GS2018-6

Metamorphism of volcanic rocks from the North Star Lake and the Fourmile Island assemblages, west-central Manitoba (parts of NTS 63K10, 15)

by M. Lazzarotto[1], D.R.M. Pattison[1] and S. Gagné

In Brief:

- Detailed petrography on metabasites from the North Star and Fourmile Island assemblages has identified a series of six mineral isograds
- Regional metamorphic grade increases from greenschist facies in the south to garnet-amphibolite facies in the north
- The West Reed-North Star shear zone is a pre-metamorphic structure that does not disrupt the continuous succession of metamorphic zones and isograds

Citation:

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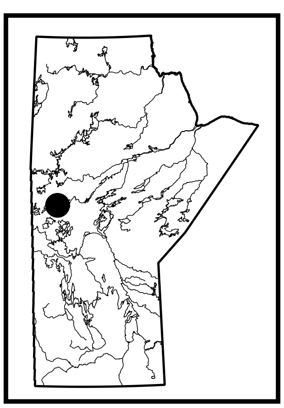

Summary

The Reed Lake–North Star Lake area is part of a tectonic collage in the Flin Flon greenstone belt, west-central Manitoba. It consists of accreted terranes of metamorphosed ocean-floor and island-arc assemblages that are unconformably overlain by sedimentary rocks and intruded by successor-arc plutons. The area is characterized by the north-trending West Reed–North Star shear zone (WRNS), which juxtaposes two packages of bimodal volcanic and volcaniclastic rocks. The well-documented volcanic-arc/arc-rift rocks of the Fourmile Island assemblage (FIA) lie east of the WRNS and can be followed continuously along the entire trace of the WRNS. The North Star assemblage (NSA), another package of bimodal volcanic and volcaniclastic rocks, lies on the west side of the WRNS.

Rocks in the area have experienced both regional and contact metamorphism. The regional metamorphic grade generally increases northward across the Flin Flon greenstone belt from lower-greenschist–facies rocks in the south, to amphibolite-facies rocks in the north. Rocks in contact metamorphic aureoles around plutons record amphibolite-facies conditions.

A sequence of regional metamorphic zones was established through field observations and thermodynamic modelling of mafic volcanic rocks. Six isograds were identified separating seven metamorphic zones. From south to north, these isograds are hornblende-in, albite-out, actinolite-out, garnet-in, epidote-out and chlorite-out. The metamorphic mineral assemblage and isograd map demonstrates that the metamorphic grade increases toward the north, from lower-greenschist facies at Reed Lake to garnet-amphibolite facies north of North Star Lake. The WRNS does not seem to disrupt the continuous metamorphic succession of zones and isograds. It is suggested that the WRNS may have been an important pathway for the transport and concentration of precious metals within metamorphic fluids.

Introduction

In 2015, a project involving the tectonic and metamorphic study of parts of the Flin Flon greenstone belt (FFB) was initiated by the University of Calgary in collaboration with the Manitoba Geological Survey. Greenstone belts are zones of variably metamorphosed bimodal volcanic sequences, associated sedimentary rocks and granitoid to gabbroic intrusive bodies that occur within Precambrian cratons. The rocks in such belts commonly record events of regional metamorphism, contact metamorphism and hydrothermal alteration. In addition to providing insight into the tectonic evolution of the area, the study of these rocks allow for the better understanding of metamorphic processes, such as the behaviour of rocks and minerals at the transition from greenschist facies to amphibolite facies, which results in the release of hydrothermal fluids. Identifying these transitions, and understanding the associated fluid release, helps researchers better understand the transport and concentration mechanisms of precious and base metals. An improved understanding of the metamorphic and alteration events that affected these areas may help to constrain exploration models for volcanogenic massive-sulphide (VMS) and orogenic gold deposits in the region.

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This metamorphic investigation is part of a larger study of the metamorphic and tectonic evolution in the FFB conducted by M. Lazzarotto as part of his Ph.D. research at the University of Calgary (Lazzarotto et al., 2016, 2017). Future research will focus on the relationships between metamorphosed mafic volcanic rocks and metamorphosed sedimentary rocks along a north-south transect in the File and North Star lakes area and building an integrated metamorphic map of the whole Flin Flon greenstone belt.

Regional geological framework

The Reed Lake–North Star Lake area is situated in the eastern-central FFB, Manitoba. The FFB is part of the Reindeer zone of the Trans-Hudson orogen, which formed through the closure of the Manikewan Ocean and convergence of the Hearne, Superior and Sask cratons (Hoffmann, 1988).

The exposed FFB contains several distinct juvenile-arc assemblages juxtaposed on ocean-floor rocks, with interlayered sedimentary and intrusive units separated by major faults (Figure GS2018-6-1; Stern et al., 1995a, b; Syme et al., 1999; Whalen et al., 2016). The arc assemblages are internally complex, comprising numerous fault-bounded and folded volcanic suites (e.g., Bailes and Syme, 1989) that are typically bimodal and include a wide range of volcanic, volcaniclastic and intrusive rocks (Bailes and Syme, 1989; Syme and Bailes, 1993; Stern et al., 1995a; Lucas et al., 1996; Bailes and Galley, 2007). The juvenile ocean-floor assemblages are composed mainly of rock similar to mid-ocean–ridge basalt (MORB) and related kilometre-scale, layered, mafic–ultramafic plutonic complexes (Syme and Bailes, 1993; Stern et al., 1995b).

Uranium-lead zircon ages for the ocean-floor assemblages in the exposed portion of the FFB indicate that the ocean-floor magmatism was coeval with tholeiitic-arc volcanism at ca. 1.90 Ga (Stern et al., 1995b). Voluminous successor-arc magmatism and deposition of sedimentary rocks occurred between ca. 1.88 and 1.83 Ga (Lucas et al., 1996). Large plutons were emplaced throughout the belt during three distinct magmatic stages. They are lithologically and geochemically variable with alkaline, calcalkaline and shoshonitic affinities. Volcanic, volcaniclastic and sedimentary rocks with ages of ca. 1.88–1.83 Ga are documented across the central and eastern parts of the exposed FFB and are termed successor-basin deposits (Ansdell et al., 1995; Lucas et al., 1996). They include the Schist-Wekusko assemblage, the Missi group and the Burntwood group. The fluvial-alluvial Missi group sedimentary deposits are characterized by thick packages of conglomerate, pebbly sandstone and massive sandstone. The marine turbidites of the Burntwood group include greywacke, siltstone, mudstone and rare conglomerate. In the low-grade metamorphic FFB, these sedimentary rocks are generally in fault contact with other units.

The Reed Lake area is characterized by a major, regionally extensive tectonite belt exposed on western Reed Lake; the WRNS, which juxtaposes rocks of the FIA on the east; and the NSA on the west (Figure GS2018-6-2). Rocks from the NSA, WRNS and FIA record a broad range of peak metamorphic conditions and will be discussed in further detail later in this report. For the sake of brevity, the prefix 'meta-' is not used in this report and the rocks are described in terms of their protoliths.

Metamorphism

With the exception of the Phanerozoic rocks south of Reed Lake, all rocks in the Reed Lake–North Star Lake area are metamorphosed. Two distinct types of metamorphism are observed: regional metamorphism and contact metamorphism. The regional metamorphic grade increases to the north from lower-greenschist facies on Reed Lake, to garnet-amphibolite facies north of North Star Lake. This work focuses on the metamorphism of mafic volcanic rocks with only limited work performed on Burntwood group sedimentary rocks and successor-arc intrusive rocks.

Metamorphic mineral assemblage and isograd map

Figure GS2018-6-3 shows a metamorphic mineral assemblage and isograd map for the Reed Lake–North Star Lake area. The map was compiled using data from Bailes and McRitchie (1978), Bailes (1980), Norquay (1997), Zwanzig and Bailes (2010) and mapping performed by the authors in recent years (e.g., Lazzarotto et al., 2016, 2017). The plotted mineral assemblages only include the diagnostic minerals used to define the metamorphic zones, which include actinolite, hornblende, albite, Ca-bearing plagioclase (oligoclase, andesine), chlorite, epidote and garnet (full mineral assemblages including nondiagnostic minerals are summarized in Table GS2018-6-1). Six isograds were identified separating seven metamorphic zones. From south to north, these isograds are hornblende-in, albite-out, actinolite-out, garnet-in, epidote-out and chlorite-out. The metamorphic mineral assemblage and isograd map demonstrates that the metamorphic grade increases toward the north, from lower-greenschist facies at Reed Lake to garnet-amphibolite facies north of North Star Lake.

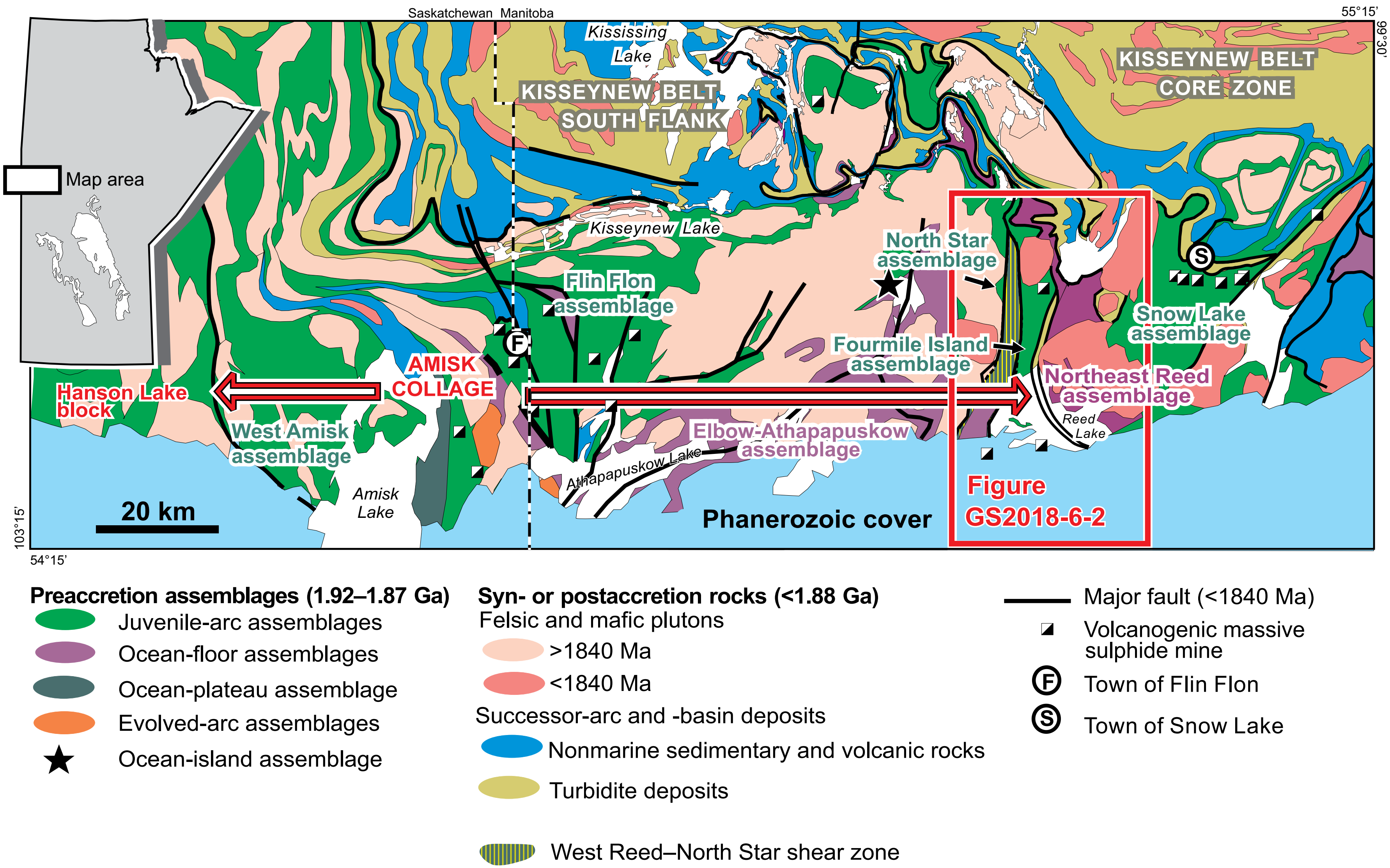

Figure GS2018-6-1: *Simplified geology of the Flin Flon greenstone belt (modified from NATMAP Shield Margin Project Working Group, 1998). The box outlined in red shows the study area (Figure GS2018-6-2).*

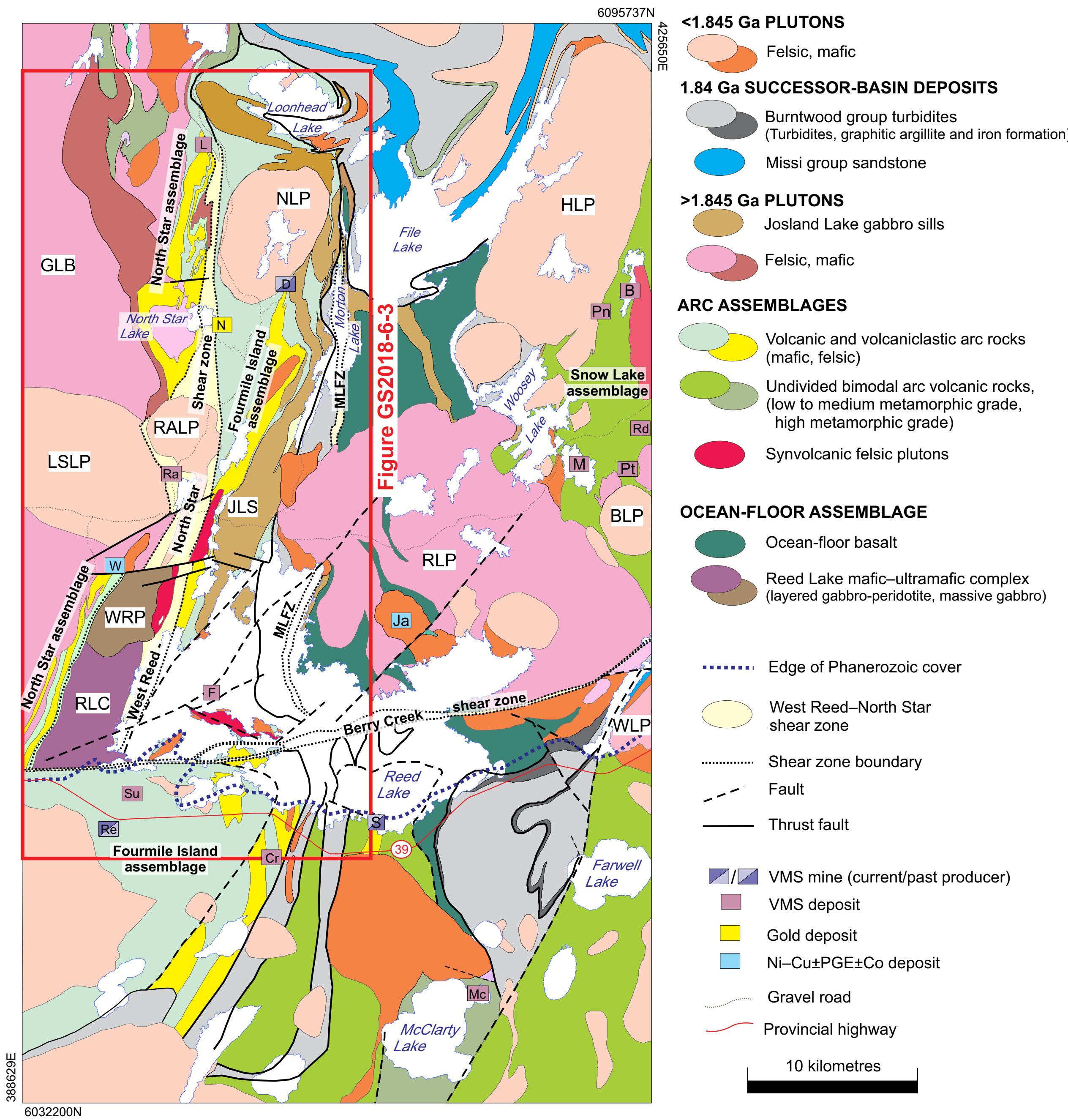

Figure GS2018-6-2: *Geology of the Reed Lake area, compiled from Syme et al. (1995a), NATMAP Shield Margin Project Working Group (1998), Gagné (2017) and Gagné et al. (2017). The box outlined in red shows the area of Figure GS2018-6-3. Intrusive rocks: GLB, Gants Lake batholith; HLP, Ham Lake pluton; JLS, Josland Lake sills; LSLP, Little Swan Lake pluton; NLP, Norris Lake pluton; RALP, Rail Lake pluton; RLC, Reed Lake complex; RLP, Reed Lake pluton; WLP, Wekusko Lake pluton; WRP, West Reed pluton. Structural feature: MLFZ, Morton Lake fault zone. Mines (active or closed), deposits and significant mineral occurrences: B, Bomber; Cr, Cowan River zone, D, Dickstone; F, Fourmile Island; Ja, Jackfish; L, Lon, M, Morgan; Mc, McClarty; N, North Star; Pn, Pen; Pt, Pot; Ra, Rail; Rd, Raindrop; Re, Reed; S, Spruce Point; Su, Super zone, W, Wine. Other abbreviations: PGE, platinum-group elements; VMS, volcanogenic massive sulphide.*

The WRNS does not appear to disrupt the continuous succession of metamorphic zones and isograds (Syme et al., 1995b; Zwanzig and Bailes, 2010). No late brittle structures disrupt the sequence either, in contrast to observations in the Athapapuskow Lake area further to the west (Lazzarotto et al., 2017).

Igneous remnants and metamorphic textures

Greenschist-facies samples show random orientations of metamorphic minerals and igneous fabrics that are well preserved; however, the preservation of igneous textures is less common in amphibolite-facies samples. The distribution of metamorphic-mineral assemblages

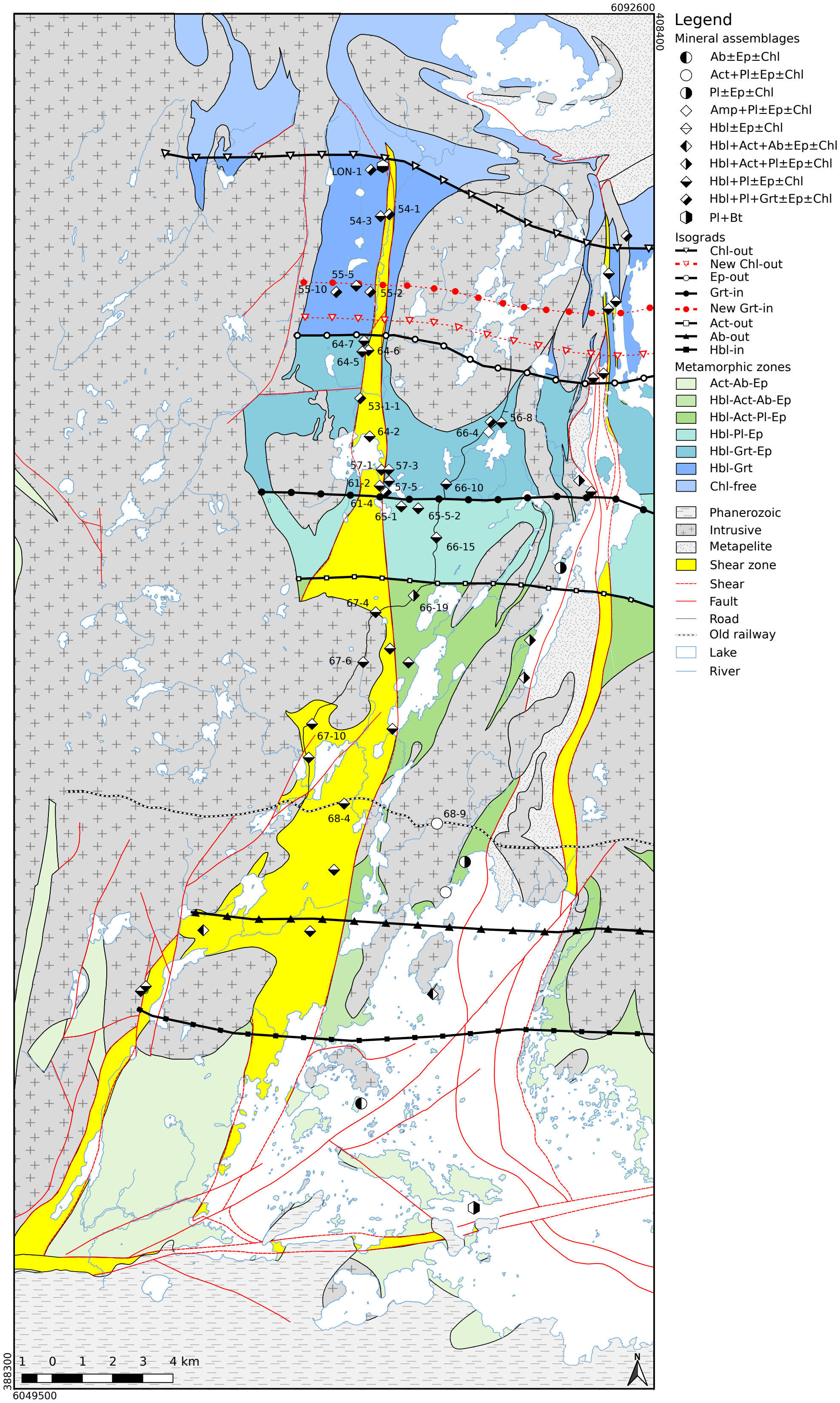

Figure GS2018-6-3: *Metamorphic mineral assemblage and isograd map of the Reed Lake–North Star Lake area; zones are coloured according to regional metamorphic grade and exclude contact metamorphic aureoles. Data compiled from Bailes and McRitchie (1978), Bailes (1980), Norquay (1997), Zwanzig and Bailes (2010) and samples collected by the authors (e.g., Lazzarotto et al., 2016, 2017). Abbreviations: Ab, albite; Act, actinolite; Amp, amphibole; Bt, biotite; Chl, chlorite; Ep, epidote; Grt, garnet; Hbl, hornblende; Pl, plagioclase.*

Table GS2018-6-1: Full metamorphic mineral assemblages recorded for the samples of the Reed Lake–North Star Lake area. Abbreviations: Ab, albite; Ap, apatite; Act, actinolite; Bt, biotite; Cb, carbonate mineral; Chl, chlorite; Ep, epidote; Grt, garnet; Hbl, hornblende; Ilm, ilmenite; Ms; white mica; Opq, opaque mineral; Pl, plagioclase; Qz, quartz; St, staurolite; Ttn, titanite; x, present; ?, uncertain (due to the fine-grained nature of the rocks).

Station number	UTM (Easting)	UTM (Northing)	Pl	Ab	Act	Hbl	Chl	Ep	Opq	Ilm	Ttn	Cb	Ap	Bt	Ms	Grt	St	Qz
0105-10-01	402693	6050881	x	?					x									x
0105-10-05	399284	6056942	x	x			x	x	x			x		x				x
110-13-009-A01	400846	6071549	x			x		x			?							x
110-13-013-A01	400235	6072013	x			x		x		x	x							x
110-13-104-A01	403565	6079523	x			x		x				x		x		x		x
110-13-136-A01	400316	6069354	x			x	x	x										x
110-15-EEL300-492	403012	6053487	x	x								x		x				x
53-1	399252	6080302	x			x	x		x			?		x		x		x
54-1	400212	6086398	?			x			x							x		x
54-3	399926	6086334	x			x			x	x				?				x
55-10	398415	6083803	x	x								x		x				x
55-2	399596	6083847	x			x	x		x	x		x		x	x	x		x
55-5	399119	6084030	x			x			x	x				?		x		x
56-8	403927	6079500	?			x						x		x				x
57-1	399952	6077937	x			x	x		x	x				?		x		x
57-3	400095	6077882	x			x			x									x
57-5	400203	6077562	?			x			x			x						x
59-1	404855	6072183	x		x	?	?	x	x									x
59-2	404717	6071218	x		?	x			x									x
59-5	405948	6074665	?						x					x				x
59-6	406854	6077196	x			x			x			x						x
59-8	406401	6077826			?	x	x		x					x				x
60-2	407534	6083331	x			x			x			x		x				x
60-3	407644	6083587	?			x			x			x						x
60-4	407412	6084555	x			x			x					x				x
60-5	407222	6084625	x			x	?		x									x
61-2	400011	6077365	?			x		x	x									x
61-4	400100	6077188	?			x			x					x		x		x
62-4	408083	6085858	?			x			x					x		x		x
63-1	402715	6064946	x											x				x
63-4	402075	6063941	x		x			x		x	x							x
63-9	401652	6060563	x	?	x	?	x	x	x			x						x
64-2	399564	6079041	x			x				x	x			x				x
64-5	399320	6081848	x			x				x	x	?		x		?		x
64-6	399522	6081893	x			x			x					x		x		x
64-7	399380	6082203	?			x		x				x		x				x
65-1	400612	6076720	?			x		x	x			x						x
65-5	401169	6076659	x			x		x	x									x
66-10	402095	6077461	?			x			x						?			x
66-15	401770	6075689	x		x	x		x	x	x								x
66-19	401022	6073769	x		x	x		x	x	x	x	x						x
66-4	403542	6079421	x		x	x		x	x	x	x							x
67-10	397654	6069515	?			x			x									x

Table GS2018-6-1 (continued): Full metamorphic mineral assemblages recorded for the samples of the Reed Lake–North Star Lake area. Abbreviations: Ab, albite; Ap, apatite; Act, actinolite; Bt, biotite; Cb, carbonate mineral; Chl, chlorite; Ep, epidote; Grt, garnet; Hbl, hornblende; Ilm, ilmenite; Ms; white mica; Opq, opaque mineral; Pl, plagioclase; Qz, quartz; St, staurolite; Ttn, titanite; x, present; ?, uncertain (due to the fine-grained nature of the rocks).

Station number	UTM (Easting)	UTM (Northing)	Pl	Ab	Act	Hbl	Chl	Ep	Opq	Ilm	Ttn	Cb	Ap	Bt	Ms	Grt	St	Qz
67-14	397546	6068402	x			x			x				x					x
67-4	399761	6073217	?			x						x		x				x
67-6	399348	6071563	x			x		x										x
68-4	398717	6066876	x		?	x	x	x		x	x	?		x	?			x
68-9	401790	6066216	x		x	x	x	x		x	x							
96-14-061-A2	398383	6064685	?	x		x			x									x
96-14-116-A2	392153	6060825	?	x		x												x
96-14-117-A2	391986	6060665	x	?		x		x										x
96-14-130-A2	394055	6062681			?	x		x										x
96-14-46-A2	397589	6062651	?	x		x		x		x	x			x				x
96-14-92-A2	392137	6060679	x	x		x		x	x					x				x
LON-1	399761	6087963	?			x	?		x	x	x		x	x		x		x
LON-2	399829	6087988	?				x							x		x	x	x

in samples is controlled by relict igneous textures such as phenocrysts and amygdules, which are common in metamorphosed basalt flows and pillows found throughout the study area. No igneous minerals are preserved. Pyroxene is generally replaced by actinolite and/or hornblende, and chlorite depending on metamorphic grade. Igneous calcic plagioclase is not present in any sample. Plagioclase is replaced by albite (<An_{10}, with minor epidote) in lower-greenschist–facies samples, whereas it is replaced by intermediate plagioclase (<An_{50}, with minor albite, epidote and carbonate) at higher metamorphic grades. In both cases these pseudomorphs generally vary in size from <0.1 to 10 mm. Amygdules are generally filled with quartz, epidote and carbonate. They are rounded to subrounded and range in size from <0.1 to 10 mm. The matrix is usually composed of finer grained crystals of the same composition as the phenocrysts or amygdules.

At outcrop scale, massive flows and pillow basalt form the best-preserved igneous structures. Typically, pillow cores are light in colour, rich in epidote and contain a few small amygdules; rims are dark coloured and contain more chlorite, actinolite and hornblende, and occasionally abundant large amygdules (e.g., Figure GS2018-6-4e). At lower metamorphic grade, plagioclase and/or pyroxene phenocrysts replaced as pseudomorphs are often aligned, preserving trachytic textures typical of magmatic flow. Igneous structures become deformed (e.g., Figure GS2018-6-4a, e) and metamorphic minerals such as amphibole or biotite define a foliation in areas of high strain (e.g., Figure GS2018-6-4c, d, g).

Regional metamorphism

Greenschist facies: actinolite-albite-epidote zone

The actinolite-albite-epidote zone is bounded to the south by the Phanerozoic sedimentary rocks of the Western Canadian Sedimentary Basin, and to the north by the hornblende-in isograd (Figure GS2018-6-3). Characteristic metamorphic minerals in this assemblage are actinolite+albite+epidote+chlorite+quartz±biotite±titanite±apatite ±opaque minerals, which is typical of greenschist-facies rocks.

Primary igneous textures are usually well preserved within samples of this zone. Pyroxene and plagioclase phenocrysts are pseudomorphed by actinolite and albite (with minor chlorite, epidote and white mica), respectively. Amygdules are typically filled with fine-grained quartz, granular or radial epidote, chlorite and carbonate. Fine-grained acicular actinolite, fine-grained albite, granular epidote, interstitial chlorite and quartz make up the bulk of the matrix. Minor titanite, carbonate, apatite and opaque minerals are also found as part of the matrix. Very fine grained biotite is present in some samples. In most cases the biotite-bearing rocks contain no actinolite.

Lower-amphibolite facies: hornblende-actinolite-albite-epidote zone

The hornblende-actinolite-albite zone is defined as the area between the hornblende-in and the albite-out isograds (Figure GS2018-6-3). The zone is characterized by the mineral assemblage hornblende+actinolite+albite

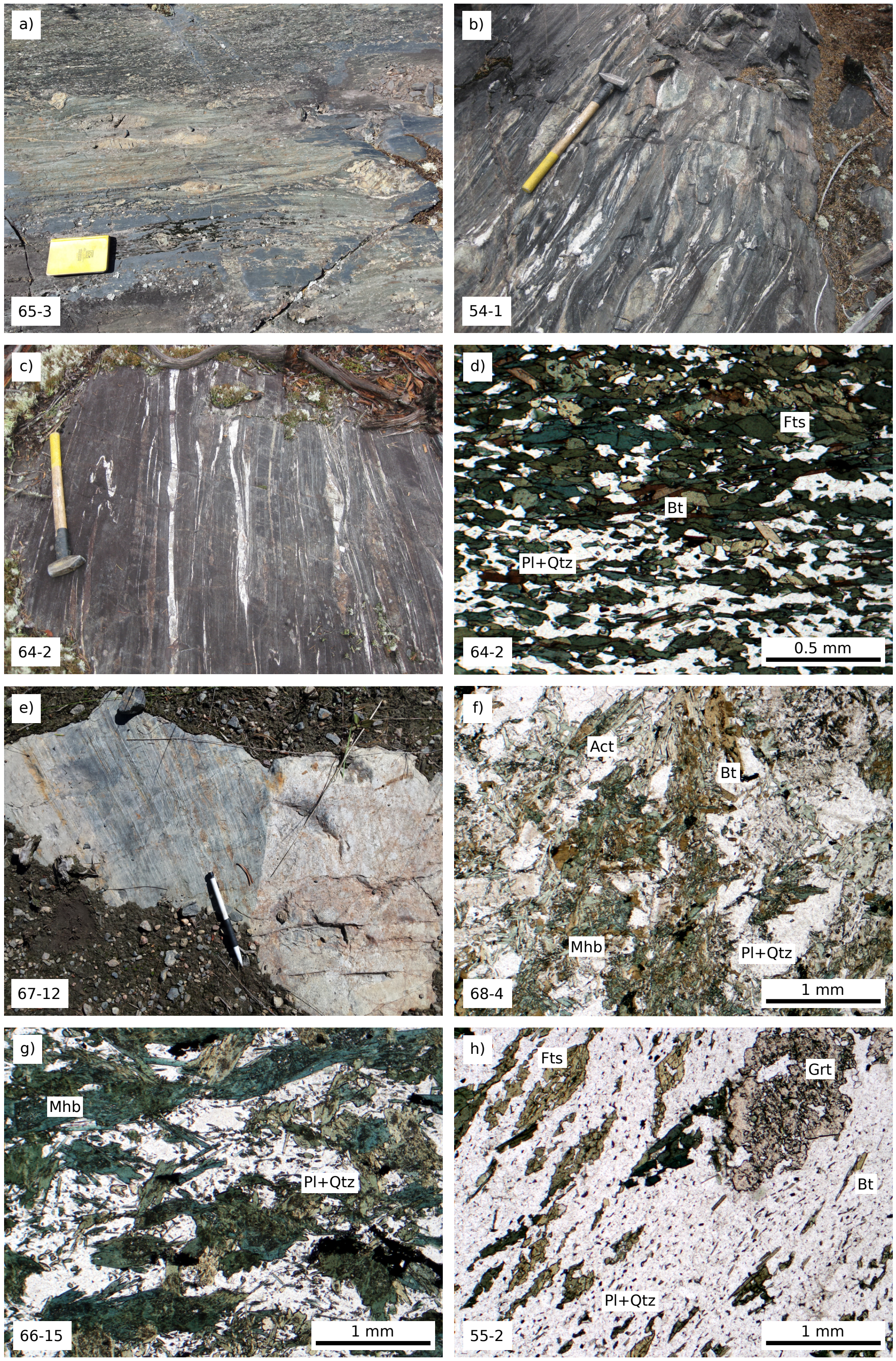

Figure GS2018-6-4: *Outcrop photo and photomicrographs of metamorphic zones in the study area:* ***a)*** *amphibolite with preserved epidotized pillow cores from the Hbl-Pl-Ep zone (station 65-3, UTM Zone 14, 400803E 6076677N [NAD 83]);* ***b)*** *amphibolite with stretched pillows of the Hbl-Grt zone (station 54-1, UTM Zone 14, 400212E 6086389N [NAD 83]);* ***c)*** *amphibolite from the Hbl-Grt-Ep zone (station 64-2, UTM Zone 14, 399565E 6079040N [NAD 83]);* ***d)*** *Fts and Bt from the Hbl-Grt-Ep zone (plane-polarized light, sample 64-2, UTM Zone 14, 399565E 6079040N [NAD 83]);* ***e)*** *strongly foliated amphibolite from the Hbl-Act-Pl-Ep zone (station 67-12, UTM Zone 14, 397404E 6069111N [NAD 83]);* ***f)*** *Mhb, Act, Bt and Pl from the Hbl-Act-Pl-Ep zone (plane-polarized light, sample 68-4, UTM Zone 14, 398720E 6066907N [NAD 83]);* ***g)*** *Mhb and Pl from the Hbl-Pl-Ep zone (plane-polarized light, sample 66-15, UTM Zone 14, 401766E 6075689N [NAD 83]);* ***h)*** *Fts, Grt and Bt from the Hbl-Grt zone (plane-polarized light, sample 55-2, UTM Zone 14, 399598E 6083847N [NAD 83]). Abbreviations: Act, actinolite; Bt, biotite; Ep, epidote; Fts, ferro-tschermakite; Grt, garnet; Hbl, hornblende; Mhb, magnesiohornblende; Pl, plagioclase; Qz, quartz.*

+epidote+chlorite+quartz±titanite±biotite±apatite ±opaque minerals.

Several textural relationships between actinolite and hornblende have been identified in all zones where these minerals coexist, including distinct grains, patchy intergrowths and core-rim microstructures. Even though the typical assemblage contains both hornblende and actinolite, assemblages containing only one of the two minerals are common. Hornblende occurs as rare, small blebs in samples from the southern part of the zone and is rich in Mg. The modal percent of hornblende increases toward the north. A similar trend is observed for the grain size. Close to the albite-out isograd, hornblende is characterized by dark green needles, needle aggregates or blades, up to 0.5 mm long. Actinolite persists throughout the zone and typically consists of pale green to green needle aggregates that vary in size depending on whether it is part of the matrix or replacing phenocrysts. Plagioclase phenocrysts are replaced by albite, which is also found as a fine-grained component within the matrix. Granular epidote, chlorite and fine-grained quartz are common in the matrix and within amygdules and fractures. Accessory titanite, apatite and opaque minerals are found as part of the matrix assemblage.

Lower-amphibolite facies: hornblende-actinolite-plagioclase-epidote zone

The area between the albite-out and actinolite-out isograds delimits the hornblende-actinolite-plagioclase-epidote zone (Figure GS2018-6-3). The characteristic metamorphic mineral assemblage observed in this zone is hornblende+actinolite+plagioclase+epidote+chlorite +quartz±biotite±ilmenite±titanite±apatite±opaque minerals, typical for lower-amphibolite–facies rocks (Figure GS2018-6-4h).

As in the hornblende-actinolite-albite zone there are textural relationships between actinolite and hornblende. Generally, the amphibole grains are too small to be visible in hand sample; however, hornblende is occasionally identifiable as fine black needles up to 1 mm long. The hornblende crystals are rich in Mg and show a slight enrichment in Si and Fe toward the north. Biotite (Mg# = Mg/[Mg+Fe] = 0.5) is present as platy and elongate, green to brown grains up to 1 mm long. Elongate hornblende, actinolite and biotite are intricately intergrown with fine-grained interstitial plagioclase (An_{50}), acicular chlorite and skeletal epidote. Ilmenite is the main Ti-bearing phase, often mantled by late (retrograde?) titanite.

Amphibolite facies: hornblende-plagioclase-epidote zone

The hornblende-plagioclase-epidote zone is defined as the area between the actinolite-out and the garnet-in isograds (Figure GS2018-6-3). The typical metamorphic-mineral assemblage is hornblende+plagioclase+epidote +chlorite+quartz±biotite±ilmenite±titanite±apatite ±opaque minerals (Figure GS2018-6-4f).

Plagioclase of intermediate composition (An_{20}–An_{30}) is common and occurs interstitial to fairly coarse grained, dark green, hornblende blades or needle aggregates up to 1 mm long. The hornblende in this area is transitional between Mg- and Fe-hornblende. Skeletal epidote, usually <0.5 mm across, and acicular or fibrous chlorite are also interstitial to the hornblende. Brown to green biotite (Mg# = 0.4) is present in most of the samples as plates or blades of variable size associated with hornblende. Ilmenite is commonly rimmed by (retrograde?) titanite.

Upper-amphibolite facies: hornblende-garnet-epidote zone

The zone up-grade of the garnet-in isograd and down-grade of the epidote-out isograd is defined as the hornblende-garnet-epidote zone (Figure GS2018-6-3). The key mineral assemblage observed in rocks from this zone is hornblende+plagioclase+garnet+epidote+chlorite+ quartz±biotite±ilmenite±titanite±apatite± opaque minerals and is characteristic of upper-amphibolite–facies mafic rocks (Figure GS2018-6-4d).

Rocks in this zone consist of up to 60–70% hornblende (Fe-tschermakite). Hornblende grains are subhedral, exhibit the typical 120°/60° cleavage and display light green/brown to dark green pleochroism. Grain sizes range between a few micrometres up to 1 mm. Euhedral brown biotite with Mg# = 0.3 occurs as flakes and blades up to 0.2 mm long and is found throughout the zone. Hornblende and biotite define a foliation resulting from strain along the WRNS. Garnet porphyroblasts are subhedral and rich in Fe (Alm_{60}). The garnet grains range from 50 µm to 1 mm and contain inclusions of ilmenite and quartz. Some garnet porphyroblasts overgrow the foliation in high-strain zones proximal to the WRNS. The observed plagioclase is of intermediate composition (An_{30}–An_{40}) and does not show any sign of late alteration. It is usually present as an interstitial phase together with quartz. Small grains of skeletal epidote, usually <0.1 mm across, and fibrous chlorite are part of the remaining matrix. Accessory ilmenite (sometimes rimmed by late titanite) is common.

Upper amphibolite facies: hornblende-garnet zone

The zone between the epidote-out and the chlorite-out isograds is defined as the hornblende-garnet zone (Figure GS2018-6-3). The characteristic metamorphic-mineral assemblage in samples from this zone is hornblende+plagioclase+garnet+chlorite+quartz±biotite±ilmenite±titanite±apatite±opaque minerals (Figure GS2018-6-4b).

Hornblende crystals are green/brown to dark green in colour and are chemically classified as Fe-tschermakites. Grains range in size from a few micrometres to 1 mm, are typically euhedral to subhedral and display 120°/60° cleavage. Hornblende generally makes up half of the rock volume. Biotite is usually associated with hornblende and has a relatively low magnesium content (Mg# = 0.25). The biotite grains display brown to green pleochroism, are euhedral to subhedral and range in size from <10 µm to 200 µm. Anhedral to subhedral garnet porphyroblasts and grain aggregates reach up to several millimetres in diameter and have locally overgrown the amphibole- and biotite-defined foliation. They are rich in Fe (Alm_{55}–Alm_{65}) and zoning can be present with relatively Ca-rich rims (Grs_{32}/Alm_{55}) and Ca-poor cores (Grs_{23}/Alm_{65}). Grains are several hundreds of micrometres across and contain inclusions of quartz, ilmenite, apatite and rare magnetite/hematite. Interstitial plagioclase of intermediate composition (An_{20}–An_{40}) is the major component in the matrix, together with quartz, ilmenite, titanite (late?) and minor chlorite. Chlorite mantling biotite and hornblende is probably a product of retrograde metamorphism.

Upper-amphibolite facies: chlorite-free zone

The chlorite-free zone is located between the chlorite-out isograd to the south and where the Kisseynew gneisses overlie the volcanic units to the north (Figure GS2018-6-3). This zone is characterized by the absence of chlorite, with a key mineral assemblage of hornblende+plagioclase+garnet+quartz±biotite±ilmenite±titanite±apatite±opaque minerals.

Hornblende (Fe-tschermakite) occurs as green subhedral blades a few hundreds of micrometres to several millimetres long with typical 120°/60° cleavage. The plagioclase is intermediate in composition (An_{40}) and is usually interstitial to the amphibole. Several samples contain brown to green biotite (Mg# = 0.25) as plates or blades varying from <0.1 mm to 0.5 mm. Garnets are anhedral to subhedral, unzoned and rich in Fe (Alm_{55}–Alm_{65}), with inclusions of quartz and ilmenite. Ilmenite is also present in the matrix and is often enveloped by titanite.

Contact metamorphism

Contact metamorphism is recognized in low-grade metamorphic zones (i.e., greenschist facies) by the presence of hornblende in mafic rocks. In high-grade metamorphic areas (i.e., amphibolite facies), the distinction between contact and regional metamorphism becomes difficult. Limited data on contact aureoles in the Reed Lake–North Star Lake area is available; based on previous work (e.g., Zwanzig and Bailes, 2010; Syme, 2015; Lazzarotto et al., 2017), they are observed to extend approximately 1 km outward from the margins of intrusions.

Contact metamorphic aureoles in mafic volcanic units are recognized in the field by a darkening of the fresh and weathered surfaces, sometimes associated with an increase in the grain size of porphyroblasts such as hornblende. Usually the rocks within these units are very fine grained and the mineral assemblages are difficult to identify in hand sample or with a petrographic microscope. It is possible to unravel contact metamorphic assemblages within aureoles with the aid of electron probe microanalyses of the samples.

Contact aureoles generally consist of dark grey to black weathering massive or pillow basalt. Fresh surfaces are dark green, with lighter epidotized patches. Igneous textures such as phenocrysts and pillow or flow structures are preserved in low-strain areas. Primary igneous minerals are replaced with pseudomorphs: pyroxene is usually replaced by actinolite and/or hornblende, whereas calcic plagioclase is replaced by more sodic varieties of plagioclase (<An_{50}). The typical mineral assemblage observed in thin section is hornblende±actinolite+plagioclase+quartz±biotite±epidote±chlorite±opaque minerals. Discrete actinolite grains are intergrown with hornblende where both amphiboles co-exist. Prograde replacement locally results in actinolite cores mantled by hornblende. Granular epidote, acicular or fibrous chlorite and fine-grained quartz occur in veins, amygdules or as part of the matrix. Biotite is present as small, brown to green, platy grains. Local red to purple garnet porphyroblasts <1 mm in diameter occur within domains of pre-metamorphic alteration (interaction with fluids?).

Thermodynamic modelling

A phase-equilibrium diagram (Figure GS2018-6-5) was calculated for a representative, juvenile-arc rock (whose bulk composition is seen in Table GS2018-6-2), to estimate peak metamorphic pressure and temperature conditions. The Gibbs free energy minimization software suite Theriak-Domino (de Capitani and Brown, 1987; de Capitani and Petrakakis, 2010) was used in conjunction with the thermodynamic dataset of Holland and Powell

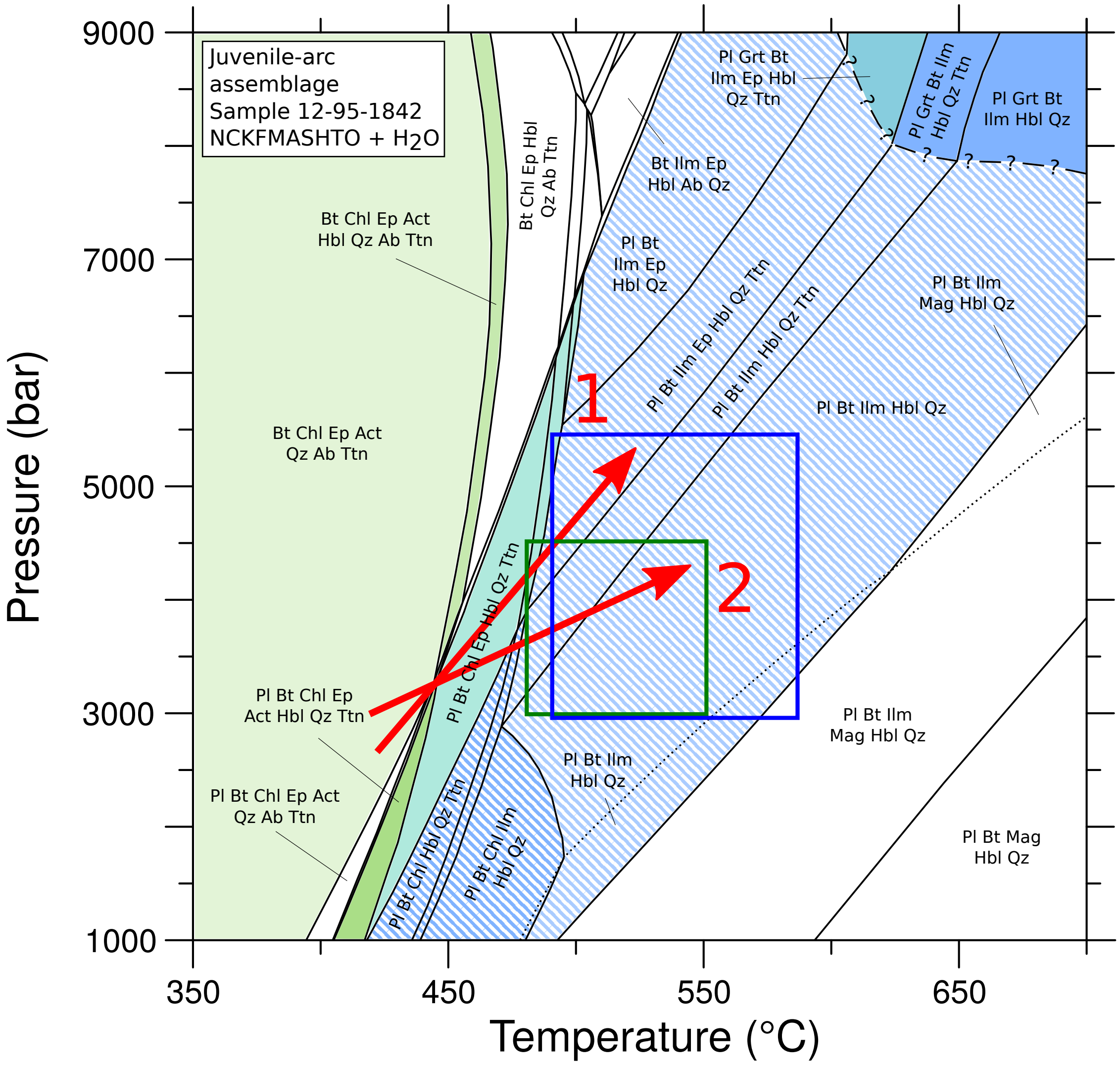

Figure GS2018-6-5: *Equilibrium phase diagram constructed for a representative juvenile-arc assemblage bulk composition in the Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3 (NCKFMASHTO) chemical system (sample 12-95-1842; Table GS2018-6-2). Assemblage fields use the same colour scheme as Figure GS2018-6-3. The red arrows represent possible metamorphic field gradients as discussed in the text. Abbreviations: Ab, albite; Act, actinolite; Bt, biotite; Chl, chlorite; Ep, epidote; Hbl, hornblende; Ilm, ilmenite; Mag, magnetite; Pl, plagioclase; Qz, quartz; Ttn, titanite.*

Table GS2018-6-2: Whole-rock geochemical data for sample 12-95-1842 used to calculate the phase-equilibrium diagram of Figure GS2018-6-5.

Sample 12-95-1842	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
wt. %	56.40	0.68	15.20	1.47	9.25	0.00	2.78	7.84	3.09	0.23	0.00	0.45	97.39

(1998; updated to version ds5.5). Activity-composition models (a-X models) for clinoamphibole (Diener et al., 2007, revised by Diener and Powell, 2012), clinopyroxene (Green et al., 2007; Diener and Powell, 2012), garnet (White et al., 2007), chloritoid (White et al., 2000), chlorite (Holland et al., 1998), white mica (Coggon and Holland, 2002), biotite (White et al., 2007), epidote (Holland and Powell, 1998), spinel (White et al., 2002), ilmenite-hematite (White et al., 2000) and feldspar (Cbar1 field; Holland and Powell, 2003) were used. Calculations were performed in the Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3 (NCKFMASHTO) chemical system. This system is a good approximation of the analyzed composition of the rocks. Ferric iron oxide (Fe_2O_3) was estimated as 15% of the total Fe, based on the presence of accessory Fe-bearing phases (magnetite), wet titration of selected samples and iterative T-XFe^{3+} and pressure-temperature (P-T) equilibrium modelling for different ferric to ferrous iron ratios and pressures. Investigations of the influence of ferric iron on the calculated phase-diagram section topology shows that by increasing the amount of Fe_2O_3 by 5%, the equilibration-pressure range of the observed assemblage is lowered by more than 1 kbar. Similarly, decreasing the amount of Fe_2O_3 by 5% yields a pressure increase of more than 1 kbar; therefore, interpreting the results of phase-equilibria modelling of rocks containing ferric and ferrous iron warrants caution. Garnet is the main phase incorporating Mn, which often results in overstabilization of the mineral in the modelled P-T space. Manganese was, therefore, not incorporated into the chemical system due to its relatively low abundance (usually MnO <0.1 wt. %) and to prevent the calculation of stable garnet in unlikely portions of P-T space. All P is assumed to be contained in apatite and Ca was subtracted from the bulk composition at a molar ratio of 5Ca:3P. The system was oversaturated in H_2O over the calculated P-T range.

Figure GS2018-6-5 shows the phase-equilibrium diagram for a representative juvenile-arc bulk composition (sample 12-95-1842) in the NCKFMASHTO chemical system. The colours used to highlight the various assemblage fields correspond to the colours of the metamorphic mineral assemblage and isograd map (Figure GS2018-6-3) and represent areas with the same key mineral assemblage.

The greenschist facies is represented by a large field containing the assemblage actinolite+albite+chlorite+epidote+biotite+quartz+titanite and occurs below 450°C. Just up-grade of this field are two relatively narrow fields (<20°C wide) representing the transition into amphibolite-facies assemblages. The lower pressure field has co-existing albite and plagioclase and is followed by a band of coexisting hornblende and actinolite spanning the full calculated pressure range. The epidote-out reaction occurs up-temperature of the actinolite-out and albite-out reactions between 1 and 6.5 kbar. It delimits a 30°C wide area where hornblende and epidote coexist in the assemblage hornblende+plagioclase+chlorite+biotite+epidote+quartz+titanite. Down-temperature of the chlorite-out reaction (approximately 500°C) and below 4 kbar is an assemblage field with coexisting plagioclase, hornblende and chlorite, with no epidote. A dashed line indicates the stability field of an additional amphibole phase upgrade of the chlorite-out reaction. This phase is an amphibole with a calculated composition, created to handle structural order-disorder of Fe, Mg and Al where the partitioning of these elements is unknown (camo1 and camo2; see Holland and Powell, 2006; Diener et al., 2007). In the sequences discussed in this paper, no amphibole other than actinolite and hornblende are present. The amphibole calculated up-grade of the dashed line is therefore interpreted as hornblende. At pressures <6.5 kbar and temperatures >500°C, magnetite is stable. Biotite is stable over the entire P-T range.

Discussion and conclusion

Comparison of the calculated phase-equilibrium diagram with the sequence of isograds observed in the field allows for the approximation of two possible metamorphic field gradients (red arrows in Figure GS2018-6-5). The observed sequence of reactions is hornblende-in, albite-out, actinolite-out, garnet-in, epidote-out and chlorite-out. The garnet-in reaction occurs at noticeably higher grade (above 7.5 kbar and 600°C, up-grade of the chlorite-out reaction) in the modelled phase-equilibrium section. Calculated garnet compositions at 700°C and 8 kbar correspond to the measured compositions in samples from the study area (Alm_{50}–Alm_{60}). Slight variations in the Fe content, Ca content and Fe^{2+}/Fe^{3+} ratio do not change the stability of garnet. The chlorite-out isograd was mapped as the northernmost (highest temperature) reaction. The location of this isograd is uncertain because it is difficult to distinguish prograde from retrograde chlorite within the rock matrix. If the chlorite-out reaction was to occur down-grade of the garnet-in reaction ('New Chl-out' and 'New Grt-in' in Figure GS2018-6-3), the sequence of observed mineral assemblages and reactions would correspond to the calculated phase-equilibrium diagram with a field gradient approximated by arrow 1 (Figure GS2018-6-5); however, a relatively large jump in pressure and temperature occurs between the chlorite-out and garnet-in reactions (4 kbar and 150°C). This suggests that the garnet a-X model is very sensitive to modelling. Calculations incorporating Mn result in garnet being stable over the entire P-T range, whereas without Mn, garnet is stable only at a P that is too high.

Independent pressure-temperature constraints from different calibrations of the hornblende-plagioclase thermobarometer (Holland and Blundy, 1994; Zenk and Schulz, 2004; Bhadra and Bhattacharya, 2007) and the garnet-biotite Fe-Mg exchange thermometer (Ferry and Spear, 1978; Hodges and Spear, 1982) yield pressures of 3–4.5 kbar and temperatures of 480–550°C for samples from the Hbl-Grt-Ep zone (green box in Figure GS2018-6-5), and pressures of 3–5.5 kbar and temperatures of 490–590°C for samples from the Hbl-Grt zone (blue box in Figure GS2018-6-5). These independent constraints partially agree with the calculated phase equilibrium diagram and are believed to better depict the stability of garnet.

Garnet porphyroblasts and aggregates are oriented with the foliation defining amphibole and biotite in most samples (Figure GS2018-6-4b). This suggests that the garnet grains grew before (or during) the deformation phase and were subjected to the strain developed by the WRNS. The garnet is interpreted to be coeval with the metamorphic amphibole and biotite. Nevertheless, it is possible that not all garnet is part of the metamorphic peak assemblage. In sample 55-5, metamorphic hornblende and biotite define the foliation, suggesting that they formed before, or during, the phase of deformation. Garnet porphyroblasts in this sample overgrow the foliation, suggesting that their growth postdates deformation along the WRNS, and therefore the interpreted timing of peak metamorphism. If garnet from areas south of sample 55-5 are of later origin and not part of the metamorphic peak assemblage, the location of the garnet-in isograd shifts up-grade of the epidote-out reaction. Dashed, garnet-free fields that otherwise match the sequence of mapped metamorphic mineral assemblages are depicted in the phase-equilibrium diagram and allow for a different field gradient indicated by arrow 2 (Figure GS2018-6-5). Late garnet could be a product of fluid infiltration along the WRNS.

Economic considerations

Volcanogenic massive-sulphide deposits

The Flin Flon greenstone belt is host to several volcanogenic massive-sulphide deposits (VMS), which form by seafloor venting of metalliferous hydrothermal fluids in active volcanic settings (e.g., Galley et al., 2007). The Reed Lake–North Star Lake area contains bimodal volcanic successions of mafic and felsic rocks that are characteristic of extensional tectonic regimes, are similar to the volcanic sequence that hosts the Flin Flon and Callinan VMS deposits (e.g., Bailes and Syme, 1989; Syme and Bailes, 1993) and indicate excellent exploration potential. These deposits are overprinted, and in some cases strongly remobilized via metamorphic and deformational processes because they formed early in the tectonic evolution of the region. Recognizing the effects of metamorphism on these deposits and the effect and extension of the associated alteration is important for exploration.

Orogenic gold deposits

Orogenic gold deposits form later with respect to regional deformation, magmatism and metamorphism, and the associated release of fluids. The controls on orogenic gold deposits are thus strongly related to metamorphic and tectonic processes. For example, dehydration reactions at the transition from greenschist to amphibolite facies in metabasites have been interpreted to provide fluids for the transport of gold (e.g., Phillips and Powell, 1993). In addition, crustal-scale shear zones can create pathways and/or traps for the transport and deposition of gold in solution (e.g., Dubé and Gosselin, 2007). The WRNS hosts several significant gold showings in the NSA. The major structures associated with gold mineralization extend continuously southward to the Reed Lake area, which is considered to have similar potential for shear-hosted (i.e., orogenic) gold mineralization.

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References

Ansdell, K.M., Lucas, S.B., Connors, K. and Stern, R.A. 1995: Kisseynew metasedimentary gneiss belt, Trans-Hudson Orogen (Canada): backarc origin and collisional inversion; Geology, v. 23, p. 1039–1043.

Bailes, A.H. 1980: Geology of the File Lake area; Manitoba Department of Energy and Mines, Mineral Resources Division, Geological Report GR78-1, 134 p.

Bailes, A.H. and Galley, A.G. 2007: Geology of the Chisel–Anderson lakes area, Snow Lake, Manitoba (NTS areas 63K16SW and west half of 63J13SE); Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Map MAP2007-1, scale 1:20 000.

Bailes, A.H. and McRitchie, W.D. 1978: The transition from low to high grade metamorphism in the Kisseynew sedimentary gneiss belt, Manitoba; *in* Metamorphism in the Canadian Shield, J.A. Fraser and W.W. Heywood (ed.), Geological Survey of Canada, Paper 7E-10, p. 155–177.

Bailes, A.H. and Syme, E.C. 1989: Geology of the Flin Flon–White Lake area; Manitoba Energy and Mines, Minerals Division, Geological Report GR87-1, 313 p.

Bhadra, S. and Bhattacharya, A., 2007: The barometer tremolite+tschermakite+2 albite=2 pargasite+8 quartz: constraints from experimental data at unit silica activity, with application to garnet-free natural assemblages; American Mineralogist, v. 92, no. 4, p. 491–502.

Coggon, R. and Holland, T.J.B. 2002: Mixing properties of phengitic micas and revised garnet-phengite thermobarometers; Journal of Metamorphic Geology, v. 20, no. 7, p. 683–696.

de Capitani, C. and Brown, T.H. 1987: The computation of chemical equilibrium in complex systems containing non-ideal solutions; Geochimica et Cosmochimica Acta, v. 51, no. 10, p. 2639–2652.

de Capitani, C.D. and Petrakakis, K. 2010: The computation of equilibrium assemblage diagrams with Theriak/Domino software; American Mineralogist, v. 95, no. 7, p. 1006–1016.

Diener, J.F.A. and Powell, R. 2012: Revised activity–composition models for clinopyroxene and amphibole; Journal of Metamorphic Geology, v. 30, no. 2, p. 131–142.

Diener, J.F.A., Powell, R., White, R.W. and Holland, T.J.B. 2007: A new thermodynamic model for clino-and orthoamphiboles in the system Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O-O; Journal of Metamorphic Geology, v. 25, no. 6, p. 631–656.

Dubé, B. and Gosselin, P. 2007: Greenstone-hosted quartz-carbonate vein deposits; *in* Mineral deposits of Canada: a synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods, W.D. Goodfellow (ed.), Geological Association of Canada, Mineral Deposits Division, Special Publication no. 5, p. 49–73.

Ferry, J.T. and Spear, F.S. 1978: Experimental calibration of the partitioning of Fe and Mg between biotite and garnet; Contributions to Mineralogy and Petrology, v. 66, no. 2, p. 113–117.

Gagné, S. 2017: Sub-Phanerozoic geology of the Reed Lake area, Flin Flon belt, west-central Manitoba (parts of NTS 63K7, 8, 9, 10); Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Preliminary Map PMAP2017-2, scale 1:30 000.

Gagné, S., Syme, E.C., Anderson, S.D. and Bailes, A.H. 2017: Geology of the exposed basement in the Reed Lake area, Flin Flon belt, west-central Manitoba (parts of NTS 63K9, 10, 15, 16); Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Preliminary Map PMAP2017-1, scale 1:30 000.

Galley, A.G., Hannington, M.D. and Jonasson, I.R., 2007: Volcanogenic massive sulphide deposits; *in* Mineral deposits of Canada: a synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods, W.D. Goodfellow (ed.), Geological Association of Canada, Mineral Deposits Division, Special Publication no. 5, p. 141–161.

Green, E., Holland, T. and Powell, R. 2007: An order-disorder model for omphacitic pyroxenes in the system jadeite-diopside-hedenbergite-acmite, with applications to eclogitic rocks; American Mineralogist, v. 92, no. 7, p. 1181–1189.

Hodges, K.V. and Spear, F.S. 1982: Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire; American Mineralogist, v. 67, p. 1118–1134.

Hoffman, P.F. 1988: United plates of America, the birth of a craton: Paleoproterozoic assembly and growth of proto-Laurentia; Annual Review of Earth and Planetary Sciences, v. 16, p. 543–603.

Holland, T., Baker, J. and Powell, R. 1998: Mixing properties and activity composition and relationships of chlorites in the system MgO-FeO-Al_2O_3-SiO_2-H_2O; European Journal of Mineralogy, v. 10, no. 3, p. 395–406.

Holland, T. and Blundy, J. 1994: Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry; Contributions to Mineralogy and Petrology, v. 116, no. 4, p. 433–447.

Holland, T.J.B. and Powell, R. 1998: An internally consistent thermodynamic data set for phases of petrological interest; Journal of Metamorphic Geology, v. 16, no. 3, p. 309–343.

Holland, T. and Powell, R. 2003: Activity-composition relations for phases in petrological calculations: an asymmetric multicomponent formulation; Contributions to Mineralogy and Petrology, v. 145, no. 4, p. 492–501.

Holland, T.J.B. and Powell, R. 2006. Mineral activity–composition relations and petrological calculations involving cation equipartition in multisite minerals: a logical inconsistency; Journal of Metamorphic Geology, v. 24, no. 9, p. 851–861.

Lazzarotto, M., Gagné, S. and Pattison, D.R.M. 2016: Tectono-metamorphic investigations in the Athapapuskow Lake area, west-central Manitoba (part of NTS 63K12); *in* Report of Activities 2016, Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, p. 87–98.

Lazzarotto, M., Pattison, D.R.M. and Gagné, S. 2017: Prehnite-pumpellyite– to amphibolite-facies metamorphism in the Athapapuskow Lake area, west-central Manitoba (parts of NTS 63K12, 13); *in* Report of Activities 2017, Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, p. 104–116.

Lucas, S.B., Stern, R.A., Syme, E.C., Reilly, B.A. and Thomas, D.J. 1996: Intraoceanic tectonics and the development of continental crust: 1.92–1.84 Ga evolution of the Flin Flon Belt, Canada; Geological Society of America Bulletin, v. 108, no. 5, p. 602–629.

NATMAP Shield Margin Project Working Group 1998: Geology, NATMAP Shield Margin Project area, Flin Flon belt, Manitoba/Saskatchewan; Geological Survey of Canada, Map 1968A, scale 1:100 000.

Norquay, L.I. 1997: Structural and metamorphic evolution of the North Star Lake area, Manitoba; M.Sc. thesis, University of Manitoba, 244 p.

Phillips, G.N. and Powell, R. 1993: Link between gold provinces; Economic Geology, v. 88, no. 5, p. 1084–1098.

Stern, R.A., Syme, E.C., Bailes, A.H. and Lucas, S.B. 1995a: Paleoproterozoic (1.90–1.86 Ga) arc volcanism in the Flin Flon Belt, Trans-Hudson Orogen, Canada; Contributions to Mineralogy and Petrology, v. 119, no. 2–3, p. 117–141.

Stern, R.A., Syme, E.C. and Lucas, S.B. 1995b: Geochemistry of 1.9 Ga MORB- and OIB-like basalts from the Amisk collage, Flin Flon Belt, Canada: evidence for an intra-oceanic origin; Geochimica et Cosmochimica Acta, v. 59, no. 15, p. 3131–3154.

Syme, E.C. 2015: Geology of the Athapapuskow Lake area, western Flin Flon belt, Manitoba (part of NTS 63K12); Manitoba Mineral Resources, Manitoba Geological Survey, Geoscientific Report GR2014-1, 209 p.

Syme, E.C. and Bailes, A.H. 1993: Stratigraphic and tectonic setting of early Proterozoic volcanogenic massive sulfide deposits, Flin Flon, Manitoba; Economic Geology, v. 88, no. 3, p. 566–589.

Syme, E.C., Bailes, A.H. and Lucas, S.B. 1995a: Reed Lake, N.T.S. parts of 63K/9, 63K/10; Manitoba Energy and Mines, Geological Services, Preliminary Map 1995F-1, scale 1:50 000.

Syme, E.C., Bailes, A.H. and Lucas, S.B. 1995b: Geology of the Reed Lake area (parts of NTS 63K/9 and 10); *in* Report of Activities 1995, Manitoba Energy and Mines, Geological Services, p. 42–60.

Syme, E.C., Lucas, S.B., Bailes, A.H. and Stern, R.A. 1999: Contrasting arc and MORB-like assemblages in the Paleoproterozoic Flin Flon Belt, Manitoba, and the role of intra-arc extension in localizing volcanic-hosted massive sulphide deposits; Canadian Journal of Earth Sciences, v. 36, p. 1767–1788.

Whalen, J.B., Perhsson, S. and Rayner, N.M. 2016: Significance of pre–1860 Ma granitoid magmatism for crustal evolution and exploration targeting in the Flin Flon assemblage, Trans-Hudson Orogen, Canada; Economic Geology, v. 111, no. 4, p. 1021–1039, doi:10.2113/econgeo.111.4.1021

White, R.W., Powell, R., Holland, T.J.B. and Worley, B.A. 2000: The effect of TiO_2 and Fe_2O_3 on metapelitic assemblages at greenschist and amphibolite facies conditions: mineral equilibria calculations in the system K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3; Journal of Metamorphic Geology, v. 18, no. 5, p. 497–512.

White, R.W., Powell, R. and Clarke, G.L. 2002: The interpretation of reaction textures in Fe-rich metapelitic granulites of the Musgrave block, central Australia: constraints from mineral equilibria calculations in the system K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3; Journal of Metamorphic Geology, v. 20, no. 1, p. 41–55.

White, R.W., Powell, R. and Holland, T.J.B. 2007: Progress relating to calculation of partial melting equilibria for metapelites; Journal of Metamorphic Geology, v. 25, no. 5, p. 511–527.

Zenk, M. and Schulz, B. 2004: Zoned Ca-amphiboles and related PT evolution in metabasites from the classical Barrovian metamorphic zones in Scotland; Mineralogical Magazine, v. 68, no. 5, p. 769–786.

Zwanzig, H.V. and Bailes, A.H. 2010: Geology and geochemical evolution of the northern Flin Flon and southern Kisseynew domains, Kississing–File lakes area, Manitoba (parts of NTS 63K, N); Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Geoscientific Report GR2010-1, 135 p.