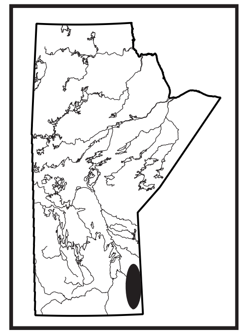
GS-4 Granitoid rocks in southeastern Manitoba: preliminary results of reconnaissance mapping and sampling

by X.M. Yang



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Summary

In 2014, the Manitoba Geological Survey (MGS) initiated a project to investigate the petrogenesis and metallogeny of granitoid rocks in Manitoba. The objectives of this project are to identify the various petrogenetic types of granitoid rocks and to investigate their geodynamic settings and mineralization potential. This project will result in a GIS-based database to capture the field relationships, petrography, lithogeochemistry and geochronology of granitoid rocks in Manitoba, and their relationships to Cu-Au-Mo, Sn-W and rare-metals mineralization.

This report presents the preliminary results of reconnaissance mapping and sampling of granitoid rocks conducted during the 2014 field season in the western Superior province of southeastern Manitoba. Granitoid rocks were examined and sampled in the field to document field relationships, textures (fabrics), mineral assemblages, magnetic susceptibilities (MS) and presence of mineralization and/or alteration. The major findings of this preliminary work are that muscovite- and/or garnet-bearing granitic rocks (i.e., strongly peraluminous or S-type), commonly characterized by low MS values ($<0.1 \times 10^3$ SI units) are intruded mainly into terrane boundaries, although they are also evidently present within metasediment-dominant areas, all of which are macro-recognizable geological criteria for subdividing tectonic units. These peraluminous granitoid rocks likely formed in thickened crustal setting(s) due to continental collision and are associated with rare-metal–enriched intrusions, or may have potential to host to Sn-W mineralization. In contrast, granitoid plutons, consisting dominantly of tonalite, trondhjemite and granodiorite (i.e., TTG suite) and characterized by higher MS values ($>0.1 \times 10^3$ SI units) and mineral assemblages typical of I-type (e.g., amphibole±biotite or biotite±amphibole), are abundant across the region, suggesting that extensive granitoid magmatism greatly contributed to the continental crustal growth and expansion in the Archean, and may have been related to plate subduction. Some of the phases in the TTG suites contain porphyry Cu-Au (e.g., Cat Lake–Euclid Lake), shear-hosted Au (e.g., Little Bear Lake) and skarn Au-Ag mineralization (e.g., Cat Lake).

Introduction

Granitoid rocks are the most abundant type exposed in the Precambrian shield and record important geological information that can be used to infer petrogenesis and sources and tectonic settings of magmas, and can help shed light on the tectonic evolution and mineral potential on regional and local scales. For example, I-type granites originated from igneous sources (Chappell and White, 1974, 1992, 2001) and usually display oxidized features with high values of magnetic susceptibility (MS), consistent with the magnetite-series granites of Ishihara (1977, 1981, 2004), and have potential for Cu-Mo (Au) mineralization (Blevin and Chappell, 1995; Blevin, 2004). In contrast, S-type granites are sourced from sedimentary rocks (Chappell and White, 1974, 1992, 2001) and commonly exhibit reduced features with low MS values, consistent with the ilmenite-series granites of Ishihara (1977, 1981, 2004), and are commonly related to Sn-W and rare-metal mineralization (Blevin, 2004). Such generalizations of granitoid types are useful in mineral exploration, despite some exceptions (e.g., reduced I-type ilmenite-series granites are potentially related to intrusion-related Au mineralization; Lang and Baker, 2001; Blevin, 2004; Yang et al., 2008).

Table GS-4-1 summarizes some of the key field and petrographic characteristics of I- versus S-type granites, and magnetite- versus ilmenite-series granites, which can be used for identification of granite petrogenetic types and to help assess exploration potential. Porphyry Cu mineralization, for example, needs Cu built up in oxidized (i.e., high fO_2) magmas that commonly result in oxidized magnetite-series and I-type granites, whereas Sn mineralization is related to relatively reduced ilmenite-series and S-type granites because Sn enrichment in magmas requires a reduced condition (i.e., low fO_2; Blevin and Chappell, 1995; Blevin, 2004). Granitoid rocks in large areas of the Precambrian shield in Manitoba have generally not been adequately characterized in this manner.

In 2014, the Manitoba Geological Survey (MGS) initiated a project to investigate petrogenesis and metallogeny of granitoid rocks in Manitoba. This project is designed as a long-term collaborative effort employing a multidisciplinary approach that includes bedrock mapping, petrography, U-Pb geochronology, Nd-isotope analysis and lithogeochemistry. All of the above techniques, together with GIS data compilation and analysis, will be used to improve understanding of granitoid petrogenesis and metallogeny, as well as the relationships to crustal growth and geodynamic setting over time. In the 2014 field season, the MGS began carrying out reconnaissance mapping and sampling of granitoid rocks in southeastern

Table GS-4-1: Field and petrographic criteria and evidence for oxidized (magnetite-series, I-type) and reduced (ilmenite-series, S-type) granitoid rocks (compiled from this study; Chappell and White, 1974, 1992, 2001; Ishihara, 1977, 1981, 2004).

Criterion	Oxidized	Reduced
K-feldspar	Pink, salmon red	Pale grey, white; rarely pinkish
Plagioclase	Commonly pale grey	Grey, white
Quartz	Pale white	Dark brown, pale white
Hornblende/amphibole	Common	Rare
Biotite	Brownish, dark brown, greenish	Fox red, brownish-red
Muscovite	Absent or rare	Common
Garnet	Absent or rare	Present
Cordierite, tourmaline, aluminosilicate	Absent	Rare to common
Magnetite	Common	Rare to absent
Ilmenite	Present	Common
Sphene (titanite)	Common	Rare
Zircon	Present	Present
Apatite	Commonly as inclusions in biotite and amphibole	Commonly as independent (discrete) crystals
Monazite	rare	Common
Magnetitic susceptibility (MS)	$>0.1\times10^{-3}$ SI	$<0.1\times10^{-3}$ SI
Inclusions	Mafic	Restite (commonly granulite)
Fabrics	Equigranular, seriate, porphyritic	Equigranular, heterogeneous
Pluton size	Stock, dike, batholith	Stock, batholith
Granite type or series (Chappell and White, 1974, 1992; Ishihara, 1977, 1981, 2004) and associated mineralization	I-type, magnetite-series; Cu, Au, Ag, Mo, Pb, Zn, ±W	S-type, ilmenite-series and reduced I-type granites (ilmenite-series) have been derived from an igneous source region, and are emplaced into a reduced setting (e.g., sedimentary rocks containing graphite or reduced carbon from organic materials) that resulted in the original oxidized magma being transformed to reduced magma/rock through a process of reduction reaction); Sn, W, Au, rare metals
Influence of wallrocks	Significant	Pronounced
Precursor (protolith)	Igneous rocks that had not undergone any sedimentary cycle and may have ultimately been derived from the mantle	Sedimentary rocks, and supracrustal rocks that had experienced the sedimentary cycle

Manitoba. This report presents the preliminary results of this work. Petrographic examinations (49) and geochemical analyses (120) of samples collected in 2014 are ongoing and will be reported in future publications.

Methods

Granitoid rocks were examined and sampled in the field to document the field relationships, textures (fabrics), mineral assemblages, magnetic susceptibility (MS) and presence of mineralization and/or alteration. A Terraplus KT-10 MS meter (maximum sensitivity 0.001×10^3 SI units) was used with a pin to measure MS values of natural outcrops or exposures in road cuts; each outcrop was measured at least 5 times and the average of the measurements was recorded to represent the MS value of the outcrop. Outcrops were sampled using a rock saw or sledgehammer for further study (e.g., petrography, lithogeochemistry). The MS values were used to assess relatively oxidized and reduced features of granitoid rocks and, together with their mineral assemblages, to classify the granite petrogenetic types (Table GS-4-1).

Field descriptions of granitoid rocks

The western Superior province in southeastern Manitoba is well known for its endowment of important deposits of Au, rare metals, Ni, Cu, platinum-group elements (PGE) and Cr. This part of the western Superior province is subdivided, from north to south, into the Uchi domain, English River basin, Bird River greenstone belt (BRGB) and Winnipeg River and Western Wabigoon terranes (cf.

Card and Ciesielski, 1986; Beakhouse, 1991; Blackburn et al., 1991; Stott and Corfu, 1991; Bailes et al., 2003; Lemkow et al., 2006; Percival et al., 2006; Anderson, 2008, 2013; Gilbert et al., 2008; Duguet et al., 2009; Stott et al., 2010). Specific granitoid plutons examined in southeastern Manitoba and referred to in the text are numbered in Figure GS-4-1. The main features of these granitoid plutons are summarized in Table GS-4-2. The following sections present brief descriptions of granitoid rocks, from north to south, starting at the Uchi domain and ending at the Western Wabigoon terrane.

Granitoid rocks in the Uchi domain

Granitoid rocks examined and sampled in the Uchi domain, which intruded into and/or are in tectonic contact with the Rice Lake greenstone belt (RLGB) of the Uchi domain, are the tonalite and granodiorite plutons of the Ross River plutonic suite and Wallace Lake pluton (labelled '1' and '2', respectively, in Figure GS-4-1 and Table GS-4-2). The Ross River plutonic suite includes two major plutons: the western pluton is a homogeneous, possibly sheet-like intrusion of ca. 2.72 Ga tonalite to granodiorite intruding metavolcanic to metavolcaniclastic rocks of the Bidou assemblage and unconformably overlain to the north by the San Antonio assemblage metasedimentary rocks; and the eastern pluton, known as the Ross River pluton, intruded volcanic and volcaniclastic rocks of the Bidou and Gem assemblages and is a roughly elliptical body that dominates the central portion of the RLGB (Anderson, 2011). Anderson (2008) reported a U-Pb zircon age of ca. 2724 Ma from granodiorite in the core of the Ross River pluton, which is interpreted to represent its crystallization age.

The southeastern portion of the Ross River pluton is composed dominantly of granodiorite to tonalite with minor quartz diorite and granite, cut by late quartz-feldspar porphyry and aplite dikes. At the past-producing Ogama-Rockland gold mine near Long Lake, granodiorite is weakly foliated, medium grained and equigranular to locally porphyritic, and consists of 30–35% quartz, ~30% plagioclase, up to 10% Kfeldspar, and 10–20% amphibole and biotite that are strongly altered to chlorite. Sericitic alteration of feldspars is common. In places, granodiorite is gradational to tonalite and contains inclusions of quartz diorite. Interestingly, quartz diorite displays higher MS values (0.829–0.930 × 10^3 SI) than granodiorite (0.1130 × 10^3 SI), which is consistent with the former being older than the latter and the MS values decreasing with differentiation. However, granodiorite with porphyritic texture (Figure GS-4-2a) has very high MS values of up to 24.8 ×10^3 SI (Table GS-4-2) where it intrudes gabbro at the northwestern margin of the pluton and includes abundant gabbroic xenoliths, suggesting the wallrocks may have influenced the magnetite content of the granodiorite. It is noted that the Ross River pluton contains shear-hosted Au deposits (e.g., Ogama-Rockland; see Zhou et al., 2012). This suggests a plausible linkage of Au mineralization to the Ross River pluton. Elsewhere, Au-bearing quartz veins in shear zones can be traced back through pegmatite-aplite dikes to the granodiorite, suggesting that they are intrusion-related Au systems (e.g., Thorne et al., 2002; Yang and Lentz, 2010; Vaughn and Ridley, 2014).

The western pluton of the Ross River plutonic suite consists of medium-grained, equigranular, weakly deformed tonalite to granodiorite. Locally, however, the granitoid rocks are porphyritic and strongly deformed and sheared. In places, numerous quartz veins cut the pluton. These granitoid rocks generally exhibit consistent MS values of 0.152–0.153 ×10^3 SI, similar to granodiorite of the Ross River pluton to the east. Collectively, the granitoid rocks of the Neoarchean Ross River plutonic suite are comparable to the magnetite-series granites of Ishihara (1977, 1981, 2004) in term of the MS values, and to the I-type granitoid rocks of Chappell and White (1974, 1992) on the basis of their mineral assemblages (e.g., amphibole±biotite). These field observations are consistent with the lithogeochemical characteristics of the granitoid rocks reported in Anderson (2008), indicating that they are mainly calcalkaline and metaluminous to moderately peraluminous.

The Wallace Lake pluton is relatively more evolved in terms of mineral assemblage (e.g., the absence of amphibole) than the Ross River plutonic suite and comprises dominantly biotite granite (Figure GS-4-2b) that is salmon red on the outcrops, medium to coarse grained, weakly to strongly deformed, and cut by dark quartz veins in places. It is structurally juxtaposed with the RLGB and has not been dated. The granite has low MS values of 0.088–0.201 × 10^3 SI (Table GS-4-2). Such low MS may reflect the fact that part of the pluton displays a relatively reduced condition, belonging to either S-type or evolved and reduced I-type. Lithogeochemical and isotopic data will assist in the resolution of this problem.

Granitoid rocks in the English River basin

Although the English River basin is underlain predominantly by Neoarchean high-grade metasedimentary rocks (Breaks, 1991), various granitoid suites are intruded into this basin, including the Tooth-Turtle intrusive suite, Black River plutonic suite, Inconnu pluton and Great Falls pluton (labelled '3', '4', '5' and '6', respectively, in Figure GS-4-1 and Table GS-4-2).

Tooth-Turtle intrusive suite

The Tooth-Turtle intrusive suite, defined by Bailes et al. (2003), is composed dominantly of biotite granite at Tooth Lake, where the granite is pale grey to whitish, fine to medium grained, equigranular and weakly foliated (Figure GS-4-3a), and consists of 5–10% biotite, 30–35% quartz and 55–60% feldspar (dominated by Kfeldspar, although it is hard to discern it from plagioclase on outcrops). In some

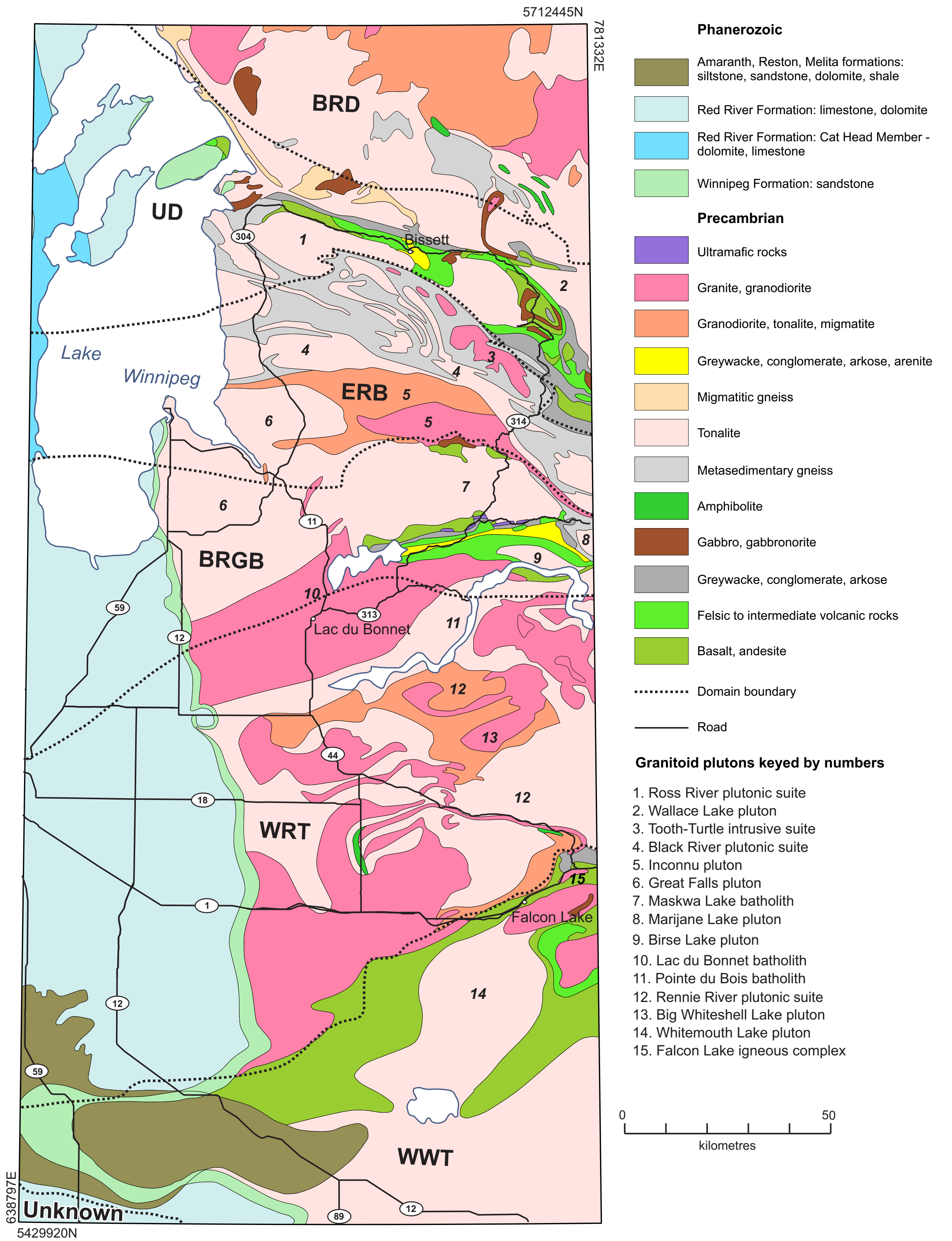

Figure GS-4-1: *Simplified geology of southeastern Manitoba, showing the dominance of granitoid rocks in the region. Abbreviations: BRD, Berens River domain; BRGB, Bird River greenstone belt; ERB, English River basin; UD, Uchi domain; WRT, Winnipeg River terrane; WWT, Western Wabigoon terrane. Numbered granitoid plutons or batholiths are referred to in the text. Nomenclature of tectonic entities or units modified from Percival et al. (2006), Gilbert et al. (2008) and Stott et al. (2010).*

Table GS-4-2: Main features of granitoid rocks in the various tectonic units of southeastern Manitoba. Abbreviation: MS, magnetic susceptibility.

Tectonic unit	Pluton	Index	MS (x 10^{-3} SI)	Index minerals	Petrogenetic types
Uchi domain	Ross River plutonic suite	1	0.113–24.8	Amphibole, biotite	Magnetite-series, I-type
	Wallace Lake pluton	2	0.088–0.201	Biotite	magnetite-series, I-type; part may be ilmenite-series, S-type
English River basin	Tooth-Turtle intrusive suite	3	1.240–2.660	Biotite	Magnetite-series, I-type
	Black River plutonic suite	4	0.050–9.85	Biotite, amphibole	Magnetite-series, I-type; part may be ilmenite-series, I-type
	Inconnu pluton	5	0.168–10.00	Amphibole, biotite	Magnetite-series, I-type
		5	0.048	Muscovite, garnet	Ilmenite-series, S-type
	Great Falls pluton	6	0.533–24.8	Amphibole, biotite	Magnetite-series, I-type
Bird River greenstone belt	Maskwa Lake batholith	7	0.044–11.70	Amphibole, biotite Biotite	Magnetite-series, I-type; part may be ilmenite-series, evolved I-type
	Marijane Lake pluton	8	0.251–1.90	Biotite	Magnetite-series, I-type
		8	0.035–0.88	Biotite, muscovite	Ilmenite-series, S-type
	Birse Lake pluton	9	0.155–1.51	Amphibole, biotite	Magnetite-series, I-type
		9	0.036–0.085	Biotite, muscovite, garnet	Ilmenite-series, S-type
Winnipeg River terrane	Lac du Bonnet batholith	10	0.089–19.4	Biotite, amphibole	Magnetite-series, I-type; part may be ilmenite-series, evolved I-type
	Pointe du Bois batholith	11	1.49–45.7	Amphibole, biotite	Magnetite-series, I-type
	Rennie River plutonic suite	12	1.13–34.5	Amphibole, biotite	Magnetite-series, I-type
		12	0.045	Garnet, muscovite	Ilmenite-series, S-type
	Big Whiteshell Lake pluton	13	31.1–62.4	Amphibole, biotite	Magnetite-series, I-type
Western Wabigoon terrane	Whitemouth Lake pluton	14	3.28–13.5 3.28	Biotite Garnet, muscovite	Magnetite-series, I-type; Magnetite-series, S-type
	Falcon Lake igneous complex	15	11.7	Amphibole, biotite	Magnetite-series, I-type

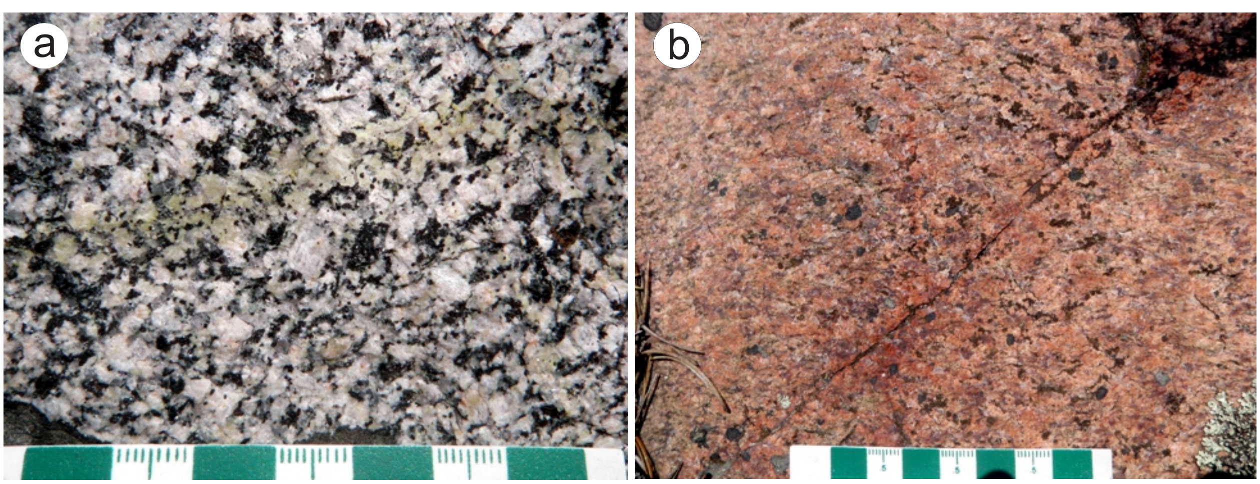

***Figure GS-4-2**: Field photographs of granitoid rocks from the Rice Lake greenstone belt, Uchi domain, southeastern Manitoba: **a)** granodiorite with euhedral feldspar phenocrysts, Ross River pluton (UTM Zone 15, 319674E, 5654294N, NAD83); **b)** salmon-red, medium- to coarse-grained biotite granite, Wallace Lake pluton (UTM 332692E, 5652521N).*

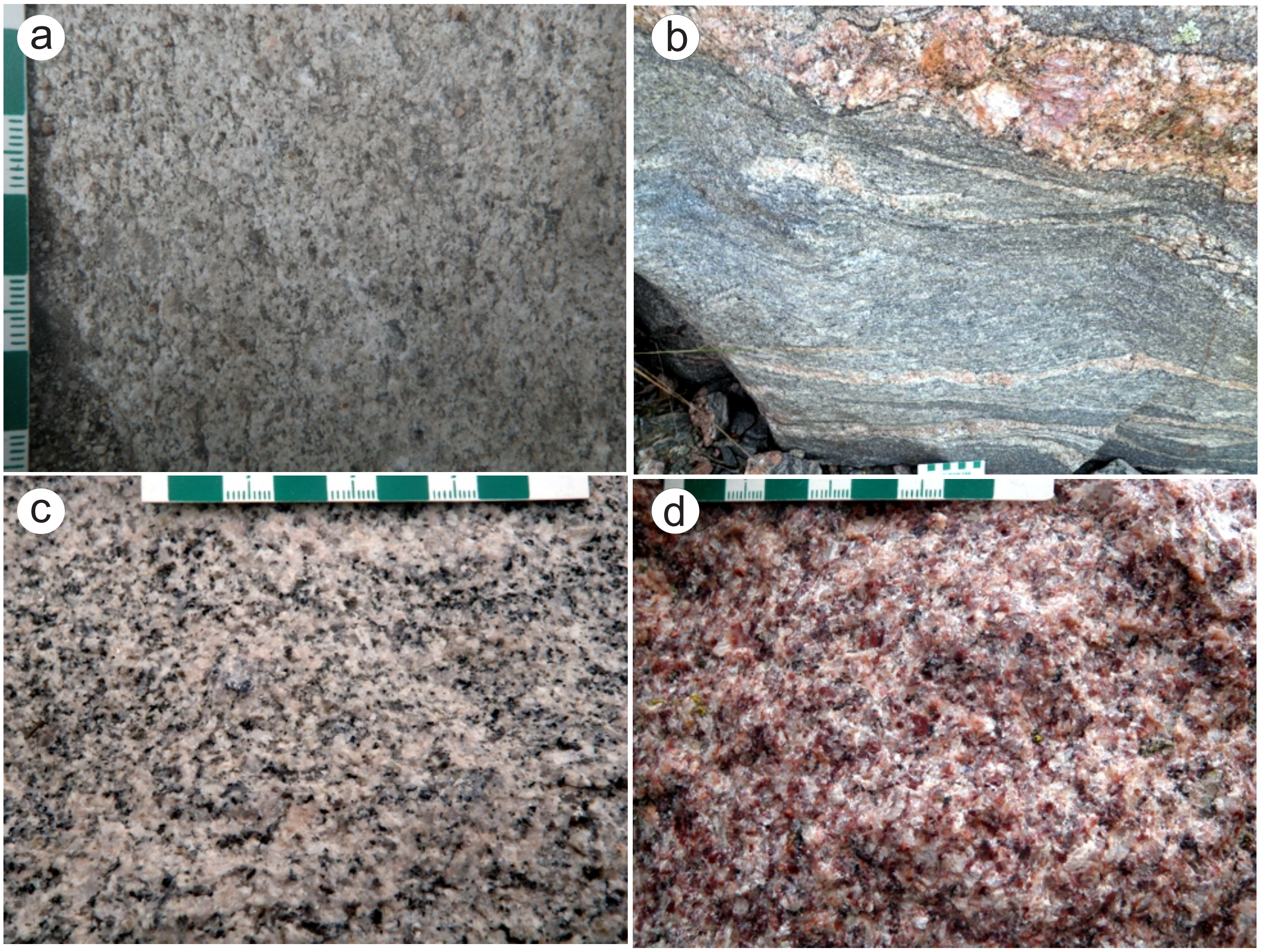

Figure GS-4-3*: Field photographs of granitoid rocks from the English River basin, southeastern Manitoba:* ***a)*** *fine- to medium–grained, weakly foliated biotite granite, Tooth-Turtle intrusive suite (UTM Zone 15N, 337889E, 5623805N, NAD83);* ***b)*** *pinkish-grey, medium- to coarse-grained gneissic granodiorite cut by pegmatite dike, Black River plutonic suite (UTM 699681E, 5627307N);* ***c)*** *weakly deformed, medium-grained muscovite-biotite granodiorite (UTM 313105E, 5613708N), Inconnu pluton II;* ***d)*** *pink to red, coarse-grained leucogranite (UTM 704262E, 5613042N), Great Falls pluton.*

places, the granite displays compositional banding, comprising alternating biotite-rich and felsic-rich layers ranging from a few to tens of centimetres in width. Chloritic and sericitic alteration is common. Notably, gossanous patches may be ascribed to weathering of sulphide minerals (e.g., pyrite) and/or iron-bearing minerals (e.g., biotite). The granite shows relatively high MS values of 1.24–2.66 × 10^3 SI, consistent with the magnetite-series granites of Ishihara (1977, 1981, 2004). Such oxidized features are commonly seen in I-type granites, but they still require further investigation. Pegmatite dikes or ponds, comprising feldspar, quartz and, in places, muscovite and tourmaline, are ubiquitous.

Black River plutonic suite

Granitoid rocks in the Black River plutonic suite vary from diorite, quartz diorite, tonalite and granodiorite to granite, and from massive to foliated or gneissic, suggesting a complex history of tectonomagmatic evolution. At outcrop scale, gneissic granodiorite to tonalite is cut by grey quartz diorite, which is, in turn, cut by pinkish to pinkish-grey, equigranular granodiorite to leucogranite (but, in most cases, only by pinkish granodiorite). Pinkish gneissic granodiorite is medium to coarse grained and consists of 25–30% quartz, 30–35% Kfeldspar, 10–15% plagioclase, 20–25% amphibole and 5–10% biotite (Figure GS-4-3b). However, ferromagnesian silicate content varies, with some outcrops containing more abundant biotite (up to 20%) than amphibole. This gneissic granodiorite normally shows very high MS values of up to 9.85 × 10^3 SI, suggesting a strongly oxidized magnetite-series granite that is comparable to I-type in terms of mineral assemblage. Some granite with a biotite and amphibole assemblage displays a very low MS value of 0.050 × 10^3 SI (Table GS-4-2), consistent with ilmenite-series I-type granites that require a relatively reduced condition (cf. Yang et al., 2008).

Grey, massive, equigranular, fine- to medium-grained tonalite is also present in the Black River plutonic suite and comprises 20–25% quartz, 45–50% plagioclase, 15–20% amphibole, 10–20% biotite and minor Kfeldspar. On many outcrops, massive tonalite is cut by pinkish, massive, equigranular, medium- to coarse-grained granite. Both tonalite and granite exhibit high MS values of 6.973–7.140 ×10^3 SI, typical of magnetite-series or I-type granites.

Inconnu pluton

The Inconnu pluton, defined by Černý et al. (1981), was partly mapped in the Cat Creek and Cat Lake–Euclid Lake areas by the MGS (Yang et al., 2012, 2013; Yang, 2014). The pluton can be subdivided into two portions: Inconnu pluton I, consisting of TTG; and Inconnu pluton II, comprising gneissic granite and muscovite±garnet granite. The Inconnu pluton I occurs in the area directly north of Inconnu pluton II, as well as in the area north of the north-northwest-trending Cat Lake–Euclid Lake fault zone. It consists mainly of coarse-grained, locally porphyritic, pinkish-grey granodiorite, granite and minor monzogranite. Some of these granitoid rocks show heterogeneous texture: very coarse grained to pegmatitic granite with heterogeneous texture that is locally transitional to homogeneous, massive or porphyritic varieties. The massive to weakly foliated granitoid rocks are characterized by a mineral assemblage of quartz-feldspar(s)-amphibole-biotite±muscovite. Late (quartz-feldspar±muscovite) pegmatite dikes are common within these granitoid rocks.

The Inconnu pluton II is confined to a narrow zone that extends from the area north of Euclid Lake northwestward to the area north of the Trans License road, and northwest of Cat Creek (Yang, 2014). Granitoid rocks are gneissic, light grey to grey and medium grained; the mineral assemblage includes dark brown (Fe-rich) biotite±greenish amphibole±muscovite±garnet. Dark brown biotite stringers (1–3 mm wide) parallel to the foliation locally wrap around feldspar porphyroclasts. Massive to weakly foliated, medium-grained, muscovite-biotite granodiorite (Figure GS-4-3c) with a very low MS value of 0.048 × 10^3 SI (Table GS-4-2) is typical of the ilmenite-series granites of Ishihara (1981, 2004) or the S-type granites of Chappell and White (1974, 1992). Some outcrops of garnet-bearing granite with MS values of up to 0.15 × 10^3 SI that intrude magnetite-bearing gabbroic rocks reflect the influence of oxidized wallrock on the MS of the granites.

Great Falls pluton

The Great Falls pluton, described by Bailes et al. (2003) and well exposed along Provincial Highway 304 (Figure GS-4-1), includes the Inconnu pluton of Černý et al. (1981), as described above. This pluton is composed dominantly of gneissic tonalite to granodiorite to granite, cut by granodiorite to leucogranite and younger phases of pegmatite and/or aplite dikes. Medium-grained gneissic tonalite normally contains 20–25% quartz (1–3 mm; locally 5–10 mm), 40–50% plagioclase, 30–35% amphibole and up to 5% biotite (Figure GS-4-3d). Massive, equigranular, medium- to coarse-grained, locally porphyritic granodiorite consists of 25–30% quartz, 30–35% plagioclase, 10–15% Kfeldspar, 20 –25% amphibole and up to 5% biotite. Leucogranite is coarse grained and pink; it consists of 30–35% quartz, 60–65% Kfeldspar, minor plagioclase (<5%) and 2–5% biotite (Figure GS-4-3d). The tonalite displays high MS values of 8.86–24.8 × 10^3 SI, whereas leucogranite has a lower MS value of 0.533 × 10^3 SI (Table GS-4-2). The MS values suggest that the Great Falls pluton is largely magnetite-series and I-type granite.

Granitoid rocks in the Bird River greenstone belt

Granitoid rocks in the BRGB that have been partly mapped and described by the MGS (Gilbert et al., 2008; Yang et al., 2012, 2013; Yang, 2014) include the Maskwa Lake batholith (Bailes et al., 2003), Marijane Lake pluton, Birse Lake pluton and part of the Lac du Bonnet batholith (labelled '7', '8', '9' and '10', respectively, in Figure GS-4-1 and Table GS-4-2). These granitoid rocks are part of the tonalite-trondhjemite-granodiorite (TTG) suite and represent either the basement of the Neoarchean BRGB (i.e., Maskwa Lake batholith I) or younger plutons (i.e., Maskwa Lake batholith II, Marijane Lake pluton, Birse Lake pluton, Lac du Bonnet batholith) that have intruded and disrupted the supracrustal rocks of the belt, which consist of mafic volcanic and synvolcanic intrusive rocks, epiclastic and minor volcaniclastic rocks, and mafic–ultramafic intrusions. The Mesoarchean granitoid basement represented by the Maskwa Lake batholith I consists mainly of coarse-grained, equigranular, locally gneissic granodiorite, which was intruded, fragmented and brecciated by mid-ocean–ridge (MORB)–type basalt at the contact zone south of the Cat Creak area (Figure GS-4-4a).[1] These rocks display moderate to high MS values of 0.585–2.580 × 10^3 SI and differentiated REE patterns, with very small negative (or no) Eu anomalies, small negative Ti anomalies and pronounced negative Nb anomalies in spider diagrams (Yang and Gilbert, 2014).

The Maskwa Lake batholith I (2782 ±11 Ma to 2844 ±12 Ma [Wang, 1993]; 2852.8 ±1.1 Ma [Gilbert et al., 2008]) is a granodioritic basement intrusion that is geochemically indistinguishable from a younger TTG phase (Maskwa Lake batholith II; 2725 ±6 Ma [Wang, 1993]) cutting the older granodiorite. The younger phase, which

[1] Note that Gilbert et al. (2008) defined MORB-type basalts in the BRGB based on the distribution patterns of trace elements and rare-earth elements (REE) similar to those of MORB. In fact, the MORB-type basalts are tholeiitic to calcalkaline and are interpreted to have formed in a back-arc environment by Yang et al. (2011).

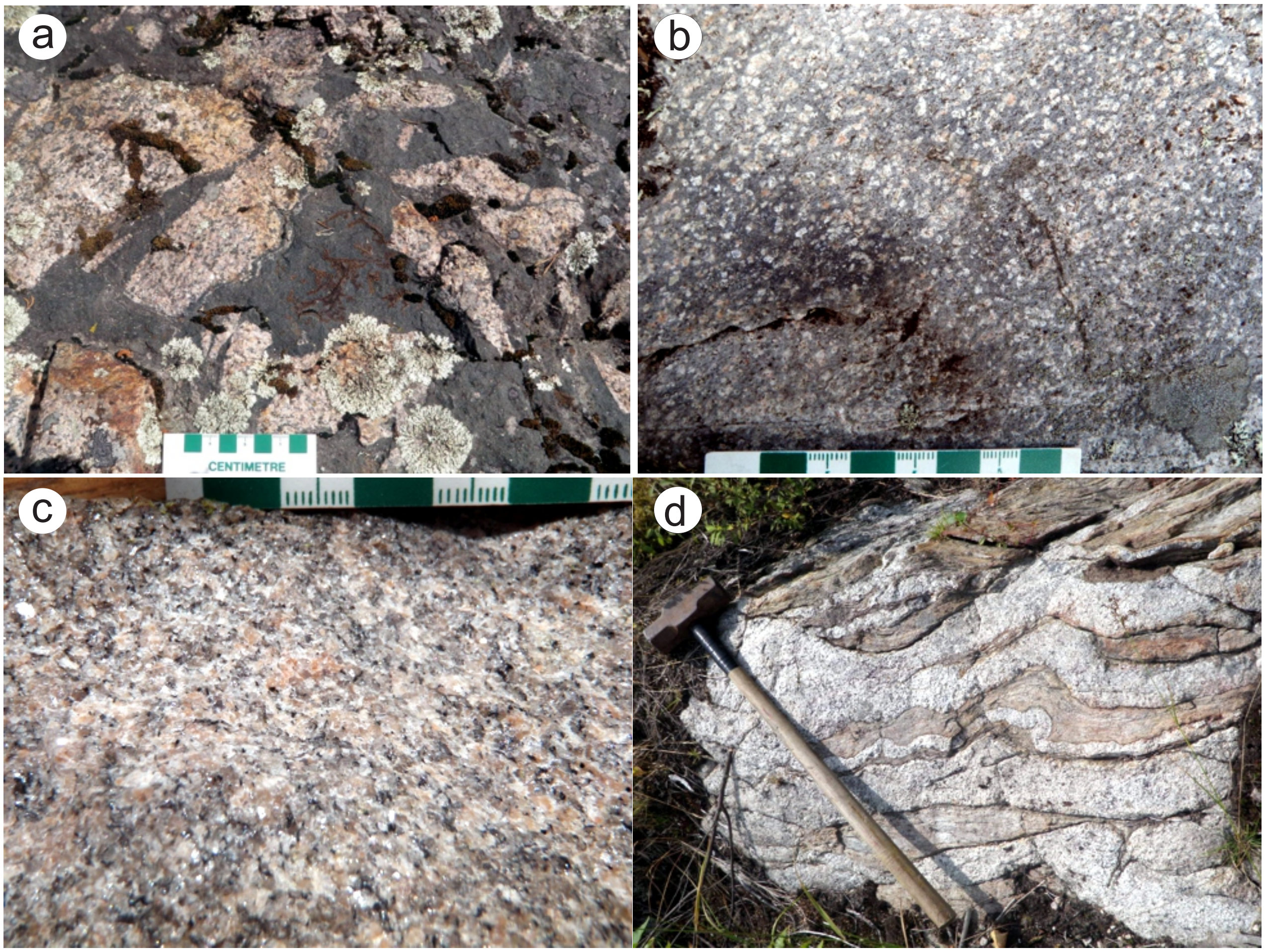

***Figure GS-4-4**: Field photographs of granitoid rocks from the Bird River greenstone belt, southeastern Manitoba: **a)** coarse-grained granodiorite fragmented and brecciated by MORB-type basalt, Maskwa Lake batholith I (UTM Zone 15N, 315328E, 5608468N, NAD83); **b)** two-feldspar porphyry, Maskwa Lake batholith II (UTM 324786E, 5597364N); **c)** undeformed, medium-grained, muscovite-biotite granodiorite, Marijane pluton (UTM 343875E, 5587802N); **d)** medium-grained, muscovite-biotite granite dikes and veins cutting cordierite porphyroblast–bearing greywacke (UTM 343421E, 5585389N).*

ranges from diorite to tonalite, trondhjemite, granodiorite and granite, intruded MORB-type basalts cut by the Mayville mafic–ultramafic intrusion (2742.8 ±0.8 Ma [Houlé et al., 2013]) and the Bird River sill (2743.0 ±0.5 Ma [Scoates and Scoates, 2013]). These granitoid rocks have variable MS values of 0.2811.70 × 10^{3} SI, consistent with magnetite-series and I-type granites. It is noted that some biotite granite outcrops have MS values as low as 0.044 × 10^{3} SI (Table GS-4-2), consistent with evolved I-type granites that exhibit an ilmenite-series signature.

Porphyritic quartz diorite and two-feldspar porphyry are cut by a fine-grained, east-trending gabbro dike, up to 15 m wide, in the southern part of the Maskwa Lake batholith II (labelled '7' in Figure GS-4-1). The porphyry is interpreted as a late-stage stock resulting from arc magmatism. It is not foliated, contains both plagioclase and Kfeldspar phenocrysts, and shows strong sericitic and chloritic alteration; no mafic minerals are discernible in outcrop (Figure GS-4-4b).

The TTG suite in the Bird River area may have been formed in a magmatic-arc setting and therefore have notable potential for porphyry Cu-(Au) mineralization (e.g., Cat Lake–Euclid Lake) associated, for example, with granitoid phases that exhibit potassic alteration. Skarn-type Cu-Au-Ag mineralization is also evident in this area (e.g., Cat Lake; Yang et al., 2013). Lode Au mineralization has been observed in shear zone(s) cutting the central part of the Maskwa Lake batholith (e.g., Little Bear Lake).

Strongly peraluminous granitoid rocks (with muscovite±garnet and biotite as the dominant ferromagnesian minerals) postdate the TTG suite and, together with associated rare-metal–bearing pegmatite intrusions, may have been emplaced during continental collision subsequent to plate subduction (Yang et al., 2013; Yang and

Gilbert, 2014). The north-northwest-trending Cat Lake–Euclid Lake shear zone is confined to gneissic, peraluminous granitoid rocks, as well as strongly foliated and mylonitic granitoid rocks. The youngest granitoid intrusive phase is represented by porphyritic sanukitoid-type rocks that occur as dikes or small stocks cutting both supracrustal and granitoid rocks in the belt. These high-Mg rocks display enrichment in both large-ion lithophile and siderophile elements, and display highly fractionated REE patterns with marked heavy REE depletion; the intrusions may have been derived from partial melting of subcontinental lithospheric mantle metasomatized by subduction-related components, associated with the collapse of a thickened orogen (Yang and Gilbert, 2014).

The Marijane Lake pluton (labelled '8' in Figure GS-4-1) is unique in the BRGB for containing both biotite granodiorite (2645.6 ±1.3 Ma; Gilbert et al., 2008) and muscovite-biotite granodiorite to granite, although their cutting relationship was not observed at outcrop scale in the field. The biotite granodiorite is medium to coarse grained and equigranular to gneissic, and comprises 25–30% quartz, 20–30% Kfeldspar, 20–35% plagioclase, 10–20% biotite and minor or no amphibole (<5%). It displays MS values of $0.251–1.90\times10^3$ SI, consistent with magnetite-series and I-type granites. In contrast, the two-mica granodiorite contains up to 5% muscovite and is massive, equigranular and medium to coarse grained in most outcrops (Figure GS-4-4c), and displays consistently very low MS values of $0.035–0.088\times10^3$ SI (Table GS-4-2), typical of ilmenite-series and S-type granites. In addition, it was noted that medium-grained muscovite-biotite granite intruding the Booster Lake formation metasedimentary rocks contains cordierite porphyroblasts (Gilbert et al., 2008); both are deformed and folded (Figure GS-4-4d). The presence of metasedimentary xenoliths in the muscovite-bearing granite, together with its low MS values and the cordierite-bearing metasedimentary country rocks, strongly suggests that the redox conditions of the granite intrusion may have been influenced by the wallrock setting to some extent, although they are considered to be largely inherited from the source rocks (see Ishihara, 1981, 2004).

The Birse Lake pluton (labelled '9' in Figure GS-4-1) was dated at 2723.2 ±0.7 Ma (Gilbert et al., 2008). This pluton varies in composition from quartz diorite to tonalite, granodiorite, muscovite-bearing granite and garnet-bearing granite. Texturally, both equigranular and porphyritic varieties are evident in the tonalite and granodiorite, and massive and foliated varieties are present. The strongly peraluminous muscovite- and garnet-bearing granites are mostly present in the eastern end of the pluton, where it was emplaced into metasedimentary rocks. However, such strongly peraluminous phases appear absent in the western end, where rare-metal pegmatite deposits occur (e.g., Tanco). Deformed, coarse-grained, porphyritic granodiorite displays moderate MS values of $0.155–1.51 \times 10^3$ SI (Table GS-4-2) and consists of 30–35% quartz, 30–35% Kfeldspar, 20–25% plagioclase and 20–25% amphibole. Locally, inclusions of fine-grained, dark mafic rock are evident in the granodiorite. Together with the MS values, this suggests that the western portion of the pluton is of magnetite-series and I-type, which may be favourable for Cu-Au mineralization (e.g., Blevin, 2004; Ishihara, 2004). Once again, the garnet/muscovite granite has very low MS values of $0.036–0.085 \times 10^3$ SI (Table GS-4-2), consistent with ilmenite-series and S-type granites that are favourable for rare-metal and/or Sn-W mineralization (Chappell and White, 1974, 1992; Ishihara, 1977, 1981, 2004). Coexistence of different petrogenetic types of granitoid rocks in the Birse Lake pluton is worthy of further study, and may provide new clues regarding the source and origin of the Tanco pegmatite (e.g., Martins and Kremer, 2012).

Granitoid rocks in the Winnipeg River terrane

Lac du Bonnet batholith

Although part of the Lac du Bonnet batholith (labelled '10' in Figure GS-4-1) extends into the BRGB, most of it is considered part of the Winnipeg River terrane (Figure GS-4-1). This batholith, dated at 2660 ±3 Ma by Wang (1993), may represent a stitching intrusion that welded the adjacent tectonic blocks of the BRGB and Winnipeg River terrane.

The Lac du Bonnet batholith (Černý et al., 1981) is a composite intrusion, dominated by pinkish, medium- to coarse-grained granodiorite, granite and leucogranite with minor quartz diorite and monzonite, that is cut by late simple pegmatite dikes (comprising quartz–Kfeldspar±biotite±muscovite) without notable internal metasomatism. Biotite granite is pinkish, massive, medium to coarse grained and equigranular, and typically contains 25–30% quartz, 45–50% Kfeldspar, 10–15% plagioclase and 10–15% biotite (Figure GS-4-5a), although some of the Kfeldspar crystals locally occur as phenocrysts up to 1.5 cm in length. Compared to the biotite granite, leucogranite (Figure GS-4-5b) has higher quartz (30–35%) and Kfeldspar (up to 60%), but low biotite (5–10%) and minor plagioclase (<5%). Notably, biotite granite has higher MS values (up to 19.4×10^3 SI) than leucogranite (up to 5.0×10^3 SI), but both fall in the field of magnetite-series and normal I-type granites. Goad and Černý (1981) felt that the biotite granite and the leucogranite were unrelated in origin because of distinctively different rare-earth element patterns. Some evolved biotite granite displays MS values as low as 0.044×10^3 SI (Table GS-4-2), consistent with reduced I-type granites that exhibit the ilmenite-series signature.

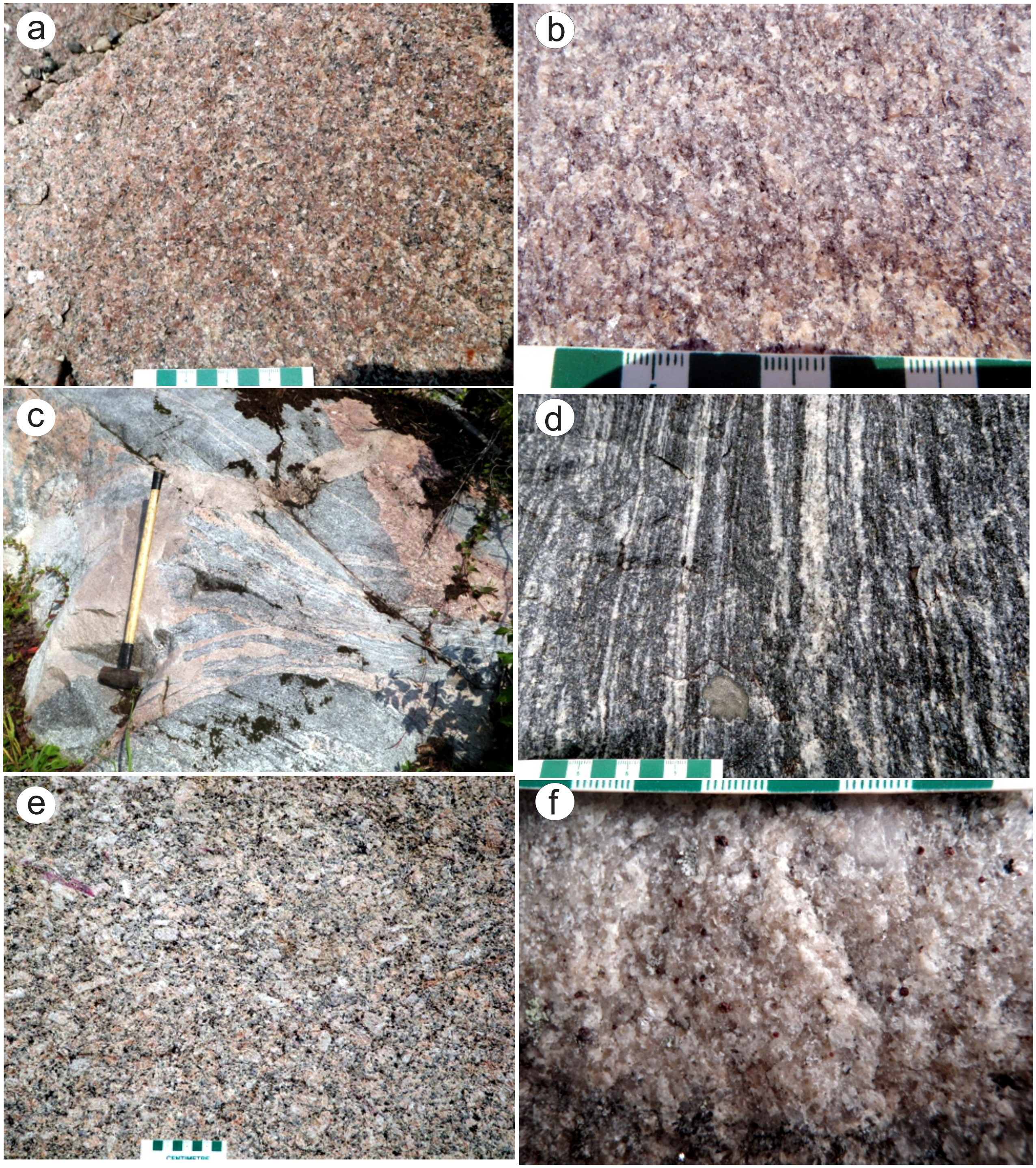

Figure GS-4-5*: Field photographs of granitoid rocks from the Winnipeg River terrane, southeastern Manitoba:* ***a)*** *pink, medium-grained biotite granite, Lac du Bonnet batholith (UTM Zone 15N, 301921E, 5578488N, NAD83);* ***b)*** *medium-grained leucogranite, Lac du Bonnet batholith (UTM 304788E, 5579115N);* ***c)*** *grey, medium-grained, gneissic tonalite cut by pink biotite granite, Pointe du Bois batholith (UTM 319078E, 5572003N);* ***d)*** *grey, medium-grained, gneissic tonalite (with very high MS values of up to 45.7 × 10^3 SI), showing gneissic fabrics consisting of alternating biotite-rich and felsic layers, Pointe du Bois batholith (UTM 294166E, 5559908N);* ***e)*** *pink porphyritic granodiorite with megacrystic Kfeldspar as phenocrysts, Rennie River plutonic suite (UTM 313534E, 5553590N);* ***f)*** *medium-grained, massive, garnet-bearing granite, Rennie River plutonic suite (UTM 339676E, 5516634N).*

Pointe du Bois batholith

The Pointe du Bois batholith (labelled '11' in Figure GS-4-1) in the Winnipeg River terrane consists mainly of gneissic tonalite, granodiorite and granite, although massive equigranular granitoid rocks, dated at 2729 ±8.7 Ma (Wang, 1993), are also present. In outcrop, the gneissic tonalite to granodiorite is commonly cut by pinkish-grey, equigranular biotite granite (Figure GS-4-5c). In places, it is also cut by mafic dikes up to 1 m thick but also contains subrounded to angular gabbroic xenoliths. Pinkish pegmatite-aplite dikes commonly crosscut the gneissic tonalite to granite. Both gneissic and massive granitoid rocks display relatively high MS values of 1.49–18.0 × 10^3 SI, although some highly evolved leucogranite has MS values as low as 0.089 × 10^3 SI. It is noted that an exposure of grey gneissic tonalite has exceptionally high MS values of up to 45.7 × 10^3 SI (Table GS-4-2). This gneissic tonalite is medium grained and magnetic, consisting of biotite-rich layers alternating with felsic layers ranging from several to tens of centimetres in width (Figure GS-4-5d). The biotite-rich layers contain 1–5% magnetite, and minor amphibole. A dark grey, fine-grained gabbro dike cuts the gneissic tonalite and is cut by pink pegmatitic granite dikes. Generally, these granitoid rocks with varied amounts of amphibole (10–25%) and biotite (5–15%) are comparable to the magnetite-series granites of Ishihara (1977, 1981, 2004) and I-type granites of Chappell and White (1974, 1992) in terms of MS values and mineral assemblages.

Rennie River plutonic suite

The Rennie River plutonic suite (labelled '12' in Figure GS-4-1) is composed of many rock types with texture ranging from porphyritic to seriate, equigranular and gneissic, and lithology from tonalite to granodiorite to granite. At the south margin, it contains muscovite-garnet–bearing granite cut by biotite(±muscovite±tourmaline)-quartz-feldspar pegmatite dikes. Pinkish, massive, porphyritic granodiorite comprises 30–35% Kfeldspar phenocrysts that are euhedral to subhedral and 2–3 cm in length, together with a few quartz phenocrysts up to 2 cm in size, in a medium- to coarse-grained groundmass of quartz, Kfeldspar, plagioclase and biotite (Figure GS-4-5e). In some outcrops, the porphyritic granodiorite varies to seriate textures and is cut by fine- to medium-grained, pinkish massive granite. It was noted that most of the granitoid rocks in this plutonic suite display consistently high MS values of 1.13–34.5 × 10^3 SI (Table GS-4-2), typical of magnetite-series and I-type granites.

The Rennie River plutonic suite contains garnet-muscovite–bearing granodiorite to granite at its southern margin; the distribution of these strongly peraluminous granites coincides with the southern boundary of the Winnipeg River terrane. The granodiorite is pale greyish-white to pinkish-grey on fresh surface, massive and equigranular, and consists of 30–35% quartz, 40–45% Kfeldspar, 20–25% plagioclase, 5% biotite, minor muscovite and up to 1% garnet (Figure GS-4-5f). It has a very low MS value of 0.045 × 10^3 SI (Table GS-4-2), consistent with ilmenite-series (Ishihara, 1977, 1981, 2004) and S-type granites (Chappell and White, 1974, 1992) and reflecting relatively reduced conditions of emplacement (cf. Blevin, 2004). W. Mandziuk (pers. comm., 2014) considers that the garnet-bearing granitoid rocks are formed from granite magmas contaminated by metasedimentary rocks. Elongated and folded greywacke xenoliths are present in the granite, which is cut by pinkish pegmatite dikes that also contain notable garnet and muscovite.

Big Whiteshell Lake pluton

The Big Whiteshell Lake pluton (labelled '13' in Figure GS-4-1) is dominated by granodiorite and granite, although tonalite and quartz diorite also occur locally. In terms of texture, massive, equigranular and foliated to gneissic varieties are present. Granitoid rocks in this pluton are characterized by high MS values of up to 62.4 × 10^3 SI (Table GS-4-2), typical of magnetite-series granites and reflecting oxidized conditions of emplacement (Ishihara, 1981, 2004; Blevin, 2004). They are ascribed to I-type granites of Chappell and White (1974, 1992), based on the presence of amphibole and biotite and the absence of aluminous silicates (i.e., muscovite, garnet, cordierite).

Granitoid rocks in the Western Wabigoon terrane

The Whitemouth Lake pluton (labelled '14' in Figure GS-4-1) is sporadically exposed in the Western Wabigoon terrane of southeastern Manitoba. A Rb-Sr isochron age of 2664 ±50 Ma was interpreted to represent its minimum age of intrusion (Manitoba Geological Survey, 2006). This large batholith consists of massive granodiorite to granite and, in places, gneissic tonalite and granodiorite. At outcrop scale, multiple phases of granitoid rocks coexist and are cut by pink pegmatite (Figure GS-4-6a). Pinkish, fine- to medium-grained leucogranite, consisting of 35–40% quartz, 55–60% Kfeldspar, 1–5% biotite and minor plagioclase, occurs in places. Notably, the leucogranite or alkali-feldspar granite shows high MS values of up to 13.5 × 10^3 SI. In addition, on the northern margin of the pluton, gneissic muscovite-garnet-biotite granite intrudes a grey foliated tonalite phase that shows moderate MS values of 3.28 × 10^3 SI (Table GS-4-2), consistent with the magnetite-series granites of Ishihara (1981, 2004). However, such strongly peraluminous granite is typical of S-type in terms of the presence of muscovite and garnet (up to 1%), suggesting that the redox condition of this S-type granite may have been buffered by oxidized wallrocks.

The Falcon Lake igneous complex (labelled '15' in Figure GS-4-1) was investigated by Mandziuk et al. (1989), who found it to be an Archean composite intrusion comprising gabbroic rocks, diorite, granodiorite and

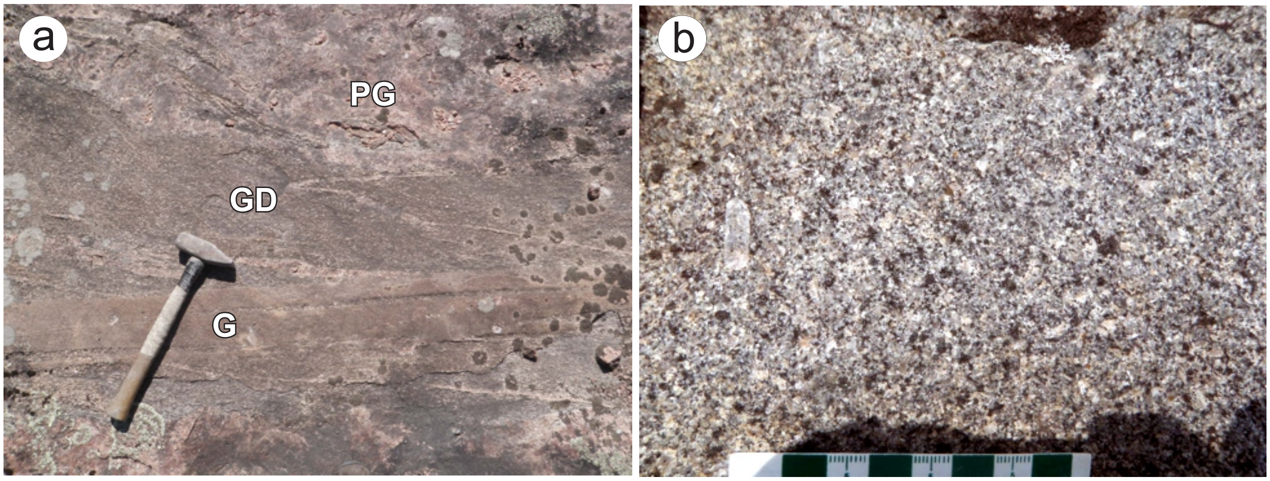

***Figure GS-4-6**: Field photographs of granitoid rocks from the Western Wabigoon terrane, southeastern Manitoba: **a)** granodiorite (GD) cut by fine-grained granite (G) and pegmatitic granite (PG), Whitemouth Lake pluton (UTM Zone 15N, 318467E, 5479806N, NAD83); **b)** medium-grained quartz monzonite with a few euhedral Kfeldspar phenocrysts, Falcon Lake igneous complex (UTM 337410E, 5511611N).*

quartz monzonite. The quartz monzonite occurs in the core of the complex and is massive and medium grained, locally with a few euhedral Kfeldspar phenocrysts up to 2.2 cm in length (Figure GS-4-6b); this rock contains 30–35% hornblende, 30–40% plagioclase, 20–25% Kfeldspar and 5–10% quartz. The quartz monzonite has a moderately high MS value of 11.7×10^3 SI. Notably, sulphide-bearing breccia pipes, occurring in the quartz monzonite or along the contact between quartz monzonite and granodiorite, are interpreted to have formed from a late volatile-rich phase of this igneous complex (Mandziuk et al., 1989).

Discussion

Archean granitoid rocks of the western Superior province in southeastern Manitoba exhibit variable mineral assemblages, fabrics and MS values, and thus can be ascribed to different petrogenetic types (e.g., magnetite-series versus ilmenite-series, proposed by Ishihara [1977, 1981, 2004]; I-type versus S-type, proposed by Chappell and White [1974, 1992, 2001]) as described above. Generally, the field and petrological features of granitoid rocks are a function of the interplay between magma sources, tectonic settings, magmatic processes and erosion levels (e.g., Blevin and Chappell, 1995; Pearce, 1996; Blevin, 2004; Yang, 2007; Yang et al., 2008), which are also reflected in their temperatures, pressures, chemical and isotopic compositions, and redox conditions of formation [i.e., $f(O_2)$]. Field relationships established by reconnaissance mapping provide important constraints for the evaluation of petrogenesis and metallogeny of granitoid rocks in southeastern Manitoba.

Although MS measurements provide a first-order means of screening different petrogenetic types of granitoid rock in the field, detailed investigations of petrography, petrology and lithogeochemistry are required for an evaluation of magmatic processes, emplacement conditions and metallogeny. Blevin (2004) suggested that metallogenic potential of granitoid rocks could be assessed by investigation of their geochemical characteristics, degree of compositional evolution, degree of fractionation and oxidation state. These parameters are largely controlled by the precursors of the granitoid rocks (Chappell and White, 1974, 2004; Ishihara, 1977, 1981, 2004), petrogenetic processes and geodynamic setting involved in their formation (Pearce et al., 1984; Whalen et al., 1987, 2004). The most important factor is their oxidation state, which greatly affects the geochemical behaviour of metals in their derivative magmas. The criteria summarized in Table GS-4-1 can be used for identification of relatively reduced and oxidized granitoid rocks in the field.

Economic considerations

Several types of granitoid rocks were identified occurring in different tectonic entities of the western Superior province in southeastern Manitoba. Granitoid rocks, the most abundant exposed rock type, preserve primary mineralogy and textures, and bear distinctively different mineral potential. Critical petrogenetic information has been acquired in this reconnaissance mapping and sampling project by focusing on the field relationships, textures (fabrics), mineral assemblages, magnetic susceptibilities and presence of mineralization and/or alteration at outcrop scale. However, systematic petrography, petrology and lithogeochemistry studies are needed for extraction of more geoscientific information on the sources, geotectonic settings, magmatic processes and metallogeny of the granitoid rocks.

The preliminary results of reconnaissance mapping and sampling of granitoids from the western Superior province in southeastern Manitoba reveal that muscovite- and/or garnet-bearing granitic rocks (i.e., strongly peraluminous granitoids or S-type) with commonly low MS values (below 0.1×10^3 SI) are mainly intruded into terrane boundaries, constituting a macro-recognizable geological criterion to assist in the subdivision of tectonic units in the western Superior province, and possibly providing a basis for recognizing crustal-scale faults favourable for Au mineralization. These peraluminous granitoid rocks likely formed in a thickened crustal setting(s) due to continental collision, are associated with pegmatite intrusions enriched in rare metals and may have potential to host Sn-W mineralization. In contrast, granitoid plutons consisting dominantly of tonalite, trondhjemite and granodiorite (i.e., TTG suite) with much higher MS values and mineral assemblages typical of I-type are widely present across the region. These granitoid rocks greatly contributed to continental crustal growth and expansion in the Archean and may have been related to plate subduction. Some of the phases in the TTG suites display porphyry Cu-Au and skarn Cu-Au-Ag mineralization, or are overprinted by shear-hosted Au mineralization.

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