GS2021-5

Bedrock mapping at Ralph Lake, Lynn Lake greenstone belt, northwestern Manitoba (part of NTS 64C14): preliminary results and geological implications

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In Brief:

- New detailed bedrock mapping provides an updated geological framework in the Ralph Lake area, tectonic evolution reflected by the emplacement of I-type, adakite-like, and S-type granitoids
- Adakite-like granitoid intrusions of the post-Sickle intrusive suite may provide an important guide to Au mineralization
- Two-mica granite is emplaced at the boundary zone between the Lynn Lake greenstone belt and Southern Indian Lake domain and may have potential for rare metals (e.g., Li, Ta, Cs)

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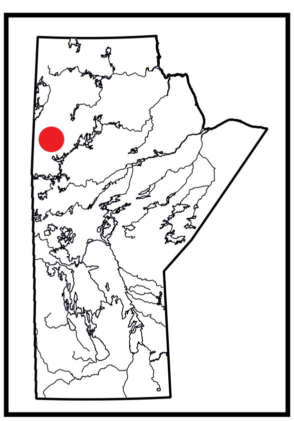

Summary

In 2021, the Manitoba Geological Survey resumed its multiyear bedrock mapping project in the Paleoproterozoic Lynn Lake greenstone belt. The mapping took advantage of outcrops exposed by bush fire east of Ralph Lake to investigate a volcano-sedimentary sequence of the Wasekwan group and overlying sedimentary rocks of the Ralph Lake and Zed Lake groups, the unconformity between them, and pre- to post-Sickle granitoid intrusions. Part of the Wasekwan group supracrustal rocks is well exposed in the burned area and, from the base to top, consists of heterolithic volcanic breccia, tuff breccia, lapillistone, lapilli tuff, tuff and plagioclase-phyric basalt to massive basalt and pillow basalt, as well as associated gabbroic intrusions. This volcanic sequence, cut by pre- and post-Sickle granitoid intrusions, is overturned and unconformably overlain by sediments of the Ralph Lake and Zed Lake groups. These sedimentary rocks are cut by a two-mica granite intrusion of the late intrusive suite. The pre- and post-Sickle intrusions are characterized by high magnetic-susceptibility (MS) values of up to 53.2×10^{-3} SI, and are typical of volcanic-arc I-type and adakite-like granitoids, respectively. The two-mica granite, displaying the lowest MS value (0.054×10^{-3} SI) in the area, is S type and was emplaced into a collisional setting. The unconformity between the Ralph Lake and Zed Lake sediments and the Wasekwan supracrustal rocks reflects a tectonic event likely linked to regional extension resulting from orogen relaxation and/or collapse triggered by slab roll-back, which may have created the synorogenic basin(s) that received sediments derived from the surrounding greenstone belt, forming the polymictic conglomerate, greywacke, psammite and siltstone. The greywacke to siltstone is characterized by porphyroblastic hornblende and muscovite (±garnet), together with hornblende-bearing matrix of the polymictic conglomerate, indicating middle amphibolite–facies metamorphism.

The pre-Sickle granitoid rocks, post-Sickle adakite-like granitoid rocks and late intrusive granite suites were emplaced into the supracrustal sequences, recording tectonic evolution from volcanic arc through extension induced by slab roll-back to terminal collision. More importantly, ore fluids related to adakite-like magmatism could be important for Au mineralization, so the adakite-like granitoids may serve as an indicator for Au exploration in the belt. Furthermore, the occurrence of late S-type granite cutting the Zed Lake greywacke suggests 1) emplacement in a collisional setting and potential association with rare-metal mineralization (e.g., Li, Cs, Ta), and 2) location of the boundary between the Lynn Lake greenstone belt and Southern Indian domain.

Introduction

The Paleoproterozoic Lynn Lake greenstone belt (LLGB; Bateman, 1945) is separated from the Kisseynew domain (basin) to the south by the Granville Lake structural zone (GLSZ; White et al., 2000; Zwanzig, 2000), which forms its southern boundary (Zwanzig, 1990; Zwanzig and Bailes, 2010). Based on modelling of seismic-reflection data and geological analysis, White et al. (2000) pointed out that the LLGB represents a volcanic-plutonic arc terrane formed by northward subduction of back-arc basin crust, and subsequent contraction and underthrusting of the Kisseynew domain beneath the LLGB during terminal collision. To the north, the LLGB is unconformably overlain by the Ralph Lake conglomerate and Zed Lake greywacke (Gilbert et al., 1980), which are likely attributed to the Southern Indian domain (SID) based on comparable rock associations. The nature of the boundary between the LLGB and SID, however, requires further investigation. The Ralph Lake area provides an excellent opportunity to decipher such relationships.

In 2021, the Manitoba Geological Survey (MGS) resumed its multiyear bedrock geological mapping program in the LLGB (Figure GS2021-5-1) of northwestern Manitoba. Detailed bedrock mapping at 1:10 000 scale was conducted in the Ralph Lake area, taking advantage of bush-fire

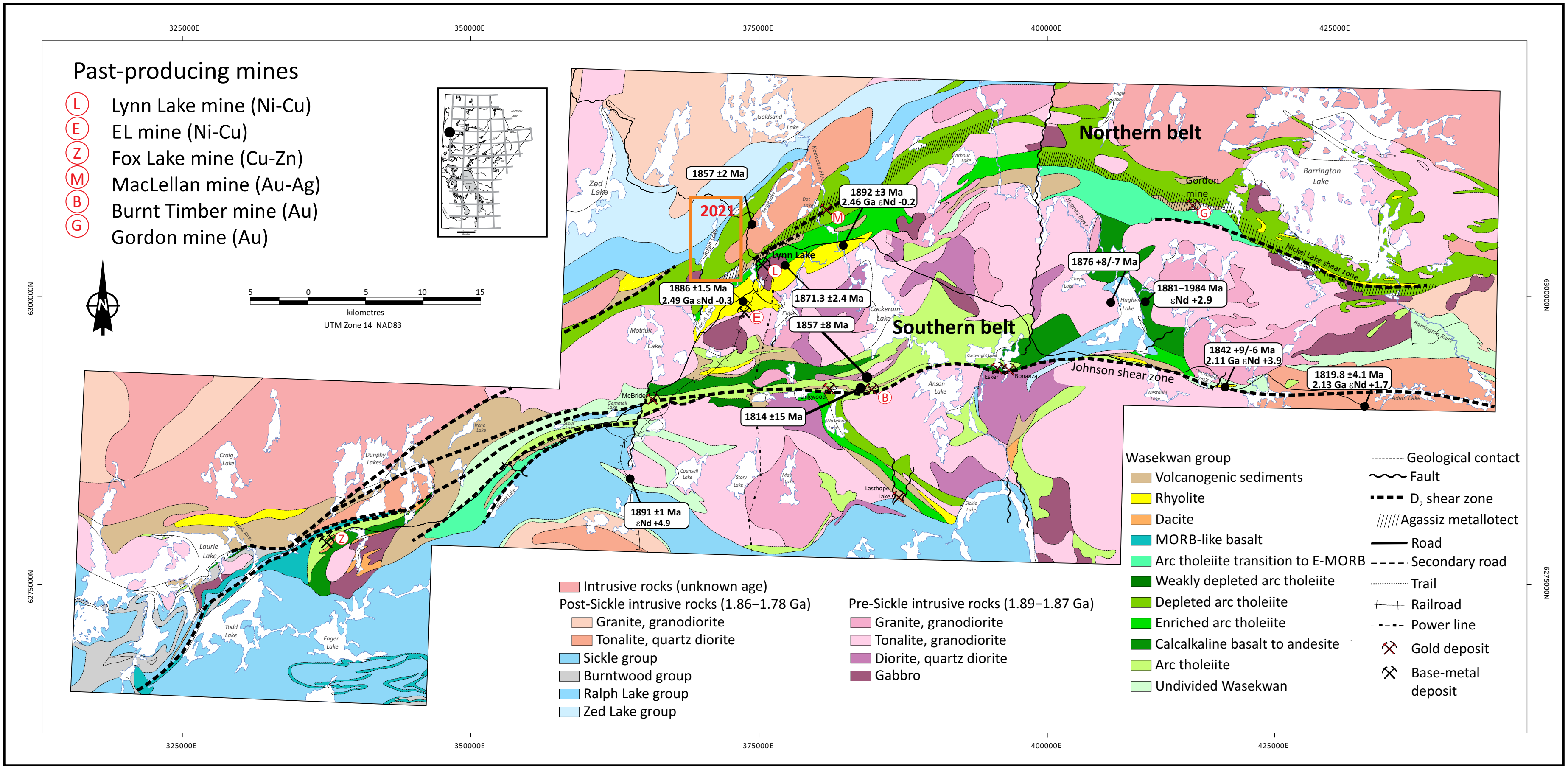

***Figure GS2021-5-1:** Regional geology of the Lynn Lake greenstone belt (modified and compiled from Gilbert et al., 1980; Manitoba Energy and Mines, 1986; Gilbert, 1993; Zwanzig et al., 1999; Turek et al., 2000; Beaumont-Smith and Böhm, 2002, 2003, 2004; Beaumont-Smith et al., 2006; Beaumont-Smith, 2008; Yang and Beaumont-Smith, 2015a, b, 2016, 2017). The 2021 map area is indicated by the orange box. Some of the relevant zircon U-Pb ages and Nd isotopic compositions are also shown. Abbreviations: E-MORB, enriched mid-ocean–ridge basalt; MORB, mid-ocean–ridge basalt.*

exposures to investigate the contact (unconformity) between the Wasekwan group and the overlying Ralph Lake conglomerate and Zed Lake greywacke (Milligan, 1960; Gilbert et al., 1980; Zwanzig et al., 1999). The supracrustal-rock sequences are intruded by granitoid intrusions of the pre– and post–Sickle group intrusive suite, and the late intrusive suite.

This report presents new data on the geology, structure and metamorphism of the Ralph Lake area; provides an updated geological and regional structural framework for the map area; and discusses implications for Au mineralization by the post-Sickle intrusive suite and potential for rare metals (Li, Ta, Cs) in the late intrusive suite. The accompanying preliminary map (Yang, 2021) was created on the basis of 154 field stations, including 156 new structural measurements, as well as compiled historical data (48 stations from Gilbert et al., 1980), a handful of historical drill data and a regional airborne magnetic image (Manitoba Mineral Resources, 2013). During the course of the mapping, a Terraplus Inc. KT-10 magnetic susceptibility (MS) meter[1] was used with a pin to measure MS values of outcrops. Each rock type of a visited outcrop was measured at least five times, at different locations if possible, and the average of the measurements was recorded to represent the MS value of the outcrop. The MS data were used together with the field observations to constrain lithostratigraphic grouping and unit definition.

Twenty-eight whole-rock samples were collected from the map area for geochemical analysis to study geological processes (e.g., Rollinson and Pease, 2021), including eight for thin-section preparation, five for Sm-Nd isotopes and one for zircon U-Pb age determination. The results of these lab analyses are pending and will be reported in subsequent MGS publications.

General geology

The LLGB is endowed with several minerals, such as orogenic Au, magmatic Ni-Cu-Co and volcanogenic massive sulphide Zn-Cu. It is a major tectonic element of the internal Reindeer zone of the Trans-Hudson orogen (Stauffer, 1984; Lewry and Collerson, 1990), which is the largest Paleoproterozoic orogenic belt of Laurentia (Hoffman, 1988; Corrigan et al., 2007, 2009; Corrigan, 2012). To the north, the LLGB is bounded by the SID, which is composed of variably migmatitic metasedimentary rocks, various granitoids and minor metavolcanic and volcaniclastic rocks (Kremer et al., 2009; Martins et al., 2019), although the precise boundary between the LLGB and SID has been debated for years (e.g., Manitoba Energy and Mines, 1986; Manitoba Agriculture and Resource Development, 2021). Synorogenic basins, including the Kisseynew metasedimentary domain, represent the southern limit of the LLGB (Gilbert et al., 1980; Fedikow and Gale, 1982; Syme, 1985; Zwanzig et al., 1999), which is separated by the GLSZ (Zwanzig, 1990, 2000; White et al., 2000; Zwanzig and Bailes, 2010). Paleoproterozoic greenstone belts with ages and lithological assemblages similar to those of the LLGB occur to the east (Rusty Lake belt), to the west (La Ronge belt) and to the far south (Flin Flon belt; e.g., Ansdell et al., 1999; Anderson et al., 2001; Park et al., 2002; Ansdell, 2005; Corrigan et al., 2007, 2009; Corrigan, 2012; Glendenning et al., 2015; Hastie et al., 2018; Lawley et al., 2019, 2020).

The LLGB consists of two east- to northeast-trending, steeply dipping belts that contain various supracrustal rocks, known locally as the Wasekwan group/series (Bateman, 1945; Milligan, 1960; Gilbert et al., 1980), along with younger, molasse-type sedimentary rocks that constitute the Sickle group/series (Norman, 1933; Milligan, 1960; Gilbert et al., 1980). The southern and northern belts are separated by granitoid plutons of the 1.89–1.87 Ga Pool Lake intrusive suite (Gilbert et al., 1980; Baldwin et al., 1987; Beaumont-Smith and Böhm, 2003, 2004; Beaumont-Smith et al., 2006), which are divided into pre- and post-Sickle intrusions based on their temporal relationships to the Sickle group. In the central and southern parts of the LLGB, the Sickle group overlies the Wasekwan group and felsic–mafic plutonic rocks of the Pool Lake intrusive suite along an angular unconformity (Gilbert et al., 1980). The Sickle group correlates well with the 1850–1840 Ma MacLennan group in the La Ronge greenstone belt of Saskatchewan in terms of lithological composition, stratigraphic position and contact relationships (Ansdell et al., 1999; Ansdell, 2005; Corrigan et al., 2009). Volcanic and plutonic rocks in the LLGB underwent peak metamorphism at 1.81–1.80 Ga. Cutting the entire LLGB are the much younger Mackenzie dikes (ca. 1267 Ma; Baragar et al., 1996), as indicated by regional aeromagnetic data.

Significant differences in the geology and geochemistry of the northern and southern belts in the LLGB may reflect regional differences in tectonic settings that were obscured by structural transposition and imbrication during multiple stages of deformation (Gilbert et al., 1980; Syme, 1985; Zwanzig et al., 1999; Beaumont-Smith, 2008). This complexity leads to the suggestion that the term 'Wasekwan group' should be abandoned because it contains disparate volcanic assemblages that were later structurally juxtaposed during tectonic evolution of the LLGB, and thus may represent a tectonic collage (Zwanzig et al., 1999) similar to that described in the Flin Flon belt (e.g., Stern et al., 1995). Although the tectonic collage concept was used in a recent geological compilation by Manitoba Agriculture and Resource Development (2021), this report retains the term 'Wasekwan group' to maintain consistency with previous LLGB-related literature.

[1] The measurement range of magnetic susceptibility (MS) is from 0.001×10^{-3} to 1999.99×10^{-3} SI unit.

Local geology: mapping results

The Ralph Lake area is located in the northern belt of the LLGB (Figure GS2021-5-1). It consists of the Wasekwan group supracrustal rocks intruded by the Pool Lake intrusive suite, which are unconformably overlain by sedimentary rocks of the Ralph Lake and Zed Lake groups (Figure GS2021-5-2; Yang, 2021). According to previous workers (e.g., Milligan, 1960; Beaumont-Smith and Böhm, 2004), intrusions that cut only the Wasekwan group (i.e., the Pool Lake intrusive suite of Gilbert et al., 1980) and those cutting the Sickle group are called, respectively, pre-Sickle and post-Sickle (e.g., Milligan, 1960) suites. Both are cut by rocks of a late intrusive suite, comparable to those identified in the areas of the MacLellan, Gordon and Burnt Timber Au mines and at Gemmell Lake (Yang and Beaumont-Smith, 2015a, b, 2017; Yang, 2019). More recently, Lawley et al. (2020) presented new detrital zircon U-Pb age data for six samples, revealing that the Ralph Lake conglomerate and the Zed Lake greywacke were deposited at ca. 1860 Ma and are therefore likely older than the Sickle group (1836 ±15 Ma).

Nine map units, with 15 subunits, were defined in the Ralph Lake area and can be grouped into six affiliations (from oldest to youngest): Wasekwan group, pre-Sickle intrusive suite, Ralph Lake conglomerate, Zed Lake greywacke, post-Sickle intrusive suite and late intrusive suite (Table GS2021-5-1). These map units are described in the following sections and their distributions are shown in Figure GS2021-5-2 (Yang, 2021). The rocks in the LLGB were deformed and metamorphosed to greenschist and amphibolite facies (Gilbert et al., 1980; Beaumont-Smith and Böhm, 2004; Yang and Beaumont-Smith, 2015a, 2016, 2017; Yang, 2019); however, for brevity, this report omits the prefix 'meta'.

Wasekwan group (units 1 to 3)

Supracrustal rocks of the Wasekwan group in the Ralph Lake area, which are divided into three units (Table GS2021-5-1), are described below.

Volcaniclastic rocks with minor volcanic rocks and volcanic sedimentary rocks (unit 1)

Unit 1 supracrustal rocks are exposed mainly in the eastern and southern parts of the map area (Figure GS2021-5-2; Yang, 2021), where a recent bush fire exposed a major part of the volcaniclastic and volcanic sequence of the Wasekwan group. Unit 1 consists of heterolithic volcaniclastic rocks and intermediate–felsic volcanic and volcaniclastic rocks that, in places, appear to have been reworked by sedimentary processes. The volcaniclastic rocks of unit 1 include mafic to intermediate volcanic breccia, tuff breccia, lapillistone, lapilli tuff and tuff; minor mafic mudstone and intermediate to felsic lapilli tuff and tuff; and volcanic sandstone that locally contains garnet porphyroblasts (e.g., south of Sheila Lake).

Intermediate (andesitic) volcaniclastic rocks cover a spectrum of rock types in terms of fragment size, composition and proportion, including volcanic breccia, tuff breccia, lapillistone, lapilli tuff and tuff (subunits 1a and 1b). Locally, minor synvolcanic rocks (subunit 2a) are also evident in the volcaniclastic package. Andesitic breccia to tuff breccia is typically foliated and consists of varied fragments of aphanitic to plagioclase-phyric basalt to andesite to felsite bedded in lapilli tuff to tuff matrix, and thus can be termed heterolithic volcanic breccia. The volcanic fragments display a large range of size, normally from 4 to 30 cm but locally as large as a few metres. These lithic fragments are commonly stretched, elongated and aligned along the dominant (S_2) foliation planes (note that this report follows the structural terms proposed in Beaumont-Smith and Böhm, 2002, 2003, 2004). Both matrix-supported and clast-supported varieties are evidently present and poorly sorted (Figure GS2021-5-3a and -3b), although some outcrops exhibit variation in size of fragments that is indicative of involvement in sedimentary processes and younging to the south (Figure GS2021-5-3b). The matrix in some of the breccia contains up to 50% plagioclase fragments (0.1–1 cm), together with mafic minerals (e.g., amphibole) and finer materials.

Intermediate (andesitic) lapillistone, lapilli tuff and tuff (subunit 1b) typically display centimetre-scale layers thought to be beds, although they are foliated and locally folded. Lapillistone to lapilli tuff contains elongated lithic fragments of variable composition (e.g., rhyolite, porphyritic andesite, and plagioclase-phyric and aphanitic basalt) and plagioclase crystals embedded in a fine-grained matrix consisting of plagioclase, amphibole, biotite, chlorite, epidote and aphanitic material, as well as local magnetite. Lapilli tuff appears to grade laterally to fine-grained tuff that contains interbedded mafic and felsic laminae (~0.5–2 mm). It was noted that the andesitic tuff lacks larger lapilli-sized lithic fragments. Noteworthy are plagioclase crystal tuff and lapilli tuff, with thin felsic layers up to 1 cm wide containing 35–40% plagioclase fragments of varied shape (e.g., angular, irregular; Figure GS2021-5-3c) that range in size from 0.1 to 20 mm and are unevenly distributed at the outcrop scale. In places, subunit 2a diabase and/or gabbroic dikes cut andesitic lapilli tuff, tuff breccia and volcanic breccia (Figure GS2021-5-3d), and both the dikes and volcaniclastic rocks are foliated, dominantly by D_2.

Mafic volcaniclastic rocks are divided into two subunits: subunit 1c lapillistone, lapilli tuff, tuff, minor mafic mudstone and derivative garnet-biotite schist; and subunit 1d mafic tuff breccia and breccia (Table GS2021-5-1). Mafic lapillistone, lapilli tuff and tuff (subunit 1c) are characterized by the presence of mafic lithic fragments in a chloritic matrix. Minor greenish grey, very fine grained, thinly bedded mafic mudstone is also included in subunit 1c, which usually weathers light greenish brown to light grey and contains disseminated pyrrhotite and pyrite. Dark green, acicular amphibole (actinolite?) porphyroblasts (up to 5–10 mm), concentrated in foliation or

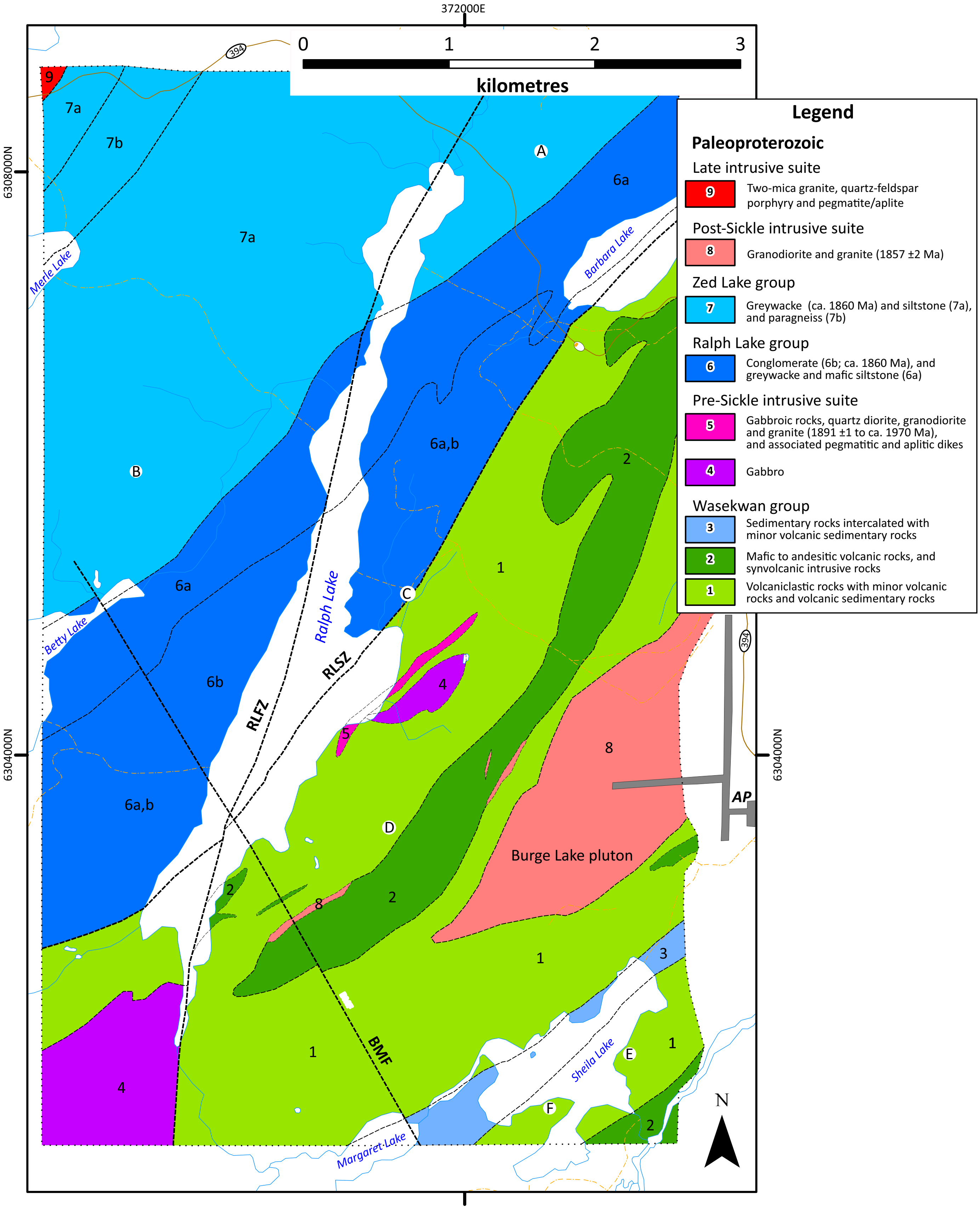

Figure GS2021-5-2: *Simplified geology of the Ralph Lake area, Lynn Lake greenstone belt, northwestern Manitoba (modified from Yang, 2021). A to E: mineral occurrences. References for zircon U-Pb ages of units are listed in Table GS2021-5-1. Abbreviations: AP, airport; BMF, Betty Lake-Margaret Lake fault; RLFZ, Ralph Lake fault zone; RLSZ, Ralph Lake shear zone.*

Table GS2021-5-1: Lithostratigraphic units of the Ralph Lake area, Lynn Lake greenstone belt, northwestern Manitoba.

Unit[1]	Rock type	Affiliation
9	Two-mica granite, quartz-feldspar porphyry, and pegmatite/aplite	Late intrusive suite
	Intrusive contact	
8	Granodiorite and granite (1857 ±2 Ma[2])	Post-Sickle intrusive suite
	Intrusive contact	
7	Metasedimentary rocks: greywacke (ca. 1860 Ma[3]), siltstone and paragneiss	Zed Lake group
7a	Greywacke and siltstone	
7b	Paragneiss	
	Conformity (?)	
6	Metasedimentary rocks: conglomerate (ca. 1860 Ma[3]) and greywacke	Ralph Lake group
6a	Greywacke and mafic siltstone	
6b	Polymictic conglomerate and minor mafic siltstone	
5	Gabbroic rocks, quartz diorite, granodiorite, granite (1891 ±1 Ma to ~1870 Ma[2, 4-5]) and associated pegmatitic and aplitic dikes	Pre-Sickle intrusive suite
4	Gabbro	
	Intrusive contact	
3	Sedimentary rocks intercalated with minor volcanic sedimentary rocks	Wasekwan group
3a	Argillite, siltstone and greywacke	
3b	Mafic to intermediate tuffaceous sandstone to tuff	
3c	Volcanic mudstone, siltstone, volcanic sandstone and minor volcanic conglomerate	
	Structural contact	
2	Mafic to andesitic volcanic rocks and synvolcanic intrusive rocks	
2a	Diabase and gabbro	
2b	Porphyritic basaltic andesite	
2c	Plagioclase-phyric basalt and aphyric basalt	
2d	Pillow basalt	
	Structural contact	
1	Volcaniclastic rocks with minor volcanic rocks and volcanic sedimentary rocks	
1a	Felsic to intermediate volcanic and volcaniclastic rocks	
1b	Intermediate lapillistone, lapilli tuff and tuff	
1c	Mafic lapillistone, mafic lapilli tuff, tuff, minor mafic mudstone and derivative garnet-biotite schist	
1d	Mafic tuff breccia and volcanic breccia	
	?	

[1] On Preliminary Map PMAP2021-2 (Yang, 2021)
[2] Beaumont-Smith et al. (2006)
[3] Lawley et al. (2020)
[4] Baldwin et al. (1987)
[5] Turek et al. (2000)

fracture planes in mafic tuff and lapilli tuff, are interpreted to have formed by retrograde metamorphism to greenschist facies. The mafic lapilli tuff and tuff (subunit 1c) are generally moderately to strongly foliated and range from texturally variable to relatively homogeneous. These rocks consist of varied amounts of aphyric lithic fragments, plagioclase (up to 40%; 0.1–5 mm) and amphibole pseudomorphs after pyroxene (up to 15%; 0.2–12 mm) in a fine-grained mafic-tuff matrix (Figure GS2021-5-3e). Mafic lapilli-sized fragments make up <25% of subunit 1c but can locally account for up to 80% of the rock, which is then termed 'mafic lapillistone'. Locally, coarse-grained to pegmatitic veins or veinlets consisting of quartz and K-feldspar crosscut subunit 3c lapilli tuff to tuff (Figure GS2021-5-3e).

Subunit 1d consists of moderately to strongly deformed and foliated heterolithic mafic tuff breccia and breccia. Volcanic fragments, ranging from 1 to 15 cm in length (typically 10–12 cm), include plagioclase-phyric basalt, aphanitic basalt, epidotic altered massive aphyric basalt, and tuff embedded in a mafic lapilli tuff and tuff matrix (Figure GS2021-5-3f). The basaltic fragments are irregular and subrounded to subangular, some exhibiting reaction rims rich in chlorite and/or epidote, and have been aligned along the generally northeast-trending foliation (S_2) planes. Again, both clast-supported and matrix-

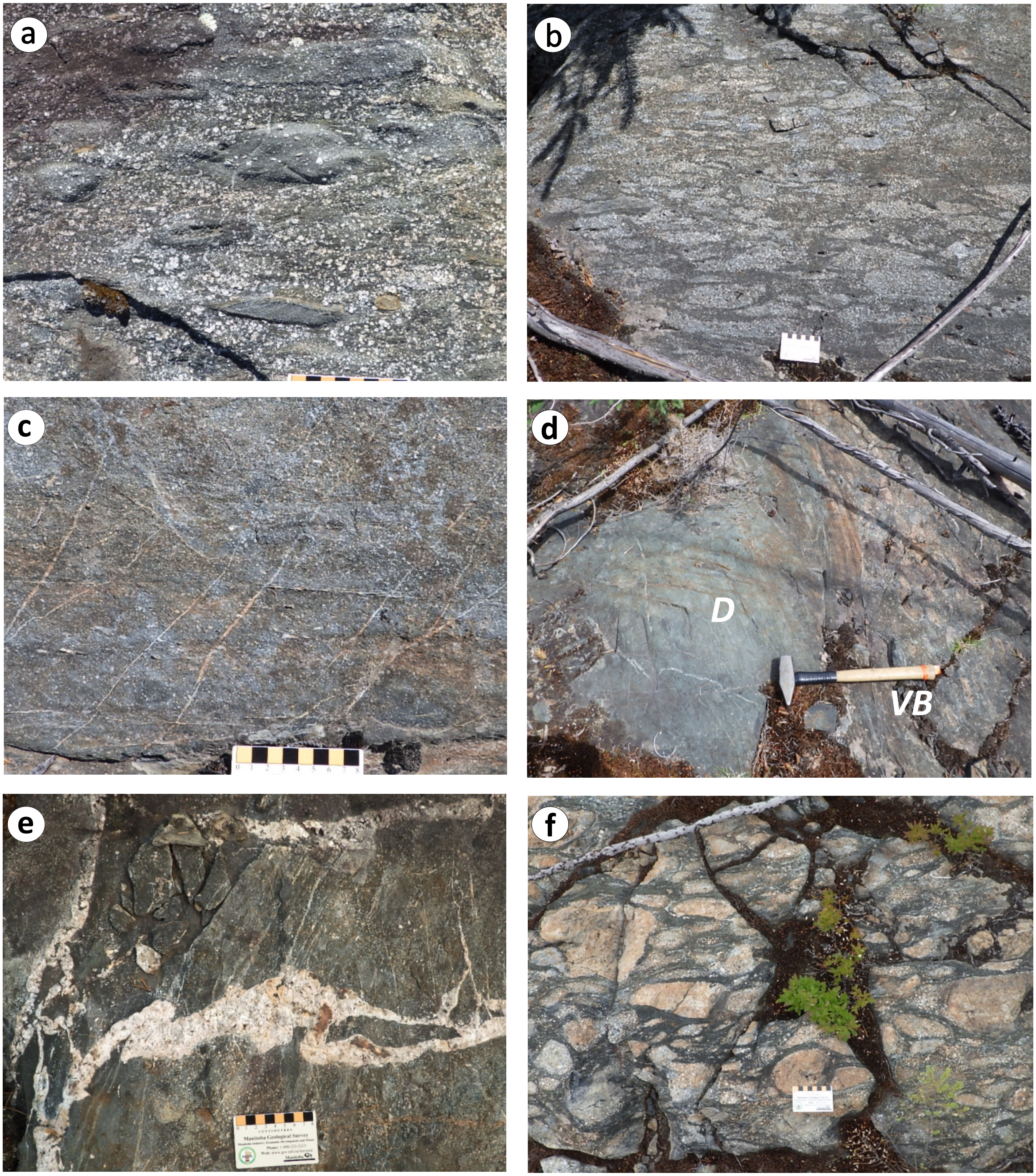

Figure GS2021-5-3: *Field photographs of unit 1 volcaniclastic rocks, with minor volcanic rocks and volcano-sedimentary rocks of the Wasekwan group in the Ralph Lake area:* ***a)*** *intermediate (andesitic) volcanic breccia, matrix supported, with varied plagioclase-phyric to aphyric volcanic fragments in plagioclase-crystal lapilli to tuff matrix (subunit 1a; UTM Zone 14N, 371349E, 6304184N, NAD 83);* ***b)*** *foliated andesitic volcanic breccia consisting mainly of varied sizes of plagioclase-rich porphyritic andesitic clasts, clast-supported, in lapilli tuff to tuff matrix (subunit 1a; UTM 3714267E, 6303962N);* ***c)*** *intermediate lapilli tuff to tuff, with up to 40% 0.1–12 mm plagioclase fragments and minor, very fine grained lithic fragments (subunit 1b; UTM 371387E, 6304007N);* ***d)*** *volcanic breccia (subunit 1b; right side of the photo) cut by 1–2 m wide diabase (gabbroic) dike (subunit 2a; UTM 371392E, 6303987N), hammer handle pointing northwest;* ***e)*** *mafic lapilli tuff to tuff (subunit 1c; UTM 371270E, 6303920N) cut by very coarse grained to pegmatitic (quartz-feldspar±muscovite) veins to veinlets (unit 9);* ***f)*** *foliated mafic volcanic breccia and breccia with varied sizes and shapes of plagioclase-phyric and aphyric basalt fragments, clast-supported, in mafic (chloritic) tuff matrix; the fragments, some of which are strongly epidote altered, are aligned along S_2 foliation (subunit 1d; UTM 371274E, 6303820N). Abbreviations: D, diabase; VB, volcanic breccia.*

supported varieties are evident in subunit 1d. In high-strain zones, lithic fragments are sheared and flattened, although the margins of some of the fragments are still discernible. Some of the aphanitic basalt fragments display epidote alteration and others show reaction rims with very fine grained assemblages of chlorite, epidote, sericite and albite. Thin- and up to 15 cm bedded layers of mafic lapilli tuff to finer tuff occur in places in the mafic tuff breccia to heterolithic breccia package(s).

Unit 1 volcaniclastic rocks with minor volcanic rocks and volcanic sedimentary rocks of the Wasekwan group have MS values mostly in the range 0.403×10^{-3} to 1.59×10^{-3} SI, although much higher values of 15.3×10^{-3} registered in three localities (station 118; UTM Zone 14N, 370690E, 6301899N, NAD 83), 21.8×10^{-3} (station 120; UTM 370349E, 6302207N) and 23.5×10^{-3} SI (station 145; UTM 373449E, 6303422N) due to the presence of fine-grained magnetite grains or a contact zone with unit 8 granodiorite (Figure GS2021-5-2).

Mafic to andesitic volcanic rocks, and synvolcanic intrusive rocks (unit 2)

Unit 2 mafic to intermediate volcanic rocks occur mainly in the northeastern (e.g., southeast of Barbara Lake), east-central (e.g., east of Ralph Lake) and southeastern (e.g., east of Sheila Lake) parts of the map area (Figure GS2021-5-2). The volcanic succession of unit 2 in the Ralph Lake area is dominated by plagioclase-phyric and aphyric basalt, with subordinate porphyritic basaltic andesite and pillow basalt, and synvolcanic diabase and gabbro dikes (Table GS2021-5-1).

Synvolcanic diabase and gabbroic rocks (subunit 2a) usually occur as dikes and small plugs intruded into unit 2 volcanic rocks and, in some cases, into unit 1 volcaniclastic rocks (Figure GS2021-5-3d). The diabase dikes weather greenish grey to grey and are greenish to dark green on fresh surfaces; they are very fine to medium grained, porphyritic and moderately to strongly foliated (Figure GS2021-5-4a). Equant to subhedral plagioclase phenocrysts (up to 10 mm) occur in a fine-grained groundmass of plagioclase, amphibole, chlorite and Fe oxides. Generally, the diabase and gabbroic rocks consist of 50–60% hornblende (after pyroxene) and 40–50% plagioclase, consistent with an amphibolite-facies metamorphic-mineral assemblage. Notably, radial aggregates of acicular amphibole (actinolite) and a few reddish euhedral garnet crystals are evidently present in some deformed subunit 2a gabbroic rocks (Figure GS2021-5-4b) that are in sheared contact with plagioclase-phyric to aphyric basalts (subunit 2c). Trace disseminated sulphide blebs (e.g., pyrrhotite; ~0.5–1 mm) are locally evident, suggesting that the magmas may have been sulphide saturated. Notably, some of the subunit 2a gabbroic intrusions contain ~1% chalcopyrite disseminations up to 3 mm (southeast side of Ralph Lake; Figure GS2021-5-4b).

Porphyritic basaltic andesite (subunit 2b) contains amphibole (±biotite) and lesser amounts of plagioclase phenocrysts in a fine-grained groundmass. Biotite and sericite alteration is a common feature of the rock. It is difficult to distinguish this from plagioclase-phyric basalt (subunit 2c) when plagioclase and amphibole phenocrysts coexist in basaltic andesite (subunit 2b), although amphibole (±biotite) phenocrysts are commonly absent in the basalt. Massive aphyric basalt (subunit 2c; GS2021-5-4c) is less common compared to plagioclase-phyric basalt in the Ralph Lake area. Vesicles and quartz±calcite amygdules are present in some outcrops (GS2021-5-4d). In most cases, the basalt is aphanitic where lacking in plagioclase phenocrysts. Chlorite and epidote alteration is common in both the plagioclase-phyric and aphyric basalts, as shown by epidote domains ranging from a few centimetres to a metre across.

Moderately to strongly foliated plagioclase-phyric to aphanitic aphyric basalt with disseminations of sulphides have a rusty appearance when weathered (subunit 2c) and locally have pyrite-bearing quartz veins along the S_2 foliation planes (GS2021-5-4e). It is common that some of the foliated, massive aphanitic basalt (subunit 2c) with disseminated pyrrhotite is invaded by late sheeted felsic veinlets (GS2021-5-4f). Pillowed basalt (subunit 2d) was reported by Gilbert et al. (1980) to occur southeast of Ralph Lake. Although preserved pillows were not encountered, hyaloclastite relicts derived from pillow selvages were observed, confirming that part of the unit 2 volcanic rocks may have formed in a subaqueous environment, as suggested by Gilbert et al. (1980).

Unit 2 mafic to intermediate rocks and synvolcanic gabbroic rocks of the Wasekwan group have MS values ranging mainly from 0.511×10^{-3} to 1.37×10^{-3} SI. An exception was a value of 24.3×10^{-3} SI for an aphanitic basalt outcrop (GPS location reading: UTM Zone 14N, 373014E, 6306963N, NAD 83), which was attributed to very fine grained magnetite in the rock.

Sedimentary rocks intercalated with minor volcanic sedimentary rocks (unit 3)

Unit 3 sedimentary rocks with minor volcanic and volcaniclastic rocks are exposed mainly on the northeastern side of Sheila Lake (Figure GS2021-5-2). This unit consists of argillite, siltstone and greywacke (subunit 3a), and mafic to intermediate tuffaceous sandstone to tuff (subunit 3b), intercalated with minor volcanic mudstone, siltstone, sandstone and conglomerate (subunit 3c; Table GS2021-5-1).

Thin- to medium-bedded quartzofeldspathic greywacke and siltstone (subunit 3a) dominate the sedimentary succession. Primary bedding (S_0) in the sedimentary rocks was transposed by the regional S_2 foliation. The medium- to coarse-grained greywacke is medium tan to yellowish grey on weathered surfaces and light grey on fresh surfaces. Quartz, feldspar,

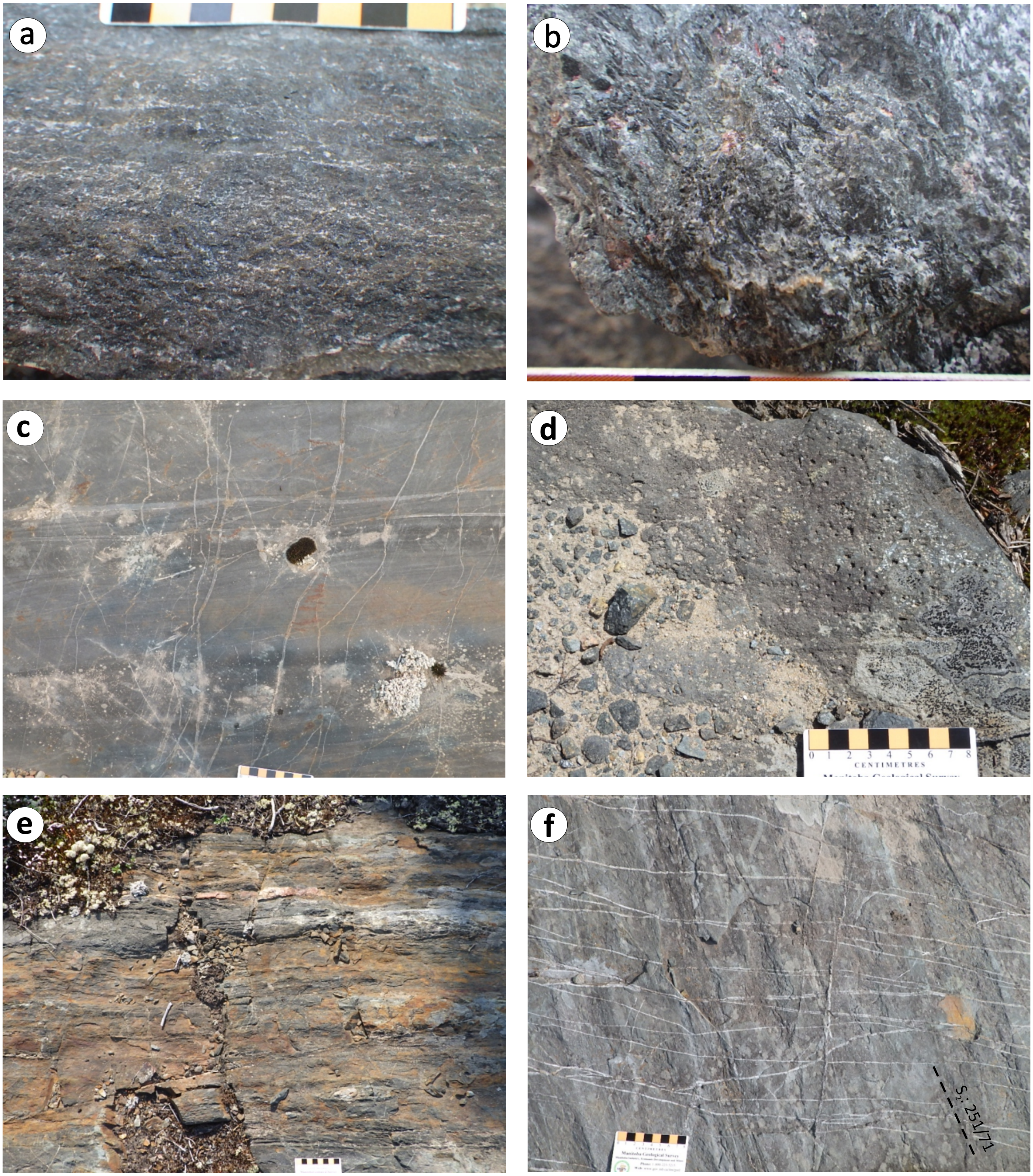

Figure GS2021-5-4: *Field photographs of mafic to intermediate volcanic rocks and synvolcanic intrusive rocks (unit 2) of the Wasekwan group in the Ralph Lake area:* ***a)*** *and* ***b)*** *synvolcanic, foliated gabbro that was recrystallized and contains acicular amphibole and reddish garnet porphyroblasts (subunit 2a; UTM Zone 14N, 370421E, 6302894N, NAD 83), interval on scale bar at bottom of photo b is 1 cm;* ***c)*** *foliated, massive, plagioclase-phyric basalt to aphanitic basalt flow (subunit 2c; UTM 372957E, 6306772N);* ***d)*** *plagioclase-phyric andesitic basalt to basaltic andesite with abundant vesicles at top of flow, indicative of younging to the southeast (subunit 2b; UTM 373296E, 6306975N);* ***e)*** *foliated, plagioclase-phyric to aphanitic basalt with disseminations of sulphides that have a rusty appearance due to weathering (subunit 2c; UTM 372735E, 6306271N); note pyrite-bearing quartz vein emplaced along the S_2 foliation planes;* ***f)*** *foliated, massive aphanitic basalt with disseminated pyrrhotite cut by sheeted felsic veinlets (subunit 2c; UTM 372766E, 6306223N).*

amphibole and lithic clasts are angular to subrounded and well aligned on foliation planes defined by biotite flakes and manifested by felsic- and mafic-rich layering that likely reflects transposed bedding (S_0; Figure GS2021-5-5a). Note that acicular amphibole, up to 1.5 mm, is present in finer matrix, suggestive of retrograde metamorphism of greenschist-facies.

Mafic to intermediate tuffaceous sandstone to tuff (subunit 3b) is fine to medium grained and contains up to 75% volcanic fragments (up to 2 mm in size). The bedding (S_0) of this subunit is strongly transposed by the dominant S_2 foliation. Thin to thick beds of minor volcanic sedimentary rocks (subunit 3c) consist of volcanic mudstone, siltstone and sandstone, and minor volcanic conglomerate (Table GS2021-5-1). Volcanic sandstone is dominated by laminated, fine- to medium-grained andesitic sandstone containing irregular plagioclase, biotite flakes and lithic fragments (0.5–2 mm) in a fine sandy matrix; locally, a few large lithic fragments occur along bedding transposed by regional S_2 foliation. Thick-bedded volcanic conglomerate and/or breccia (subunit 3c) consists dominantly of felsic and intermediate to mafic volcanic clasts in a coarse-grained sandy matrix (Figure GS2021-5-5b). These clasts, 2–5 cm in length, are stretched, flattened and well aligned along S_2 planes that transposed primary bedding (S_0). Although strongly deformed, the breccia appears to grade upward to volcanic sandstone, suggesting that the beds are younging to the north at this locality (Figure GS2021-5-5b).

Unit 3 sedimentary rocks of the Wasekwan group displayed consistent MS values of 0.490×10^{-3} to 0.542×10^{-3} SI.

Pre-Sickle intrusive suite (units 4 and 5)

Igneous rocks of the pre-Sickle intrusive suite occur as intrusions crosscutting the supracrustal rocks of the Wasekwan group (Gilbert et al., 1980; Baldwin et al., 1987; Beaumont-Smith and Bohm, 2004). Unit 4 gabbro and unit 5 granitoid, diorite, quartz diorite and minor gabbroic rocks are assigned to this suite (Table GS2021-5-1).

Gabbro (unit 4)

Unit 4 gabbro occurs mainly in the southwestern part of the map area and along the eastern shore of Ralph Lake (Figure GS2021-5-2). It occurs as small sill-like bodies intruding the Wasekwan group supracrustal rocks. The gabbro weathers greenish grey and is dark greenish grey to dark grey on fresh surfaces. It is medium to coarse grained, equigranular, massive and moderately to locally strongly foliated. It consists of 35–45% plagioclase laths (1–3 mm), 50–55% hornblende (pseudomorphs after pyroxene), minor magnetite and trace pyrrhotite (Figure GS2021-5-6a). In addition, foliated coarse-grained gabbro comprises euhedral to subhedral hornblende (6–8 mm) and interstitial anhedral plagioclase grains, suggestive of a cumulate phase (Figure GS2021-5-6b). The edges of both plagioclase and hornblende crystals are diffuse due to chlorite and sericite alteration. Locally, epidote veins and veinlets are evidently present along or cutting the regional foliation (S_2) planes.

Unit 4 gabbro in the southwestern Ralph Lake area yielded very high MS values of 10.5×10^{-3} to 53.2×10^{-3} SI, whereas this unit in the east-central Ralph Lake area showed much lower MS values of 0.604×10^{-3} to 0.839×10^{-3} SI, similar to the unit 1 volcaniclastic rocks.

Gabbroic rocks, quartz diorite, granodiorite, granite and associated pegmatitic and aplitic dikes (unit 5)

Unit 5 granitoid intrusions of the pre-Sickle intrusive suite are exposed mainly in the east-central Ralph Lake area (Figure GS2021-5-2), cutting the Wasekwan group supracrustal rocks.

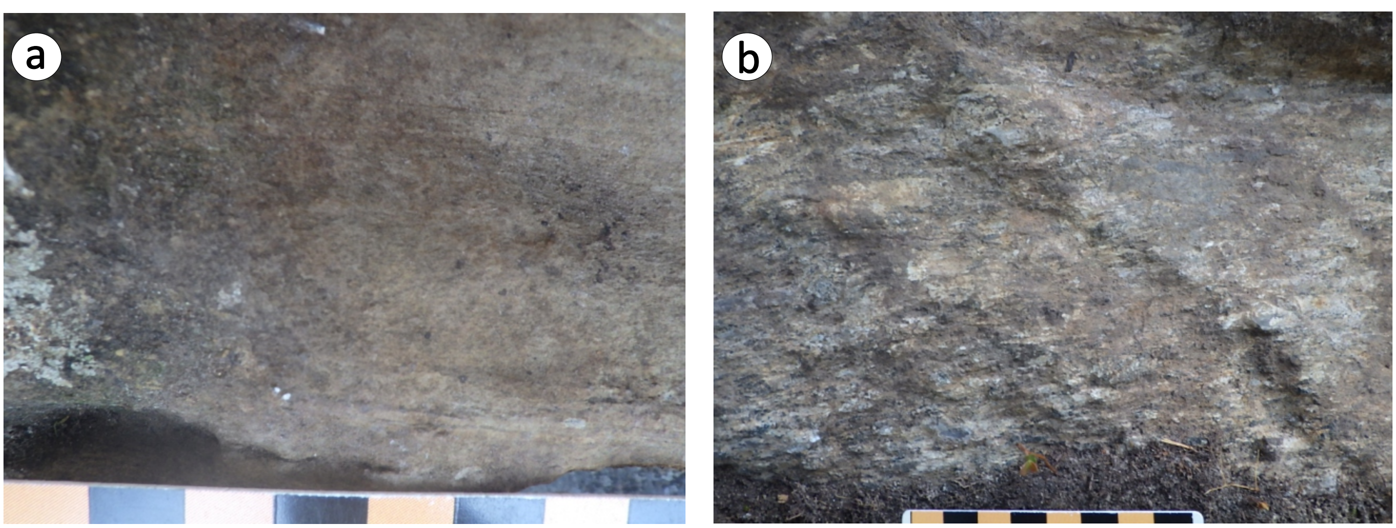

Figure GS2021-5-5: *Field photographs of sedimentary rocks intercalated with minor volcano-sedimentary rocks (unit 3) of the Wasekwan group in the Ralph Lake area:* ***a)*** *fine- to medium-grained, foliated siltstone to pebbly greywacke with recrystallized biotite along S_0/S_2 planes and acicular amphibole porphyroblasts in fine matrix (subunit 3a; UTM Zone 14N, 373361E, 6302614N, NAD 83);* ***b)*** *foliated volcanic conglomerate with felsic and mafic lithic fragments in a felsic to intermediate sandy matrix; bedding (S_0) transposed by S_2 foliation (subunit 3c; UTM 373410E, 6302547N).*

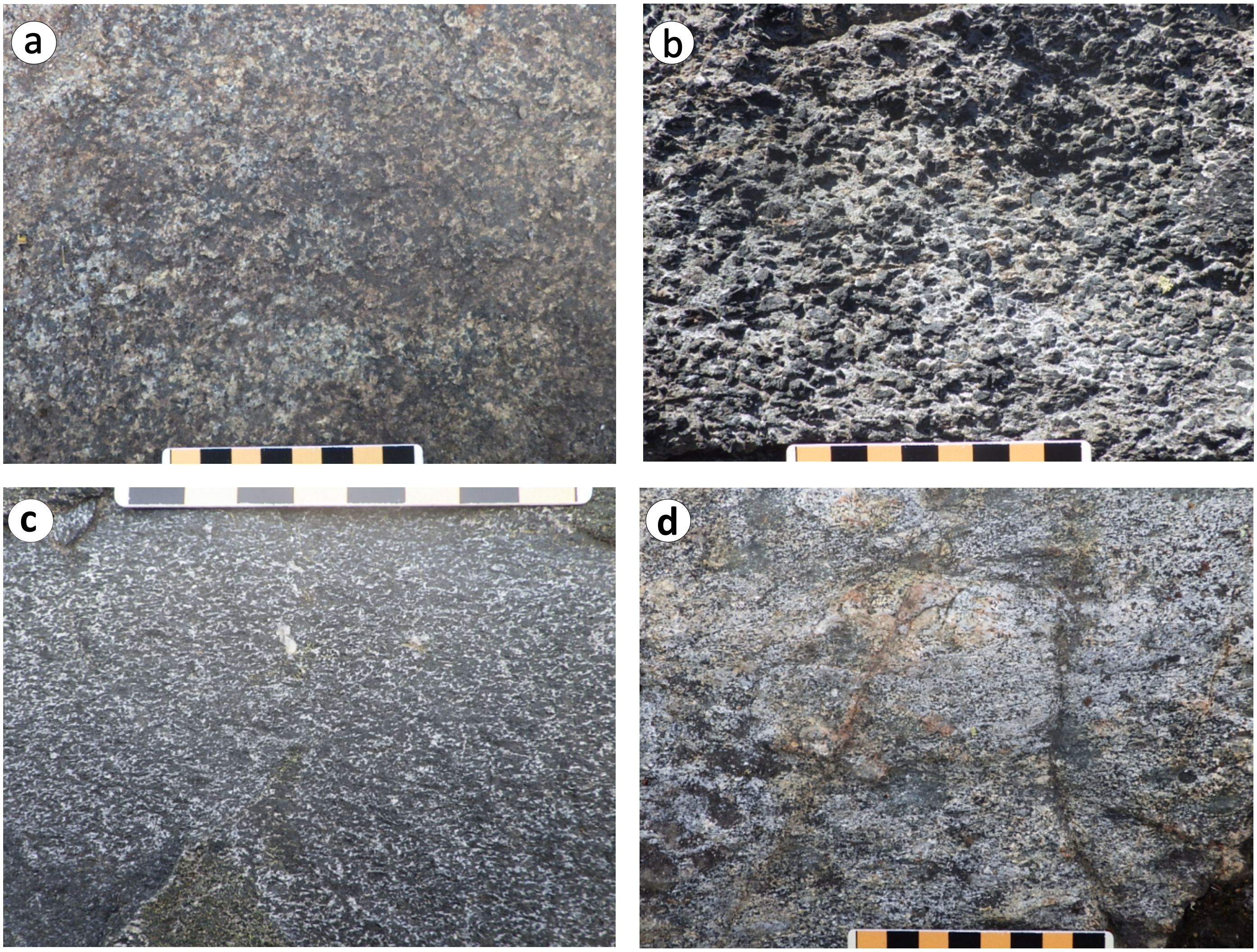

Figure GS2021-5-6: *Outcrop photographs of units 4 and 5 in the Ralph Lake area:* ***a)*** *massive, medium- to coarse-grained, equigranular gabbro (unit 4; UTM Zone 14N, 369600E, 6302010N, NAD 83);* ***b)*** *weakly foliated, coarse-grained gabbro comprising euhedral to subhedral hornblende (pseudomorph of pyroxene) and interstitial anhedral plagioclase grains mostly altered to finer felsic aggregates, suggestive of a cumulate phase (unit 4; UTM 371860E, 6304410N);* ***c)*** *foliated quartz gabbro (unit 5; UTM 371898E, 6304728N); and* ***d)*** *foliated, porphyritic quartz diorite (unit 5; UTM 371884E, 6304756N).*

Unit 5 consists of a range of rocks from gabbro to quartz diorite, tonalite, granodiorite, granite and associated pegmatitic and aplitic dikes. The field relationships indicate that a minor gabbroic phase occurs at the margin of a granitoid intrusion, where the quartz gabbro appears to display flow foliation even though it is largely overprinted by the regional S_2 foliation (Figure GS2021-5-6c). From the contact into the intrusion, the granitoid rocks tend to change from quartz diorite to granodiorite and granite. Locally, the quartz diorite is porphyritic and uneven in texture, and contains disseminated pyrite and pyrrhotite; both feldspar and quartz phenocrysts are present (Figure GS2021-5-6d) in association with plagioclase, hornblende ±biotite.

Granodiorite and granite of unit 5 are medium to coarse grained, massive, equigranular to locally porphyritic and weakly to moderately foliated. They weather greyish pink to light beige and consist of quartz, plagioclase, K-feldspar, hornblende (±biotite) and accessory Fe-oxide minerals. Some of the porphyritic variety contains 5% quartz phenocrysts up to 1.2 cm across, suggesting relatively shallow emplacement. Minor pegmatite and/or aplite of unit 5 occur as dikes ranging from a few centimetres to a few metres wide and consisting of quartz, feldspar and minor biotite.

Unit 5 granitoids yielded a range of MS values from 1.59×10^{-3} to 11.2×10^{-3} SI, but more evolved granite and related pegmatitic and aplitic dikes had lower MS values (as low as 0.41×10^{-3} SI). This large range in MS values is consistent with I-type granites elsewhere in the LLGB (e.g., Yang and Beaumont-Smith, 2015b; Yang and Lawley, 2018; Yang et al., 2019).

Ralph Lake group (unit 6)

The term 'Ralph Lake group' (unit 6) is used in this report instead of Ralph Lake conglomerate (Milligan, 1960; Gilbert et al., 1980; Zwanzig et al., 1999; Yang and Beaumont-Smith, 2015a) because of the presence of diverse lithologies other than just conglomerate. Unit 6 is exposed mainly between the northeastern part of Ralph Lake and the southwestern side of Barbara Lake, and occurs sparsely in the western and southwestern parts of the map area (Figure GS2021-5-2). Unit 6 sedimentary rocks seem to overlie supracrustal rocks of the Wasekwan group (Gilbert et al., 1980; Manitoba Energy and Mines, 1986; Zwanzig et al., 1999). This unit, in fact, is structurally juxtaposed with the Wasekwan rocks to the south, and separated from the Wasekwan supracrustal rocks by the northeast-trending Ralph Lake shear zone (RLSZ), which shows dextral movement, indicated by the structural fabrics, and dips subvertically to the southeast. Unit 6 consists mainly of greywacke, mafic siltstone (subunit 6a) and polymictic conglomerate (subunit 6b), which were recrystallized and metamorphosed to an assemblage of biotite, hornblende, epidote, quartz, plagioclase (±K-feldspar±muscovite±garnet) and magnetite.

Greywacke and mafic siltstone (subunit 6a)

Subunit 6a consists dominantly of thin-bedded, laminated, mafic siltstone to greywacke. In places, some of the mafic greywacke bands, characterized by porphyroblastic hornblende crystals up to 3 mm and biotite flakes, are evidently intercalated with mafic siltstone within this sedimentary package (Figure GS2021-5-7a). Such mafic-enriched wacke bands manifest the transposition of primary bedding (S_0) by the regional S_2 foliation, which strikes northeast and dips consistently to southeast. Notably, the mafic greywacke and siltstone contain very fine magnetite crystals that could be either metamorphic or detrital in origin, resulting in very high MS values of 106×10^{-3} to 111×10^{-3} SI.

Polymictic conglomerate and minor mafic siltstone (subunit 6b)

Both matrix- and clast-supported polymictic pebble to cobble conglomerates are poorly sorted (subunit 6b). Lithic clasts are variable in composition, size and shape, and are stretched and mostly well aligned along the regional foliation (S_2), which has transposed primary bedding (S_0); the S_2 foliation strikes northeast and dips to the southeast. Gradational variation in clast size appears, in places, to suggest fining upward to the northwest for the sequence and transition into unit 7 Zed Lake greywacke to the northwest. The polymictic conglomerate contains clasts of epidotic volcanic rocks, gabbro, diorite, granitoids and vein quartz; the matrix is wacke that was recrystallized to an assemblage of quartz, feldspar, hornblende, biotite, epidote and magnetite (Figure GS2021-5-7b). In many locations, thin- to thick-bedded mafic siltstone (to minor wacke) that resembles the matrix in composition occurs within the conglomerate sequence.

In moderate- to high-strain domains related to the RLSZ, subunit 6b conglomerate is moderately to intensely foliated and sheared (Figure GS2021-5-7c), and is locally protomylonitic (Figure GS2021-5-7d) to mylonitic in the high-strain domains. Based on the asymmetry of some flattened clast relicts, deformed fabrics and stretching lineations, the conglomerate experienced dextral transpressive shearing, as shown by the RLSZ.

Similar to the mafic greywacke and siltstone of subunit 6a, the polymictic conglomerate of subunit 6b yielded high MS values ranging from 10.1×10^{-3} to 99.2×10^{-3} SI, consistent with the presence of fine-grained magnetite in its recrystallized, hornblende-bearing, sandy matrix.

It is noted that maturity of the Ralph Lake conglomerate seems lower than that of its Sickle group counterpart. The presence of abundant finer grained silt to clay materials is indicative of immature sediments, although they had been metamorphosed and/or recrystallized to form biotite (±muscovite±garnet) and hornblende in the matrix and/or as porphyroblasts, suggesting that it underwent metamorphism up to middle amphibolite faces. The Ralph Lake conglomerate, together with the Zed Lake greywacke (see below), are thought in this study to be part of the Southern Indian Lake domain, based on their rock associations (Manitoba Agriculture and Resource Development, 2021) that are characterized by variably migmatitic metasedimentary rocks, various granitoids, and minor metavolcanic and volcaniclastic rocks (Kremer et al., 2009; Martins et al., 2019 and references therein).

Zed Lake group (unit 7)

The Zed Lake group (unit 7) consists dominantly of fine- to medium-grained greywacke and siltstone (subunit 7a) and derived paragneiss (subunit 7b). Rocks of this unit are exposed northwest of Ralph Lake (Figure GS2021-5-2) and its contact with the Ralph Lake sedimentary rocks (unit 6) was not observed, although the two units are distinguishable on regional airborne magnetic images and using the MS values measured as part of this study. The Zed Lake greywacke displays much lower MS values than the Ralph Lake conglomerate (see below). Detrital zircons recovered from a greywacke sample collected from an outcrop ~3 km west of Ralph Lake yielded a maximum depositional age of ca. 1860 Ma (Lawley et al., 2020), identical to that of the Ralph Lake conglomerate. Therefore, the contact between units 6 and 7 is believed to be sedimentary, which is also supported by their similar S_0/S_2 relationship (i.e., the same relationship of the fabrics), although it is unknown if a sedimentary hiatus occurred.

Greywacke and siltstone (subunit 7a)

Subunit 7a consists mainly of medium- to thick-bedded, fine- to medium-grained greywacke and siltstone. It weathers

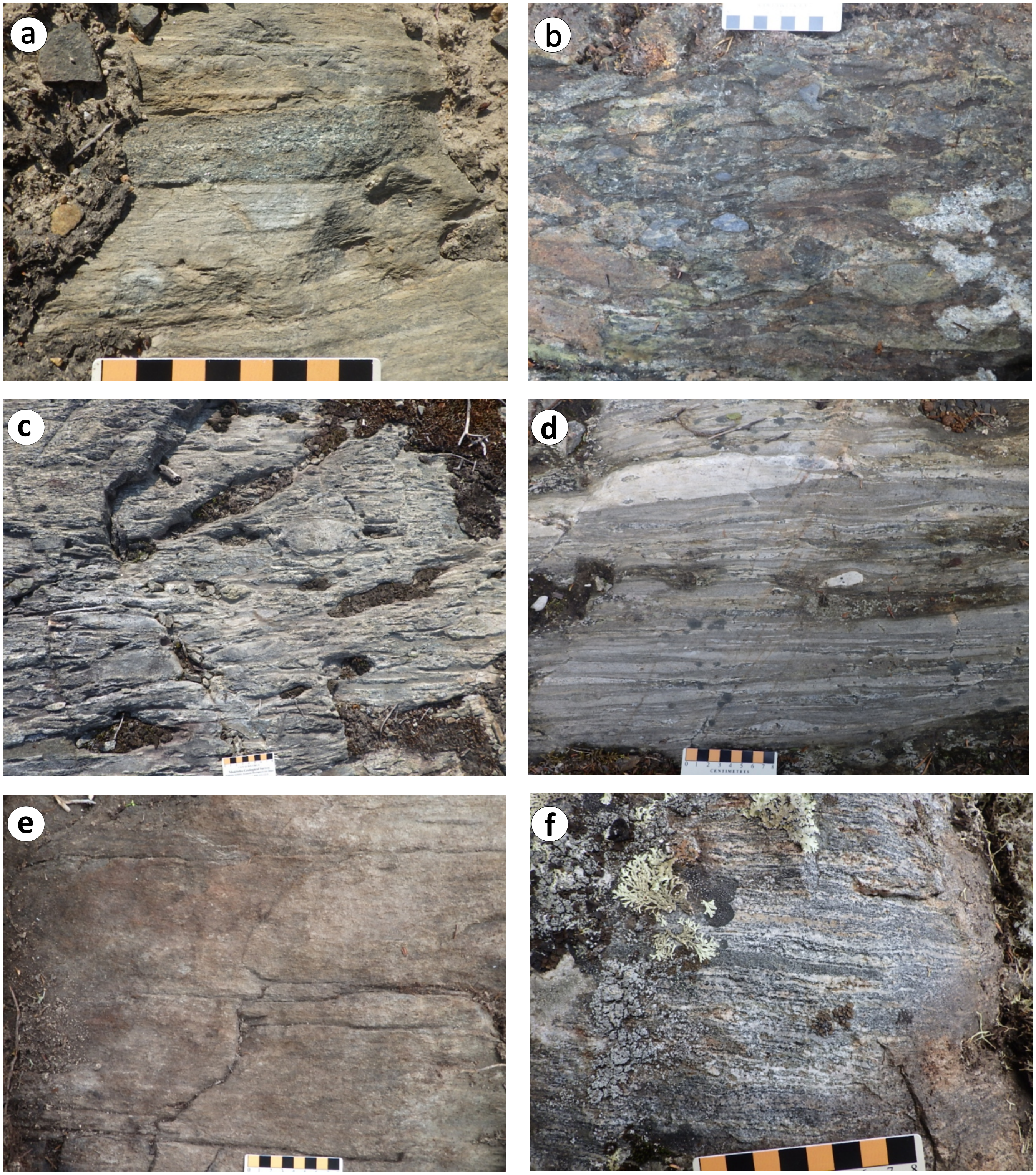

Figure GS2021-5-7: *Outcrop photographs of units 6 and 7 metasedimentary rocks in the Ralph Lake area:* ***a)*** *thin-bedded, laminated, mafic siltstone to greywacke (subunit 6a****;*** *UTM Zone 14N, 371601E, 6306735, NAD 83) with mafic wacke bands characterized by porphyroblastic hornblende crystals up to 3 mm;* ***b)*** *moderately foliated, poorly sorted, clast-supported, polymictic conglomerate with sandy matrix that was recrystallized to an assemblage of quartz, feldspar, hornblende, biotite, epidote and magnetite (subunit 6b; UTM 369994E, 6304865);* ***c)*** *strongly foliated, poorly sorted, polymictic cobble conglomerate with medium- to coarse-grained greywacke matrix (subunit 6b; UTM 364101E; 6286914N) related to the Ralph Lake shear zone (RLSZ; see Yang, 2021); the asymmetry of some deformed lithic clasts suggests a dextral sense of movement;* ***d)*** *intensively foliated to protomylonitic, poorly sorted, polymictic pebble to cobble conglomerate (subunit 6b; UTM 372417E; 6306693N); the geometry of some relict clasts reveals a dextral movement associated with the RLSZ;* ***e)*** *moderately foliated, medium-grained greywacke to siltstone containing biotite and muscovite porphyroblasts along S_2 planes that transposed original S_0 bedding (subunit 7a; UTM 3715250E; 6308525N); and* ***f)*** *medium-grained paragneiss consisting of leucosome and melanosome banding and migmatitic veins and/or veinlets containing an assemblage of quartz, plagioclase, K-feldspar, biotite, ±hornblende, ±garnet (subunit 7b; UTM 369735E; 6308374N).*

yellowish grey to grey but is light grey to grey on fresh surfaces. Texturally, the greywacke to siltstone is mostly homogeneous, consisting of quartz, feldspar, biotite flakes and finer material. Thus, it may be termed psammite (Lawley et al., 2020). Locally, coarser lithic clasts are evident in the sandy matrix; thin argillite layers up to 10 cm in thickness are present. Rocks of this subunit are moderately foliated and recrystallized, and contain biotite and muscovite porphyroblasts along S_2 planes that transposed the original S_0 bedding (Figure GS2021-5-7e).

The Zed Lake greywacke and siltstone (subunit 7a) has low MS values of 0.22×10^{-3} to 0.54×10^{-3} SI, much lower than those of the Ralph Lake greywacke (MS values >100×10^{-3} SI; see above).

Paragneiss (subunit 7b)

Subunit 7b is composed dominantly of paragneiss characterized by alternating mafic and felsic bands that show compositional layering (a few millimetres to a few centimetres in width), forming a typical gneissic texture (Figure GS2021-5-7f). Leucosome bands and/or migmatitic veinlets are common and occur along gneissosity that appears to follow the regional foliation (S_2), although late granitic pegmatite veins or veinlets crosscut the S_2 planes that are folded by F_4 folding. The paragneiss, locally varying to migmatite, is mainly medium grained and has a mineral assemblage of feldspar, quartz, biotite±hornblende±muscovite±garnet. Note that subunit 7b was mapped as conglomerate in the map area by Gilbert et al. (1980).

The subunit 7b paragneiss also has low MS values ranging from 0.317×10^{-3} to 0.378×10^{-3} SI, similar to the greywacke and siltstone of subunit 7a, and much lower than those of the Ralph Lake conglomerate (and greywacke and mafic siltstone).

Post-Sickle intrusive suite (unit 8)

Post-Sickle intrusive rocks of unit 8, represented by the Burge Lake pluton (Beaumont-Smith et al., 2006; Yang and Beaumont-Smith, 2015b), occur mainly in the east-central part of the map area (Figure GS2021-5-2). Unit 8 rocks are mainly granodiorite and granite (Table GS2021-5-1) that intruded supracrustal rocks of the Wasekwan group. Granodiorite of unit 8 is pinkish on fresh surfaces, weathers beige to tan and is medium to coarse grained, massive, moderately foliated and equigranular (Figure GS2021-5-8a) to locally porphyritic. It consists of 5–7% hornblende (partly altered to biotite), 10–15% discrete biotite flakes, 25–30% quartz, 40–50% plagioclase and 5–10% K-feldspar. Granite is minor in the Burge Lake pluton, typically containing higher K-feldspar and less plagioclase compared to the granodiorite.

Unit 8 rocks have relatively high MS values (4.79×10^{-3} to 35.7×10^{-3} SI), typical of I-type granites (Yang and Beaumont-Smith, 2015b; Yang et al., 2019) and geochemically resemble adakite-like granitoid rocks (Yang and Lawley, 2018). Interestingly, the granodiorite at the contact with the unit 1 volcaniclastic rocks (i.e., lapilli tuff to tuff) of the Wasekwan group contains disseminated pyrite, is rusty and is cut by pyrite-bearing quartz veinlets. The volcaniclastic rocks at the contact zone also display much higher MS values (up to 23.5×10^{-3} SI) than commonly seen in unit 1 rocks (<1.0×10^{-3} SI) elsewhere in the map area. Hydrothermal fluids associated with such oxidized intrusion(s) can effectively scavenge and transport Au (e.g., Boyle, 1979) and thus may have played a role in Au mineralization in the study area and the LLGB (Yang and Beaumont-Smith, 2015a; Yang and Lawley, 2018; Yang et al., 2021).

Late intrusive suite (unit 9)

Unit 9 comprises two-mica granite, quartz-feldspar porphyry and pegmatite/aplite, mainly exposed and occurring as

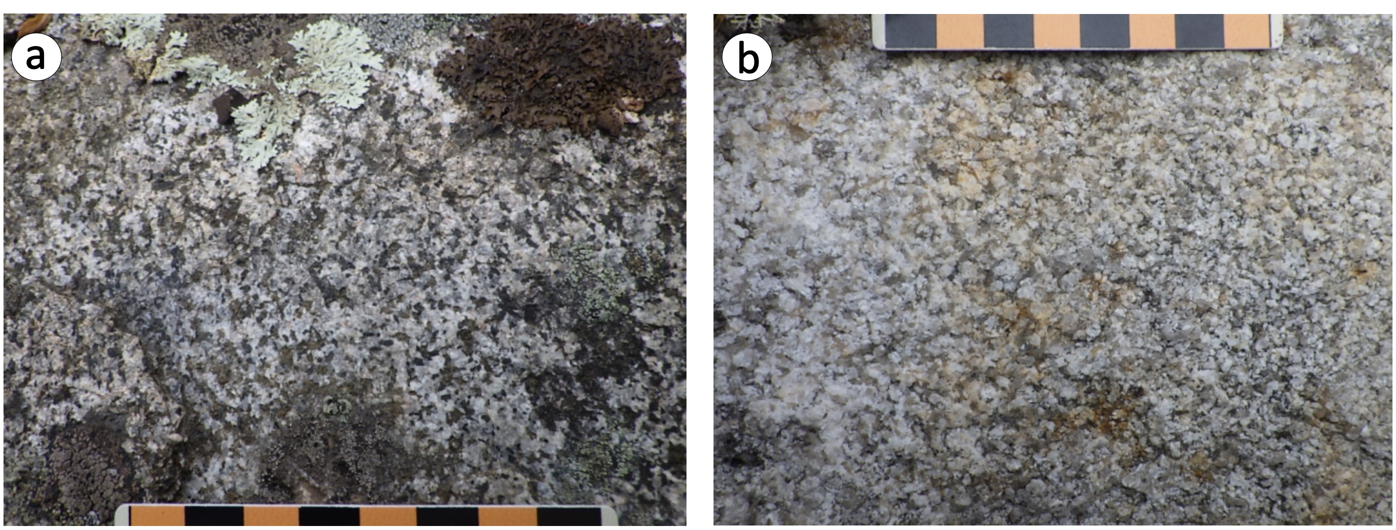

Figure GS2021-5-8: *Outcrop photographs of units 8 and 9 in the Ralph Lake area:* ***a)*** *massive, medium- to coarse-grained granodiorite with high magnetic susceptibility (MS) value of 35.7×10^{-3} SI (unit 8; UTM Zone 14N, 373715E, 6305052, NAD 83);* ***b)*** *massive, equigranular, medium- to coarse-grained two-mica granite with MS value as low as 0.054×10^{-3} SI (unit 9; UTM 369166E; 6308570N).*

small intrusions and dikes in Zed Lake greywacke (unit 7) in the northwestern corner of the map area (Figure GS2021-5-2). The two-mica granite is medium to coarse grained, undeformed, massive, equigranular and locally porphyritic, and consists of 25–35% anhedral quartz (2–4 mm), 55–60% subhedral to euhedral feldspar (2–4 mm), 4–5% biotite and about ~1% muscovite (Figure GS2021-5-8b). Thus, this two-mica granite can be termed leucogranite, and it becomes finer in grain size toward the contact with hostrocks (i.e., subunit 7a greywacke). The contact between the greywacke and two-mica granite is sharp and wavy to irregular, and concentrates biotite aggregates on the greywacke side, typical of contact metamorphism caused by the two-mica granite intrusion.

The unit 9 quartz-feldspar porphyry dikes tend to be isolated, relatively less deformed and apparently not associated with any of the larger intrusions mapped at surface. Pegmatite and aplite (unit 9) commonly have muscovite (±tourmaline) in addition to biotite, suggesting that they are not likely to be related to the pre-Sickle (subunit 5) or post-Sickle (subunit 8) intrusive suites (Yang and Beaumont-Smith, 2017).

Notably, unit 9 granitic rocks have extremely low MS values of 0.054×10^{-3} to 0.090×10^{-3} SI, consistent with typical S-type granites (Yang and Beaumont-Smith, 2015b; Yang et al., 2019).

Structural geology

The LLGB was involved in six generations of regional deformation (D_1 to D_6) according to Beaumont-Smith and Böhm (2002, 2004), although all structures formed by these events are not necessarily encountered in one area. In the Ralph Lake area, D_2 structures are dominant, are mostly penetrative and manifest as a steeply northwest-dipping S_2 foliation and tight to isoclinal folds (F_2) that have shallowly north-northeast plunging hinges and associated minor chevron folds. Foliations of this deformation (S_2) were observed in all map units except the late intrusive suite (unit 9). Typically, S_2 foliations in the Wasekwan group dip steeply to the northwest with steeply plunging mineral and stretching lineations. These L_2 lineations are well defined by a preferred orientation of minerals (e.g., amphibole, biotite, feldspar), stretched pillows and flattened pebbles and cobbles (e.g., Figure GS2021-5-7c, d).

Ductile shear zones that generally define map-unit contacts are commonly related to D_2 deformation, as the intensity of S_2 fabrics and tightness of F_2 folds increase toward contacts. The D_2 shear zones are characterized by dominantly dextral shear-sense indicators (e.g., Figure GS2021-5-7d) on horizontal surfaces and steeply plunging, generally down-dip to slightly oblique (easterly pitch) stretching lineations. The northeast-trending Ralph Lake shear zone (RLSZ) is a dextral transpressional shear zone dipping subvertically to the southeast that separates the Ralph Lake conglomerate (to the north) from the Wasekwan group (to the south; Figure GS2021-5-2); the Wasekwan rocks appear to move up along the shearing plane(s). Thus, the RLSZ is interpreted as a transpressional shear zone, separating the Wasekwan group supracrustal rocks from the Ralph Lake–Zed Lake sediments (Figure GS2021-5-2).

The regional S_2 foliation penetrating the Wasekwan volcaniclastic (unit 1), volcanic (unit 2) and volcanic-sedimentary (unit 3) rocks dips steeply to the northwest, whereas the S_2 foliation transposing the Ralph Lake–Zed Lake sediments dips to the southeast. This is interpreted to be the result of underthrusting of the Ralph–Zed lakes sedimentary package along the RLSZ beneath the Wasekwan supracrustal package. Numerous dextral shear-sense indicators (e.g., shear bands, S-C fabrics, asymmetric quartz boundins, rotated volcanic fragments) were observed on the horizontal surfaces. The development of narrow zones of shallowly plunging stretching lineations in the core of the shear zone reflects kinematics consistent with shear-zone development in response to dextral transpression. Such transpressive shear resulted in the greenstone belt appearing to 'pop-up' along the shear zone. Zircon U-Pb dating indicates that there was likely a pause between deposition of the unit 6 Ralph Lake sediments (ca. 1860 Ma; Lawley et al., 2020) and prior uplifting of volcanic rocks (ca. 1892–1870 Ma; Beaumont-Smith and Bohm, 2002, 2004; Beaumont-Smith et al., 2006; Manitoba Agriculture and Resource Development, 2021).

The D_3 deformation is represented by close to tight, S-asymmetric F_3 folds and northwest-trending, axial-planar S_3 crenulation cleavage. The Betty Lake–Margaret Lake fault strikes north-northwest and displays dextral movement, which is likely associated with D_3 deformation. F_4 folds are pervasive throughout the map area. These folds plunge steeply to the northeast and are associated with steeply dipping, northeast-striking, axial-planar S_4 cleavage (Figure GS2021-5-9a). Along the S_4 planes in folded paragneiss (subunit 7b) are muscovite-bearing pegmatitic veins/veinlets (Figure GS2021-5-9b), suggesting that this pegmatite phase is likely to be part of a late intrusive suite related to the D_4 event. A 40–45 cm wide dextral shear zone, striking 060° and dipping to the southeast at 72°, cuts foliated medium-grained gabbro (subunit 2a) and is likely the result of D_4 deformation. This shear zone consists of 30–35% dark reddish euhedral garnet crystals, together with amphibole, epidote and chlorite (Figure GS2021-5-9c, d), and quartz veins. Interestingly, the garnet grains are present in the hangingwall gabbro but are virtually absent in the footwall gabbro, suggesting that the garnet could have been formed by fluid associated with the D_4 shearing. The northeast-trending Ralph Lake fault zone (Figure GS2021-5-2) is thought to be related to the D_4 event that resulted in the structures having such orientations (Beaumont-Smith and Böhm (2002, 2004).

Economic considerations

The dominance in the Ralph Lake area of volcaniclastic rocks rich in plagioclase fragments, together with synvol-

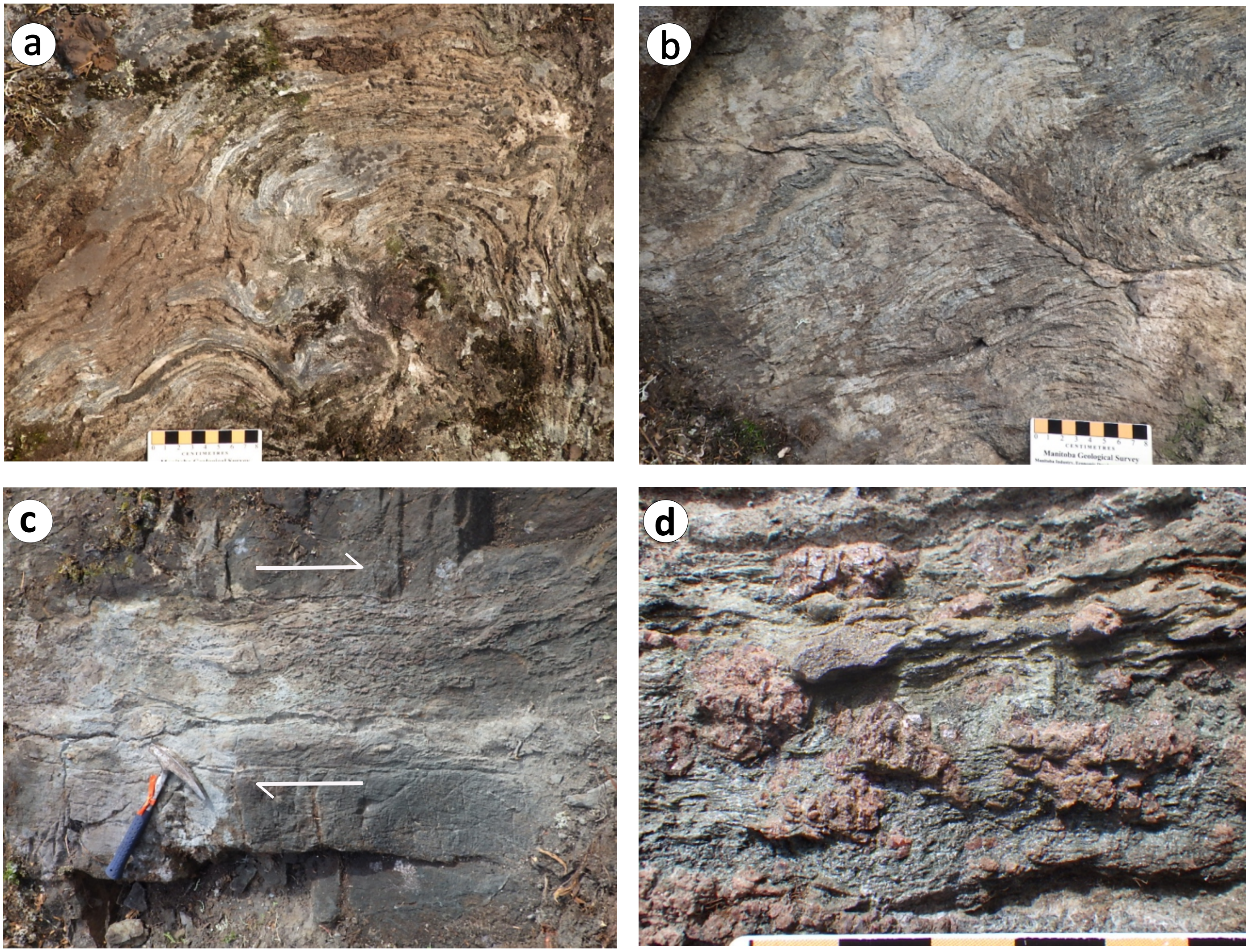

***Figure GS2021-5-9:** Outcrop photographs of some mesoscopic structures and structure-related rocks evident in the Ralph Lake area: **a)** complex folding in unit 7b paragneiss (subunit 7b; UTM Zone 14N, 369735E, 6308374N, NAD 83), which is likely attributed to an F_4 fold; **b)** folded paragneiss cut by quartz-feldspar±muscovite pegmatitic veins and veinlets (unit 9; UTM 369835E; 6308478N); **c)** a 40–50 cm wide high-strain hydrothermal-alteration zone with dextral movement, striking 060° and consisting of 30–45% dark-reddish euhedral garnet porphyroblasts associated with amphibole, chlorite and quartz (UTM 363619E; 6283902N), cuts medium-grained gabbroic rock (unit 2a); hammer handle points north; **d)** closeup of part of this zone, showing the megacrystic garnets (same location as photo c).*

canic gabbroic intrusions, suggest that the Wasekwan group (units 1–3) may have been derived from hydrous, high-Al andesitic to tholeiitic magmas in a volcanic-arc to back-arc setting (e.g., Sotiriou et al., 2020). This volcanic package is intruded by the pre-Sickle intrusive suite (units 4 and 5), post-Sickle granitoid (unit 8) and, subsequently, late intrusive suite (unit 9) rocks. Unit 4 gabbroic intrusions contain disseminated pyrrhotite and locally chalcopyrite, and thus need to be further evaluated for magmatic Ni-Cu-PGE minerals. Unit 8 granitoid rocks display adakite-like signatures and may have played a role in Au mineralization (Yang and Lawley, 2018; Yang, 2019). The occurrences of I-type adakite-like to S-type granitoids in the Ralph Lake area suggest that tectonic settings may have evolved from volcanic-arc extension induced by slab roll-back to terminal collision. This interpretation, combined with the association of the supracrustal rocks in the Paleoproterozoic LLGB and much older (Mesoarchean) greenstone belts elsewhere, is a key to address the fundamental question of ‘when did plate tectonics begin?’ (e.g., Windley et al., 2021).

The occurrences of subunit 7b paragneiss, characterized by the assemblage quartzofeldspathic minerals, biotite±hornblende±muscovite±garnet, and unit 6 polymictic conglomerate (and mafic siltstone) with wacke matrix containing recrystallized hornblende suggest that the Zed Lake and Ralph Lake sedimentary rocks are likely part of the Southern Indian domain in terms of their similar rock associations. These sedimentary rocks are separated by the RLSZ from the volcaniclastic to volcanic rocks of the Wasekwan group of the LLGB (Figure GS2021-5-2) to the southeast, suggesting that the contact is likely a structural one or an unconformity reactivated by the RLSZ. The S-type granite (unit 9) occurs near the boundary zone, suggesting its emplacement in a collisional setting and the resulting potential for rare metal (Li, Cs, Ta) mineralization (e.g., Yang et al., 2019).

There are six mineral occurrences within the map area (Baldwin, 1989), based on the Manitoba Mineral Inventory Cards (https://mrsearch.gov.mb.ca/ltm-cat/web/minsearch.html), indicating diverse styles of mineralization (Ferreira and Baldwin, 1984). These are labeled A to F on Figure GS2021-5-2 (Yang, 2021). At location A, for example, disseminated layers and/or stringers of sulphide (pyrrhotite, pyrite) mineralization occur in quartz-biotite schist (subunit 7a). Location B contains disseminated pyrite in a 1 m thick zone of graphitic greywacke and argillite (subunit 7a). A mineralized felsic tuff (subunit 1a) at location C contains disseminated sulphide (pyrrhotite, sphalerite, chalcopyrite and pyrite) over a width of ~12 m and along a strike length of ~250 m. Amphibolite-hosted (subunit 1c mafic volcaniclastics) mineralization at location D has up to 7.8 m of disseminated to thin stringer sulphides (pyrrhotite, pyrite and minor chalcopyrite), with a 40 cm drillhole intercept containing 0.37% Cu, 2 g/t Au and 8.5 g/t Ag (Assessment File 9949, Manitoba Agriculture and Resource Development, Winnipeg). Volcaniclastic rocks (subunit 1b) at location E are host to massive-sulphide mineralization consisting of a 0.5–1 m thick zone of sulphide layers comprising mostly of pyrrhotite, lesser pyrite and minor chalcopyrite. At location F, a 40 m thick, siliceous, felsic pyritic volcanic sandstone and siltstone (subunits 1a and b) contains 2–5% disseminated pyrite and/or arsenopyrite stringers.

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