., Wang, X.-J. and Meintzer, R.E. 2012: Extreme fractionation and deformation of the leucogranite-pegmatite suite at Red Cross Lake, Manitoba, Canada. IV. mineralogy; Canadian Mineralogist, v. 50, p. 1839–1875.

du Bray, E.A. 1994: Compositions of micas in peraluminous granitoids of the eastern Arabian Shield: implications for petrogenesis and tectonic setting of highly evolved, rare-metal enriched granites; Contributions to Mineralogy and Petrology, v. 116, p. 381–397.

Fleet, M.E., Deer, W.A., Howie, R.A. and Zussman, J. 2003: Rock-Forming Minerals. 3A. Sheet Silicates: Micas (Second Edition); The Geological Society, London, United Kingdom, 758 p.

Foord, E.E., Černý, P., Jackson, L.L., Sherman, D.M. and Eby, R.K. 1995: Mineralogical and geochemical evolution of micas from miarolitic pegmatites of the anorogenic Pikes Peak batholith, Colorado; Mineralogy and Petrology, v. 55, p. 1–26.

Galeschuk, C.R. and Vanstone, P.J. 2005: Exploration for buried rare-element pegmatites in the Bernic Lake area of southeastern Manitoba; in Rare-Element Geochemistry and Mineral Deposits, R.L. Linnen and I.M. Samson (ed.), Geological Association of Canada, Short Course Notes, v. 17, p. 153–167.

Galeschuk, C.R. and Vanstone, P.J. 2007: Exploration techniques for rare-element pegmatite in the Bird River greenstone belt, southeastern Manitoba; in Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, B. Milkereit (ed.), 2007, p. 823–839.

Galley, A.G., Ames, D.E. and Franklin, J.M. 1989: Results of studies on the gold metallogeny of the Flin Flon Belt; Geological Survey of Canada, Open File 2133, p. 25–32.

Gilbert, H.P. 2006: Geological investigations in the Bird River area, southeastern Manitoba (parts of NTS 52L5N and 6); in Report of Activities 2006, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 184–205.

Gilbert, H.P. and Bailes, A.H. 2005a: Geology of the southern Wekusko Lake area, Manitoba (NTS 63J12NW); Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, Geoscientific Map MAP2005-2, scale 1:20 000.

Gilbert, H.P. and Bailes, A.H. 2005b: Lithological and lithogeochemical data and field photographs for the southern Wekusko Lake area, Manitoba (NTS 63J12NW); Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, Data Repository Item DRI2005003, Microsoft® Excel® file.

Gilbert, H.P., Davis, W.D., Duguet, M., Kremer, P.D., Mealin, C.A. and MacDonald J. 2008: Geology of the Bird River Belt, southeastern Manitoba (parts of NTS 52L5, 6); Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Map MAP2008-1, scale 1:50 000.

Halden, N.M., Meintzer, R.E. and Černý, P. 1989: Trace element characteristic and controls of element mobility in the metasomatic aureole to the Tanco pegmatite; in Report of Field Activities 1989, Manitoba Energy and Mines, Minerals Division, p. 152–155.

Heinrich, E.W. 1965: Holmquistite and pegmatitic lithium exomorphism; Indian Mineralogist, v. 6, p. l–13.

Kremer, P.D. 2010: Structural geology and geochronology of the Bernic Lake area in the Bird River greenstone belt, Manitoba: evidence for syn-deformational emplacement of the Bernic Lake pegmatite group; M.Sc. thesis, University of Waterloo, Waterloo, Ontario, 91 p.

Linnen, R.L., Galeschuk, C. and Halden, N.M., 2015: The use of fracture minerals to define metasomatic aureoles around rare-metal pegmatites; 27th International Applied Geochemistry Symposium, Tucson, Arizona, 5 p., URL <https://www.appliedgeochemists.org/images/stories/IAGS_2015/Abstracts/27th%20IAGS_Linnen%20et%20al_Fracture%20Chlorites%20in%20Exploration.pdf> [October 2017].

Linnen, R.L., Galeschuk, C, Halden, N.M. and Lau, L. 2009: Dispersion haloes around rare-metal pegmatites: a case study of the Dibs LCT pegmatite, Manitoba, Canada; Estudos Geológicos, v. 19, no. 2, p. 25–29.

Linnen, R.L., van Lichtervelde, M. and Černý, P. 2012: Granitic pegmatites as sources of strategic metals; Elements, v. 8, p. 275–280.

London, D. 1986: Holmquistite as a guide to pegmatitic rare-metal deposits; Economic Geology, v. 81, p. 704–712.

London, D. 2008: Pegmatites; Canadian Mineralogist, Special Publication 10, 347 p.

Martins, T., Lima, A., Simmons, W.B., Falster, A.U. and Noronha, F. 2011: Geochemical fractionation of Nb-Ta oxides in Li-bearing pegmatites from the Barroso-Alvão pegmatite field, northern Portugal; Canadian Mineralogist, v. 49, p. 777–791.

Martins, T. and Linnen, R.L. 2017: Whole-rock and mineral geochemistry as an exploration tool for rare-element pegmatites in Manitoba: examples from the Cat Lake–Winnipeg River and the Wekusko Lake pegmatite fields (parts of NTS 52L6, 63J13); Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Data Repository Item DRI2017004, Microsoft® Excel® file.

Martins, T., Roda-Robles, E., Lima, A. and Parseval, P. 2012: Geochemistry and evolution of micas in the Barroso-Alvão pegmatite field, northern Portugal; Canadian Mineralogist, v. 50, p. 1117–1129.

Morgan, G.B. and London, D. 1987: Alteration of amphibolitic wallrocks around the Tanco rare-element pegmatite, Bernic Lake, Manitoba; American Mineralogist, v. 72, p. 1097–1121.

NATMAP Shield Margin Project Working Group 1998: Geology, NATMAP Shield Margin Project Area (Flin Flon Belt), Manitoba/Saskatchewan; Geological Survey of Canada, Map 1968A, scale 1:100 000.

Norton, J.J. 1984: Lithium anomaly near Pringle, southern Black Hills, South Dakota, possibly caused by unexposed rare-mineral pegmatite; United States Geological Survey, Circular 889, p. 1–7.

Ryan, J.G. and Langmuir, C.H. 1987: The systematics of lithium abundances in young volcanic rocks; Geochimica et Cosmochimica Acta, v. 51, p. 1727–1741.

Selway, J.B., Breaks, F.W. and Tindle, A.G. 2005: A review of rare-element (Li-Cs-Ta) pegmatite exploration techniques for the Superior Province, Canada, and large worldwide tantalum deposits; Exploration and Mining Geology, v. 14, no. 1–4, p. 1–30.

Selway, J.B., Novák, M., Černý, P. and Hawthorne, F.C. 2000: The Tanco pegmatite at Bernic Lake, Manitoba. XIII. Exocontact tourmaline; Canadian Mineralogist, v. 38, p. 869–876.

Shearer, C.K. and Papike, J.J. 1988: Pegmatite-wallrock interaction: holmquistite-bearing amphibolite, Edison pegmatite, Black Hills, South Dakota; American Mineralogist, v. 73, p. 324–337.

Shearer, C.K., Papike, J.J., Simon, S.B. and Laul, J.C. 1986: Pegmatite-wallrock interactions, Black Hills, South Dakota: interaction between pegmatite-derived fluids and quartz-mica schist wallrock; American Mineralogist, v. 71, p. 518–539.

Stott, G.M., Corkery, M.T., Percival, J.A., Simard, M. and Goutier, J. 2010: Project units 98-006 and 98-007: a revised terrane subdivision of the Superior Province; in Summary of Field Work and Other Activities 2010, Ontario Geological Survey, Open File Report 6260, p. 20-1–20-10.

Tindle, A.G., Selway, J.B. and Breaks, F.W. 2002: Electron microprobe and bulk analyses of fertile peraluminous granites and related rare-element pegmatites, Superior province, northwest and northeast Ontario: Operation Treasure Hunt; Ontario Geological Survey, Miscellaneous Release–Data 111.

Tischendorf, G., Gottesmann, B., Förster, H.-J. and Trumbull, R.B. 1997: On Li-bearing micas: estimating Li from electron microprobe analyses and an improved diagram for graphical representation; Mineralogical Magazine, v. 61, p. 809–834.

Trueman, D.L. 1978: Exploration methods in the Tanco Mine area of southeastern Manitoba, Canada; Energy, v. 3, p. 293–297.

Trueman, D.L. 1980: Stratigraphy, structure and metamorphic petrology of the Archean greenstone belt at Bird River, Manitoba; Ph.D. thesis, University of Manitoba, Winnipeg, Manitoba, 150 p.

Trueman, D.L. and Černý, P., 1982: Exploration and processing; in Granitic Pegmatites in Science and Industry, Mineralogical Association of Canada, Short Course Notes, v. 8, p. 463–493.

Vieira, R., Roda-Robles, E., Pesquera, A. and Lima, A. 2011: Chemical variation and significance of micas from the Fregeneda-Almendra pegmatitic field (Central Iberian Zone, Spain and Portugal); American Mineralogist, v. 96, p. 637–645.