GS-6 Geochemistry and updated geology of the Squall–Varnson lakes area, west-central Manitoba (part of NTS 63K16)

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Summary

During this past season, two weeks of fieldwork were completed along the western side of Snow Creek and north of Lalor Lake. The resulting data have been combined with the detailed geology acquired by Bailes and Schledewitz during the 1997–1999 field seasons to update the geological map of the area. The project area consists mainly of felsic gneiss and amphibolite that represent recrystallized and deformed equivalents of the Chisel and Snow Creek sequences of the Snow Lake arc assemblage, which occurs immediately south of the map area. In the southern third of the map area, protolith can still be identified locally, but further north, recrystallization and deformation typically have obliterated all primary features and thus prevent protolith recognition. The package of volcanic rocks is dominated by relatively homogeneous felsic gneiss with local minor alteration. Subordinate amounts of amphibolite, likely derived from mafic volcanic and volcaniclastic rocks, occur intercalated within the felsic rocks. Whole-rock geochemistry data was acquired from 29 samples. Felsic volcanic rocks represent a homogeneous chemical package that plots fairly tightly together and shares strong similarities with the North Balloch rhyodacite to the south; the exception to this is a few samples that are correlative to the South Balloch rhyodacite. Mafic volcanic rocks dominantly display a geochemical signature similar to that of the Balloch basalt. A few samples from the southeastern area display an ocean-floor signature similar to that of the Snow Creek basalt. Overall, the ~3.2 km thick sequence of volcanic rocks from the Squall–Varnson lakes area forms a chemically homogeneous package with little to no systematic variation throughout its stratigraphy, which typically strikes north-northwest. Deformation structures in the metavolcanic rocks are characterized by a main, well-developed, layer-parallel foliation and a prominent north-northeast–trending, shallow-plunging, stretching lineation**.** Macroscopic open folding is evidenced by changes in foliation direction.

Introduction

The Snow Lake area, which forms the eastern portion of the Paleoproterozoic Flin Flon–Snow Lake greenstone belt, is host to more than 18 exploited and undeveloped volcanogenic massive sulphide (VMS)-type base-metal deposits. These deposits are hosted in oceanic-arc–related volcanic rocks and all but a few (Bur, Osborne Lake and Wim) are located within the main package of Snow Lake arc assemblage (SLA) rocks (Bailes and Schledewitz, 1998; Bailes and Galley, 1999) in the footwall of the Snow Lake Fault. All VMS deposits in the Snow Lake area occur in volcanic rocks that display oceanic-arc geochemical characteristics (Syme and Bailes, 1993; Stern et al., 1995; Bailes and Galley, 1996). Because of the numerous base-metal deposits within them, volcanic rocks of the SLA south of Snow Lake have received much attention and have been mapped at scales varying from 1:5 000 to 1:20 000. The gneiss and volcanic-derived rocks of the Squall Lake–Varnson lakes area have been previously mapped at the 1:20 000 scale (Schledewitz and Bailes, 1998; Bailes and Schledewitz, 1999b). The objective of the 2011 field program was to acquire a set of representative samples from the Squall–Varnson lakes area for geochemical analysis and to re-examine keys areas. The project goal is to reassess the geological interpretation of these volcanic rocks by combining previous mapping with new geochemical data and geological data, and in the light of new interpretations of the SLA geology (Bailes and Galley, 2007), reconcile it with the geology immediately south of the map area. The results will be a new 1:20 000 compilation of the geology of this area, compatible with that already existing for the VMS-hosting volcanic rocks to the south. Fieldwork in 2011 was focused on a 3.5 by 8 km northeast-striking sequence of metavolcanic and metavolcaniclastic rocks. The 2011 preliminary map provides better constraints on the spatial distribution of the various lithological and structural elements of the Squall–Varnson lakes area; this revised 1:20 000 scale geological map (Gagné et al., 2011) integrates data from this latest field season with results from mapping done in previous years. This paper briefly discusses the geology of the area and geochemical results, and assesses their implications for mineral exploration east of Snow Creek.

Regional geology and local setting

Arc-volcanic and volcaniclastic rocks immediately south of the Snow Lake area are referred to as the Snow Lake arc assemblage (SLA; Stern et al., 1995; Lucas et al., 1996). A detailed description of the SLA stratigraphy and geochemistry is presented in Bailes and Galley (1996; 1999; 2007) and Bailes (1997). The SLA is exposed in a volcanic succession >6 km-thick and 15–20 km wide, which hosts most producing and past-producing mines in the Snow Lake area (Figure GS-6-1). The dominantly juvenile to crustally contaminated SLA volcanic succession is, and has been, subdivided into three distinct sequences, based on geochemical and lithological characteristics (Bailes and Galley, 1996, 1999, 2007):

- The lowermost Anderson sequence is a bimodal mafic-felsic succession dominated by flows
- The medial Chisel sequence is dominated by volcaniclastic rocks of highly variable composition
- The uppermost Snow Creek sequence is composed almost entirely of pillowed basalt

Geochemical variations between the three distinct volcanic sequences have been interpreted as representing the evolution of the SLA from a 'primitive-arc' (Anderson sequence) to a 'mature-arc' (Chisel sequence) setting, and then to an 'evolved-arc–rift' setting (Snow Creek sequence).Volcanogenic massive sulphide deposits occur in both the Anderson and the Chisel sequences, which contain evidence of intra-arc rifting.

The 3.5 by 8 km package of gneiss and volcanic-derived rocks that occur between Snow Creek and Varnson Lake correlates chemically with the mature-arc portion (Chisel sequence) of the SLA to the south. However, these rocks generally experienced higher-grade metamorphism, with peak-metamorphic conditions that ranged from middle- to upper-amphibolite facies, as compared with their southern equivalents. The Snow Lake area is characterized by a northward increase in peak-metamorphic temperature from ~500 to 700°C, accompanied by only a minor increase in pressure from 4 kbar in the south to 6 kbar in the north (Kraus and Menard, 1997). In the Squall–Varnson lakes area, this northward increase is clearly reflected in the metamorphic mineral assemblages of the Burntwood Group turbidites, which show a progression from the biotite-staurolite zone around the southern end of Snow Creek, to the biotite-sillimanite zone near the southern end of Squall Lake, and culminates with the assemblage sillimanite–almandine–biotite about halfway through Squall Lake. Due to their protolith composition, the gneiss and volcanic-derived rocks do not show systematic changes in metamorphic mineral assemblage; however, the increase in metamorphic grade is reflected in these rocks by a progressive northward increase in the degree of recrystallization, to the point where protolith recognition is no longer possible.

Volcanic rocks in the Squall–Varnson lakes area

In the southern portion of the Squall–Varnson lakes area, the rocks of the SLA consist mostly of massive felsic volcanic rocks and lesser amounts of heterolithic mafic breccia, mafic flows and synvolcanic intrusions (Schledewitz and Bailes, 1998; Bailes and Schledewitz, 1999a). In the northern half of the map area, the SLA is characterized by felsic quartzofeldspathic gneiss and amphibolite interpreted as the recrystallized equivalents of the recognizable volcanic and volcaniclastic rocks observed in the south. The area is characterized by massive monotonous lithological units, which extend along strike over several kilometres (Figure GS-6-2). Very few facing directions are observed in these rocks as a consequence of the intensity of regional metamorphism. Primary rock units are recognized only in the southern half of the map area. A brief outline of the main characteristics of each unit is presented below; unit numbers correspond to those on Preliminary Map PMAP2011-2 (Gagné et al., 2011) and 1999F-1 (Bailes and Schledewitz, 1999b). A further detailed description of the lithological units is presented in Bailes and Schledewitz (1999a).

Porphyritic basalt flows of unit 1 outcrop east and southwest of Tern Lake. At both localities the flows are pillowed and are continuous with mature-arc basalt to the south. The basalt flows east of Tern Lake correlate with the Threehouse basalt, whereas those west of Tern Lake correlate with a unit of mafic volcanic rocks stratigraphically below the Threehouse basalt (Bailes et al., 1997), within the Photo Lake rhyolite.

Massive aphyric basalt and basaltic andesite flows of unit 2 include rare pillowed flows and amoeboid pillow breccia, as well as subordinate horizons of volcaniclastic rocks (Figure GS-6-3a, b). The flows locally contain quartz-filled amygdules. In field appearance, they look very similar to the Balloch basalt, which outcrops just south of the map area (Bailes et al., 1997). This unit occurs throughout the map area as thin (50–300 m) horizons within felsic volcanic rocks.

Rocks equivalent to the Photo Lake rhyolite (unit 3; Bailes et al., 1997; Bailes and Schledewitz, 1999a) outcrop just south of Tern Lake (Figure GS-6-2) and consist of a monotonous sequence of massive aphyric to sparsely porphyritic felsic rocks and derived felsic gneiss.

The massive, featureless, quartzofeldspathic biotite-bearing gneiss of unit 4 dominates the map area. As discussed in Bailes and Schledewitz (1999a), these rocks are interpreted as deriving largely from felsic metavolcanic rocks. In the southern part of the map area, various facies of felsic volcaniclastic rocks can be recognized locally (Figure GS-6-3c). The quartzofeldspathic felsic gneiss locally includes felsic intrusive bodies (unit 10), which are very difficult to distinguish from their extrusive equivalents due to their high level of metamorphic recrystallization. No facing directions were observed in the felsic gneiss of unit 4.

A unit consisting of plagioclase-phyric rhyodacite tuff and lapilli tuff (unit 5) 200 m wide outcrops in the southwestern corner of the map area. This unit extends south of the map area where it is known as the 'Powderhouse dacite' (Bailes, 1997; Bailes and Galley, 2007). This very distinct package of felsic volcaniclastic rocks occupies the stratigraphic footwall of the Lalor Lake and Chisel Lake

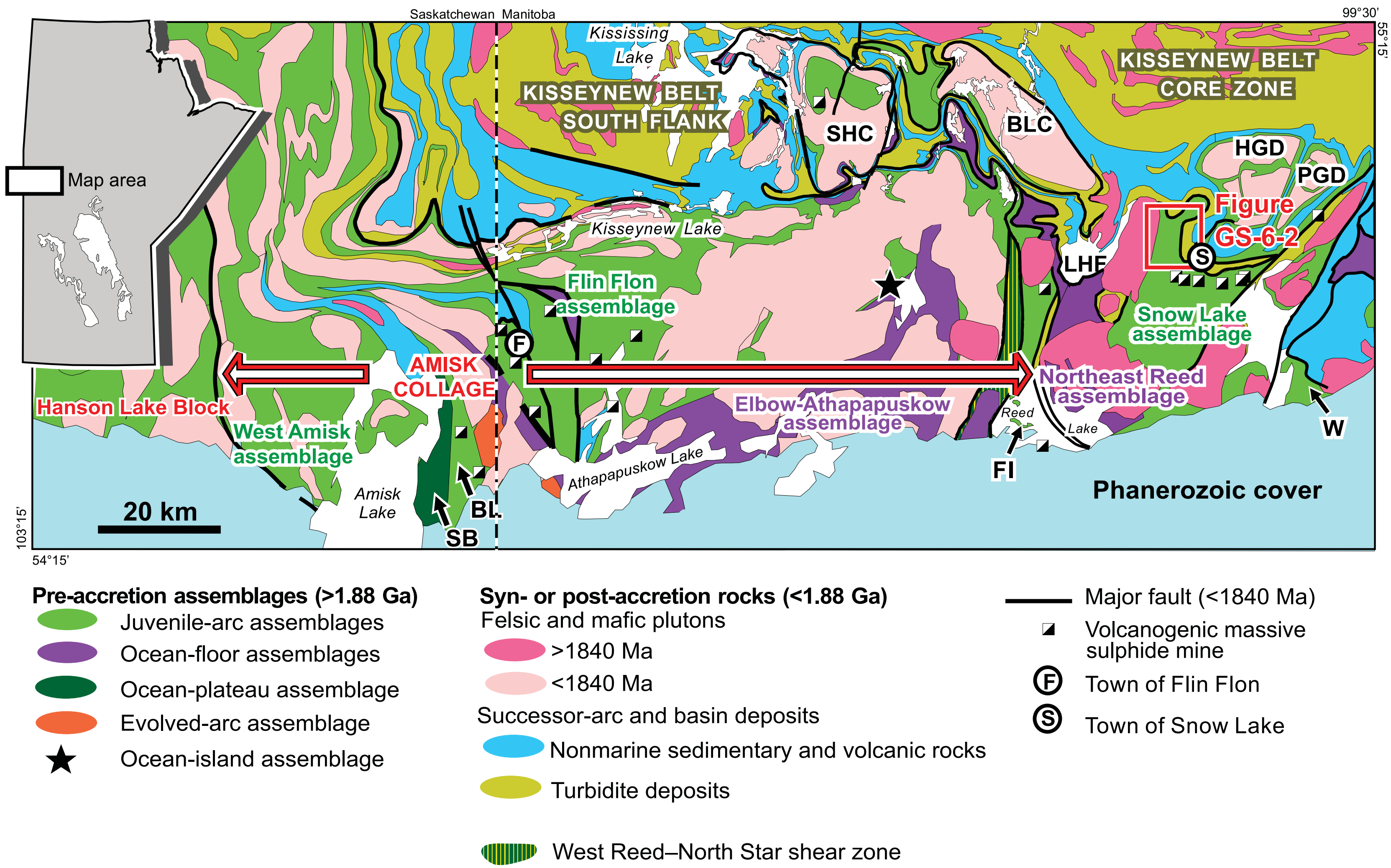

Figure GS-6-1: *Geology of the Flin Flon–Snow Lake greenstone belt, in west-central Manitoba, showing the location of Figure GS-6-2. Abbreviations: BL, Birch Lake; BLC, Batty Lake complex; FI, Fourmile Island; HGD, Herblet gneiss dome; LHF, Loonhead Lake Fault; PGD, Pulver gneiss dome; SB, Sandy Bay; SHC, Sherridon–Hutchinson Lake complex.*

VMS deposits; the type area lies south of the Chisel Lake mine. It is typically massive, characterized by 5–15% of 0.5–3 mm plagioclase phenocrysts and small plagioclase-phyric felsic fragments. The dacite is commonly strongly altered with hornblende and garnet in amounts varying from 10–30% and 10–25%, respectively. Mafic volcaniclastic rocks (unit 6; Figure GS-6-3d) comprise thin units that are locally intercalated within mafic (unit 2) and felsic (unit 4) gneiss west of Snow Creek.

The volcanic stratigraphy in the map area is cut by a number of small intrusions, including pyroxenite, melagabbro, gabbro (unit 7); a fractionated gabbro sill (unit 8); gabbro, diorite, quartz diorite and derived amphibolite (unit 9); and quartz- and quartz-plagioclase porphyry (unit 10). Many of these intrusions are interpreted as synvolcanic but some could be younger. Pyroxenite, melagabbro and gabbro (unit 7) outcrop southeast of Tern Lake (Figure GS-6-2) and correlate to the south with a suite of mafic intrusions that have been interpreted by Bailes et al. (1997) as feeders for the Threehouse basalt. A fractionated gabbro sill (unit 8), south of Snow Lake and north of Tern Lake, is composed of equigranular fine- to medium-grained gabbro, coarse-grained gabbro with bladed amphiboles and interstitial plagioclase and coarse-grained quartz diorite, also with bladed amphiboles. Gabbro, diorite, quartz diorite and derived amphibolite (unit 9) form small bodies throughout the map area (Gagné, 2011). Although the age of these intrusions is unknown, similar intrusions south of the map area have been interpreted as synvolcanic (Bailes et al., 1997). Small bodies of quartz- and quartz-plagioclase porphyry (unit 10) occur southwest of Squall Lake (Gagné, 2011). In the Balloch Lake area to the south, Bailes et al. (1997) has demonstrated some of these intrusions to be synvolcanic.

There are outcrops of greywacke, siltstone and mudstones of the Burntwood Group (unit 11) on the eastern side of Squall Lake and Snow Creek. Post-1.84 Ga intrusive rocks in the map area include the layered Chisel Lake ultramafic intrusion (unit 12), the Ham Lake felsic pluton (unit 13) and some small bodies of late granite pegmatite (unit 14). Medium-grained, foliated granitic rocks (unit 15) of uncertain age form the core of the Squall Lake dome.

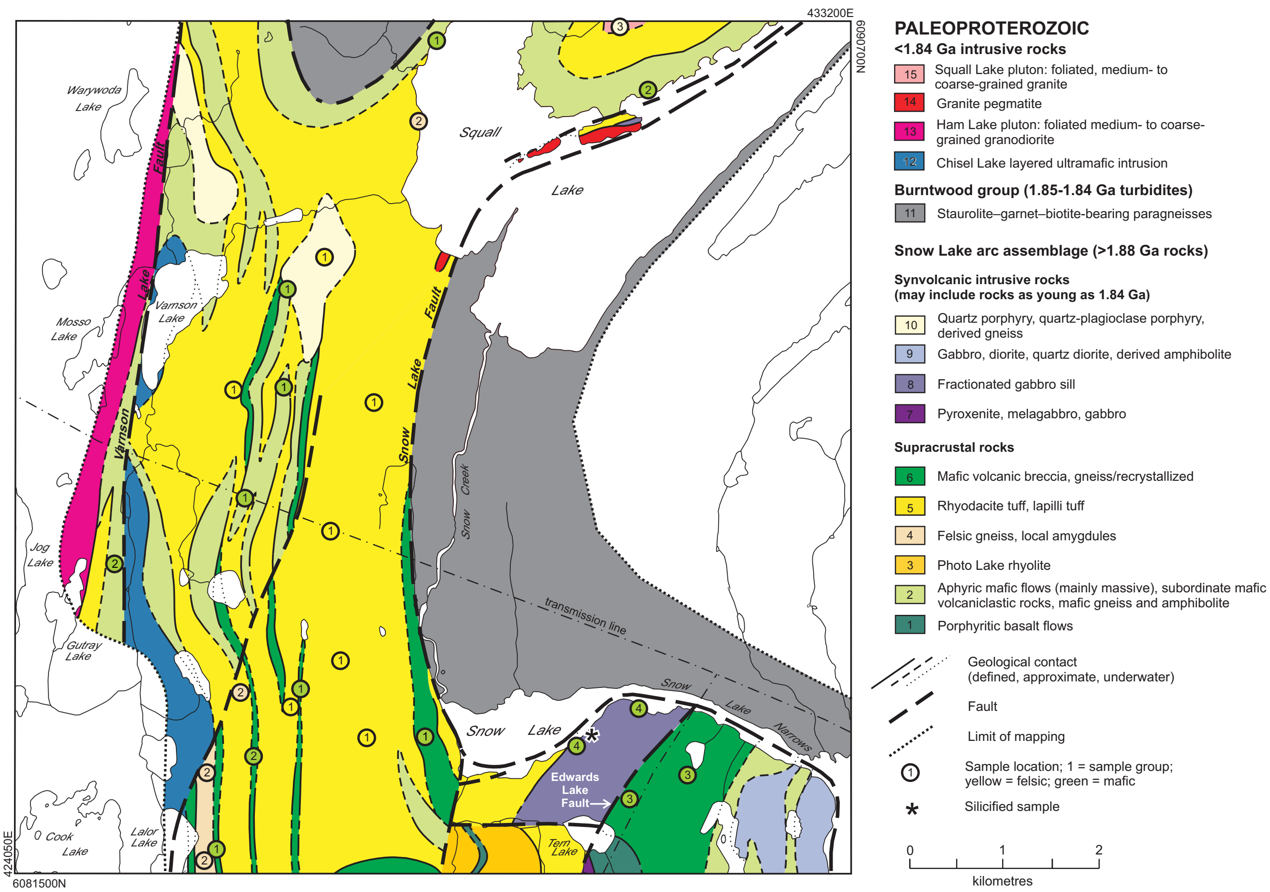

Figure GS-6-2: *Simplified geology of the Squall–Varnson lakes area, west-central Manitoba (modified from Bailes and Schledewitz, 1999a). Unit numbers correspond to those on Preliminary Map PMAP2011-2 (Gagné et al., 2011) and 1999F-1 (Bailes and Schledewitz, 1999b).*

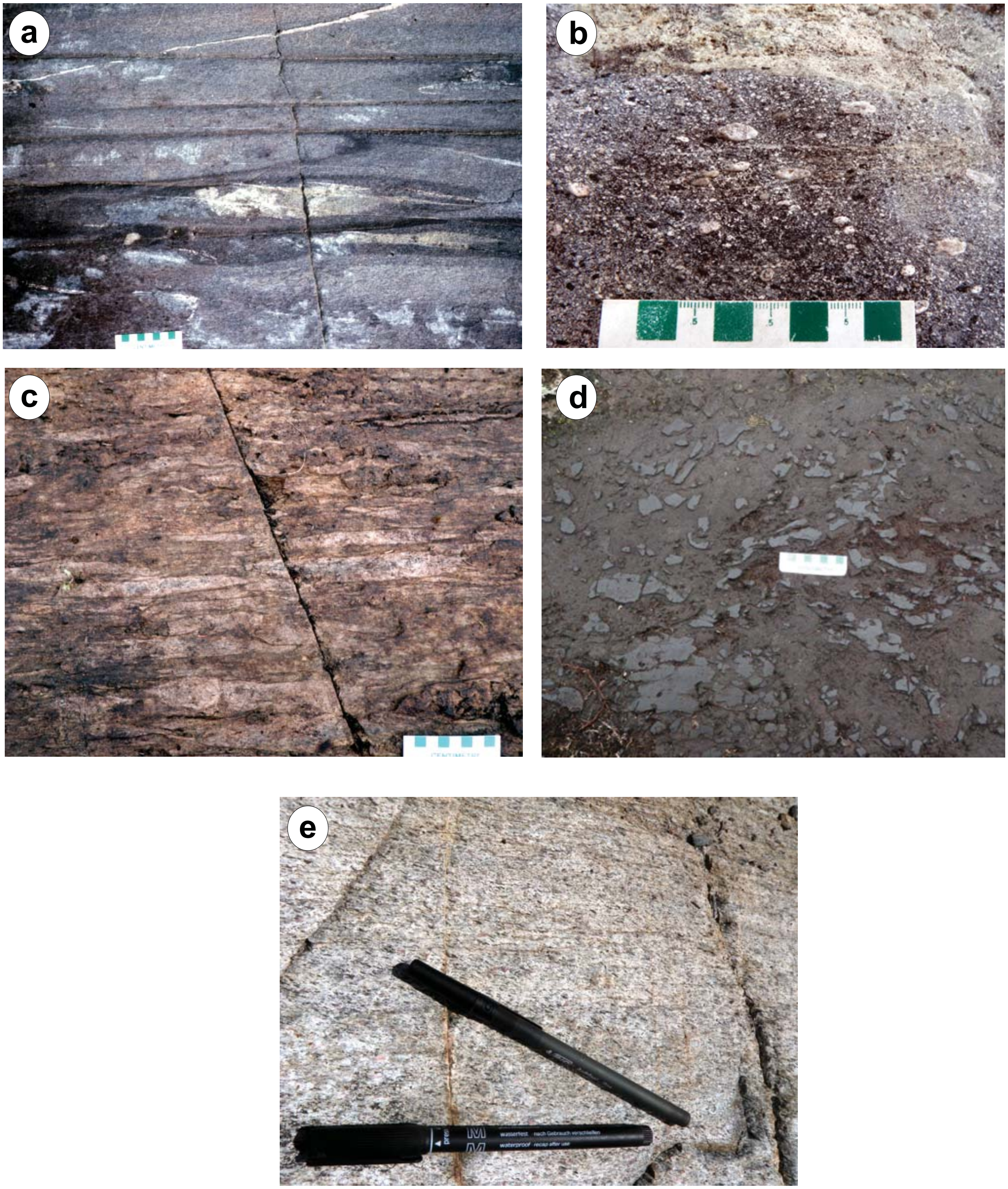

Figure GS-6-3: *Volcanic rocks in the Squall–Varnson lakes area, west-central Manitoba:* ***a)*** *elongated aphyric basalt pillows from unit 2, observed 1 km northeast of Erzinger Lake (scale bar is 9 cm);* ***b)*** *subordinate horizon of plagioclase–pyroxene-phyric mafic lapilli tuff in unit 2, including 0.3–1.0 cm quartz amygdules, east of Tern Lake along the power line (scale bar is 8.5 cm);* ***c)*** *felsic lapilli tuff from unit 4, at the western end of Snow Lake (scale bar is 8.5 cm);* ***d)*** *monolithic mafic breccia from unit 6 east of Hurlin Lake, with clasts of aphyric basalt in positive relief (scale bar is 8.5 cm);* ***e)*** *thinly laminated felsic crystal tuff from unit 4 displaying two planar fabrics (S_1 and S_2), 500 m east of Lalor Lake (pens are 14 cm).*

Whole-rock geochemistry

Twenty samples representing several of the major rock types from the Squall–Varnson lakes area were collected for chemical analysis during a two week geological mapping program. Nine additional samples were selected from archive material to complete the dataset. The geochemical sampling program was designed primarily to assemble a representative suite of samples from most lithological units of the Squall–Varnson lakes area for the purpose of characterizing the trace and rare earth element (REE) geochemistry of the rocks. The program further aims to aid in the correlation and comparison with other volcanic rocks from the Snow Lake area, as well as with identification of chemical variations within map units.

Sampling and analytical procedures

The samples collected specifically for geochemical analysis are mainly from mesoscopically least-altered rocks but do include some altered rocks. All samples were trimmed to remove weathered surfaces, joints and veinlets; some samples contain minor amygdules. Altered samples are not included on any of the geochemical plots in this report, except where noted. The trimmed samples were crushed with a tungsten-carbide mill in the Manitoba Geological Survey rock laboratory; chemical analyses were carried out by Activation Laboratories Ltd. (Ancaster, Ontario). Major and minor elements were analyzed by inductively coupled plasma–emission spectrometry (ICP-ES) and trace elements were analyzed using inductively coupled plasma–mass spectrometry (ICP-MS); analysis results are presented in Data Repository Item DRI2011007[1].

Felsic volcanic rocks

Felsic volcanic rocks dominate the volcanic sequence and could not be subdivided on the basis of macroscopic description. Thus whole-rock geochemistry of representative samples is used to check for chemical variation and may allow for recognition of chemically distinct horizons. The new data also facilitates comparisons with potentially correlative felsic rocks south of the map area. With these objectives in mind a total of 13 samples of felsic rocks were collected from units 4, 5 and 10.

Seven samples collected from unit 4 and 10 (felsic sample 1; Figure GS-6-2) throughout the map area share a very similar geochemical signature and plot tightly together (Figures GS-6-4a, -5a, -6a). These samples are characterized by moderate Nb/Y ratios (0.35–0.5; Figure GS-6-4a) indicative of a subalkaline affinity. The REE patterns on a chondrite-normalized REE diagram show negative slopes with marked enrichment in light REE (LREE; GS-6-5a). They also show pronounced negative Nb, Zr and Ti anomalies on a mantle-normalized trace-element diagram (Figure GS-6-6a). These rocks have similar geochemical characteristics to those of the rocks in the footwall of the Chisel sequence deposits (Bailes, 1997, Figure GS-8-7, "Powderhouse dacite–Chisel Lake area"). Rocks from the North Balloch rhyodacite, an unofficial unit of felsic volcanic and volcaniclastic rocks from the immediate hanging wall of the Balloch basalt, also display a very similar geochemical signature (HudBay Minerals Inc., unpublished data, 2011). Based on their stratigraphic and map positions, it appears likely that 'felsic sample 1' rocks are correlative to the North Balloch rhyodacite.

Four other samples share a similar geochemical signature (felsic sample 2; Figures GS-6-4a; -5b, -6b). Two of the samples were collected from unit 4 and the two other samples came from a felsic horizon (unit 5; Figure GS-6-2) directly along strike from dacitic volcaniclastic rocks immediately to the south. These samples are characterized by moderate Nb/Y ratios (0.15–0.35; Figure GS-6-4a) indicative of a subalkaline affinity. The REE patterns on a chondrite-normalized REE diagram have negative slopes with lesser enrichment in LREE (Figure GS-6-5b) than 'felsic sample 1' rocks (Figure GS-6-5a). They also display pronounced negative Nb, Zr and Ti anomalies on the mantle-normalized trace-element diagram (Figure GS-6-6b). The four samples display a broader range in composition than 'felsic sample 1' rocks. Dacitic rocks south of the map and along strike from unit 5 (Bailes, 1997, Figure GS-8-7, "Powderhouse Dacite–Photo Lake area"), the South Balloch rhyodacite (Bailes 1997, Figure GS-8-7, Bolloch Rhyodacite [sic])—an unofficial unit of felsic volcanic and volcaniclastic rocks from the immediate hanging wall of the Balloch basalt—and the Chisel Lake and Photo Lake rhyolite (Bailes, 1997, Figure GS-8-7) all have a geochemical signature similar to that of 'felsic sample 2'. Three of the four samples with a 'felsic sample 2' signature come from the southwestern corner of the map. Their location and chemical signature suggested that 'felsic sample 2' rocks are likely correlative with the South Balloch rhyodacite. The other sample from 'felsic sample 2' was collected along the western shore of Squall Lake in an outcrop-poor area, where there are too few geological constraints to clearly establish its relationship with the other felsic volcanic rocks.

One felsic rock sample taken from the Squall Lake gneiss dome ('felsic sample 3'; Figures GS-6-2) shows a geochemical signature very similar to that of 'felsic sample 1' (Figures GS-6-4a, -5c, -6c). The sample was

[1] MGS Data Repository Item DRI2011007, containing the data or other information sources used to compile this report, is available online to download free of change at http://www2.gov.mb.ca/itm-cat/web/freedownloads.html, or on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Innovation, Energy and Mines, 360–1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

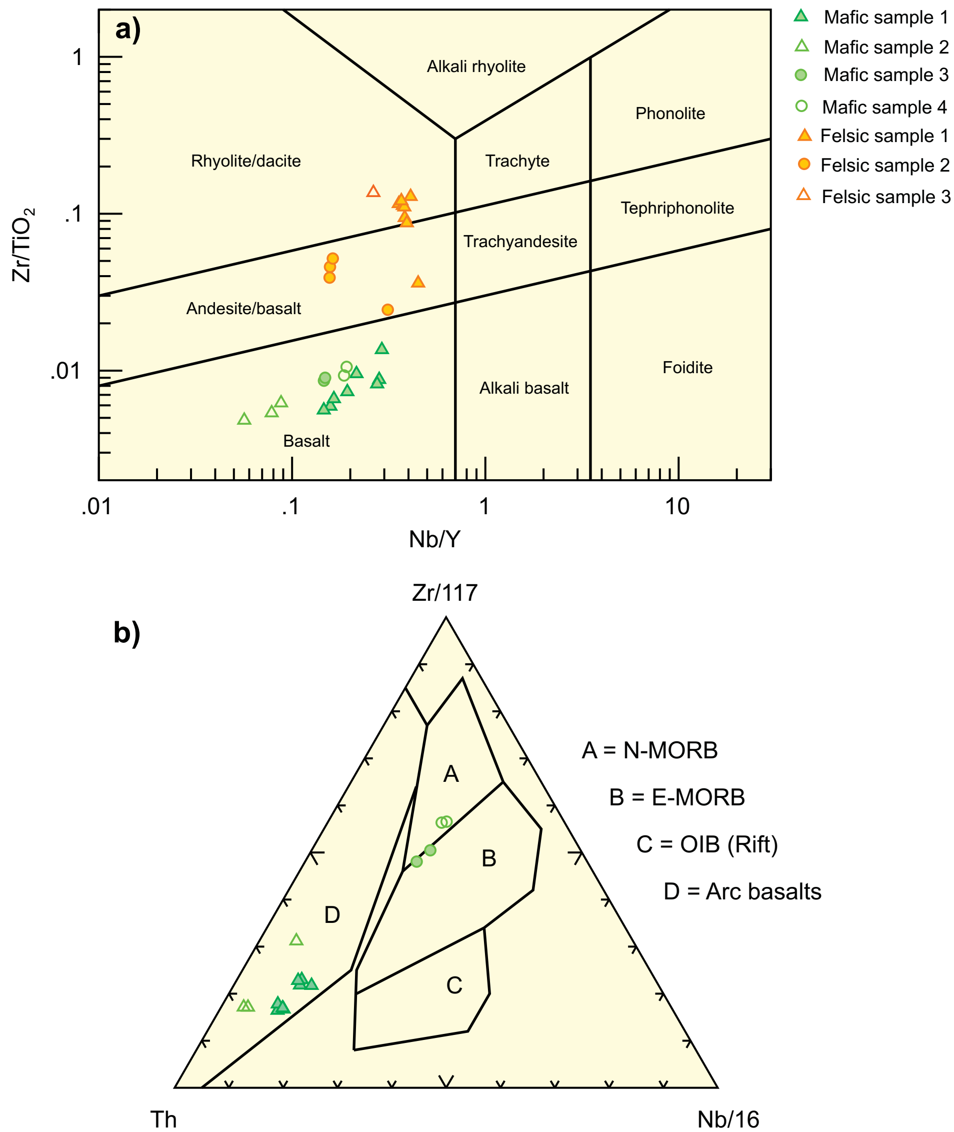

***Figure GS-6-4:** Geochemical characteristics of selected samples from the Squall–Varnson lakes area, west-central Manitoba: **a)** Zr/TiO_2 vs. Nb/Y classification diagram (modified from Winchester and Floyd, 1977); **b)** Th-(Zr/117)-Nb/16 discriminant diagram of Wood (1980). Abbreviations: E-MORB, enriched mid-ocean–ridge basalt; N-MORB, normal mid-ocean–ridge basalt; OIB, ocean-island basalt.*

a homogeneous medium-grained foliated leucogranite. This gneiss dome is part of a series of domes that extends more than 80 km west from the Pulver gneiss dome, just east of Herblet Lake, to the Sherridon–Hutchinson Lake complex (Figure GS-6-1). David et al. (1996) obtained a mixture of zircon ages from the Herblet Lake gneiss dome, which they interpreted as the product of a high-grade metamorphic overprint (1.81 Ga) upon older (1.89 Ga) volcanic and intrusive protoliths. Gordon et al. (1990) also obtained a U-Pb zircon age of 1890 +8/-6 Ma from a sample from the southern tip of the Herblet Lake gneiss dome and similarly interpreted it as an igneous crystallization age; they further suggested that the granodiorite was a subvolcanic intrusion coeval with pre-1.88 Ga volcanism. Taking these data into account, it is very possible that the Squall Lake pluton also represents a synvolcanic intrusion. The similar geochemical signatures of the Squall Lake granitic dome and felsic volcanic rocks of the Squall Lake area, although non-conclusive, support that hypothesis.

Mafic volcanic rocks

Although mafic rocks represent a minor component of the bedrock in the Squall–Varnson lakes area (Figure GS-6-2), they are widely distributed as minor intercalations within thick sequences of undivided felsic gneiss. Whole-rock geochemistry of representative samples is therefore used to test for chemical variations in the mafic rocks and to compare them with rocks south of the map, which comparison is made equivocal by

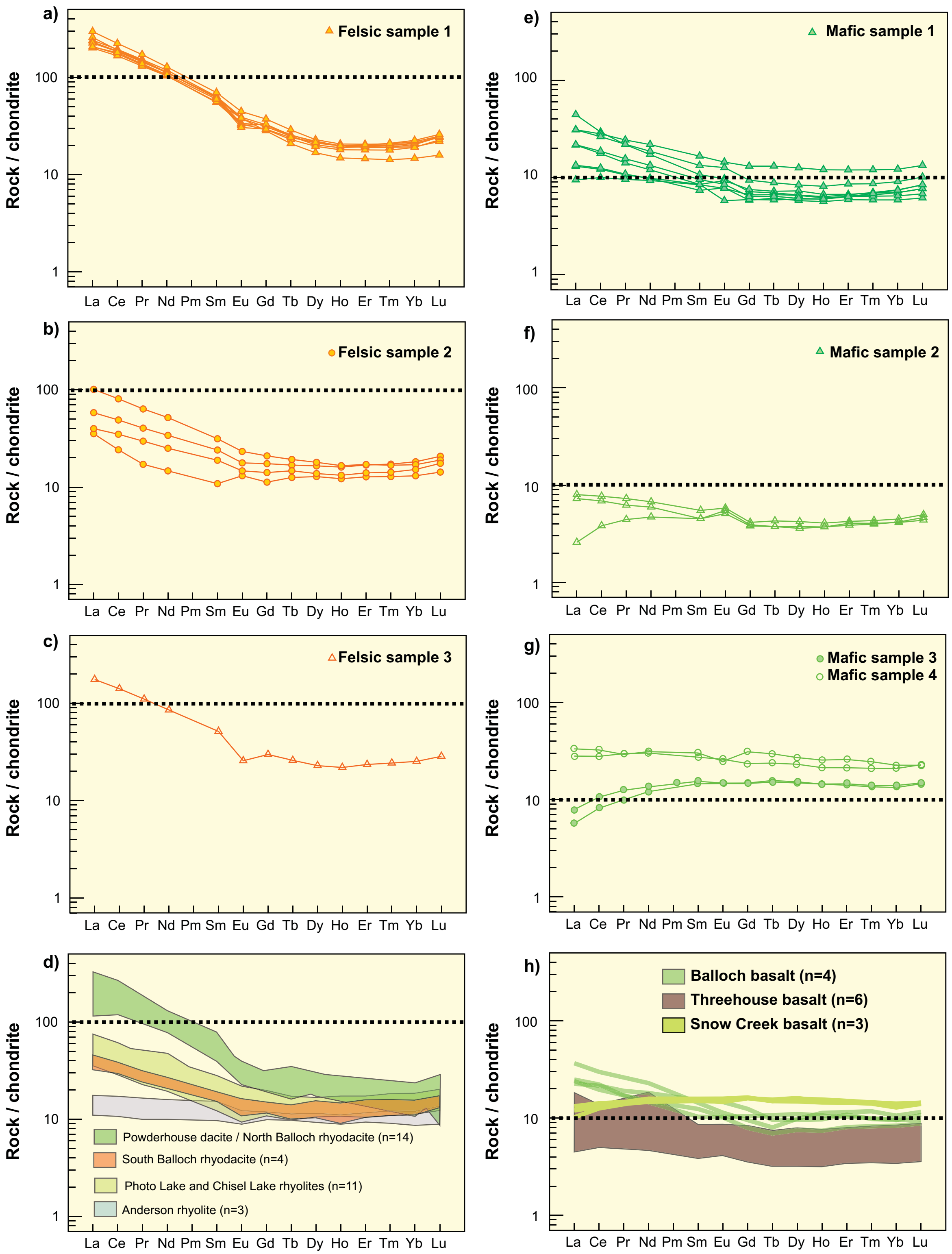

***Figure GS-6-5:** Chondrite-normalized rare earth element (REE) patterns (normalizing values from McDonough and Sun, 1995) for rocks of the Squall–Varnson lakes area, west-central Manitoba: **a)** felsic gneiss and volcanic rocks with North Balloch rhyodacite-like trace-element pattern (felsic sample 1); **b)** felsic gneiss and volcanic rocks with Chisel Lake rhyolite/ South Balloch rhyodacite-like trace-element pattern (felsic sample 2); **c)** Squall Lake gneiss dome (felsic sample 3); **d)** SLA reference felsic samples (Bailes and Galley, 2001; HudBay Minerals Inc., unpublished data, 2011); **e)** mafic gneiss and volcanic rocks with Balloch basalt-like trace-element pattern (mafic sample 1); **f)** mafic gneiss and volcanic rocks with Threehouse basalt-like trace-element pattern (mafic sample 2); **g)** mafic gneiss and volcanic rocks with ocean-floor signature (mafic sample 3 and mafic sample 4); **h)** SLA reference mafic samples (Bailes and Galley, 2001).*

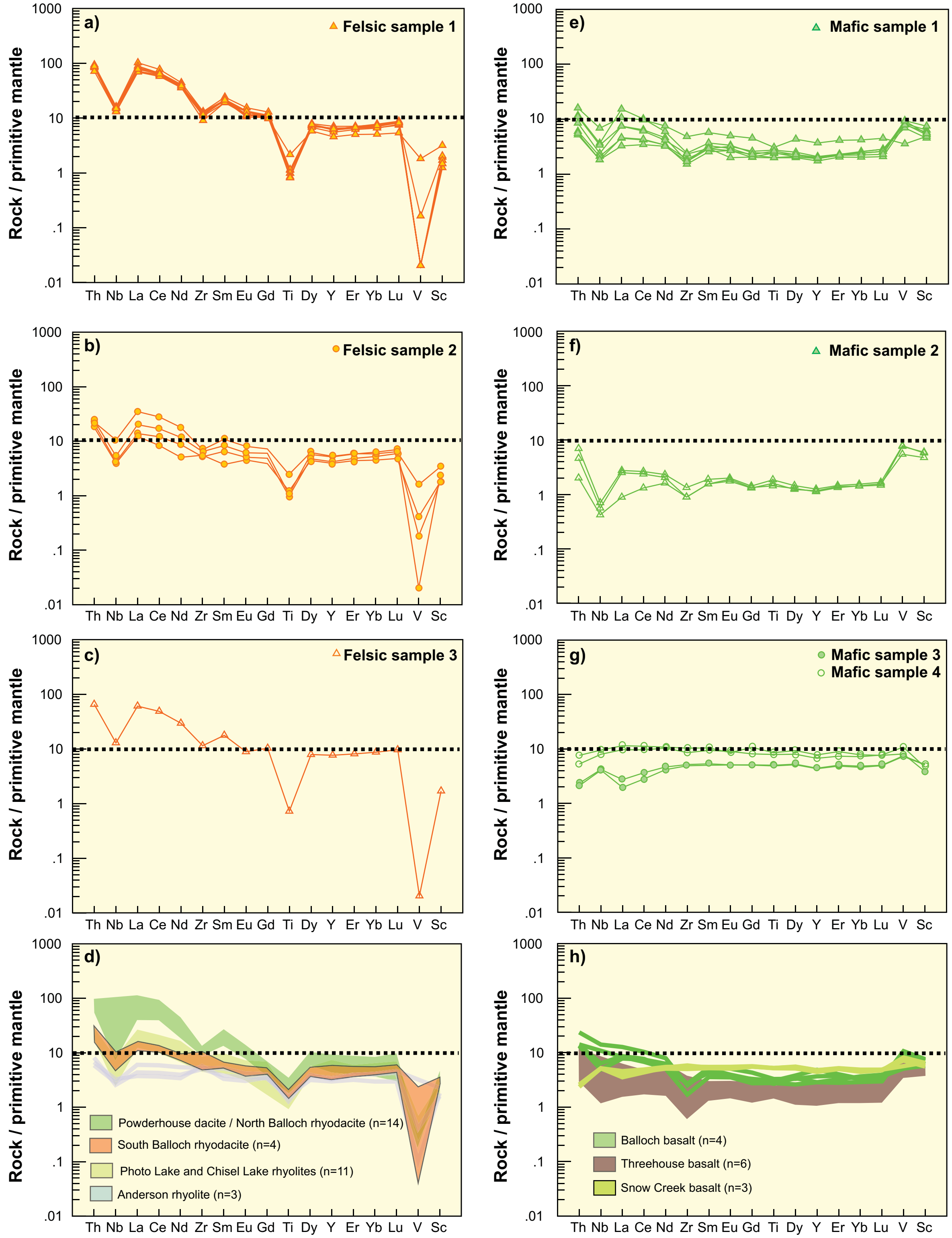

Figure GS-6-6: *Primitive mantle-normalized incompatible trace-element patterns (normalization values from Sun and McDonough, 1989) for rocks of the Squall–Varnson lakes area, west-central Manitoba:* ***a)*** *felsic gneiss and volcanic rocks with North Balloch rhyodacite-like trace-element pattern (felsic sample 1);* ***b)*** *felsic gneiss and volcanic rocks with Chisel Lake rhyolite/South Balloch rhyodacite-like trace-element pattern (felsic sample 2);* ***c)*** *Squall Lake gneiss dome (felsic sample 3);* ***d)*** *SLA reference felsic samples (Bailes and Galley, 2001; HudBay Minerals Inc., unpublished data, 2011);* ***e)*** *mafic gneiss and volcanic rocks with Balloch basalt-like trace-element pattern (mafic sample 1);* ***f)*** *mafic gneiss and volcanic rocks with Threehouse basalt-like trace-element pattern (mafic sample 2);* ***g)*** *mafic gneiss and volcanic rocks with ocean-floor signature (mafic sample 3 and mafic sample 4);* ***h)*** *SLA reference mafic samples (Bailes and Galley, 2001).*

the presence of several faults. With these objectives in mind, a total of 15 samples, including eight basalt, three amphibolite, two gabbro, one mafic tuff and one intensely altered gabbro were collected from units 2, 6, and 8.

Using their REE geochemical signature, the mafic rocks are subdivided into four distinct groups (mafic sample 1, 2, 3, 4; Figure GS-6-4a, b). All mafic samples plot within the basalt field on the Zr/TiO_2 vs. Nb/Y diagram (Figure GS-6-4a). On a Th-(Zr/117)-Nb/16 discriminant diagram (Figure GS-6-4b), all mafic samples fall within the arc-basalt field except for four samples (mafic sample 3 and mafic sample 4), which fall into the ocean-floor domain near the boundary between the N-MORB and the E-MORB fields.

The majority of mafic samples (mafic sample 1) display a typical arc signature on a primitive mantle-normalized incompatible trace-element diagram (Figure GS-6-6e), including positive Th and negative Nb anomalies, and depleted Zr. They display slight enrichment in LREE (GS-6-5e) and low Nb/Y ratios (0.15–0.3; Figure GS-6-4a). Their geochemical signature is very similar to that of the Balloch basalt (Figures GS-6-5h, -6h); low La/Yb (~2.5–4) ratios indicate a tholeiitic to transitional magmatic affinity (Barrett and MacLean, 1999).

Three mafic samples (mafic sample 2) are characterized by a lower rock/chondrite ratio than ‘mafic sample 1’ and show slight enrichment or depletion of LREE (Figure GS-6-5f). They also display a typical arc signature on a primitive mantle-normalized incompatible trace-element diagram (Figure GS-6-6f), including positive Th and negative Nb anomalies, and depleted Zr. They have low Nb/Y ratios (0.04–0.09; Figure GS-6-4a) and low La/Yb (~2.5) ratios, which indicate a tholeiitic magmatic affinity (Barrett and MacLean, 1999). These rocks share geochemical similarities with the Threehouse basalt (Figures GS-6-5h, -6h). One of the samples was taken just east of Gutray Lake and is clearly massive, very fine-grained aphyric basalt. Rocks from that area are separated from the rest of the Squall–Varnson lakes area volcanic rocks by the Varnson Lake Fault. The other samples are from an area northeast of Lalor Lake and from the northern shore of Squall Lake, just south of the gneiss dome. These two samples show a high degree of metamorphic recrystallization (i.e., they consist of homogeneous, fine- to medium-grained, foliated amphibolite) and a clear identification of the protolith is not possible. The sample collected near Gutray Lake may represent an extrusive equivalent of the Threehouse basalt, but it could equally represent a less fractionated equivalent of the Balloch basalt. Interpretation of the two other samples is more challenging because of their geographic spread. These samples may represent a less fractionated equivalent of the Balloch basalt, or dikes related to the Threehouse basalt magmatism.

The four samples that display an ocean-floor signature on the Th-(Zr/117)-Nb/16 discriminant diagram (Figure GS-6-4b) were all collected north and northeast of Tern Lake (Figure GS-6-2). Two of these samples (mafic sample 3) were collected from a basalt-dominated sequence (unit 6) just east of Tern Lake. One of these samples is slightly plagioclase-phyric massive basalt, whereas the other is medium-grained gabbro. They are characterized by low Nb/Y values (0.15; Figure GS-6-4a), indicating a subalkaline affinity, and their trace-element and REE patterns are flat, with depleted LREE relative to HREE (Figure GS-6-5g). The samples show depletion in the strongly incompatible elements, with no significant Ti or Th anomalies and a slight positive Nb anomaly typical of N-MORB (Figure GS-6-6g). These features are similar to those of the Snow Creek sequence to the south. Both ‘mafic sample 3’ samples overlap on most diagrams, indicating that they likely shared a similar source; the gabbro may have been synvolcanic with the basalt.

The two other samples (mafic sample 4; unit 8) were collected from a sequence of fractionated gabbro just north of Tern Lake. One of the samples is gabbro, whereas the other one is a highly silicified (SiO_2 ~76%) mafic rock, which was initially interpreted as a felsic rock. The two samples display an identical geochemical signature (Figures GS-6-5g, 6g). They are characterized by low Nb/Y values (0.20; Figure GS-6-4a), indicating a subalkaline affinity, and their trace-element and REE patterns are flat (Figures GS-6-5g, -6g). The samples show only a slight depletion in the strongly incompatible elements, with no significant Nb or Ti anomalies (Figure GS-6-6g).

The difference in the geochemical signature between these two pairs of samples (mafic sample 3 and mafic sample 4) indicates that, although they both have an ocean-floor affinity, they were produced from a distinct magmatic source. The Snow Creek sequence, to which they are correlative, shows the same general geochemical characteristics.

Synthesis of geochemical data

One goal of this geochemical study was to identify potential geochemical correlations with known units of the SLA and thus attempt to establish the stratigraphic affiliation of the volcanic and volcaniclastic rocks from the Squall–Varnson lakes area. The presence of faults and intrusions prevents unequivocal correlation with rocks directly to the south in the SLA.

The geochemical data show that ‘felsic sample 1’ samples, which were collected over most of the map area, display a signature very similar to that of both the North Balloch rhyodacite and Powderhouse dacite. ‘Felsic sample 2’ samples, which were collected in the southwestern corner of the map, except for one sample, have chemical characteristics similar to that of the South

Balloch rhyodacite and the Chisel Lake rhyolite. Finally, a sample taken from the gneiss dome (felsic sample 3) displays a geochemical signature very similar to that of most felsic gneiss (felsic samples 1).

Amphibolite and volcanic-derived mafic rocks of the Squall–Varnson lakes area display, for the most part, geochemical characteristics similar to those of the Balloch basalt. A few scattered samples show a slightly different geochemical signature with lower rock/chondrite ratios. These samples can be interpreted as Threehouse basalt equivalents or as less fractionated Balloch-basalt–related rocks. A set of four samples from the southeastern corner of the map area shows an ocean-floor signature, and thus potentially correlates with Snow Creek sequence rocks immediately to the south.

Overall, the mafic and felsic volcanic and volcaniclastic rocks of the Squall–Varnson lakes area define a tholeiitic, bimodal sequence with an island-arc chemical signature and thus display the typical geochemical signature of the SLA 'evolved arc' (Bailes and Galley, 1996). Bailes and Schledewitz (1999a) suggested that the mafic and felsic volcanic rocks of the Squall–Varnson lakes area are correlative with the North Balloch rhyodacite and Balloch basalt, which would indicate that the bulk of the Squall–Varnson lakes area rocks belong to the upper Chisel sequence of the SLA (Bailes and Galley, 2007), which correlation is strongly supported by the current data. The large extent and great thickness of Balloch-related rocks indicate that the volcanic system generated a significant amount of volcanic and volcaniclastic material.

Structural geology

Bedding in fine-grained felsic tuffs and mafic volcaniclastic rocks indicates an overall northerly strike for volcanic rocks of the Squall–Varnson lakes area. To the north, changes in bedding orientation and foliation define a pair of large-scale-F_3 folds. To the southeast, rocks within fault-bounded blocks trend more to the northeast. Top indicators were not identified within the map area except for a few outcrops in the southeastern corner, where the sequence appears to be in an upright position, younging to the east.

Typically, the rocks record a strong layer-parallel foliation (S_1), which dips moderately to the east. A late, less prominent foliation (S_2) is locally recognizable (Figure GS-6-3e) and strikes 10–15° clockwise from the main foliation, with a steeper dip. The prominent foliation (S_1) dips steeply in the southern half of the map area, but becomes progressively more shallow-dipping and locally folded (F_2) in the northern half.

Large-scale northeast-trending F_3 open folds (Kraus and Williams, 1999) and orthogonal F_4 open folds control the macroscopic map pattern in the north. The Squall Lake gneiss dome is a good example of a structural antiform generated by F_3-F_4 interference folding.

A well-developed stretching lineation (L_1) is recorded by the volcanic rocks throughout the map area. The lineation can be observed as elongated lapilli, stretched amygdules, as well as a mineral lineation defined by amphibole. Typically, the lineation trends to the northeast (020–030°) and varies in plunge, from about 25 to 30° in the south, to subhorizontal in the north. The lineation plunges shallowly to the southwest in the southern half of the Squall Lake gneiss dome as a result of F_4 folding.

Several major faults occur in the Squall–Varnson lakes area. The Snow Lake Fault (Figure GS-6-2) separates younger (1.84 Ga–1.85) Burntwood Group greywacke in the hangingwall from older (1.89–1.9 Ga) SLA volcanic rocks in the footwall. The fault runs along the southern side of Snow Lake, bends 90° to the north to follow Snow Creek and wraps eastward around the Squall Lake gneiss dome. The Snow Lake Fault has been correlated, to the west, with the Loonhead Lake Fault at File Lake (Connors, 1996) and it has been interpreted as a regional-scale F_1 structure by Kraus and Williams (1999). The northeast-trending Varnson Lake Fault runs on the western side of the map area through Lalor Lake and Varnson Lake. The Edwards Lake Fault trends northeast through Tern Lake and terminates against the Snow Lake Fault. It separates two blocks of mafic rocks with ocean-floor signature. Just to the west of Tern Lake, another fault, which splays off the Edwards Lake fault to the south, separates rocks from the Photo Lake area from the rest of the Squall–Varnson lakes area volcanic rocks.

Economic implications

Snow Lake arc-assemblage volcanic rocks of the map area share geochemical characteristics and, on this basis, can be correlated with the upper Chisel sequence (in particular, to the Balloch basalt and the North and South Balloch rhyodacite). Historically, all of the VMS deposits from the Chisel sequence have been found within the lower sequence. The Photo Lake VMS deposit, just south of the map area, may possibly belong to the upper Chisel sequence, but its stratigraphic position is still uncertain. Rocks from the Squall–Varnson lakes area appear to contain only minor alteration zones, unlike the lower Chisel sequence. A zone of strongly altered rocks (unit 3) is present southwest of Tern Lake, but is truncated to the north and west by faults. An area of rusty-weathering outcrops with bleaching and garnet–amphibole-rich zones (unit 4) is reported by Bailes and Schledewitz (1999a) in the vicinity of a small lake, 2.5 km south of Varnson Lake.

Despite the apparent absence of intense synvolcanic alteration and the historical lack of base-metal mineralization associated with the upper Chisel sequence, the Squall–Varnson lakes area is considered to represent a prospective area for fertile VMS systems at depth. The large, base-metal poor, subeconomic Cook Lake deposit lies beneath the northern shore of Cook Lake, in the southwestern corner of the map area. Although the volcanic hostrocks to the Cook deposit are located on the western side of the Varnson Lake Fault, and their stratigraphic relationship to the remainder of the Squall–Varnson lakes area volcanic rocks is not clear, they can be traced on the surface trending north for 4 km to Varnson Lake.

The geochemical data suggest that the bulk of the bimodal volcanic rocks on the western side of Snow Creek likely correlate with the upper Chisel sequence. The presence of upper Chisel rocks throughout the area and the lack of Snow Creek sequence rocks within the main package of volcanic rocks west of Snow Creek indicate that present-day surface consists of rocks from a relatively narrow stratigraphic range. Hence, it is possible that at depth, below the upper Chisel sequence, rocks of the lower Chisel sequence extend through the western side of Snow Creek. The presence of a large-scale antiformal structure and the reversal in the plunge direction of the stretching lineation suggest that the stratigraphy may be brought up closer to the surface in the northern portion of the map area.

The Snow Lake Fault and the McLeod Road Thrust form the upper and lower structural boundaries, respectively, of a tectonic panel of Burntwood Group turbidites that runs through Snow Lake. Major gold deposits occur in the Snow Lake area and have been shown to be located in proximity to, and in the structural hanging wall of, the McLeod Road Thrust (Galley et al., 1988; Schledewitz, 1997, 1998; Beaumont-Smith, 2008)

Although there has been no significant gold deposit found in association with the Snow Lake Fault, Bailes and Schledewitz (1999a) suggested that the sharp bend of the fault west of Snow Lake is a structural ramp, which could have contributed to the formation of prospective dilatant zones. Prominent arsenic- and gold-grain anomalies in till near Tern Lake were reported in Kaszycki et al. (1996). This area also appears favourable due to the presence of several faults, which intersect the Snow Lake Fault, creating a fault system perhaps analogous to the one in the vicinity of the New Britannia deposit. One sample from this study was collected 700 m north of Tern Lake (sample marked by an asterisk; Figure GS-6-2) and was initially identified as a rhyolite. Whole-rock geochemical analysis of the sample revealed that, despite its 76% SiO_2 content, the sample is in fact a highly silicified gabbro, which has preserved its ocean-floor REE pattern (mafic sample 4). Similarly, the Birch Lake basalt, near the No 3 Zone deposit west of the New Britannia mine, also shows strong silicification, which is associated with gold mineralization in this location.

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