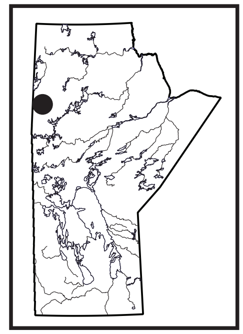
GS-4 Geological investigations of the Keewatin River area, Lynn Lake greenstone belt, northwestern Manitoba (parts of NTS 64C14, 15)

by X.M. Yang and C.J. Beaumont-Smith



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Summary

In 2015, the Manitoba Geological Survey (MGS) renewed bedrock mapping in the Lynn Lake greenstone belt (LLGB), northwestern Manitoba. The objectives of this multiyear project are to further define the geological and geodynamic evolution of this belt, and to identify key factors controlling the formation of its various mineral deposits (e.g., orogenic gold, volcanogenic base metals, magmatic Ni-Cu-PGE). In the 2015 field season, the Keewatin River area—which includes the MacLellan Au-Ag and Lynn Lake Ni-Cu-Co deposits—was targeted for detailed geological mapping at a scale of 1:20 000. The preliminary results of this mapping indicate that the Keewatin River area contains a variety of volcanic rocks comprising basalt, andesite, dacite and rhyolite (BADR) and related volcaniclastic rocks, along with sedimentary rock units. The BADR sequence is overlain by reworked volcaniclastic and epiclastic rocks, suggesting deposition in a setting comparable to modern volcanic arcs or back-arc basins. These rocks were crosscut by several intrusive suites.

The mapping results summarized in this report have several implications, in particular: 1) picrite (and synvolcanic pyroxenite) of unit 3 may have served as a chemical trap and locus for high-strain zones, favourable for Au mineralization; 2) middle-amphibolite–facies metamorphism is recorded by mineral assemblages observed in some metasedimentary rocks (unit 4); 3) Au mineralization controlled by shear zones at the MacLellan mine is likely to postdate magmatic Ni-Cu-Co mineralization at the Lynn Lake mine associated with the unit 5 metagabbro intrusion; and 4) quartz-feldspar porphyries (unit 9) locally contain magnetite phenocrysts, suggesting that they are derived from relatively oxidized intrusions. Hydrothermal fluids associated with such oxidized intrusions can effectively scavenge and transport gold (e.g., Boyle, 1979), and may have played a role in Au mineralization.

Introduction

In 2015, the Manitoba Geological Survey (MGS) renewed bedrock mapping in the Lynn Lake greenstone belt (LLGB), northwestern Manitoba (Figure GS-4-1) in order to investigate its geological and geodynamic evolution, and to study metallogeny and key factors controlling the formation of various types of mineral deposits. This study involves new bedrock geological mapping, coupled with lithogeochemical characterization, radiogenic isotope analysis, and GIS compilation. In the 2015 field season, the Keewatin River area was the focus of detailed mapping by the MGS at a scale of 1:20 000. The mapped area includes the MacLellan Au-Ag deposit, a number of Au occurrences (e.g., K2 zone, Rushed zone), as well as the Lynn Lake Ni-Cu-Co deposit. Gold mineralization is hosted in the Agassiz metallotect (Fedikow and Gale, 1982; Fedikow, 1992; Ma et al., 2000; Ma and Beaumont-Smith, 2001; Park et al., 2002; Ewert et al., 2012) of the northern LLGB (Gilbert et al., 1980; Syme, 1985; Gilbert, H.P. 1993; Zwanzig et al., 1999; Figure GS-4-1), and magmatic Ni-Cu-Co mineralization is associated with the Lynn Lake gabbroic intrusion (Pinsent, 1980; Jurkowski, 1999).

This report presents the preliminary results of the 2015 mapping, including: 1) delineation of a lithostratigraphic sequence consisting of 9 map units (20 subunits); 2) recognition of synvolcanic pyroxenite in a mafic to intermediate volcanic package (unit 3); 3) characterization of a locally Au mineralized sequence, which is dominated by mafic to intermediate volcaniclastic rocks overlain by mafic volcanic and associated synvolcanic intrusive rocks (units 2, 3); and 4) documentation of middle-amphibolite–facies metamorphism indicated by the mineral assemblage observed in parts of the metasedimentary section (unit 4). The associated preliminary map (PMAP2015-3) of the Keewatin River area (Yang and Beaumont-Smith, 2015) provides new data and updates the geology from previous mapping.

Regional geology

The LLGB (Bateman, 1945) is an important 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). The LLGB is bounded to the north by the Southern Indian domain, a mixed metasedimentary and metaplutonic domain; to the south, it is bounded by the Kisseynew metasedimentary domain (Gilbert et al., 1980; Syme, 1985; Zwanzig et al., 1999; Beaumont-Smith and Böhm, 2004). Similar Paleoproterozoic greenstone belts also occur to the east (Rusty Lake belt), to the west (La Ronge belt), and to the far south (Flin Flon belt; e.g., Park et al., 2002; Corrigan et al., 2007, 2009; Hastie, 2014; Glendenning et al.,

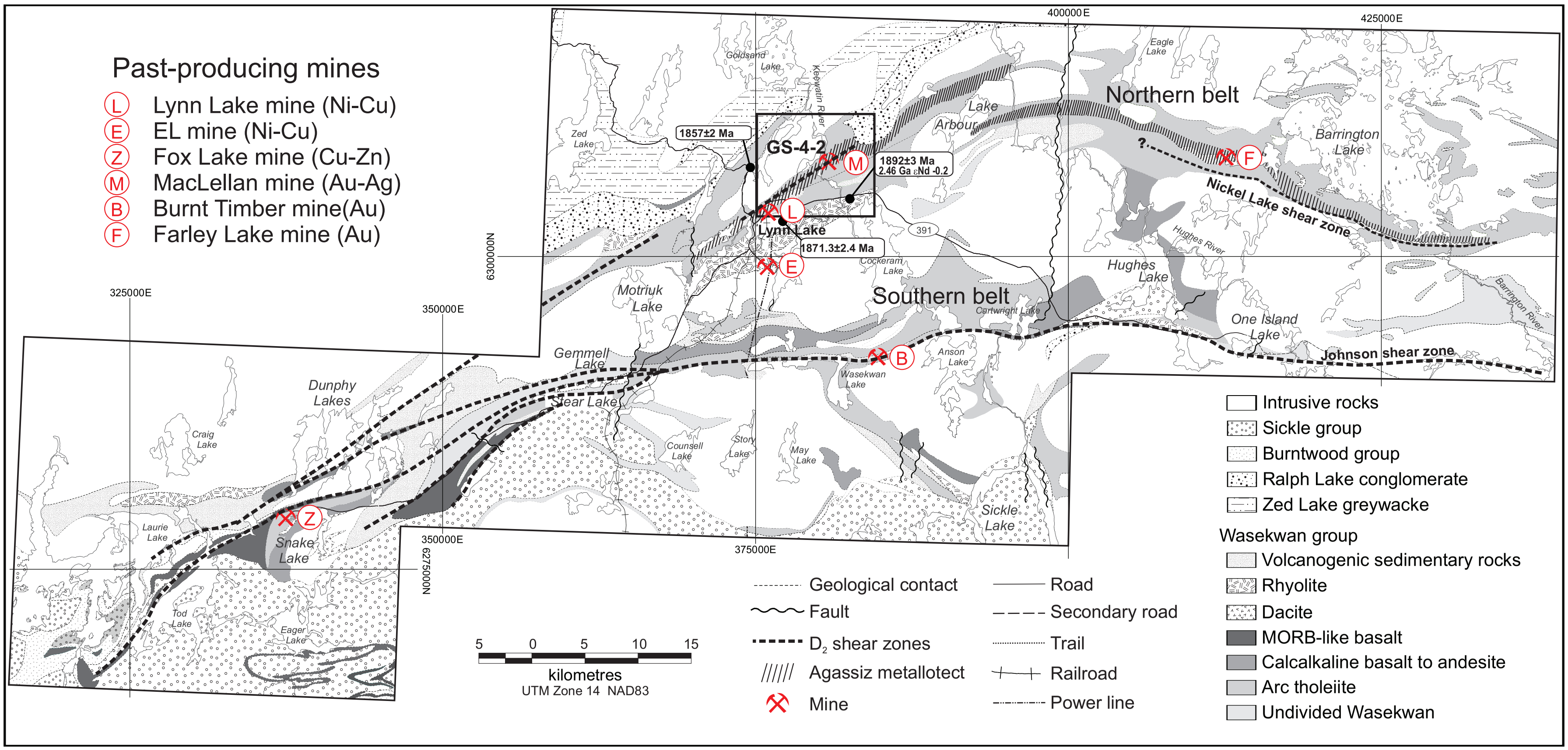

Figure GS-4-1: *Regional geology map with zircon U-Pb ages and Nd isotopic compositions of the Lynn Lake greenstone belt (modified and compiled from Gilbert et al., 1980; Manitoba Energy and Mines, 1986; Gilbert, 1993; Zwanzig et al., 1999; Turek et al., 2000; Beaumont-Smith and Böhm, 2002, 2003, 2004; Beaumont-Smith et al., 2006; Beaumont-Smith, 2008). The detailed mapping area is indicated in the box, and includes the MacLellan Au-Ag deposit (labelled). Abbreviation: MORB, mid-ocean–ridge basalt.*

2015). The LLGB consists of two east-trending, steeply dipping belts that contain various volcanic, volcaniclastic and epiclastic rocks of the Wasekwan group (Bateman, 1945; Gilbert et al., 1980), along with younger molasse-type sedimentary rocks of the Sickle group (Norman, 1933; Figure GS-4-1). The southern and northern belts are separated by granitoid plutons of the Pool Lake intrusive suite (Gilbert et al., 1980; Figure GS-4-1), 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 LLGB, the Sickle group overlies the Wasekwan group and felsic–mafic plutonic rocks of the Pool Lake intrusive suite along an angular unconformity.

The northern Lynn Lake belt consists of subaqueous, tholeiitic, mafic metavolcanic and metavolcaniclastic rocks interpreted as an overall north-facing, steeply dipping succession that occupies the upright limb of a major antiformal structure (Gilbert et al., 1980). Included in the northern belt is the Agassiz metallotect (Fedikow and Gale, 1982; Fedikow, 1986, 1992), a relatively narrow, stratigraphically and structurally distinct entity consisting of ultramafic flows (picrite), banded oxide-facies iron formation and associated exhalative and epiclastic rocks (Ma et al., 2000; Ma and Beaumont-Smith, 2001; Park et al., 2002). The Agassiz metallotect contains Au mineralization (Figure GS-4-1) and intense deformation fabrics (Beaumont-Smith and Böhm, 2004).

The southern belt consists largely of subaqueous tholeiitic to calcalkalic metavolcanic and metavolcaniclastic rocks, including minor amounts of metabasalt with geochemical signatures comparable to modern mid-ocean–ridge basalt. The tholeiitic to calcalkalic rocks include older (ca. 1890 Ma) contaminated arc rocks as well as younger (ca. 1855 Ma) juvenile arc-volcanic rocks (Peck and Smith, 1989; Zwanzig et al., 1999; Zwanzig, 2000; Beaumont-Smith and Böhm, 2003, 2004). Structural analysis of the LLGB suggests that it is highly transposed (Beaumont-Smith and Rogge, 1999; Beaumont-Smith and Böhm, 2002), calling into question previous structural interpretations. Significant differences in the geology and geochemistry of the northern and southern belts may reflect a more complex structural scenario or regional differences in tectonic settings (Syme, 1985; Zwanzig et al., 1999).

Both the southern and northern belts are unconformably overlain by clastic rocks of the Sickle group. To the south, the southern belt is structurally underlain by unconformably overlying (i.e., inverted) fluvial-alluvial conglomerate and arkosic rocks of Sickle group. It also unconformably overlies the Pool Lake intrusive suite (Gilbert et al., 1980). Any tectonic juxtaposition of the northern and southern belts must have occurred prior to emplacement of the Pool Lake suite and deposition of Sickle group (Beaumont-Smith and Böhm, 2004). The minimum depositional age of the Sickle group is ca. 1830 Ma based on detrital zircon U-Pb ages (Beaumont-Smith et al., 2006). The Sickle group correlates well with the 1850–1840 Ma MacLennan group in the La Ronge greenstone belt in Saskatchewan in terms of composition, stratigraphic position, and contact relationships (Ansdell et al., 1999; Ansdell, 2005), although it could be as old as 1865 Ma based on regional correlations in Trans-Hudson orogen (Corrigan et al., 2007, 2009).

The northern belt is unconformably overlain to the north by marine metaconglomerate and turbiditic metasedimentary rocks, known as the Ralph Lake conglomerate and Zed Lake greywacke, respectively (Gilbert et al., 1980; Manitoba Energy and Mines, 1986; Zwanzig et al., 1999). This clastic succession is largely derived from the supracrustal rocks of Wasekwan group and older plutonic rocks, with the majority of the detrital zircons returning Wasekwan ages (ca. 1890 Ma; Beaumont-Smith and Böhm, 2004).

Geology of the Keewatin River area

The Keewatin River area is situated in the northern belt of the LLGB (Figure GS-4-1), and consists mostly of Wasekwan group supracrustal rocks intruded by plutons of the Pool Lake intrusive suite (Figure GS-4-2). Both the supracrustal sequence and the Pool Lake suite are unconformably overlain by the Ralph Lake conglomerate, which is intruded by the Burge Lake granitoid pluton (Figure GS-4-2). Younger quartz-feldspar porphyry, pegmatite and aplite dikes cut the entire sequence. Following the convention of previous workers (e.g., Beaumont-Smith and Böhm, 2004) the intrusions cutting the Wasekwan group, those cutting the Ralph Lake conglomerate, and those cutting the entire sequence are respectively termed pre-Sickle (i.e., the Pool Lake intrusive suite of Gilbert et al., 1980), post-Sickle (e.g., Milligan, 1960), and late intrusive suites.

Nine map units, including 20 subunits, were defined during the course of bedrock mapping, and are listed in Table GS-4-1. These map units are described in the following sections, and displayed in Figure GS-4-2 (Yang and Beaumont-Smith, 2015). All supracrustal rocks in the LLGB were metamorphosed to greenschist to amphibolite facies (Gilbert et al., 1980; Beaumont-Smith and Böhm, 2004), however, for brevity, the prefix 'meta' is omitted in parts of this report.

Lynn Lake rhyolite (unit 1)

The Lynn Lake rhyolite (Gilbert et al., 1980) of unit 1 is the largest felsic volcanic unit in the Keewatin River area in the northern belt of the LLGB (Figure GS-4-2). The lower parts of this felsic volcanic unit display gneissic fabrics manifested by compositional banding, and by the presence of migmatitic veinlets. To the south, the Lynn Lake rhyolite is cut by granitoid plutons of the pre-Sickle intrusive suite (Figure GS-4-2). The northern contact of this unit with overlying mafic volcaniclastic rocks of

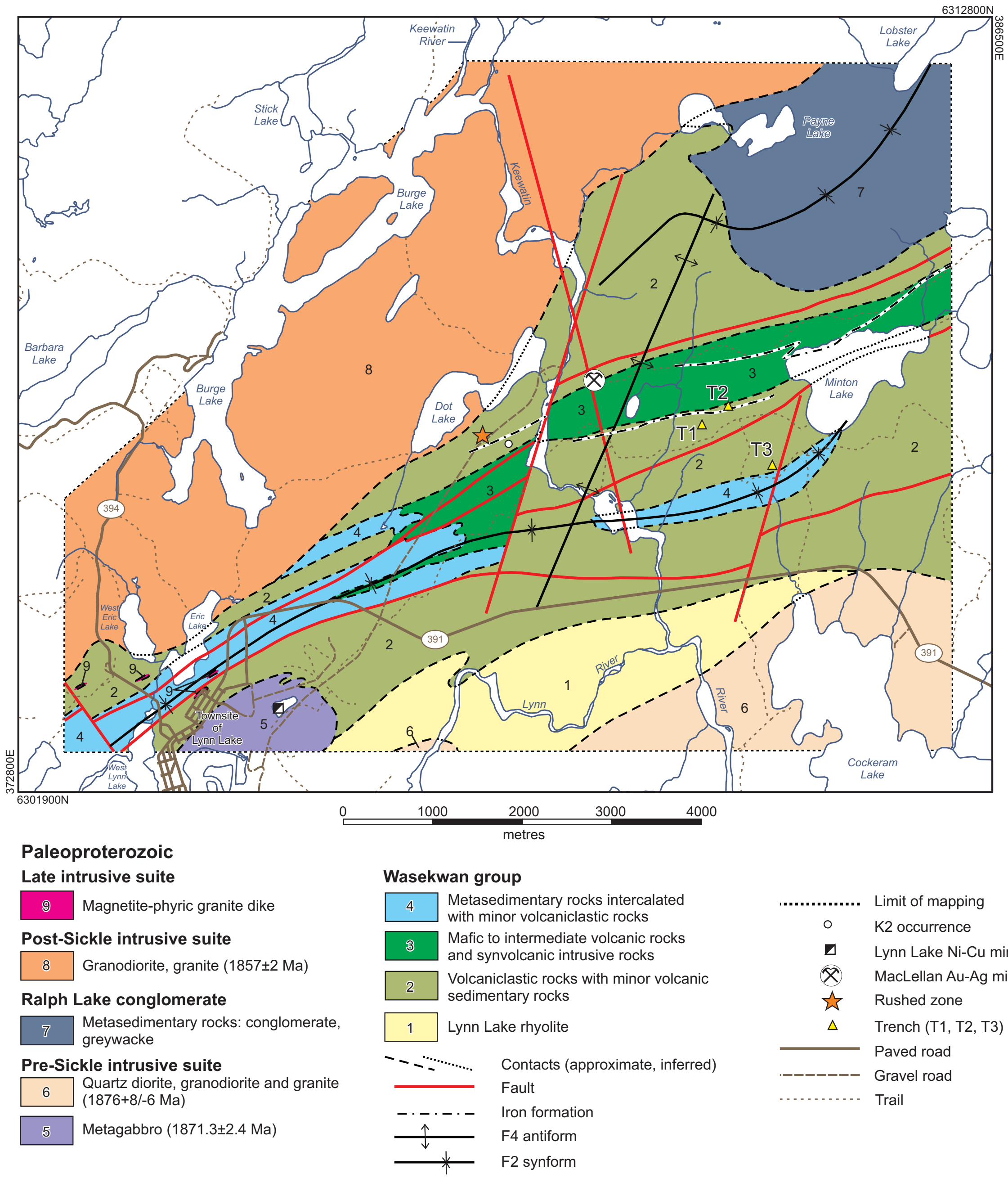

***Figure GS-4-2**: Simplified geology of the Keewatin River area, Lynn Lake greenstone belt, northwestern Manitoba (modified from Yang and Beaumont-Smith, 2015).*

unit 2 is not exposed, but is inferred to be structural based on relatively lower but linear magnetic features. The Lynn Lake rhyolite was dated by U-Pb zircon geochronology at 1910 ±12 Ma and 1915 ±6.5 Ma (Baldwin et al., 1987), and 1892 ±3 Ma (Beaumont-Smith and Böhm, 2002), making it the oldest lithostratigraphic unit identified in the LLGB.

The Lynn Lake rhyolite (subunit 1a; Table GS-4-1) is strongly recrystallized and contains a penetrative foliation (S_2; Beaumont-Smith and Böhm, 2002). It weathers light grey to buff, and is medium grey on fresh surfaces. The rhyolite is very fine to fine grained, with subhedral to euhedral feldspar (0.5–2.0 mm) and/or equant quartz phenocrysts (0.5–1.5 mm). Brownish-red, euhedral garnet porphyroblasts (0.2–0.5 mm) are present in the foliated rhyolite; these porphyroblasts are commonly concentrated along foliation planes and associated with biotite and/or muscovite, and rarely with hornblende and epidote (Figure GS-4-3a).

In places, the rhyolite flow contains interflow felsic volcaniclastic layers, with up to 20% fragments, from 2 to 20 mm in size, comprising plagioclase and quartz crystals,

Table GS-4-1: Lithostratigraphic units of the Keewatin River area, Lynn Lake greenstone belt, northwestern Manitoba.

Map unit[1]	Rock types	Affiliation
9	Magnetite-phyric granite dike; quartz-feldspar porphyry; pegmatite/aplite	Late intrusive suite
	Intrusive contact	
8	Granodiorite and granite (1857 ±2 Ma[2])	Post-Sickle intrusive suite
	Intrusive contact	
7	Metasedimentary rocks: conglomerate and greywacke	Ralph Lake conglomerate
	Inferred unconformity	
6	Quartz diorite, granodiorite and granite (1876 +8/-6 Ma[3]), and associated pegmatic and aplitic dikes	Pre-Sickle intrusive suite
5	Metagabbro (1871.3 ±2.4 Ma[4])	
	Intrusive contact	
4	Metasedimentary rocks intercalated with minor volcaniclastic rocks	Wasekwan group
4a	Metamudstone, metasandstone and metagreywacke	
4b	Banded iron formation	
4c	Volcaniclastic mudstone and sandstone	
	Structural contact	
3	Mafic to intermediate volcanic rocks and synvolcanic intrusive rocks	
3a	Plagioclase-phyric basalt and aphyric basalt	
3b	Picrite and pyroxenite	
3c	Diabase or amphibolite dike	
3d	Porphyritic basaltic andesite	
3e	Mafic autobreccia	
	Structural contact	
2	Volcaniclastic rocks with minor volcanic sedimentary rocks, chert and iron formation	
2a	Mafic tuff breccia and breccia	
2b	Mafic lapillistone and mafic lapilli tuff	
2c	Intermediate lapillistone, lapilli tuff and tuff	
2d	Felsic lapillistone, lapilli tuff and tuff	
	Structural contact	
1	Lynn Lake rhyolite: rhyolite, dacite and felsic volcaniclastic rocks (1892 ±3 Ma[5]; 1910 ±12 Ma to 1915 ±6.5 Ma[3])	
1a	Rhyolite and dacite	
1b	Felsic volcaniclastic rocks	
1c	Gneissic rhyolite and gneissic dacite	
	?	

[1] on Preliminary Map PMAP2015-3, Yang, X.M. and Beaumont-Smith, C.J. 2015
[2] Beaumont-Smith et al., 2006
[3] Baldwin et al., 1987
[4] Turek et al., 2000
[5] Beaumont-Smith and Böhm, 2002

and lithic (very fine grained) clasts. These rocks comprise felsic lapillistone and felsic tuff breccia (subunit 1b) that contain over 75% volcanic-derived materials, including very fine to fine grained rhyolitic to dacitic fragments (subangular to irregular shape; from 4 mm to 50 cm in size, and usually elongate along S_2 foliation), and some plagioclase and quartz crystal fragments (2–3 mm). The matrix contains 1–2 mm lithic fragments, as well as plagioclase, K-feldspar, quartz, muscovite, and biotite (Figure GS-4-3b). Randomly distributed, dark green, euhedral hornblende porphyroblasts up to 1 cm long are evident along some foliation planes. Locally, garnet is also present in some of the felsic lapillistone and felsic tuff breccia.

Gneissic rhyolite and dacite (subunit 1c) are exposed in the southern part of the mapping area (Figure GS-4-2). These rocks are characterized by gneissic banding and concordant to discordant migmatitic veinlets (Figure GS-4-3c). The biotite and felsic (quartz+feldspar) enriched

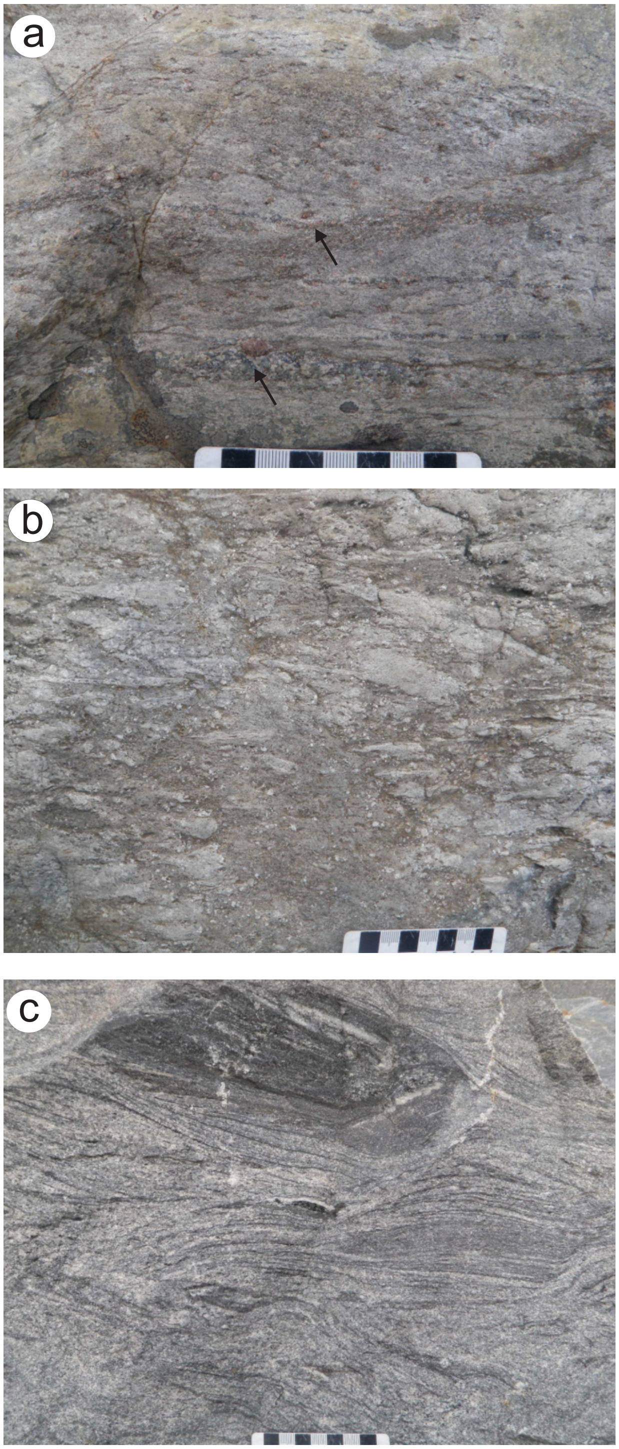

***Figure GS-4-3**: Field photographs of representative outcrops of Lynn Lake rhyolite (unit 1) of the Wasekwan group: **a)** foliated rhyolite (subunit 1a) with garnet porphyroblasts (arrow points to larger porphyroblast; UTM Zone 14N, 378295E, 6302677N, NAD83); **b)** foliated felsic lapillistone (subunit 1b; 380227E, 6304019N); **c)** gneissic dacite (subunit 1c 376839E, 6301570N).*

layers or bands in the gneissic rhyolite and dacite suggest that compositional differentiation may have occurred during ductile deformation at the lower portion of unit 1.

Volcaniclastic rocks with minor volcanic sedimentary rocks, chert and iron formation (unit 2)

Rocks of unit 2 occur in northwestern, middle and southeastern portions of the mapping area (Figure GS-4-2). Unit 2 is dominated by mafic volcaniclastic rocks with minor volcanic sedimentary rocks, chert and iron formation. The volcaniclastic rocks include mafic breccia, tuff breccia, lapillistone and tuff, and minor intermediate lapillistone and tuff. The mafic breccia (subunit 2a) consists of more than 80% plagioclase-phyric basalt clasts, with local aphyric basalt clasts, from 7 to 21 cm long in a compositionally similar matrix (Figure GS-4-4a). The irregular basaltic fragments are subrounded to subangular, and are normally elongated along the generally northeast- to east-northeast-trending foliation. 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. Locally, rare pyrrhotite and pyrite disseminations are evident in both the basaltic fragments and the matrix in unit 2, suggesting that the basaltic magmas may have been sulphide saturated.

In the upper part of unit 2, mafic tuff breccias contain plagioclase-phyric and aphyric basalt fragments as well as strongly magnetic iron formation and nonmagnetic chert fragments (Figure GS-4-4b). The fragment abundance varies between 25 and 75%. Mesoscopic folds are commonly exhibited in some of the iron-formation fragments, which are strongly magnetic and readily identified in the field. Unit 2 mafic volcaniclastic rocks can be mistakenly identified as massive basalt (either porphyritic or aphanitic) due to the presence of very large fragments or portions lacking fragments (Park et al., 2002).

Mafic (subunit 2b), intermediate (subunit 2c) and felsic (subunit 2d) lapillistone, lapilli tuff, and tuff are subordinate in unit 2. They contain over 75% volcanic fragments ranging from <2 to 60 mm across. The various types of rock fragments can be identified according to their mineralogy. Specifically, fragments in the mafic rocks have abundant amphibole and plagioclase, but lack biotite and quartz (Figure GS-4-4c). Intermediate rocks consists of plagioclase and biotite (±amphibole)–rich lithic and/or crystal fragments, or clasts that contain little or no quartz (GS-4-4d). Abundant magnetite veinlets are locally present in layered intermediate tuff breccia, breccia and lapilli tuff (GS-4-4d). Quartz and biotite are important components of the felsic lapillistone, lapilli tuff and tuff (subunit 2d), although this subunit is minor in the Keewatin River area.

In the upper part of the unit 2 succession, a volcanic sandstone up to 15 m thick is interbedded with fine-grained volcaniclastic conglomerate (or gritstone), which

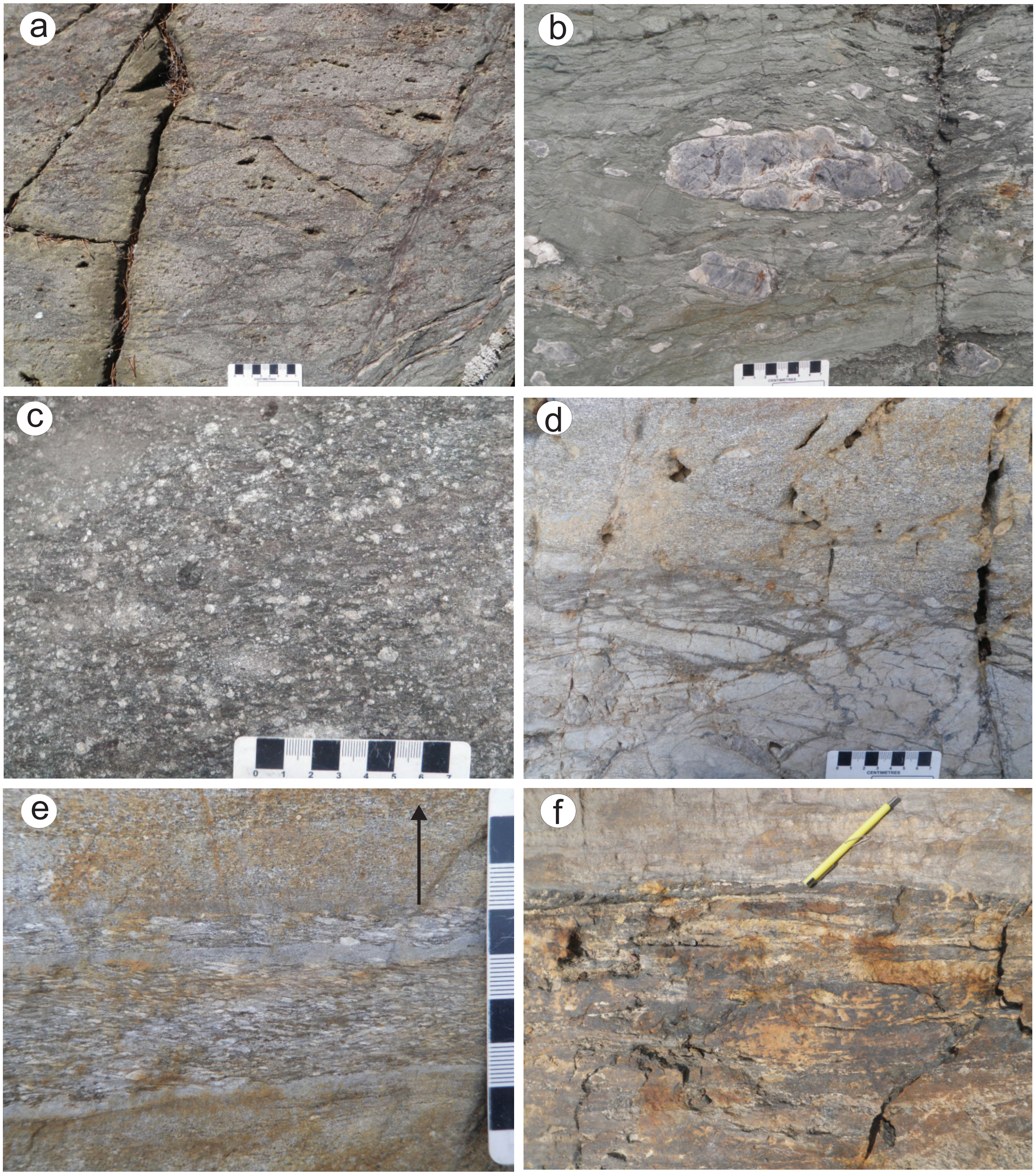

***Figure GS-4-4**: Field photographs of unit 2 volcaniclastic rocks with minor volcanic sedimentary rocks, chert and iron formation of the Wasekwan group: **a)** mafic breccia with plagioclase-phyric basalt fragments in a plagioclase-phyric basaltic matrix (subunit 2a; UTM Zone 14N, 376000E, 6203464N, NAD83); **b)** mafic tuff breccia with aphyric basalt and iron formation fragments at the top of unit 2 (382359E, 6307110N; Trench 1); **c)** mafic crystal-lithic lapillistone to lapilli tuff (subunit 2c; 379440E, 6307310N); **d)** intermediate tuff breccia and breccia with abundant magnetite veinlets overlain by intermediate lapilli tuff (unit 2c; 3826672E, 6307245N; Trench 2); **e)** interbedded volcanic sandstone and pebble conglomerate (younging to northwest as indicated by the arrow; 3826672E, 6307245N; Trench 2); **f)** chert and banded iron formation (3826672E, 6307245N; Trench 2).*

contain up to 25% andesitic–dacitic fragments, occurring together with a bed (1–4.5 m thick) of chert and banded iron formation (Figure GS-4-4e, f). The volcanic sandstone beds fine to the north, indicative of younging to the north, although this subunit is strongly foliated, and bedding (S_0) is overprinted and transposed by the regional foliation (S_2).

Mafic to intermediate volcanic rocks and synvolcanic intrusive rocks (unit 3)

The volcanic succession of unit 3 is dominated by plagioclase-phyric and aphyric basalt, picrite and pyroxenite that together constitute an important part of the Agassiz metallotect (Fedikow and Gale, 1982; Ma et al., 2000; Park et al., 2002), along with subordinate dikes of diabase, amphibolite and porphyritic basaltic andesite (Figure GS-4-2; Table GS-4-1). The plagioclase-phyric basalt (subunit 3a) weathers greenish-grey to dark grey, and is green to dark green on fresh surfaces. Distinctly yellow-green to light greenish-grey epidote-altered domains are common (Figure GS-4-5a). This basalt is composed of varied amounts of plagioclase phenocrysts and glomerocrysts ranging from 5 to 50% (commonly 20 to 30%), and rare amphibole phenocrysts (pseudomorphs after pyroxene) in a fine-grained groundmass of plagioclase, amphibole, epidote, chlorite, carbonate and iron-oxide minerals (cf. Gilbert et al., 1980). The plagioclase phenocrysts are subhedral and commonly equant, from 0.5 to 5 mm in size, although some glomerocrysts or single plagioclase grains are up to 15 mm in size. The plagioclase-phyric basalt is commonly homogeneous in mineral contents, and is typically strongly foliated (Figure GS-4-5a, b). In high-strain zones, relict plagioclase phenocrysts occur as finer recrystallized aggregates aligned along the foliation (Figure GS-4-5c). Quartz amygdules occur in some deformed plagioclase-phyric basalt flows, and are aligned along foliation (Figure GS-4-5b). Trace disseminated pyrrhotite and/or chalcopyrite are evident in many outcrops, and pyrite is common in fractures and faults cutting basalt flows.

Aphyric basalt of subunit 3a (Figure GS-4-5d) is not commonly seen in the Keewatin River area, occurring as sparse interflow units within the more abundant plagioclase-phyric basalt. It is greyish-green to dark greenish-grey on weathered surfaces, and dark greyish-green on fresh surfaces. Epidote alteration is more commonly seen in aphyric basalt, as epidosite domains a few centimetres to a metre across, as described by Gilbert et al. (1980). These epidosite domains are ovoid, angular or irregular, displaying sharp to gradational contacts with host aphyric basalt; some are fracture controlled. It is worthy of note that porphyritic basaltic andesite (subunit 3d) contains both amphibole and plagioclase phenocrysts, although it is similar in appearance to plagioclase-phyric basalt that lacks amphibole phenocrysts. In some places (e.g., Trench 2; Figure GS-4-2), mafic autobreccia (subunit 3e), present in layers up to 1.5 m thick, and containing angular to irregular fragments of dark grey to black, very fine grained basalt, occurs at the margins of aphyric basalt flows. These breccias are interpreted as flow-top breccias.

Picrite (subunit 3b) described here is equivalent to the ‘high Mg-Cr-Ni’ basalt of Gagnon (1991); texturally, it can be termed ‘amphibole-chlorite schist’ due to its strong penetrative foliation (Figure GS-4-5e). It outcrops south of the MacLellan mine and west of the Keewatin River. The picrite weathers green to greyish-green and medium to dark green on fresh surfaces. It is fine to medium grained, strongly magnetic, and is composed dominantly of amphibole (pseudomorphs after pyroxene) with variable amounts of chlorite, actinolite, magnetite, chromite, talc, biotite and carbonate minerals (Park et al., 2002). Trace sulphide (e.g., pyrrhotite, chalcopyrite) disseminations are ubiquitously evident in picrite, suggesting that its original high-Mg magma was sulphide saturated. Based on mineral assemblage, texture and geochemical characteristics (Gagnon, 1991), parts of the picrite may be pyroxenite cumulates. The MacLellan deposit is associated with a thick (>30 m) highly deformed and altered picrite that contains finely disseminated pyrite, arsenopyrite, chalcopyrite and pyrrhotite (Fedikow, 1986; Gagnon, 1991; Ma and Beaumont-Smith, 2001).

Diabase and amphibolite (subunit 3c) occur as dikes cutting unit 2 and unit 3 (Figure GS-4-5f). The dikes weather greenish-grey to medium grey, and are medium to dark green on fresh surfaces. They are very fine to medium grained, porphyritic and deformed. Plagioclase laths up to 5 mm occur in a fine-grained groundmass of plagioclase, amphibole, chlorite and iron oxides. Generally, these rocks consist of 50 to 60% amphibole and 40 to 50% plagioclase. The dikes are interpreted to be synvolcanic with unit 3, on the basis of a lack of chill margins along some of the sharp contacts with plagioclase-phyric basalt.

Metasedimentary rocks intercalated with minor volcaniclastic rocks (unit 4)

Unit 4 metasedimentary rocks of the Wasekwan group are mostly exposed in the southwestern portion of the Keewatin River area (Figure GS-4-2). They consist of mudstone, and greywacke (subunit 4a), with minor intermediate to felsic volcanic sandstone (subunit 4c), distinguished by the dominant fragment types. Locally, beds of banded iron formation (subunit 4b) up to 1 m thick occur in the lower section of unit 4.

Very thin bedded mudstone and greywacke (subunit 4a) are laminated in outcrop, and are locally folded. The original bedding planes (S_0) of mudstone are transposed completely in these outcrops (Figure GS-4-6a). In a section of alternating light greenish-grey and beige mudstone layers, lamina and beds vary from 1 to 50 mm in thickness and contain up to 15% hornblende (1–5 mm)

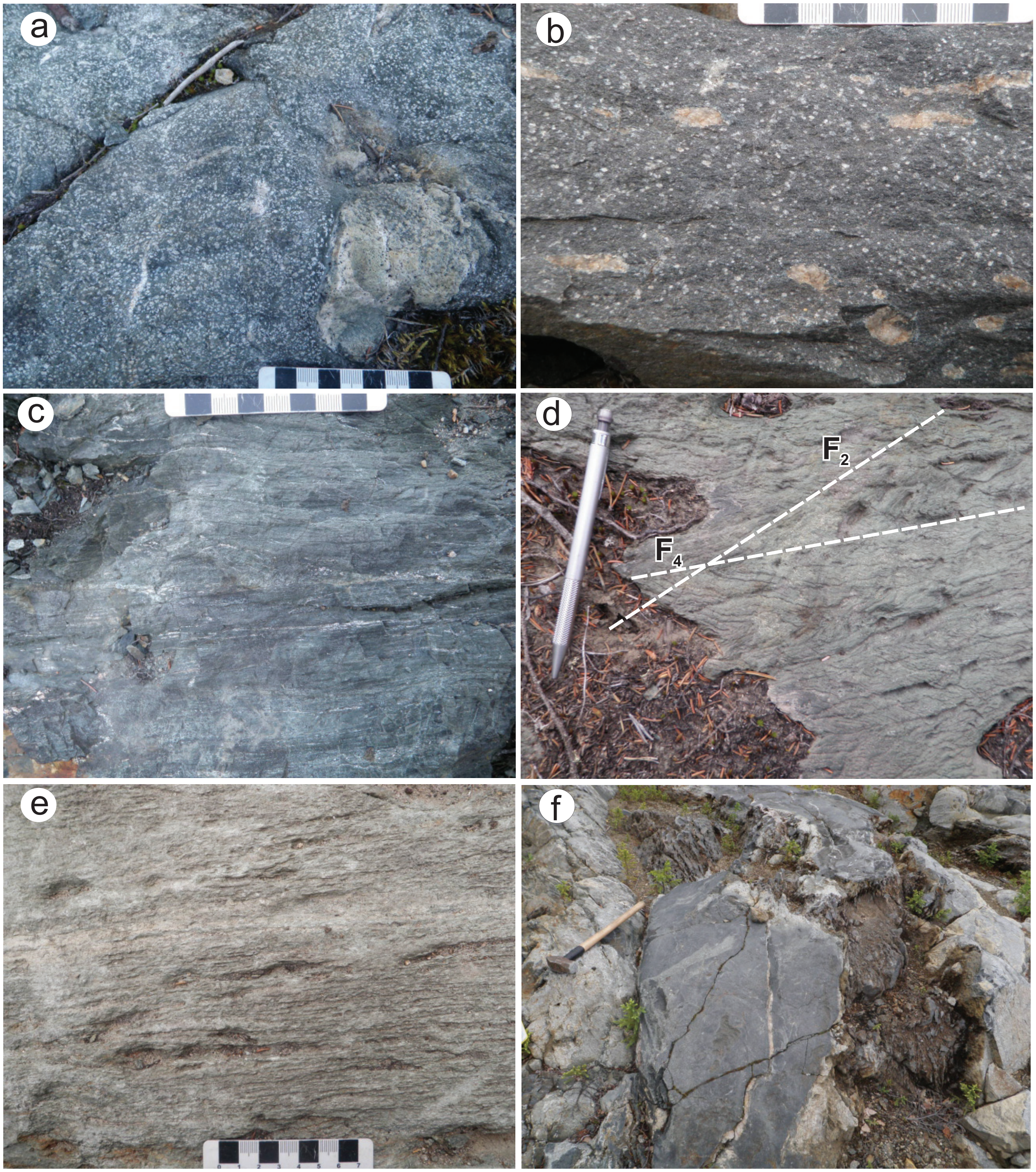

Figure GS-4-5*: Field photographs of mafic to intermediate volcanic rocks and synvolcanic intrusive rocks (unit 3) of the Wasekwan group:* ***a)*** *massive plagioclase-phyric basalt (subunit 3a) with epidote alteration (UTM Zone 14N, 381705E, 63095104N, NAD83);* ***b)*** *foliated plagioclase-phyric basalt with elongate quartz amygdules aligned along foliation (subunit 3a; 378892E, 6303943N);* ***c)*** *strongly foliated plagioclase-phyric basalt with relict plagioclase phenocrysts together with felsic veinlets occurring along and/or cutting foliation (subunit 3a; 379749E, 6307004N);* ***d)*** *aphanitic basalt (subunit 3a) with overprinting chevron folds and crenulation cleavages (378948E, 6306335N);* ***e)*** *strongly magnetic chlorite-amphibole schist, interpreted to have a picrite protolith (subunit 3b, see text; 380720E, 6306702N);* ***f)*** *a 1.5 m wide diabase dike (subunit 3c) cutting plagioclase-phyric basalt (subunit 3a; 383372E, 6306431N; Trench 3).*

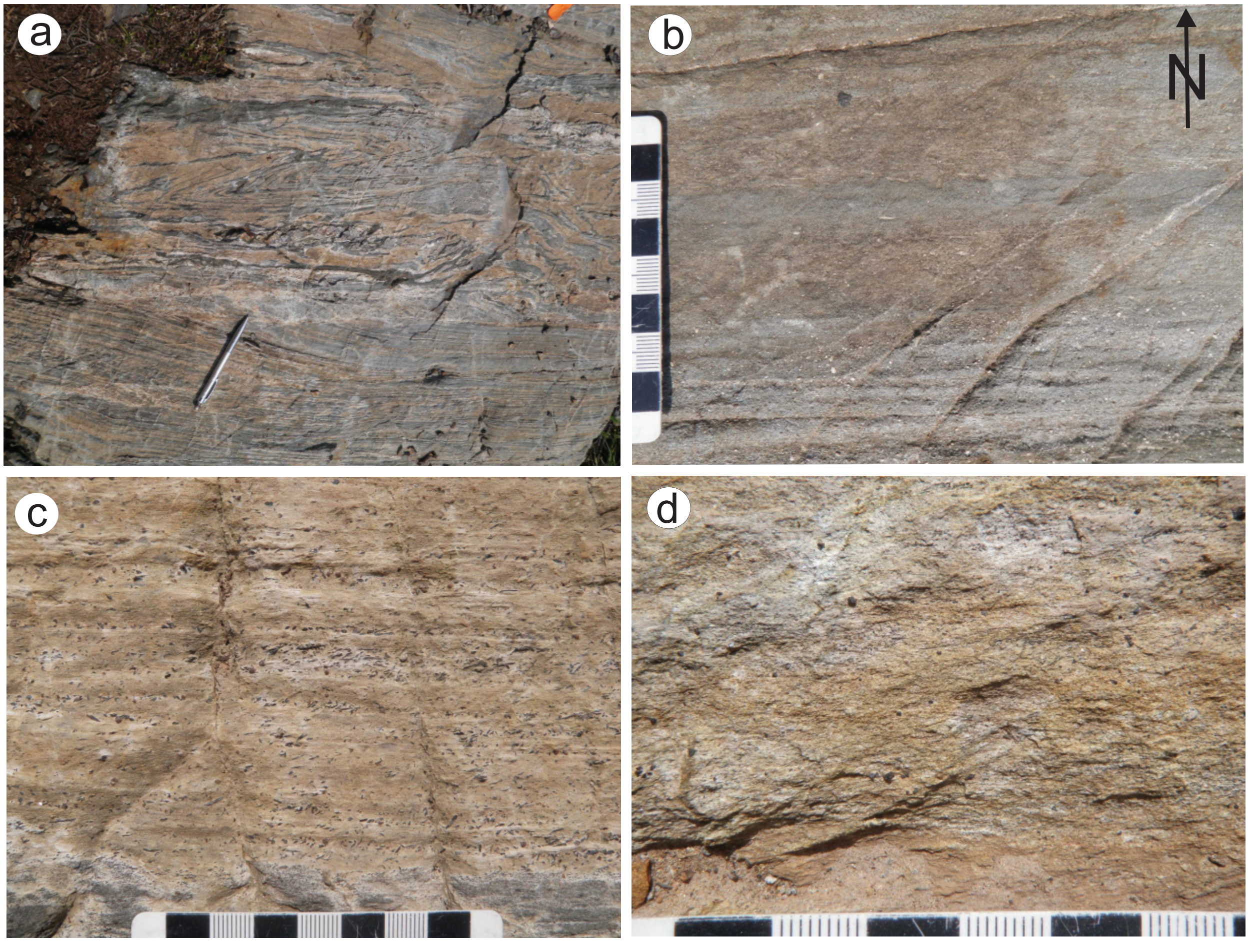

***Figure GS-4-6**: Field photographs of metasedimentary rocks intercalated with minor volcaniclastic rocks (unit 4) of the Wasekwan group: **a)** laminated mudstone and greywacke, folded by F_2 folds and transposed into S_2 foliation (subunit 4a; UTM Zone 14N, 378774E, 6305482N, NAD83); **b)** northward fining beds of pebbly greywacke, indicative of younging to the north; some of the lithic clasts are elongated parallel to the S_2 foliation (location as in a); **c)** euhedral garnet, hornblende and staurolite porphyroblasts (1 to 10 mm in diameter or in length) in bedded mudstone (location as in a); **d)** euhedral cubic and octahedral magnetite porphyroblasts up to 2 mm in intermediate tuff (subunit 4c; 377656E, 6304871N).*

and ~1% dark brown garnet porphyroblasts. In outcrops of pebbly greywacke, beds fine northward, suggesting that the stratigraphic sequence is younging to the north (Figure GS-4-6b). Staurolite occurs locally with garnet and hornblende in mudstone beds (Figure GS-4-6c), indicating that these rocks underwent middle-amphibolite–facies metamorphism (cf. Winter, 2009).

A ten metre thick layer of volcanic sandstone and strongly magnetic intermediate to felsic tuff (subunit 4c) occurs in the upper section of unit 4. This intermediate volcaniclastic bed can be correlated with intermediate tuff (>75% volcanic fragmental material) to tuffaceous sandstone (25–75% volcanic fragmental material) in the northwestern limb of the northeast- to east-northeast-trending Minton-Sheila lakes synform (Figure GS-4-2). This synform was identified originally by Gilbert et al. (1980), and is interpreted as an F_2 generation fold (Beaumont-Smith and Böhm, 2004). The volcanic sandstone contains from 10 to 25% volcanic fragments, while tuffaceous sandstone has relatively more volcanic fragments (25–75%), 0.1–2 mm in size. The intermediate tuff is characterized by 1 to 2% euhedral cubic and octahedral magnetite porphyroblasts from 0.5 to 2.0 mm in size (Figure GS-4-6d). This fine- to medium-grained tuff is strongly foliated and recrystallized, consisting of 40 to 50% plagioclase fragments (0.1–1.5 mm) in addition to magnetite porphyroblasts, and minor chloritic amphibole fragments (1–2 mm) in a fine-grained matrix of biotite, plagioclase, amphibole, lithic material and iron-oxide minerals. Sulphides are disseminated in some of the intermediate tuff and sandstone beds.

Metagabbro (unit 5)

Metagabbro of unit 5 intruded the Lynn Lake rhyolite (unit 1) and volcaniclastic package (unit 2) in the southwest part of the mapping area (Figure GS-4-2). The metagabbro weathers greenish-grey, and is dark greenish-grey to black on fresh surfaces. It is medium grained and massive, although it is strongly foliated near its northern contact. The metagabbro consists of 40 to 45% plagioclase laths from 2 to 5 mm long, 55 to 60% amphibole (pseudomorphs after pyroxene), minor iron-oxide minerals, and trace-disseminated pyrrhotite and chalcopyrite. Parts of the metagabbro in the south of unit 5 contain dense disseminated to net-textured pyrrhotite, chalcopyrite and pentlandite. The unit 5 metagabbro was metamorphosed to an assemblage of chlorite, actinolite, epidote and albite, but its primary texture is well preserved. The metagabbro was intruded by fine-grained granitoid dikes (unit 6), and crosscut by felsic veinlets. Unit 5 metagabbro displays a consistent range of magnetic susceptibility (MS) values (0.521×10^{-3}–0.937×10^{-3} SI); mineralized zones are characterized by slightly lower MS values, similar to unit 2 volcaniclastic rocks

The unit 5 metagabbro is genetically associated with and hosts the Lynn Lake Ni-Cu-Co deposit, which historically produced 22.2 Mt of ore grading 1.0% Ni and 0.5% Cu (Pinsent, 1980; Jurkowski, 1999). The intrusion was dated at 1871.3 ±2.4 Ma by Turek et al. (2000), an age ascribed to the pre-Sickle intrusive suite (Table GS-4-1) or to the Pool Lake intrusive suite of Gilbert et al. (1980).

Quartz diorite, granodiorite, granite, and associated pegmatitic and aplitic dikes—pre-Sickle intrusive suite (unit 6)

Unit 6 granitoid rocks and associated pegmatite and aplite dikes are mainly distributed in the southeast of the mapping area, represented by the Corkeram Lake composite granitoid pluton (Figure GS-4-2). This pluton is assigned to the pre-Sickle intrusive suite (Table GS-4-1), which was dated at 1876 +8/–6 Ma by Baldwin et al. (1987) using zircon U-Pb geochronology. This pluton constitutes a major component of the Pool Lake intrusive suite of Gilbert et al. (1980), stitching the northern and southern belts of the LLGB (Figure GS-4-1).

Granitoid rocks of unit 6 are exposed on the shore of Corkeram Lake and along Highway 391, and range from quartz diorite, granodiorite and granite to related minor pegmatitic and aplitic dikes. The dominant phase of unit 6 is a grey, medium to coarse grained, equigranular to locally porphyritic but foliated granodiorite, in which xenoliths of mafic to intermediate volcanic rocks, similar to those of the Wasekwan group, are present. The granodiorite (Figure GS-4-7a) consists of 20–25% anhedral quartz (0.5–0.8 mm), 25–35% subhedral plagioclase laths (0.5–1.2 cm), 20–25% K-feldspar (1–1.2 cm) and 10–15% hornblende (0.5–1 mm; mostly altered to biotite), along with accessory iron-oxide minerals. It has magnetic susceptibility (MS) values of up to 17.5×10^{-3} SI, typical of the I-type granites of Chappell and White (1974) or magnetite-series granites of Ishihara (1981). The granodiorite is cut by a fine- to medium-grained granite that contains up to 35% quartz, but less than 10% biotite (Figure GS-4-7b), and much lower MS values near 0.63×10^{-3} SI, which can be also attributed to I-type or magnetite-series granites (Yang and Beaumont-Smith, GS-5, this volume).

Pegmatite and/or aplite of unit 6 commonly occur as dikes that are a few centimetres to a few metres wide, consisting of quartz, feldspars and minor biotite. Muscovite and tourmaline are rarely present.

Ralph Lake conglomerate (unit 7)

Outcrops of the Ralph Lake conglomerate (unit 7) are sparse in the northeastern corner of the mapping area (Figure GS-4-2), where they are interpreted to overlie supracrustal rocks of the Wasekwan group (Gilbert et al., 1980; Manitoba Energy and Mines, 1986). Unit 7 consists of polymictic conglomerate and subordinate greywacke, which have been recrystallized and metamorphosed to an assemblage of biotite (±muscovite), hornblende, epidote, quartz, plagioclase (±K-feldspar) and iron oxides. The conglomerate contains pebble- to cobble-sized clasts derived from the greenstone belt and older plutonic rocks, with the majority of detrital zircon grains giving Wasekwan ages (ca. 1890 Ma; Beaumont-Smith and Böhm, 2004).

Granodiorite and granite—post-Sickle intrusive suite (unit 8)

Unit 8 granitoid rocks are represented by the Burge Lake pluton that intrudes the Wasekwan group in the west and the Ralph Lake conglomerate in the northeast of the mapping area (Figure GS-4-2). At Dot Lake, a number of granitoid dikes, assigned to unit 8, cut volcaniclastic rocks of unit 2. Beaumont-Smith et al. (2006) report a zircon U-Pb age of 1857 ±2 Ma for the Burge Lake granodiorite, suggesting that it is part of the post-Sickle intrusive suite (Table GS-4-1).

Most of the granodiorite of unit 8 is foliated, medium to coarse grained, and equigranular. Typically, it is composed of 10–15% biotite (3–5 mm), interstitial to feldspar (50–55%) that is composed of subhedral to euhedral laths (3–8 mm) in which plagioclase is dominant with subordinate pinkish K-feldspar; 25–30% anhedral or subrounded quartz (2–5 mm); and accessory minerals including magnetite, zircon, apatite and titanite (Baldwin et al., 1987). Hornblende is mostly replaced by biotite. Sericitic and chloritic alteration is common. The granodiorite at Burge Lake displays a range of MS values from 0.272×10^{-3} to 12.6×10^{-3} SI, consistent with normal I-type or magnetite-series granites (Ishihara, 1981; Yang and Beaumont-Smith, GS-5, this volume).

Quartz-feldspar porphyry and pegmatite/aplite—Late intrusive suite (unit 9)

Quartz-feldspar porphyry, pegmatite and/or aplite occur mostly as dikes in the southwest and southeast portions of mapping area. Some of the porphyries contain

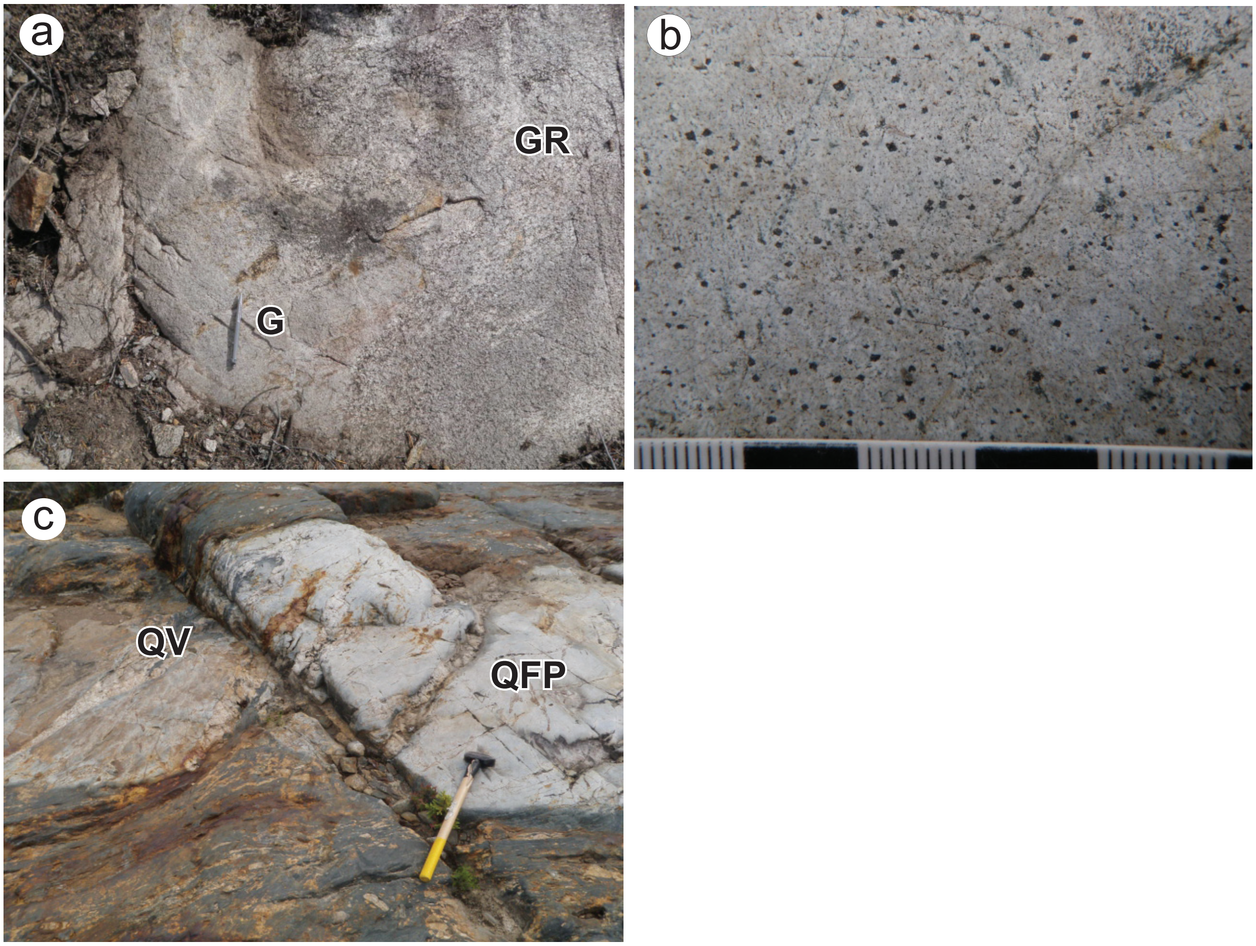

Figure GS-4-7*: Outcrop photographs of map units 6 and 9 in the Keewatin area, Lynn Lake greenstone belt:* ***a****) coarse-grained, foliated granodiorite intruded by fine-grained granite with an angular xenolith of the former just above the pencil (unit 6; UTM Zone 14N, 385233E, 6304092N, NAD83);* ***b****) magnetite-phyric quartz-feldspar porphyry (unit 9) dike cutting unit 2 volcaniclastic rocks (382365E, 6307111N; Trench 1); c) a set of north-northwest-trending en échelon quartz veins that contain sulphides, cutting quartz-feldspar porphyry dike (382359E, 6307110N). Abbreviations: G, granite; GR, granodiorite; QFP, quartz-feldspar porphyry; QV, quartz veins.*

euhedral to subhedral magnetite phenocrysts up to 2 mm in size (Figure GS-4-7b), and display very high MS values of up to 75.9×10^{-3} SI. Some porphyry dikes are cut by en échelon sulphide-bearing quartz veins that trend north-northwest (Figure GS-4-7c) and are confined restrictively within the dikes, strongly suggesting the activity of associated hydrothermal fluids.

Magnetite phenocrysts in the porphyry dikes of unit 9 provide evidence for relatively oxidized magmas. Because hydrothermal fluids associated with highly oxidized intrusions are capable of effectively scavenging and transporting gold (e.g., Boyle, 1979), these rocks warrant further investigation to determine their geochemical characteristics and potential relationships with younger granitoid rocks within the Trans-Hudson orogen (e.g., Halden and Fryer, 1999; Whalen et al., 1999; Hollings and Ansdell, 2002).

Intrusive rocks of unit 9 have an unknown association with the pre- and post-Sickle intrusive suites. Unit 9 pegmatite and aplite commonly have muscovite (±tourmaline) in addition to biotite, suggesting that they are less likely to be related to I-type or magnetite-series granitoid of both the pre-Sickle and post-Sickle intrusive suites, which typically lack muscovite (Yang and Beaumont-Smith, GS-5, this volume; Table GS-4-1).

Structural geology

Multiple phases of deformation (D_1 to D_5) were identified in the LLGB during the MGS mapping of Gilbert et al., (1980) and Gilbert (1993). More recent structural investigations were carried out at both regional scales (including stratigraphic studies of the Agassiz metallotect) and deposit scales (Peck et al., 1998; Beaumont-Smith and Rogge, 1999; Beaumont-Smith and Edwards, 2000; Ma et al., 2000; Ma and Beaumont-Smith, 2001; Anderson and Beaumont-Smith, 2001; Beaumont-Smith et al., 2001; Park et al., 2002; Beaumont-Smith and Böhm, 2002, 2003, 2004; Jones et al., 2006). At the belt scale, Beaumont-Smith and Böhm (2002, 2004) described six deformation events (D_1 to D_6): D_1 deformation is thought to be related to the assembly of volcanic terranes comprising the LLGB, although D_1 fabrics and structures are mostly obscured by later deformation; D_2 is represented by tight to isoclinal folds, regional penetrative foliation and regional-scale transcurrent shear zones, which postdate the Sickle group; D_3 is characterized by northwest-trending S-asymmetric chevron folds and associated crenulation cleavages; D_4 is represented by northeast-trending Z-asymmetric chevron folds and associated crenulation cleavages; D_5 is characterized by north-trending kilometre-scale gentle to open folds; and D_6 is indicated by brittle reactivation of D_2 transcurrent shear zones, evidenced by the formation of narrow pseudotachylite zones.

In the Keewatin River area, the D_2 deformation structures are typically the most obvious in outcrop, manifested by a steeply north-dipping S_2 foliation (which varies from rare differentiated crenulation cleavage to differentiated layering in mafic metavolcanic rocks), tight to isoclinal folds (F_2) with shallow plunges, and minor chevron folds (e.g., Figure GS-4-6a). Ductile shear zones that generally define the unit contacts are thought to be related to D_2 deformation. The intensity of S_2 fabric and tightness of F_2 folds increase toward contacts; intense shear fabrics are developed particularly in the picrite, where regional D_2 strain is concentrated (Ma et al., 2000; Park et al., 2002). The D_2 shear zones are characterized by dextral shear-sense indicators on horizontal surfaces and steeply plunging, generally down-dip to slightly oblique (easterly pitch) stretching lineations.

Generally rare in the mapping area, D_3 fabrics are represented by close to tight, S-asymmetrical F_3 folds and northwest-trending, axial-planar S_3 crenulation cleavages. The D_4 fabrics comprise dextral kink to chevron folds and steeply dipping, northeast-striking, axial-planar S_4 crenulation cleavages (e.g., Figure GS-4-5d). The F_4 folds plunge steeply to the northeast, and are penetratively developed throughout the map area. Mesoscopic structures associated with D_5 deformation include open F_5 conjugate folds, kink bands and crenulations. A north-trending, spaced S_5 fracture cleavage is also common. These structures are pervasive at regional scale, but not necessarily developed in every outcrop (Beaumont-Smith and Böhm, 2002, 2004). The D_6 deformation was brittle to ductile, represented by sinistral reactivation of D_2 shear zones, which produced pseudotachylite zones that overprint earlier deformation fabrics (Beaumont-Smith and Rogge, 1999; Ma et al., 2000).

The structural geometry of the Keewatin River area is overall characterized by shallowly plunging F_2 fold axes (e.g., Figure GS-4-6a), which steepen to subvertical within D_2 shear zones (Park et al., 2002). This geometry persists west of the MacLellan mine area, although F_4 refolding results in significant F_2 plunge variability. The intensity of F_4 development and its commensurate reorientation of older fabric elements define a macroscopic F_4 antiform that trends south-southwest from the MacLellan mine area (Figure GS-4-2). At map scale, the F_4 antiform is also manifested by the discontinuous distribution of Wasekwan group sedimentary rocks south of the MacLellan mine, and the transposition of the macroscopic F_2 synform hinge that controls the distribution of Ralph Lake conglomerate northeast of the MacLellan mine (Figure GS-4-2). The absence of the metasedimentary rocks may be an erosional effect, at the intersection of a major F_2 synformal hinge with an F_4 hinge.

Economic considerations

The LLGB is well endowed with a variety of mineral deposits and occurrences, including volcanogenic Cu-Zn (e.g., Fox Lake mine), magmatic Ni-Cu-Co (e.g., Lynn Lake mine), and orogenic Au-Ag (e.g., MacLellan mine). These disparate deposit styles record distinct stages in the geodynamic evolution of the LLGB.

The preliminary results of this report indicate that the Keewatin River area is underlain by volcanic and related volcaniclastic rocks varying in composition from basalt to andesite, dacite and rhyolite (BADR), with minor epiclastic rocks, consistent with a volcanic-arc or back-arc depositional setting (Syme, 1985; Zwanzig et al., 1999). The BADR sequence is intruded by pre-Sickle, post-Sickle and late intrusive suites. Picrite and synvolcanic pyroxenite of unit 3 may represent an important chemical trap and focus of strain, favourable for Au mineralization. Temporally, epigenetic Au mineralization at the MacLellan deposit (Samson and Gagnon, 1995) is controlled by D_2 shear zones (Ma and Beaumont-Smith, 2001; Beaumont-Smith and Böhm, 2002, 2004) and hosted in mafic volcanic and volcaniclastic rocks (units 2, 3) with a retrograde mineral assemblage of chlorite, actinolite, epidote and albite, and thus postdates magmatic Ni-Cu-Co mineralization at the Lynn Lake deposit hosted in unit 5 metagabbro intrusions. The formation of the magmatic Ni-Cu-Co deposit requires a significant amount of external sulphur either at a continental margin or a back-arc setting. Some of the late intrusive suite quartz-feldspar porphyries (unit 9) contain magnetite phenocrysts, suggesting that they are derived from highly oxidized magmas. Any hydrothermal fluids associated with such oxidized intrusions can effectively scavenge and transport gold (e.g., Boyle, 1979), and may have played a role in Au mineralization in the LLGB.

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