GS2022-7

Preliminary observations on emplacement controls of pegmatite dikes from the Wekusko Lake pegmatite field, north-central Manitoba (parts of 63J13, 14, 63O4)

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In Brief:
- Wekusko pegmatite field is comprised of multiple types of pegmatites including spodumene-bearing pegmatite dikes
- Pegmatite dikes are temporally related to brittle-ductile deformation events, and structurally related to major shear zones and faults
- Pegmatite dikes emplacement is associated with three hostrock dilation modes: (1) tension gashes; (2) tension gashes en échelon; and (3) pull-apart shearing

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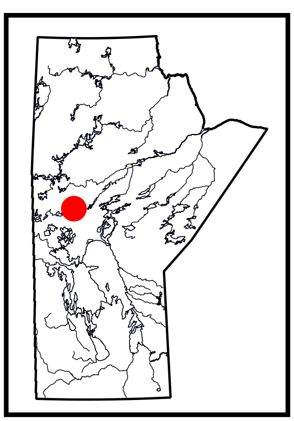
Summary

This report outlines recent field observations of lithium-bearing pegmatite dikes in the Wekusko pegmatite field in north-central Manitoba, along with possible mechanisms of pegmatite emplacement. Two main categories of pegmatite dikes are defined in the Wekusko pegmatite field: 1) barren pegmatite dikes, and 2) spodumene-bearing pegmatite dikes. Most of the spodumene-bearing pegmatite dikes have a coarse-grained mineral assemblage of albite, quartz, K-feldspar, muscovite, spodumene and tourmaline, and are located close to regional-scale fault zones (Crowduck Bay shear zone, Herb Lake and Roberts Lake faults). These regional discontinuities facilitated melt transport, and emplacement at mid-crust level. Three mechanisms of emplacement of the spodumene-bearing pegmatites are proposed: 1) oriented subparallel to the strike of shear zones in pull-apart openings (Violet-Thompson group of pegmatite dikes); 2) oriented subparallel to the main tectonic stress direction in tension-gash openings (Sherritt-Gordon group of pegmatite dikes); and 3) oriented subparallel to the main tectonic stress direction, at a high angle to probable second-degree shear faults and aligned in en échelon formation (Green Bay group of pegmatite dikes).

Introduction

Electric-powered transportation and the transition towards more sustainable electrical storage and energy production has increased the demand for lithium, nickel, cobalt, tantalum and rare-earth elements. Canada identifies these elements as 'critical minerals', in part because of the risk of supply to the manufacturing industry, or their economic and/or military importance (Natural Resources Canada, 2021). Rare-element pegmatites play a strategic role in the green revolution because they contain high concentrations of critical minerals, particularly lithium, making them targets for mineral exploration.

Manitoba is a well-established jurisdiction for lithium-bearing pegmatite exploration and mining due to the large number of known occurrences and large size of some deposits (e.g., Tanco deposit in southeast Manitoba; Černý et al., 2005). This report focuses on the Wekusko Lake pegmatite field located in north-central Manitoba, which is known to be enriched in lithium. The Wekusko Lake pegmatite field is located approximately 25 km east of the town of Snow Lake. Because of the high lithium potential, there are currently several exploration campaigns targeting spodumene pegmatites in the region (Foremost Lithium Resource & Technology Ltd., 2022; Snow Lake Lithium, 2022). This report is a summary of mineralogical and structural observations of dikes from the Wekusko Lake pegmatite field during the summer of 2022, and includes a preliminary interpretation of the mode and structural controls on emplacement of the lithium-mineralized pegmatite dikes in the region.



Regional geology

The Wekusko Lake pegmatite field is located within the Snow Lake subdomain of the Flin Flon domain (Černý et al., 1981; Gordon et al., 1990; Lucas et al., 1996; Ansdell, 2005; Zwanzig and Bailes, 2010). The Snow Lake subdomain lies within the southeastern exposed Reindeer zone of the Trans-Hudson orogen (David et al., 1996; Connors et al., 1999). It is bounded to the north and east by the Kisseynew domain (Figure GS2022-7-1; David et al., 1996; Connors et al., 1999). The Snow Lake subdomain is underlain by three major Paleoproterozoic tectonostratigraphic packages dated 1.88–1.83 Ga: 1) accreted Flin Flon arc and ocean-floor assemblages forming the Flin Flon–Glennie complex

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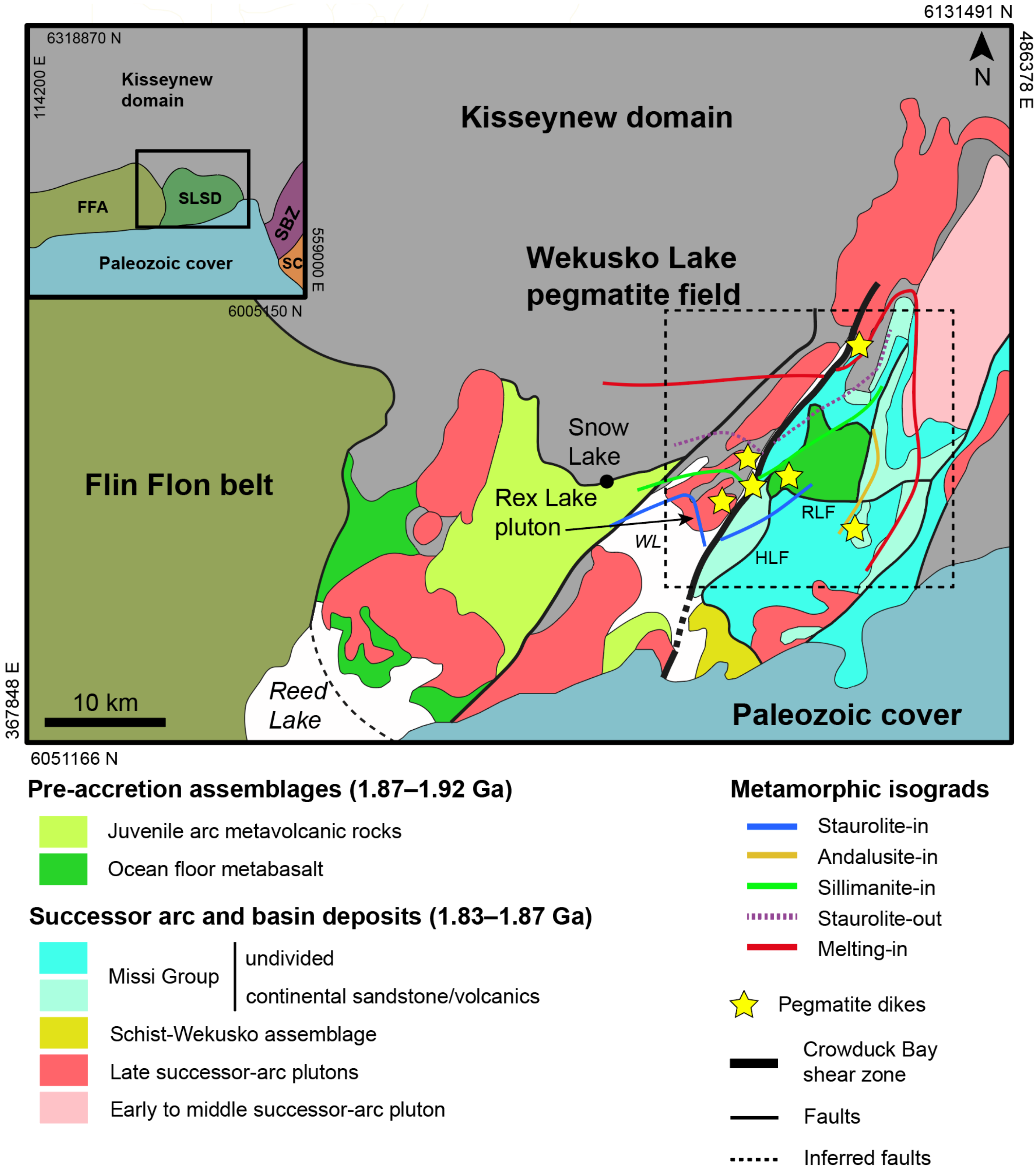

Figure GS2022-7-1: *Simplified geology of the Snow Lake subdomain (modified after Galley et al., 2007), with the Wekusko Lake pegmatite field outlined by dashed black box. Inset tectonic elements map of the Trans-Hudson orogen of central Saskatchewan and Manitoba is modified after Hoffman (1988). Metamorphic isograds after Lazzarotto (2020). Abbreviations: FFA, Flin Flon arc assemblage; HLF, Herb Lake fault; RLF, Roberts Lake fault; SBZ, Superior boundary zone; SC, Superior craton; SLSD, Snow Lake subdomain; WL, Wekusko Lake. All co-ordinates are in UTM Zone 14, NAD83.*

(Gordon et al., 1990; Stern et al., 1993; Stern and Lucas, 1994; David et al., 1996; Ansdell et al., 1999; Machado et al., 2000; Reid, 2021a, b); 2) Burntwood group turbidite deposits (Bailes, 1980; Zwanzig, 1990); and 3) Missi group alluvial-fluvial sandstones (Figure GS2022-7-1; Ansdell, 1993; Ansdell and Connors, 1995; Ansdell and Norman, 1995; Reid, 2021a, b). All these units are intruded by 1.84–1.83 Ga late successor-arc plutons in the Snow Lake region (Gordon et al., 1990; David et al., 1996; Whalen et al., 1999). In the south, the Reindeer zone is unconformably overlain by a Paleozoic dolomitic limestone cover (Connors et al., 1999). The Flin Flon domain has a metamorphic field gradient that ranges from lower greenschist facies in the south to upper amphibolite facies in the north, at the boundary with the Kisseynew domain (Černý et al., 1981; Lewry et al., 1994; Kraus and Menard, 1997). In the Snow Lake area, the metamorphic field gradient ranges from upper greenschist–lower amphibolite facies to upper amphibolite facies, with migmatitic zones towards the north, northeast and east from Wekusko Lake (Bailes, 1985; Lazzarotto, 2020).

The Snow Lake region has undergone four deformational events (D_1–D_4) before craton stabilization at 1.70–1.65 Ga (Schneider et al., 2007). Deformation event D_1 is associated with accretion of the Flin Flon–Glennie arc at 1.88–1.87 Ga (Lucas et al., 1996; Connors et al., 1999; Schneider et al., 2007; Stewart et al., 2018). This was followed by D_2, which recorded south to southwest compression at 1.84–1.81 Ga and involved the collision of the Kisseynew domain and Flin Flon–Glennie arc with the Sask craton (Zwanzig, 1990; Connors, 1996; Connors et al., 1999). Peak metamorphism was attained at ca. 1.81 Ga and coincided with the transition between D_2 and D_3 in the east Snow Lake area (Connors et al., 2002). The main tectonic stress direction changed from northeast-southwest to northwest-southeast compression during the D_3 event and is linked to the formation of the Crowduck Bay shear zone, Herb Lake and Roberts Lake regional transpressional faults (Connors and Ansdell, 1994; Kraus and Williams, 1994; Connors et al., 2002). The D_4 phase could be a continuation of D_3 and recorded mostly brittle deformation (Lucas et al., 1994; Fedorowich et al., 1995).

Pegmatite dikes of the Wekusko Lake field intruded several lithologies, including conglomerate to quartzofeldspathic gneiss from the Missi group, and metabasalt to basaltic andesite of N-MORB (normal mid-ocean–ridge basalt) affinity from the Snow Lake arc assemblage (Syme et al., 2000; Benn et al., 2018). The pegmatite dikes range from barren to lithium-bearing, with spodumene as the dominant lithium ore mineral (Černý et al., 1981; Martins et al., 2017). Černý et al. (1981) subdivided the Wekusko Lake pegmatite field into three mineralized groups: Sherritt-Gordon, Green Bay, and Violet-Thompson. One pegmatite from the Green Bay group yielded a U-Pb columbite age of 1780 ±8.1 Ma (Martins et al., 2019), while the other two groups remain undated. Benn et al. (2019) interpreted this pegmatite emplacement to be late D_3 to D_4, which postdates the ca. 1.81 Ga peak metamorphism. Černý et al. (1981) interpreted the evolved pegmatite dikes to be the product of fractional crystallization of surrounding successor-arc granite suites; however, this leaves a roughly 50 m.y. time gap between the crystallization of the granite suites and the emplacement of the pegmatite dikes. Alternatively, Benn et al. (2019) relate the petrogenesis of the pegmatite dikes to the partial melting of metasedimentary rocks.

Field description of pegmatite dikes

Numerous occurrences of pegmatite dikes were visited for this study, mainly in the areas of 1) north to northeast Wekusko Lake (Wekusko Lake/Crowduck Bay, Sherritt-Gordon, Green Bay and Violet-Thompson pegmatite groups), 2) Dion Lake, and 3) North Grass River. The subdivisions of Černý et al. (1981) are used to simplify the general description of the pegmatite occurrences. In addition, descriptions of the Rex Lake pluton outcrops and drillcore from 1911 Gold Corporation's exploration campaign are briefly discussed. All localities presented in Figure GS2022-7-2 were sampled for future geochemical and microstructural work.

Wekusko Lake/Crowduck Bay pegmatite dikes

The Wekusko Lake/Crowduck Bay pegmatite dikes occur as multiple, 1 to 2 m thick intrusions along the northeast arm of Wekusko Lake and on islands located in Crowduck Bay (Figure GS2022-7-3a). These pegmatite dikes are medium grained to very coarse grained, and have a simple mineralogy of albite, quartz, K-feldspar and muscovite, with trace tourmaline and garnet (Figure GS2022-7-3b–d). The muscovite content of the dikes varies, with greater abundances typically close to the country rock contact. Tourmaline is rarely present, and garnet is commonly observed adjacent to mafic xenoliths or hostrock contacts. No lithium mineralization was observed in this group of pegmatites. Based on mineralogy, these pegmatite dikes can be categorized as part of the muscovite class of Černý and Ercit (2005).

Books of muscovite are subparallel to the 038° strike of the pegmatite dikes observed on some of the islands in Crowduck Bay (Figure GS2022-7-3c). The muscovite books are also oriented subparallel to the Crowduck Bay shear zone (Figure GS2022-7-3c). The dikes intrude metasedimentary rocks of the Missi group. The pegmatite dikes commonly feature postemplacement hematization along crosscutting fractures. Postemplacement hematization is common in pegmatite dikes of the Wekusko Lake pegmatite field (Benn et al., 2018) and can make the identification of feldspars difficult due to the pink colouring associated with the metasomatic process (e.g., Gysi et al., 2016; Benn et al., 2018). Tourmalinization of the hostrock is commonly observed adjacent to pegmatite contacts.

Sherritt-Gordon group (B1, B2 and Grass River dikes)

Pegmatite dikes from the Sherritt-Gordon group contain lithium mineralization, which places them in the category of lithium-cesium-tantalum (LCT) rare-element pegmatites, based on

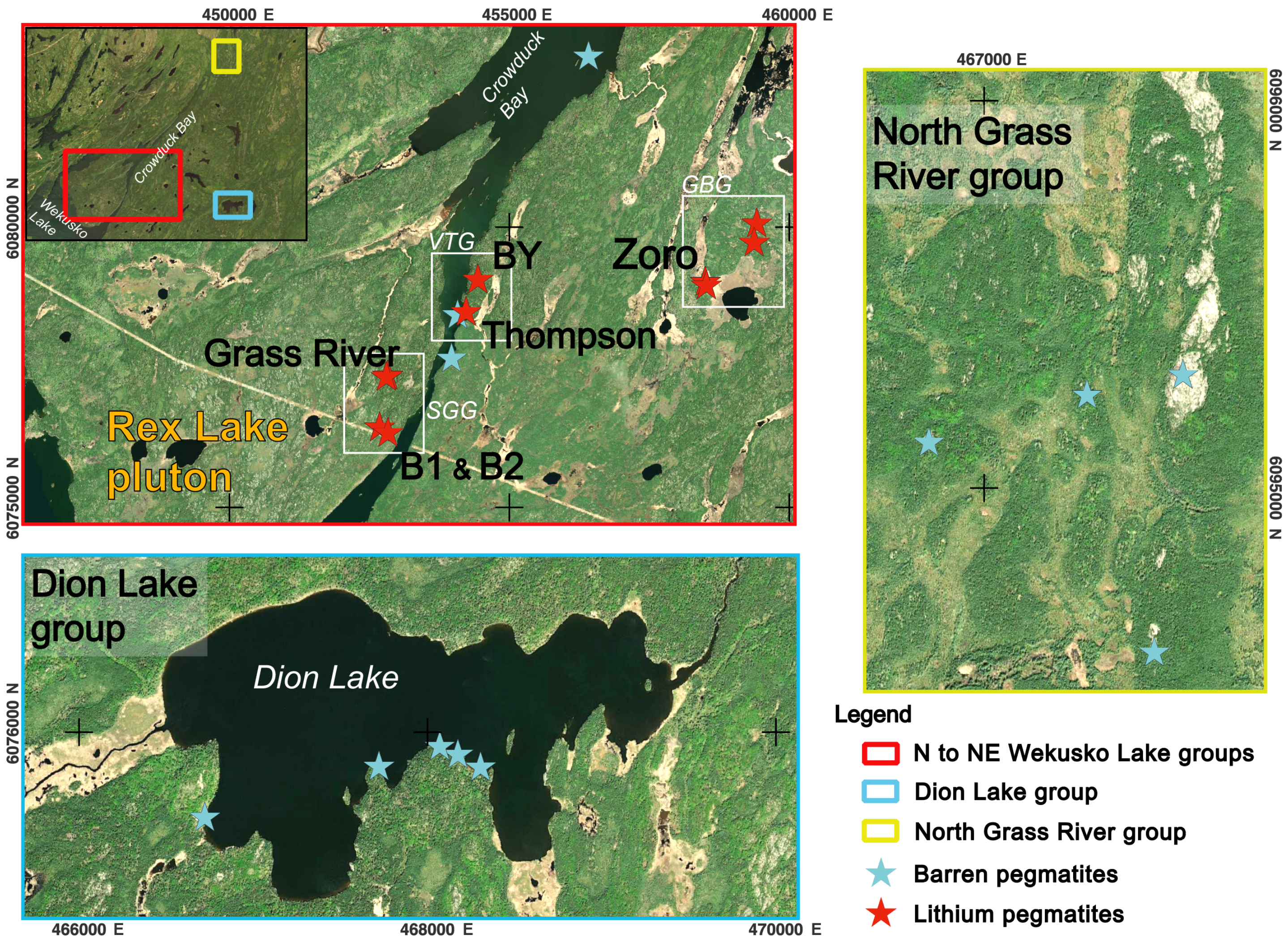

Figure GS2022-7-2: *Satellite imagery showing the locations of the pegmatite dikes visited and sampled during the summer 2022 fieldwork. Abbreviations: GBG, Green Bay pegmatite group; N, north; NE, northeast; SGG, Sherritt-Gordon pegmatite group; VTG, Violet-Thompson pegmatite group. Satellite images are copyright 2022 Maxar. All co-ordinates are in UTM Zone 14, NAD83.*

the classification of Černý and Ercit (2005). The lithium mineralization occurs as green spodumene (Figure GS2022-7-4a–c). This group of metre-scale pegmatite dikes is located east-northeast of the Rex Lake pluton (Figure GS2022-7-2) and intrudes bodies of leucocratic gabbro west of the Crowduck Bay shear zone. The main orientation of these pegmatite dikes ranges between 110 and 140°, with steep east dips of 60–70°. The pegmatite dikes are the focus of exploration by Foremost Lithium Resource & Technology Ltd. (Foremost Lithium; pegmatite occurrences B1, B2 and barren B3 pegmatite dike) and Snow Lake Lithium Ltd. (Snow Lake Lithium; Grass River pegmatite occurrences) in this region. All the dikes in this group are extremely coarse grained (i.e., main crystal size is >10 cm), with varying amounts of albite, K-feldspar, quartz, muscovite and spodumene within a single pegmatite body. There is no clear mineral zonation within the dikes apart from a more fine-grained, centimetre-scale border zone (Figure GS2022-7-4a). Accessory phases include tourmaline, apatite, garnet, and less commonly albite with a cleavelandite habit. Increased concentration of tourmaline is observed close to dike margins, locally as parallel bands or tourmaline that is perpendicular to the contact.

Spodumene occurs as elongate prisms up to 50 cm in length and 8 cm in width, or as equant basal sections 0.5–2.0 cm across (Figure GS2022-7-4a–c). The spodumene prisms in the Grass River dikes are oriented 045° and suborthogonal to the pegmatite orientation. Spodumene grains in the B1 and B2 occurrences have two main orientations, at 160° and 230° (Figure GS2022-7-4c).

Green Bay group

This group consists of at least 13 previously defined LCT-type pegmatite dikes that intruded mostly metabasalt to basaltic andesite of the Snow Lake arc-assemblage, and less commonly quartzofeldspathic gneiss of the Missi group (Figure GS2022-7-1; Benn et al., 2018). This group is located ~4 km east of the Crow-

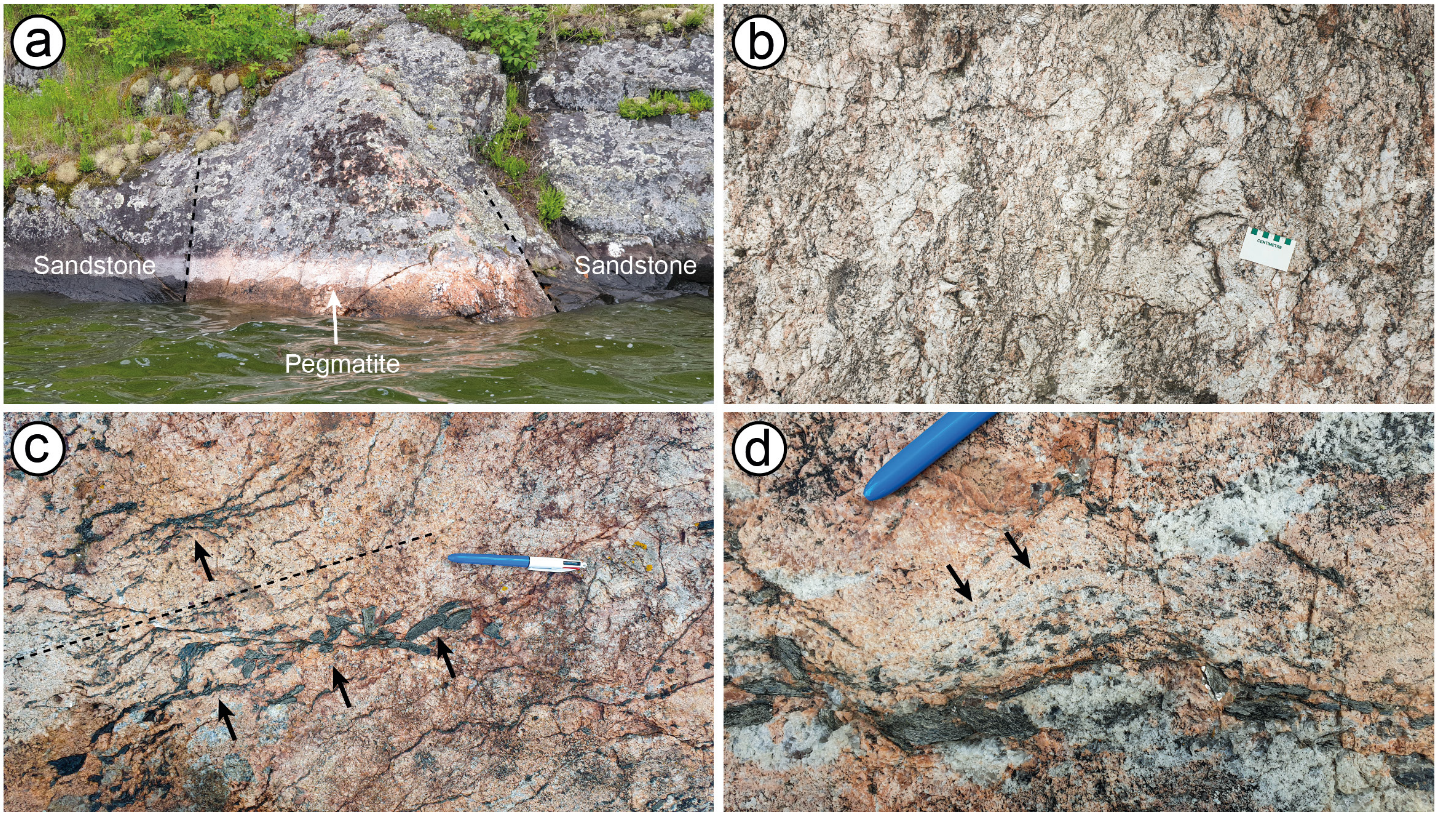

Figure GS2022-7-3: *Outcrop photographs showing pegmatite dikes from Wekusko Lake and Crowduck Bay:* ***a)*** *subvertical, hematized pegmatite dike (within black dashed lines) intruding Missi group sandstone;* ***b)*** *example of simple mineralogical composition (albite-quartz-muscovite) of this group of pegmatite dikes;* ***c)*** *preferred orientation of muscovite books (orientation is subparallel to dashed line; black arrows point to muscovite books);* ***d)*** *garnet trails (arrows) in pegmatite located in Crowduck Bay. Scale bar in (b) is in centimetres, pen for scale in panels (c) and (d) is 15 cm long.*

duck Bay shear zone, proximal to the Roberts Lake thrust fault (Figure GS2022-7-2). The Green Bay group is composed of multiple lithium-mineralized pegmatite dikes, in which the Zoro dike 1 is the largest of the group, with a similar style of mineralization as the Sherritt-Gordon group. The Zoro dike 1 is well characterized by 23 drillholes completed by Foremost Lithium (Fedikow and Zelligan, 2018). The pegmatite is zoned and trends roughly north-south for over 300 m (Benn et al., 2018). The dike contains a coarse-grained mineral assemblage of albite, quartz, K-feldspar, muscovite and spodumene (Figure GS2022-7-5a; Černý et al., 1981). The spodumene is green and up to 10 cm in length in the intermediate and core zones of the pegmatite dike (Figure GS2022-7-5a and -b). Benn et al. (2018) observed additional mineral phases such as beryl, apatite, iron and manganese phosphate minerals, garnet, zircon and columbite-group minerals. In outcrops visited during this study, spodumene appeared to be evenly distributed in the intermediate and central zones of the pegmatite. As previously reported by Benn et al. (2018), the dike has a discrete border zone characterized by smaller grain-size, sequential millimetre-size tourmaline bands close to the contact, and the presence of spodumene close to the boundary between the intermediate and border zones (Figure GS2022-7-5a). Columbite-group mineral U-Pb ages yielded a crystallization age of 1780 ±8.1 Ma (Martins et al., 2019). Deformation of feldspar and muscovite in the Zoro pegmatite dike 1 was previously reported by Martins et al. (2017), and field observations by Benn et al. (2018) suggest pegmatite emplacement and crystallization prior to the latest stages of regional deformation.

Violet-Thompson group (Thompson Brothers and BY dikes)

The Thompson Brothers and BY pegmatite occurrences are located adjacent to the Crowduck Bay shear zone, northeast of the Rex Lake pluton (Figure GS2022-7-2). The Violet-Thompson pegmatite group intruded a sequence of Missi group pebble to cobble conglomerate. Both occurrences are classified as LCT rare-element pegmatites and contain spodumene, albite, quartz, K-feldspar, muscovite and black tourmaline (Figure GS2022-7-6a–d). The outcrop of the Thompson Brothers dike is up to 10 m wide. The pegmatite is steeply dipping and is exposed for about 130 m along a strike of 035°. Drilling has traced the continuation of the dike for an additional 900 m (Snow Lake Lithium, 2022). The Thompson Brothers pegmatite shows a preferred alignment of spodumene crystals (overall trend is 160°) oblique to the dike orientation. The spodumene fabric is subperpendicular to the orientation of the Crowduck Bay shear zone (Figure GS2022-7-6a–c), which is consistent with the observations of Černý et al. (1981). This mineral fabric is possibly magmatic, and is dis-

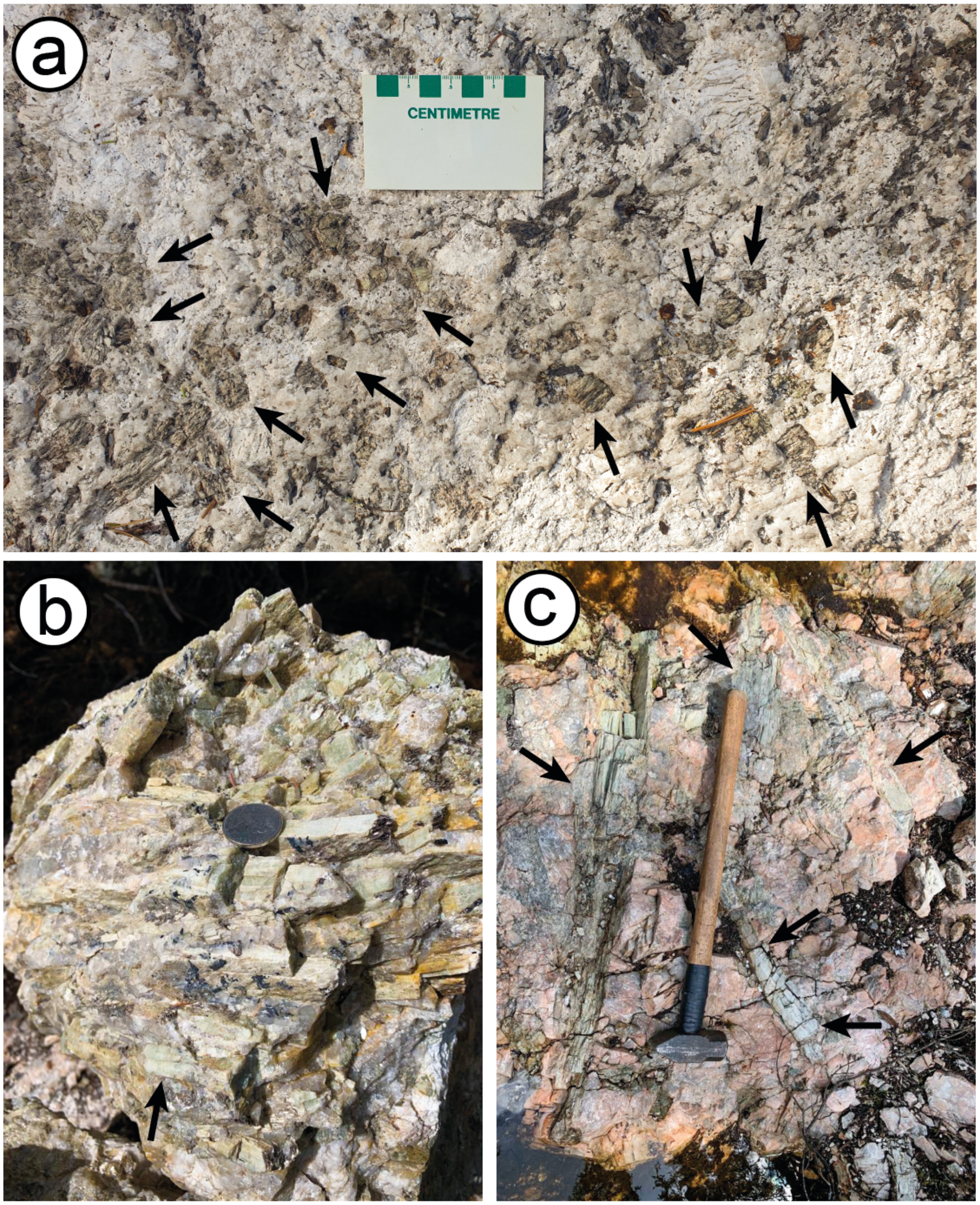

Figure GS2022-7-4: *Outcrop photographs of spodumene mineralization in the Sherritt-Gordon group of pegmatite dikes:* ***a)*** *spodumene (black arrows) in albite-quartz matrix, B2 pegmatite;* ***b)*** *very coarse-grained, elongate green spodumene crystals (black arrow) in B2 pegmatite (coin for scale is 2.4 cm in diameter);* ***c)*** *large spodumene crystals (black arrows) in B1 pegmatite (hammer for scale is 50 cm long).*

rupted by shear zones oriented subparallel to the pegmatite contact. The spodumene is reoriented closer to the trend of the dike by the shear zones (Figure GS2022-7-6a, -c). The BY pegmatite occurrence is mineralogically similar to the Thompson Brothers dike; however, a spodumene fabric is only developed as a comb structure close to the dike margin.

Dion Lake and North Grass River pegmatite dikes

These pegmatite occurrences are described separately from the previous groups because they are peripheral to the Wekusko Lake area. The North Grass River pegmatite dikes are located farther north, and the Dion Lake pegmatite dikes are located farther east (Figure GS2022-7-2). These spatially distinct occurrences are described together because they are both characterized by 1) a lack of observed lithium or other rare-element mineralization; 2) simple, medium- to coarse-grained mineralogy of albite, quartz and muscovite, with only apatite, garnet and possibly tourmaline as accessory mineral phases (Figure GS2022-7-7a); and 3) large size (one pegmatite body in the main north-south-oriented North Grass River pegmatite group is up to 1 km

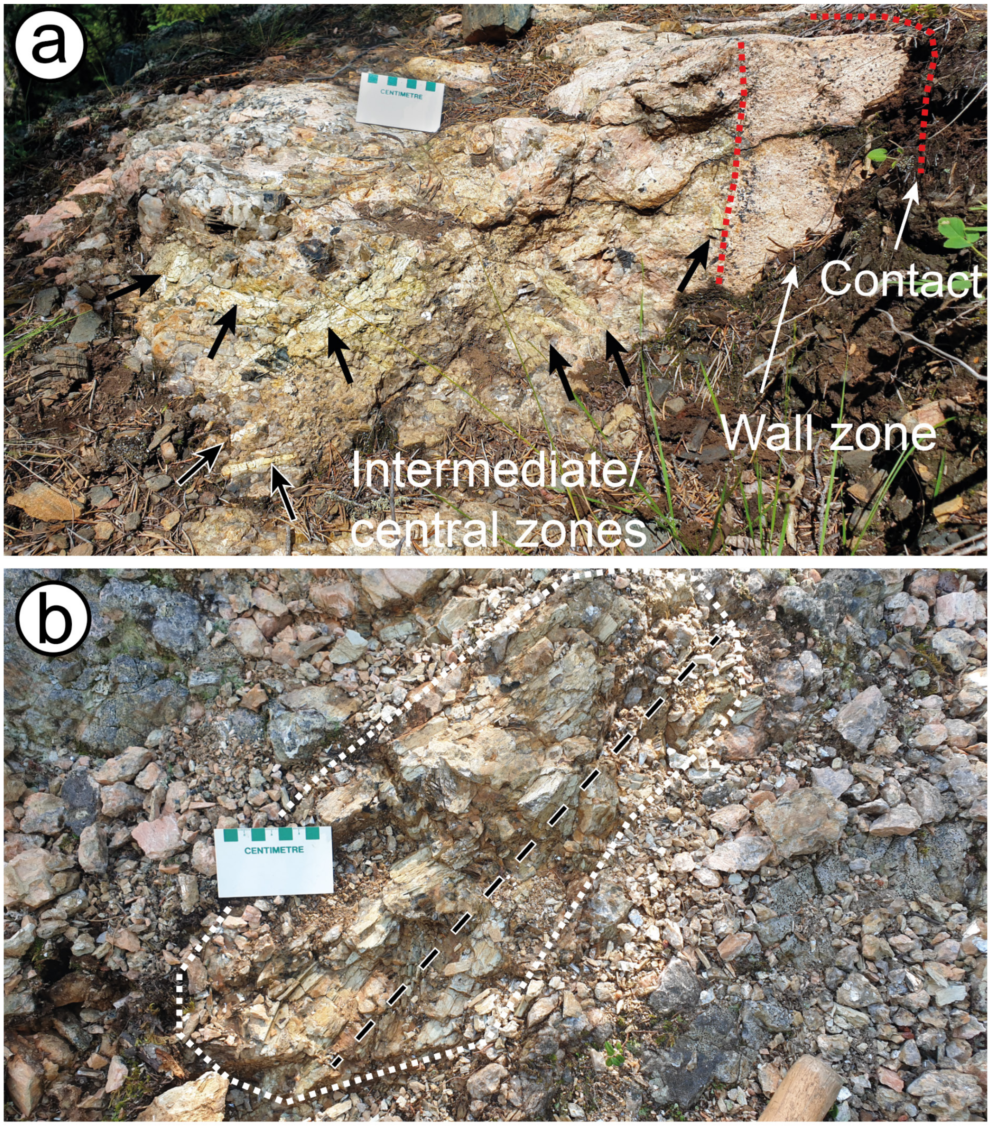

***Figure GS2022-7-5:** Outcrop photographs of the Zoro pegmatite dike 1 (Green Bay group): **a)** spodumene crystals (black arrows) within the intermediate/central zones and the contact with the wall zone (within red dashed lines) of the dike; **b)** example of spodumene crystals' main orientation in the Zoro pegmatite dike (black and white dashed lines).*

in length and 80 m in thickness; Figure GS2022-7-2). Based on their mineralogy, these pegmatite occurrences are classified as muscovite-type (Černý and Ercit, 2005).

The Dion Lake dikes are locally hematized and locally contain oxide and sulphide minerals close to fractures oriented approximately 040°. These pegmatite dikes intruded rocks of high metamorphic grade of the Missi group east of the Wekusko Lake area.

Rex Lake pluton

The Rex Lake pluton (1832 ±4 Ma; Gordon et al., 1990) was documented and sampled in both outcrop and drillcore to assess if it could be parental to part of the Wekusko Lake pegmatite field via crystal fractionation, and to determine the structural mechanisms of pegmatite dike emplacement within and around the pluton. The Rex Lake pluton consists dominantly of medium-grained granodiorite, with local, weak to strong hematization near fractures. Small, subvertical felsic dikes with varying orientations (i.e., 160°, 235°, 300°) crosscut the main granodiorite (Figure GS2022-7-7b). Local tourmaline occurs as grains up to 1–2 cm long in the cores of the felsic dikes. Mafic xenoliths up to 20–30 cm wide are prevalent throughout the pluton (Figure GS2022-7-7b). Drillcore from 1911 Gold Corporation shows weak chlorite alteration, with local sulphides in fractures. Local pegmatitic dikes up to 1 m wide are mineralogically simple, as described in 1911 Gold Corporation's diamond-drill core confidential logs. More mafic subdomains of the pluton consist of porphyritic leucocratic gabbro with plagioclase phenocrysts up to 4 cm.

Preliminary two-dimensional emplacement model of lithium-mineralized pegmatite dikes

The location, strike, and in some cases spodumene fabrics, of lithium-mineralized dikes in the Wekusko Lake pegmatite field

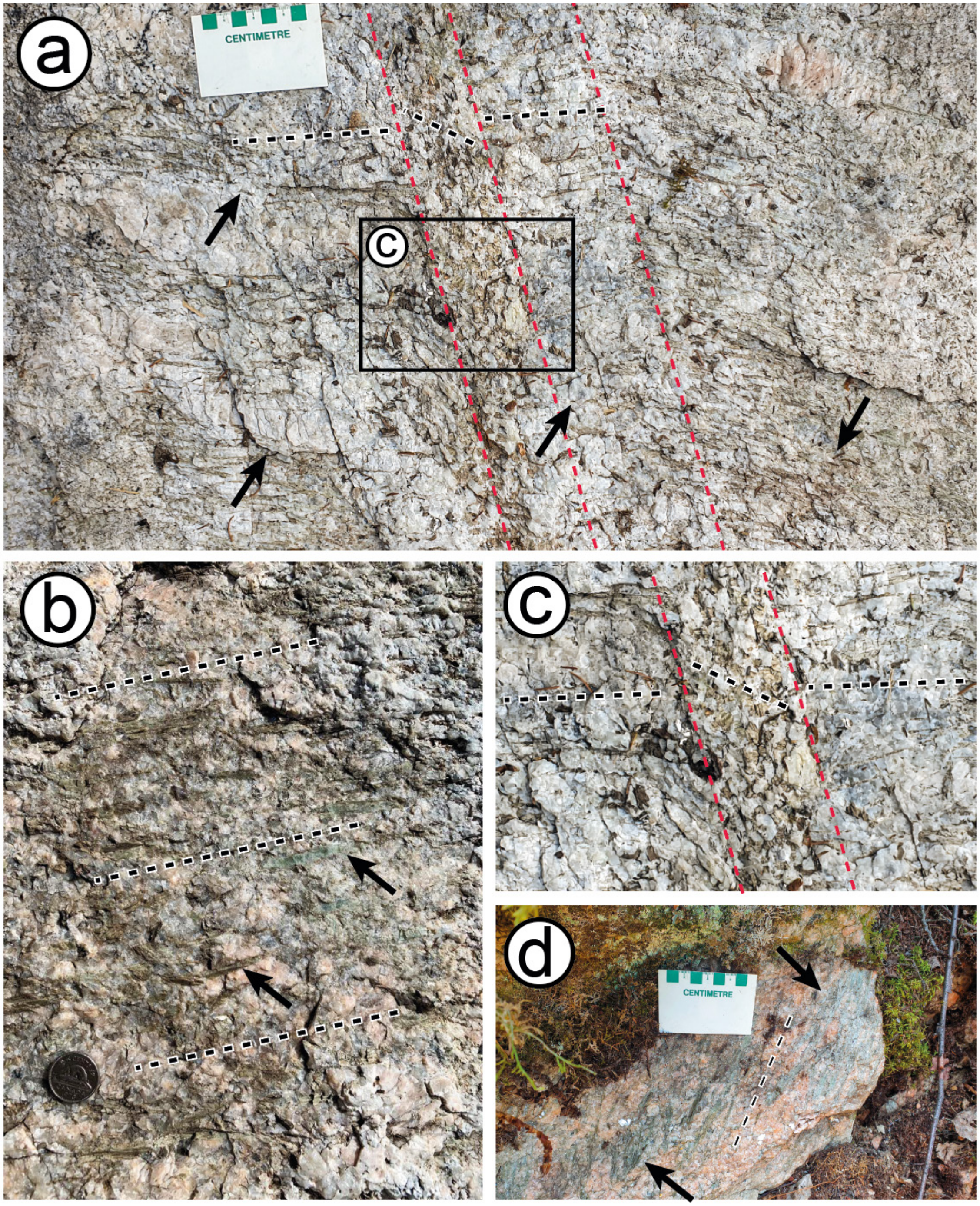

***Figure GS2022-7-6:** Outcrop photographs showing pegmatite dikes from the Violet-Thompson group: **a)** and **b)** pervasive mineral fabric (black dashed lines) in the Thompson Brothers pegmatite dike and post- to late-crystallization shear planes (red dashed lines) slightly rotating the mineral fabric (black arrows pointing at aligned spodumene crystals; coin for scale in b) is 2.1 cm in diameter); **c)** close-up of shear planes (red dashed lines) at high angle to mineral fabric (black dashed lines) observed in the Thompson Brothers pegmatite dike; **d)** aligned spodumene crystals (comb structure; black arrows) close to pegmatite contact (contact outside of photograph) in BY pegmatite dike. Fabric orientation is represented by black dashed line with white outline.*

suggest that emplacement was structurally controlled. The strike of the Sherritt-Gordon group of dikes, located west of the Crowduck Bay shear zone, is oriented subparallel to the D_3 maximum compressional stress (northwest-southeast). This orientation suggests emplacement in Mode-I (extensional; Irwin, 1957) tension-gash openings, with spodumene crystals oriented perpendicular to the contact of the pegmatites (Figure GS2022-7-8).

The Violet-Thompson pegmatite group is located east of, and proximal to, the Crowduck Bay shear zone. The dikes are oriented subparallel to the adjacent structure, and are probably related to shear corridors formed subparallel to the Crowduck Bay shear zone (Figure GS2022-7-8; Černý et al., 1981). Syndeformational, dilational crystallization of the Thompson Brothers pegmatite is inferred from the dominant mineral fabric, which is oblique to

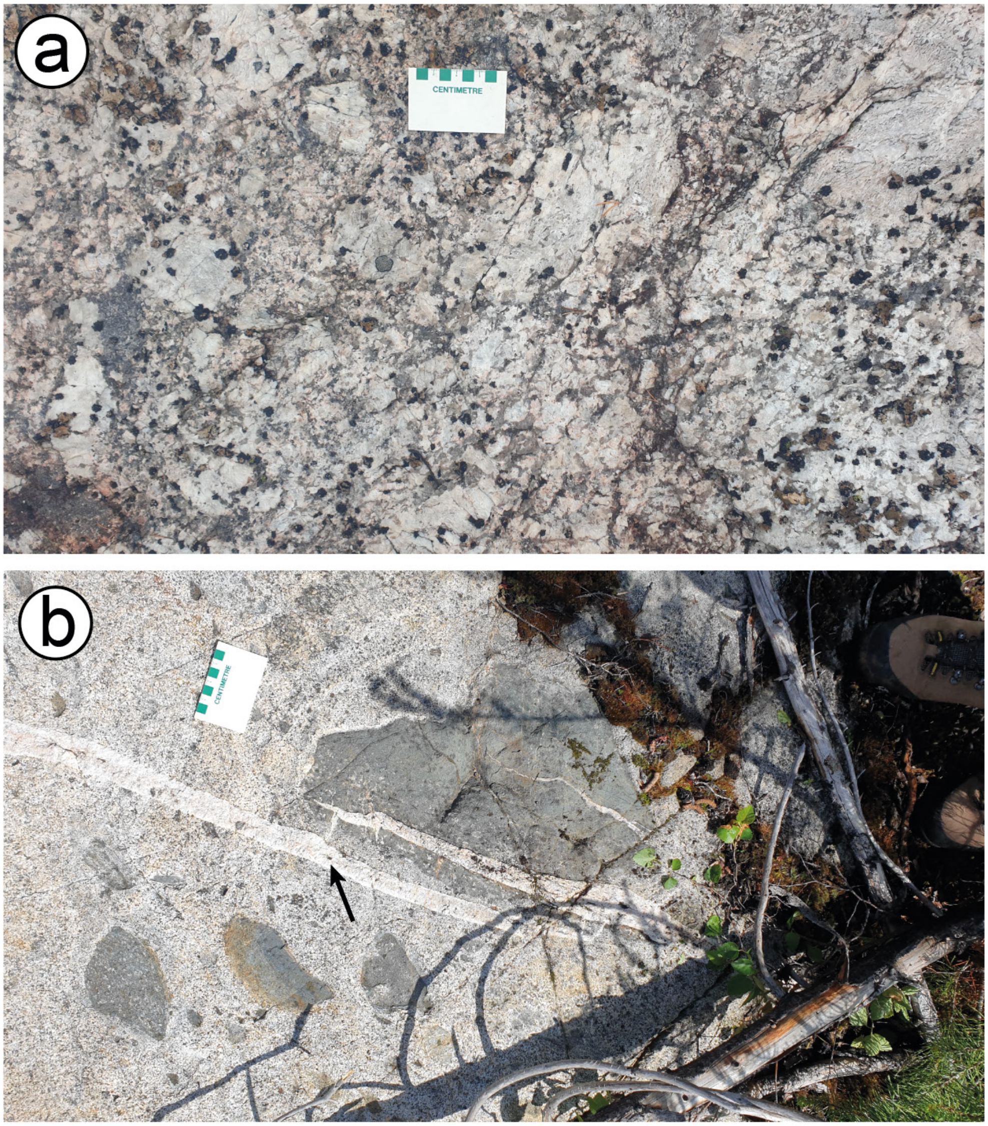

Figure GS2022-7-7: *Outcrop photographs of nonmineralized rocks:* ***a)*** *North Grass River pegmatite dike with simple mineralogical composition (albite-quartz-muscovite);* ***b)*** *Rex Lake pluton granodiorite with mafic xenoliths and crosscut by felsic dikes (black arrow indicates tourmaline in felsic dike). Scale card in both photos is in centimetres.*

the dike margins (Figure GS2022-7-6a, -d; Černý et al., 1981). Pegmatite-hosted shear planes are oriented subparallel to the dike margins, and mineral fabrics proximal to these shear planes are rotated in the direction of shearing (Figure GS2022-7-6a, -c).

Pegmatite dikes of the Green Bay group are emplaced as a series of northwest-trending en échelon–like dikes. Regional-scale, east-northeast-trending lineaments present in the area could represent shear structures. The pegmatite dikes appear to be emplaced between these lineaments as a succession of en échelon tension gashes (Figure GS2022-7-8; Černý et al., 1981). This area is also proximal to the intersection of two main thrust faults (Roberts Lake and Herb Lake faults). Similar regional-scale structures have been proposed as conduits for the transportation of melt within the crust (Deveaud et al., 2013; Piazolo et al., 2020; Silva et al., 2018, 2022). The strike of the Zoro dike 1 appears to be rotated towards a north-trending orientation by the proximity of the north-northeast-trending Herb Lake fault (Figure GS2022-7-8).

Economic considerations

Canada, and particularly Manitoba, are major players in the green revolution because of an abundance of lithium-bearing pegmatite occurrences such as the Tanco pegmatite and pegmatites in the Wekusko Lake field. The Wekusko Lake pegmatite field has considerable economic potential because of a high concentration of lithium-mineralized dikes, favourable mineralogy for lithium extraction, and central location for the Canadian lithium market.

The increasing need for critical minerals, and growing necessity to reduce our dependence on fossil fuels, highlights the political and economic importance of discovering new rare-element pegmatite deposits and increasing our knowledge of already

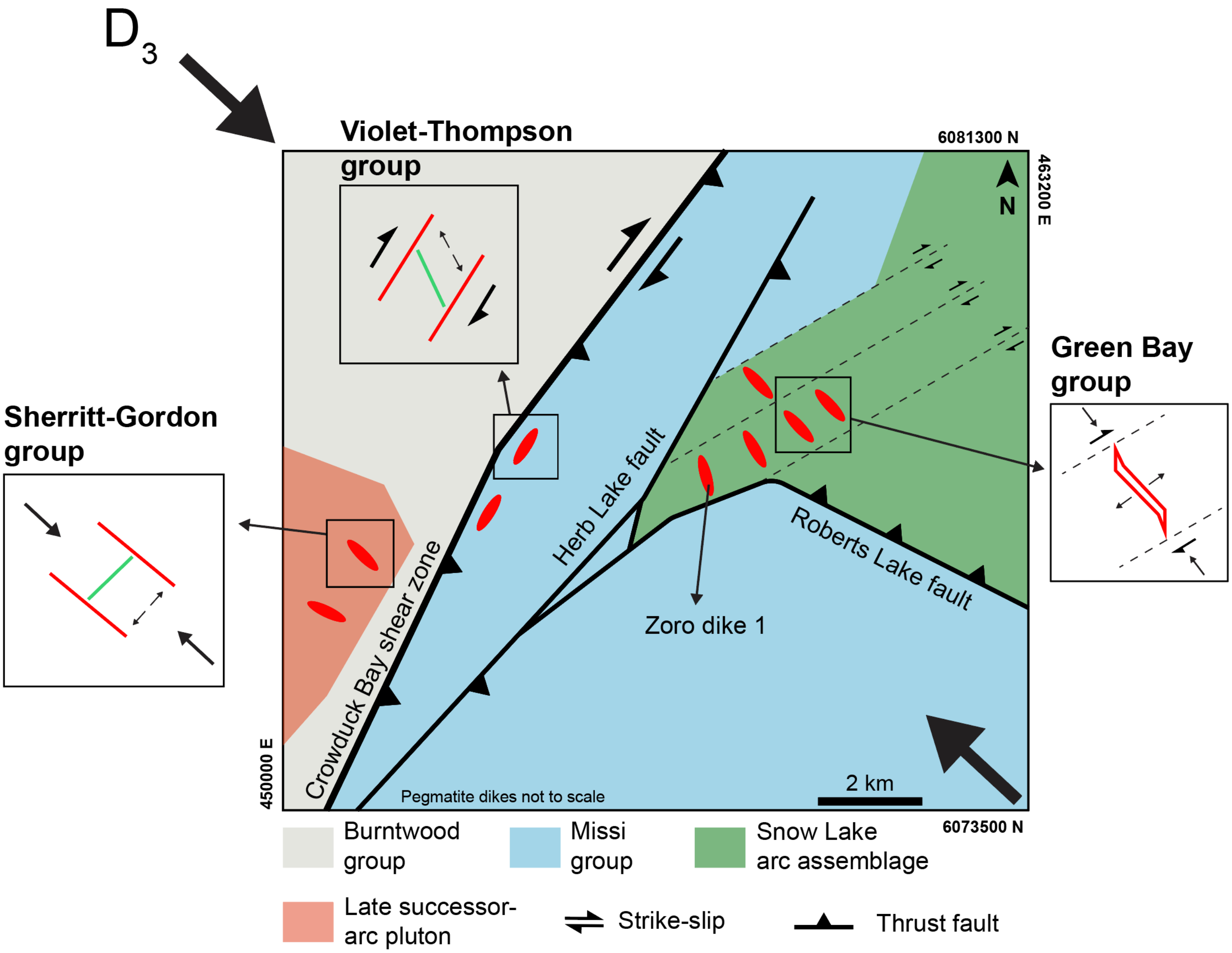

Figure GS2022-7-8: *Preliminary schematic model for the structurally controlled emplacement of lithium-mineralized dikes in the Wekusko Lake pegmatite field. In main portion of figure and in insets, thick black arrows indicate the direction of main tectonic stress during D_3. In the Sherritt-Gordon and Violet-Thompson group insets, the red lines indicate the longitudinal boundaries of the pegmatite dikes and the green lines indicate the elongation of the spodumene crystals. In the Green Bay group inset, the dashed black lines indicate probable strike-slip fault discontinuities.*

known deposits. To achieve these goals, it is necessary to assess probable emplacement mechanisms, the relationship between pegmatite bodies and tectonic structures, and the style and mode of lithium mineralization. The Wekusko Lake pegmatite field in north-central Manitoba is located within a historical and active mining district, with excellent access and developed infrastructure, and a well-studied regional geology. Its lithium resources are the focus of ongoing research as well as active exploration by two companies (Foremost Lithium and Snow Lake Lithium).

Acknowledgments

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