GS2017-10

Prehnite-pumpellyite– to amphibolite-facies metamorphism in the Athapapuskow Lake area, west-central Manitoba (parts of NTS 63K12, 13)

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In Brief:

- Regional metamorphic grade increases from prehnite-pumpellyite-facies in the south to amphibolite-facies in the north
- Key isograds associated with major fluid release (hornblende-in and chlorite-out) have been mapped and quantified
- Isograd mapping has implications for understanding the genesis and localization of orogenic gold deposits

Citation:

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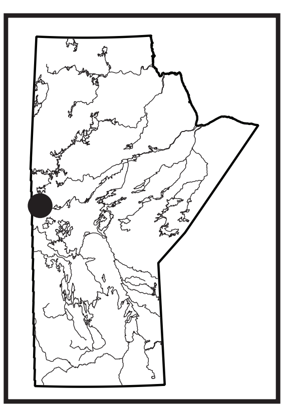

Summary

The Athapapuskow Lake area is part of a tectonic collage situated in the Flin Flon greenstone belt, Manitoba. It consists of accreted terranes comprising metamorphosed ocean-floor and island-arc assemblages that are unconformably overlain by sedimentary rocks and intruded by successor-arc plutons. The area consists of blocks bound by faults and major shear zones, within which both regional and contact metamorphism are observed. The regional metamorphic grade generally increases northward across the Flin Flon greenstone belt from prehnite-pumpellyite–facies rocks in the south, through to amphibolite-facies rocks in the north. Rocks in contact metamorphic aureoles around plutons record amphibolite-facies conditions. Late shear zones disrupt the regional metamorphic grade and overprint contact aureoles. A preliminary map of metamorphic-mineral assemblages and isograds of the area is presented. Isograds that were identified include actinolite-in, prehnite- and pumpellyite-out, hornblende-in, oligoclase-in, actinolite-out, chlorite-out and garnet-in. Two spatially important isograds are the hornblende-in and chlorite-out isograds. These have been demonstrated to be associated with major fluid release that can have implication for the generation of orogenic gold deposits. Isochemical phase diagram modelling of equilibration conditions of the rocks indicates that, in the Athapapuskow Lake area, for both contact and regional metamorphic sequences, the hornblende-in isograd occurs at pressures of 3.7–4.2 kbar and temperatures around 450°C, whereas the chlorite-out isograd yields similar pressures but higher temperatures (500–550°C).

Introduction

In 2015, a new project involving the tectonic and metamorphic study of parts of the Flin Flon greenstone belt, was initiated by the University of Calgary, in collaboration with the Manitoba Geological Survey. Greenstone belts are zones of variably metamorphosed mafic to ultramafic volcanic sequences, associated sedimentary rocks and granitoid 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, study of such rocks allows better understanding of metamorphic processes, such as the behavior of rocks at the transition from low-grade (prehnite-pumpellyite facies) to medium–high-grade (greenschist- to amphibolite-facies) metamorphism, that result in the release of hydrothermal fluids. An improved understanding of the metamorphic and alteration events that affected these areas provides information to constrain exploration models for volcanogenic massive sulphide (VMS) and orogenic gold deposits in the region.

The objective of the project is to refine the metamorphic and tectonic history of the Athapapuskow Lake area established by previous workers (e.g., Bailes and Syme, 1989; Gilbert 2012; Syme, 2015) based on new field mapping and petrography. Previous workers in the area have identified rocks of prehnite-pumpellyite to amphibolite facies in the region (e.g., Digel and Gordon, 1995; Starr, 2016).

The Athapapuskow Lake area was selected for several reasons: 1) the area straddles the transition from prehnite-pumpellyite, through greenschist, to amphibolite facies; 2) several different shear zones and faults of regional tectonic relevance cut the area, juxtaposing blocks of sometimes considerably different origin and metamorphic grade; and 3) relationships between metamorphism in contact aureoles and the later regional metamorphic overprint can be studied around several plutons. Investigation of these different aspects will allow to test the traditional model for the tectonic evolution of the western Flin Flon belt (i.e., early intra-oceanic accretion, followed by successor-arc plutonism, followed by regional thermotectonism; Lucas et al., 1996).

During three field seasons (summers of 2015, 2016 and 2017), targeted mapping and sampling was completed in the Athapapuskow Lake area and in the nearby North Star and File lakes areas. This report focuses on results from the Athapapuskow Lake area. A new map of metamorphic-mineral assemblages and isograds of the Athapapuskow Lake area is presented, together with preliminary results from thermodynamic phase-equilibria modelling. All mineral abbreviations are after Whitney and Evans (2010).

Future research will focus on the investigation of relationships between metamorphosed mafic volcanic rocks and metamorphosed sedimentary rocks along a north–south transect in the File and North Star lakes areas, and building an integrated metamorphic map of the whole Flin Flon–Snow Lake greenstone belt.

Regional geology

The Athapapuskow Lake area is situated in the western Flin Flon belt, Manitoba (part of NTS 63K12, 13). It is part of the juvenile Reindeer zone of the Trans-Hudson orogen (Figure GS2017-10-1; Hoffmann, 1988), a domain formed from the convergence between the Hearne, Superior and Sask cratons. The result is a geological setting characterized mainly by the juxtaposition of juvenile-arc and juvenile–ocean-floor rocks, accompanied by contaminated-arc, ocean-island and ocean-plateau rocks (Stern et al., 1995a, b; Syme et al., 1999; Whalen et al., 2016).

Circa 1920–1880 Ma juvenile-arc and ocean-floor rocks, including tholeiitic, calcalkalic and lesser shoshonitic and boninitic rocks, were juxtaposed in an accretionary collage, probably as a consequence of arc-arc collision at about 1880–1870 Ma (Lucas et al., 1996). This became the starting point for postaccretion and successor-arc magmatism, which resulted in the emplacement of calcalkalic plutons ca. 1870–1830 Ma (Lucas et al., 1996). Between 1850 and 1840 Ma, continental sediments of the Missi and Burntwood groups were deposited (Ansdell et al., 1995; Lucas et al., 1996). The complex imbrication of sedimentary and volcanic assemblages along pre-peak metamorphic structures (Lucas et al., 1996; Stern et al., 1999) is the consequence of two additional collisional events: the first involving the Sask craton at 1840–1830 Ma and, immediately afterwards, a second event involving the Superior craton at 1830–1800 Ma (Bleeker, 1990; Ellis et al., 1999; Ashton et al., 2005), resulting in what is known as the 'Amisk collage' (Lucas et al., 1996).

Today the Athapapuskow Lake area of the Flin Flon–Snow Lake greenstone belt consists of imbricated juvenile-arc, ocean-floor and sedimentary rocks, intruded by granitoid plutons, and is characterized by internally complex patterns of faults and folds (Figure GS2017-10-2a; Bailes and Syme, 1989; Stern et al, 1995a; Lucas et al, 1996). The arc-related assemblages comprise a wide range of volcanic, volcaniclastic and related synvolcanic intrusive rocks, whereas the ocean-floor assemblages are mainly composed of mid-ocean-ridge–like basalt and related mafic–ultramafic complexes (Syme and Bailes, 1993; Stern et al., 1995b; Lucas et al., 1996). Sedimentary rocks principally consist of thick sequences of continentally derived conglomerate and sandstone, and marine turbidites.

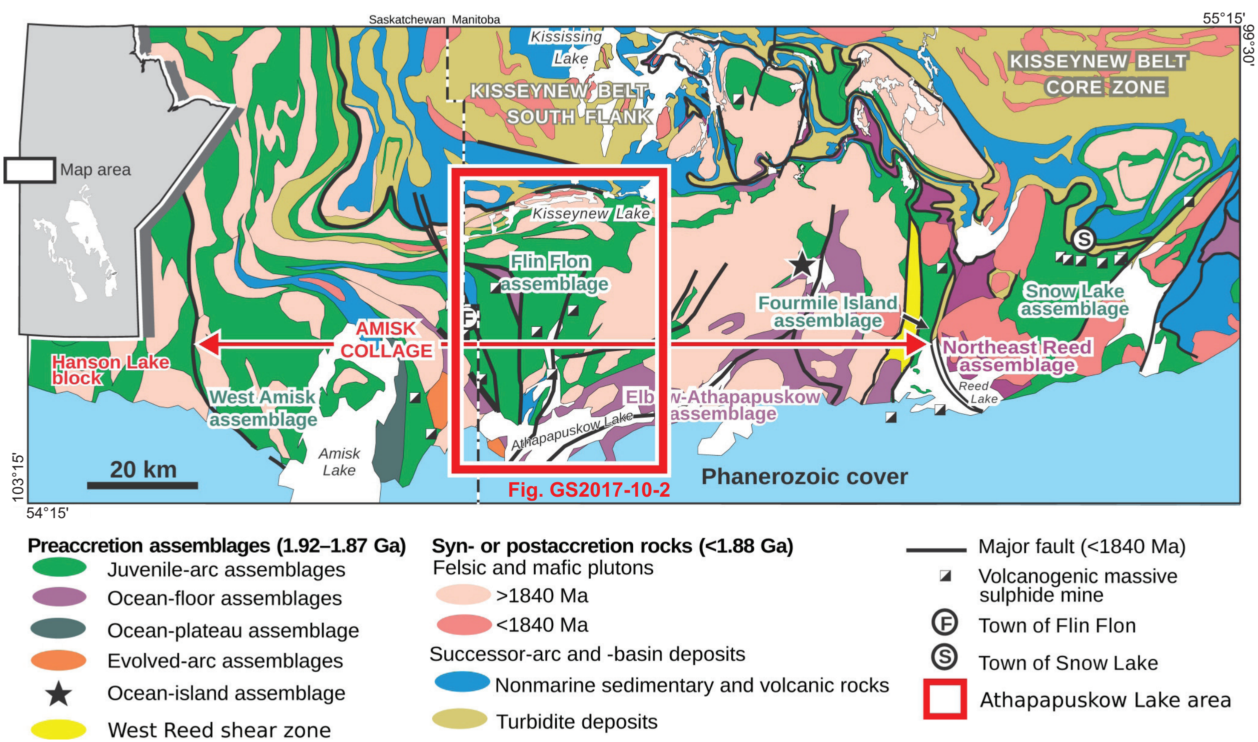

Figure GS2017-10-1: *Simplified geology of the Flin Flon–Snow Lake greenstone belt (modified from NATMAP Shield Margin Project Working Group, 1998). The box outlined in red indicates the Athapapuskow Lake area (Figure GS2017-10-2a, b).*

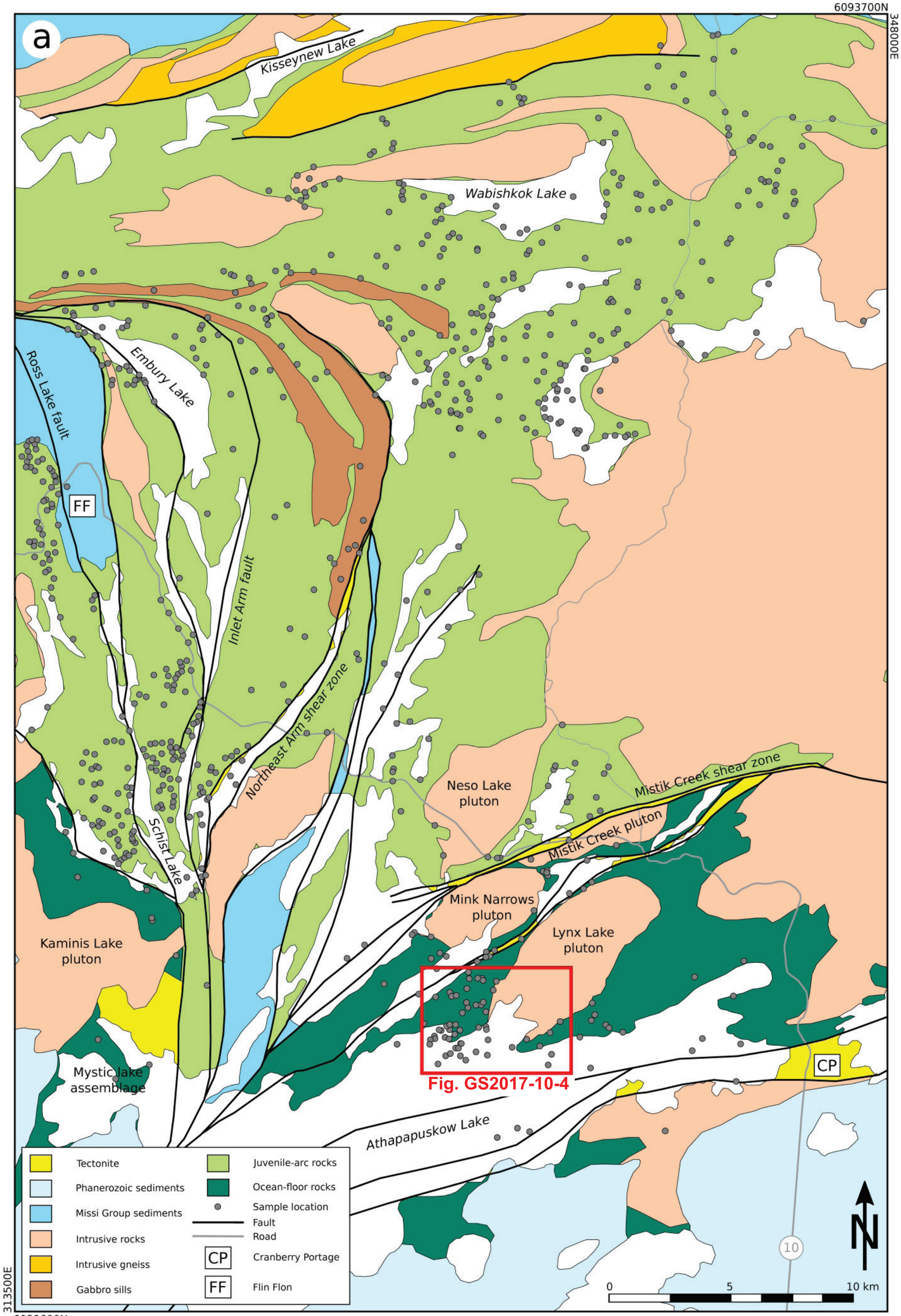

Figure GS2017-10-2a: *Simplified geology of the Athapapuskow Lake study area. Box outlined in red indicates location of Figure GS2017-10-4.*

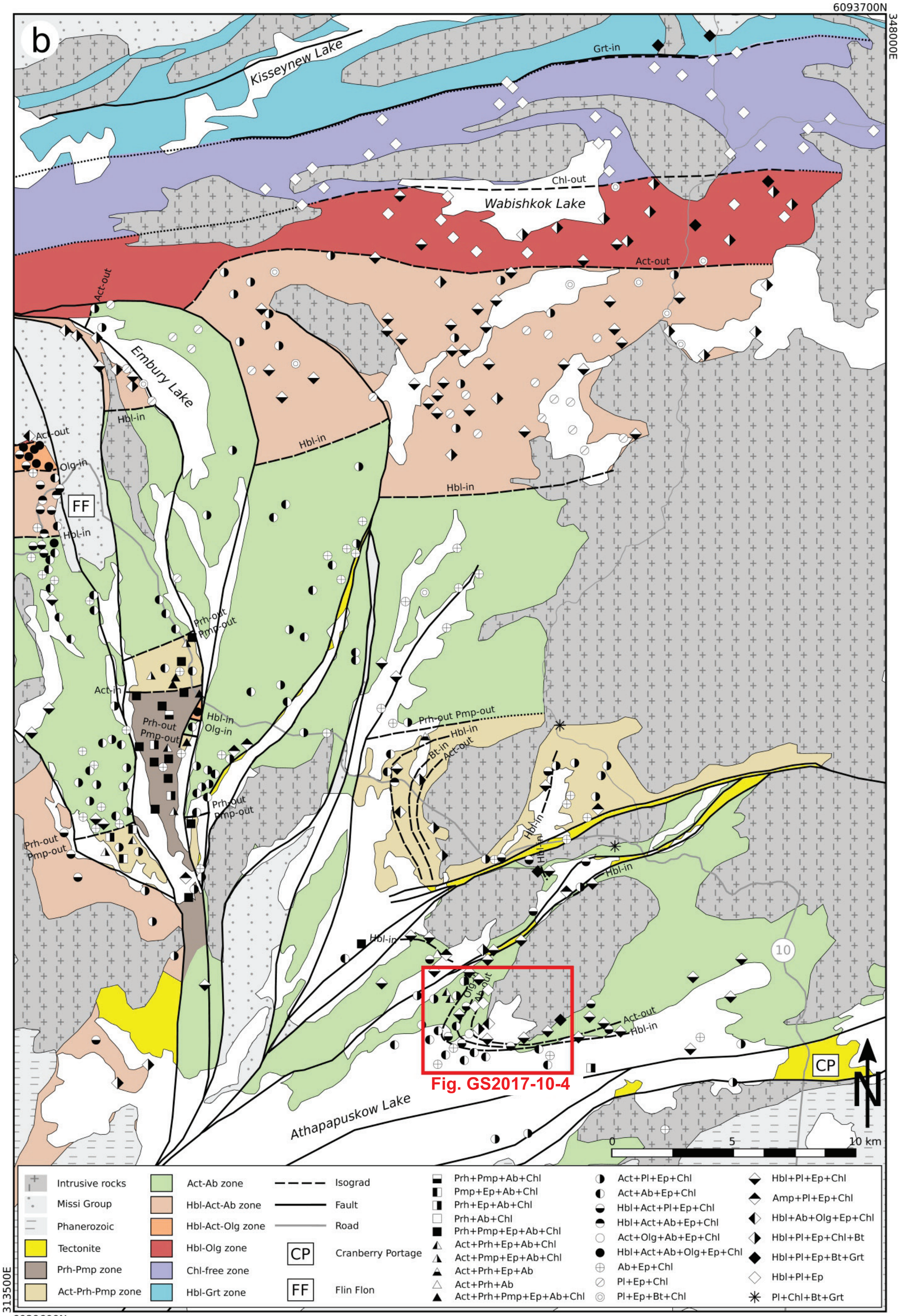

***Figure GS2017-10-2b:** Preliminary map of metamorphic-mineral assemblages and isograds of the Athapapuskow Lake study area; zones are coloured according to regional metamorphic grade and thus exclude contact metamorphic areas. Data compiled from Bailes and Syme (1989), Gilbert (2012), Syme (2015) and Starr (2016), and samples collected by the authors. Abbreviations: Ab, albite; Act, actinolite; Amp, amphibole; Bt, biotite; Chl, chlorite; Ep, epidote; Grt, garnet; Hbl, hornblende; Olg, oligoclase; Pl, plagioclase; Prh, prehnite; Pmp, pumpellyite.*

Fedorowich et al. (1995) and Schneider et al. (2007) suggested three main episodes of metamorphism in the Flin Flon–Snow Lake greenstone belt: 1) early amphibolite-facies contact metamorphism due to the emplacement of successor-arc plutons ca. 1860–1840 Ma; 2) regional subgreenschist to amphibolite metamorphism (Digel and Gordon, 1995; Syme, 2015) ca. 1820–1790 Ma; and 3) retrograde overprint at 1790–1690 Ma. A northward increase in metamorphic grade within single fault-bounded blocks is observed (Bailes and Syme, 1989; Digel and Gordon, 1995; Syme, 2015; Starr, 2016). In general, the grade changes northward from prehnite-pumpellyite, through greenschist, to amphibolite facies.

Metamorphism

With the exception of the Phanerozoic sedimentary cover south of Athapapuskow Lake, all rocks in the Athapapuskow Lake area are metamorphosed. Two distinct types of metamorphism are recognized in the area: regional metamorphism and contact metamorphism. In this study, the Missi group sediments and the successor-arc intrusive rocks were not investigated due to limited access to samples and data.

Metamorphic textures and igneous remnants

In most analyzed samples from the subgreenschist and greenschist facies, metamorphic-minerals are randomly oriented and igneous fabrics are well preserved, whether in contact or regional metamorphic setting. Preservation of igneous texture is less common in samples from the regional-metamorphic amphibolite facies.

Distribution of metamorphic-mineral assemblages in individual samples is controlled by relict igneous textures such as phenocrysts and amygdules, which are common in metamorphosed flow and pillow basalt, and are found throughout the study area. Metamorphic pseudomorphs after pyroxene and calcic plagioclase phenocrysts, are mainly composed of actinolite, hornblende or sodic plagioclase, respectively. They vary in size from < 0.1 to 10 mm. Amygdules are generally filled with quartz, epidote and carbonate (with the addition of prehnite and pumpellyite in the subgreenschist facies). They are rounded to subrounded and range in size from <0.1 to 20 mm. The matrix is usually composed of crystals with considerably finer grain size than phenocrysts or amygdules.

At outcrop scale, igneous structures are preserved in the form of pillows and flows (Figure GS2017-10-3a). Typically, pillow cores are rich in epidote and contain few, small amygdules, whereas the rims contain more chlorite and actinolite/hornblende, with lots of large amygdules. Pseudomorphed plagioclase and/or pyroxene porphyroblasts are often aligned, preserving the trachytic texture typical for magmatic flows. Only in areas of high strain do metamorphic minerals such as chlorite or amphibole define a foliation.

Preservation of igneous mineralogy is rare. Only a few samples within the subgreenschist-facies contain relict igneous pyroxene. Generally, pyroxene is replaced by actinolite or hornblende (or both) and chlorite, depending on metamophic grade. Igneous calcic plagioclase was not identified in any sample. In the subgreenschist facies, plagioclase is usually replaced by albite (with minor prehnite, pumpellyite and epidote), whereas at higher grade it is replaced by oligoclase (with minor albite, epidote and carbonate).

Regional metamorphism

Map of metamorphic-mineral assemblages and isograds

Figure GS2017-10-2b shows a preliminary map of metamorphic-mineral assemblages and isograds for the entire study area. The map was compiled using data from Bailes and Syme (1989), Gilbert (2012), Syme (2015) and Starr (2016), and samples collected by the authors during fieldwork between 2015 and 2017. The plotted mineral assemblages only comprise diagnostic minerals used to define the different metamorphic zones (full mineral assemblages are recorded, but are not shown in this report). The grouping of mineral assemblages allows for the definition of a pattern of regional metamorphic zones, ranging from prehnite-pumpellyite to amphibolite facies. These metamorphic zones are defined through combinations of key minerals, including prehnite, pumpellyite, actinolite, hornblende, albite, oligoclase, chlorite, epidote and garnet. A series of seven isograds were identified separating the different metamorphic zones. From south to north, these isograds are actinolite-in, prehnite- and pumpellyite-out, hornblende-in, oligoclase-in, actinolite-out, chlorite-out and garnet-in. A northerly increase in metamorphic grade is visible, from prehnite-pumpellyite facies in the southern part of Schist Lake to garnet-amphibolite facies at the contact with the Kisseynew domain at Kisseynew Lake. An exception is the cryptic amphibolite-facies domain, referred to as the 'Mystic lake assemblage' after its type area in Saskatchewan (Thomas, 1991), outcropping in the southwestern part of the study area. Major shear zones (e.g., Northeast Arm shear zone) and late brittle faults (e.g., Ross Lake fault, Inlet Arm fault) disrupt the otherwise continuous metamorphic succession of zones and isograds.

Subgreenschist facies: prehnite-pumpellyite zone

The prehnite-pumpellyite zone is defined as the area down-grade of the actinolite-in isograd and is characterized by the mineral assemblage Prh+Pmp+Ab+Chl+Ep+Qtz±Ttn±Cb±Ap (Figure GS2017-10-3b). Prehnite and pumpellyite typically, but not always, coexist within samples of this zone, with prehnite being present in considerably higher modal amount compared to pumpellyite. These two minerals are easily identified in amygdules, but are also found as very fine-grained crystals in the matrix intergrown with albite, chlorite and epidote, which are the most abundant minerals found in rocks from the prehnite-pumpellyite zone. These minerals replace phenocrysts or are found as part of the matrix assemblage. Radial or granular epidote and chlorite, together with quartz, can also fill amygdules. Rare igneous pyroxene is preserved in a few samples of this zone, mostly within partially replaced phenocrysts.

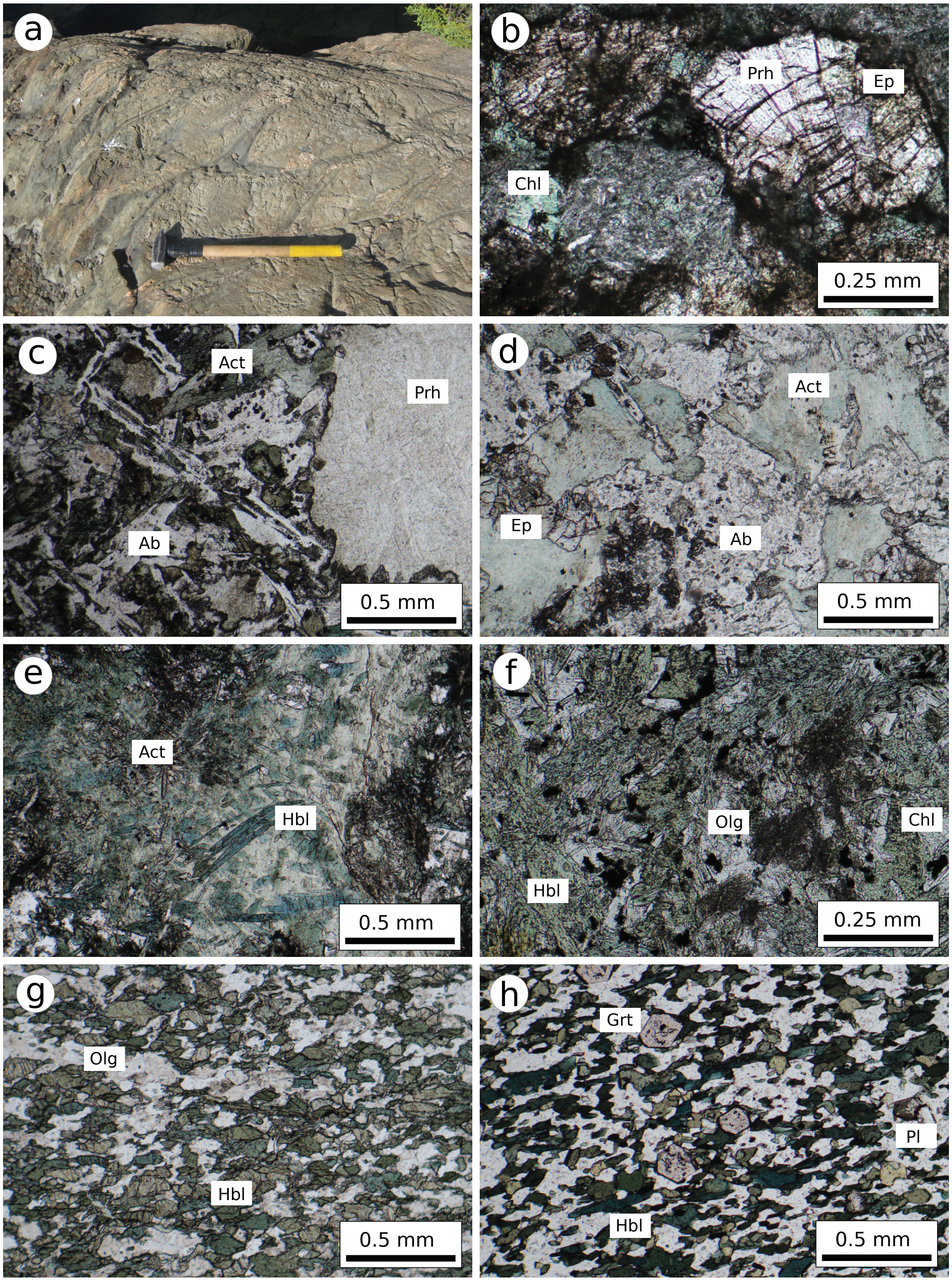

Figure GS2017-10-3: *Outcrop picture and photomicrographs of different metamorphic zones in the study area:* ***a)*** *metamorphosed basalt with well-preserved pillow structure from Act-Ab zone (sample 47-4, UTM Zone 14U, 315657E, 6067795N, NAD 83);* ***b)*** *prehnite, epidote and chlorite in amygdule of sample from the prehnite-pumpellyite zone, in plane polarized light (ppl; sample 52-85-342-1, UTM 320372E, 6059778N);* ***c)*** *prehnite-filled amygdule in contact with actinolite in sample from the actinolite-prehnite zone (ppl; sample 71-1, UTM 330568E, 6061945N);* ***d)*** *actinolite, epidote and albite in sample from the actinolite-albite zone (ppl; sample 52-88-3010-1, UTM 316899E, 6062467N);* ***e)*** *distinct crystals of hornblende and actinolite in sample from the hornblende-actinolite-albite zone (ppl; sample 52-86-1010-1, UTM 316412E, 6057885N);* ***f)*** *hornblende and oligoclase in matrix of sample from the hornblende-oligoclase zone (ppl; sample 32-01-0362-1, UTM 343722E, 6085680N);* ***g)*** *hornblende and oligoclase in matrix of sample from the chlorite-free zone (ppl; sample 32-01-0198-1, UTM 338638E, 6088670N);* ***h)*** *hornblende and garnet in sample from the hornblende-garnet zone (ppl; sample 32-03-0062-1, UTM 342677E, 6092696N). Abbreviations: Ab, albite; Act, actinolite; Chl, chlorite; Ep, epidote; Grt, garnet; Hbl, hornblende; Olg, oligoclase; Pl, plagioclase; Prh, prehnite.*

Subgreenschist facies: actinolite-prehnite-pumpellyite zone

The actinolite-prehnite-pumpellyite zone is defined as the area between the actinolite-in and prehnite- and pumpellyite-out isograds. The characteristic metamorphic-mineral assemblage of rocks within this zone is Act+Prh+Pmp+Ab+Chl+Ep+Qtz±Ttn±Cb±Ap (Figure GS2017-10-3c). Even though the characteristic assemblage implies the coexistence of actinolite with either or both of prehnite and pumpellyite within the same sample, the more common assemblages in the zone are Prh+Pmp+Ab+Chl+Ep+Qtz±Ttn±Cb±Ap and Act+Ab+Chl+Ep+Qtz±Ttn±Cb±Ap. Usually, actinolite occurs as fine acicular grains (only visible using scanning electron microscopy) intergrown with prehnite and pumpellyite (where present) within the matrix. Prehnite and pumpellyite are typically present in amygdules, and as very fine grained crystals in the matrix. Epidote is usually found as subidiomorphic grains overgrowing the matrix. Chlorite fills vesicles or grows interstitially within the matrix. Carbonate is usually associated with prehnite, pumpellyite, chlorite, epidote and quartz within amygdules. In the actinolite-prehnite-pumpellyite zone, the nondiagnostic assemblage Ab-Chl-Ep is common.

Greenschist facies: actinolite-albite zone

The actinolite-albite zone defines the greenschist facies and occupies the area between the prehnite- and pumpellyite-out and the hornblende-in isograds. This zone is the largest metamorphic zone in the study area. Rocks in this area contain the typical greenschist-facies assemblage Act+Ab+Ep+Chl+Qtz±Ttn±Bt±Ap±Opq (Figure GS2017-10-3d). Primary igneous textures are usually well preserved within samples of this zone. Pyroxene and plagioclase phenocrysts are pseudomorphed by actinolite and albite, respectively. Amygdules are typically filled with fine-grained quartz, granular or radial epidote, chlorite and carbonate. Tiny, green needles of actinolite, together with 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 are missing the diagnostic mineral actinolite.

Lower-amphibolite facies: hornblende-actinolite-albite zone

The hornblende-actinolite-albite zone is defined as the area found between the hornblende-in and the oligoclase-in isograds. The zone is characterized by the mineral assemblage Hbl+Act+Ab+Ep+Chl+Qtz±Ttn±Bt±Ap±Opq (Figure GS2017-10-3e). Several different textural relationships between actinolite and hornblende have been identified, including distinct grains, patchy intergrowths and core–rim microstructures. Even though the typical assemblage contains both hornblende and actinolite, some assemblages contain only one of the two minerals. Hornblende occurs as rare, small blebs in samples from the southern part of the zone. The modal amount of hornblende, together with its grain size, increases toward the north. Close to the oligoclase-in isograd, hornblende is characterized by dark green needles, needle aggregates or blades, up to several millimetres long, in the eastern part of the study area. 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 present as a fine-grained component of the matrix. Granular epidote, chlorite and fine-grained quartz are common in the matrix and within amygdules. Minor titanite, apatite and opaque minerals are found as part of the matrix assemblage.

Lower-amphibolite facies: hornblende-actinolite-oligoclase zone

The hornblende-actinolite-oligoclase zone is defined as the area between the oligoclase-in and actinolite-out isograds. This zone was only identified in the Flin Flon block. The typical metamorphic-mineral assemblage is Hbl+Act+Olg+Ab+Ep+Chl+Qtz±Ilm±Ttn±Bt±Ap±Opq. In this zone only large amygdules and phenocrysts are preserved. Hornblende is identifiable in the field as fine black needles, just north of the oligoclase-in isograd, and coarsens toward the north. Relatively coarse-grained intergrown hornblende and actinolite build a network of elongate crystals. Fine-grained interstitial oligoclase (accompanied in some cases by albite), acicular chlorite and skeletal epidote fill the space between, and in some cases overgrow, the amphibole network. Ilmenite is the main Ti-bearing phase, replacing titanite. Late retrograde(?) titanite rims the ilmenite.

Amphibolite facies: hornblende-oligoclase zone

The zone between the actinolite-out and chlorite-out isograd is defined as the hornblende-oligoclase zone. The characteristic metamorphic-mineral assemblage for this zone is Hbl+Ab+Olg+Ep+Chl+Qtz±Bt±Ilm±Ttn±Ap±Opq (Figure GS2017-10-3f). The most common plagioclase is oligoclase, with minor to no albite. Oligoclase is found as interstitial grains between fairly coarse-grained, dark green, hornblende blades or needle aggregates up to 1 mm long. Brown to green biotite is present in most of the samples as plates or blades of variable size in association with the hornblende crystals. Skeletal epidote, usually <1 mm across, and acicular or fibrous chlorite are also present between the hornblende grains. Ilmenite is commonly rimmed by retrograde(?) titanite.

Amphibolite facies: chlorite-free zone

The zone north of the chlorite-out and south of the garnet-in isograd is defined as the chlorite-free zone. This zone is characterized by the absence of chlorite, with the key mineral assemblage being Hbl+Pl+Ep+Qtz±Bt±Ilm±Ttn±Ap±Opq (Figure GS2017-10-3g). Hornblende is found as green blades, less than a millimetre to several millimetres long, or as tiny, pale green needles, typically creating a tight network of crystals. The main plagioclase is oligoclase, which is usually present as an interstitial phase filling the spaces in the amphibole network. Rare pseudomorphed igneous plagioclase phenocryst relicts are found in the eastern part of the chlorite-free zone. Epidote crystals are skeletal to granular and range in size from <0.1 to 0.5 mm. Several samples contain brown to green biotite as plates or blades varying in size from <0.1 mm to 0.5 mm. Ilmenite is enveloped by titanite.

Amphibolite facies: hornblende-garnet zone

The northernmost zone begins just north of the garnet-in isograd and is defined as the hornblende-garnet zone. It occurs south of the transition into the Kisseynew gneiss belt. The characteristic mineral assemblage for this zone is Hbl+Pl+Ep+Bt+Grt +Qtz±Ilm±Ttn±Ap±Opq (Figure GS2017-10-3h). Green to blue hornblende grains less than a millimetre to several millimetres long create a decussate texture. Garnet porphyroblasts overgrowing the amphibole reach up to 3 mm in diameter. Plagioclase is present as interstitial fill between hornblende grains. Small epidote grains are found dispersed within the matrix. In some cases skeletal epidote is present, as are subidiomorphic brown to green biotite plates or blades.

Contact metamorphism

Contact metamorphic aureoles around plutons are usually recognized in the field through a general darkening of the fresh and weathered surfaces. The rocks are very fine grained and the mineral assemblages difficult to identify in hand sample or optically. With the aid of electron-microprobe analysis of thin sections, contact metamorphic assemblages within the aureole could be identified. For the purpose of this study, a contact aureole is defined as the area around an intrusive pluton where mafic rocks consist of a metamorphic-mineral assemblage containing hornblende, rather than only actinolite, typical for unaffected rocks outside the contact aureole in areas of low-grade metamorphic overprint.

In the eastern part of the Athapapuskow Lake area, contact aureoles extend for approximately 1 km outward from the margins of the Lynx Lake (1847 ±4 Ma; Gordon et al, 1990) and Neso Lake (1858 ±3 Ma; Syme et al., 1991) plutons. Narrower aureoles surround the Mink Narrows and the Mistik Creek plutons (Figure GS2017-10-2a). Rocks in the contact aureole of the intrusions generally consist of metamorphosed massive or pillowed basalt showing little to no deformation and characterized by dark grey to black weathering. Fresh surfaces are dark green, with some lighter patches due to epidotization. Igneous textures, such as phenocrysts and pillow or flow structures, are typically preserved, whereas primary igneous minerals are pseudomorphed. Primary pyroxene is usually replaced by actinolite and/or hornblende, whereas calcic plagioclase is replaced by sodic plagioclase. The typical mineral assemblage observed in thin section is Hbl±Act+Pl(Ab or Olg)+Qtz+Bt±Ep±Chl±Opq. Discrete actinolite grains are intergrown with hornblende where the two amphiboles are present together. 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. Red to purple garnet porphyroblasts <1 mm in diameter are locally found. The garnet occurs in mafic domains, within rhyolitic units. The mafic domains are interpreted as zones of premetamorphic alteration.

A well-developed aureole surrounds the Lynx Lake pluton (Figure GS2017-10-4) within the regional actinolite-albite zone. Several observations indicate the presence of this contact aureole around the Lynx Lake pluton: 1) a slight increase in grain size of amphibole is observed with proximity to the pluton; 2) the metamorphic-mineral assemblage changes from Act+Ab+Ep+Chl+Qtz±Ttn±Opq outside the aureole, to Hbl+Olg+Ep+Chl+Qtz±Ilm±Ttn±Opq close to the pluton; and 3) the modal amount of epidote decreases toward the intrusion. Garnet porphyroblasts are locally found in the internal part of the contact aureole at one locality on the southern side of the Lynx Lake pluton in an assemblage comprising Hbl+Olg+Ep+Grt+Qtz+Opq. The limited occurrence of this assemblage suggests local variations in bulk composition. The aureole is narrower south of the Lynx Lake pluton, where greenschist-facies assemblages occur about 800 m from the pluton. These greenschist-facies assemblages are interpreted as the result of regional metamorphism and are therefore outside of the contact aureole as defined in this study.

A contact aureole was interpreted by Syme (2015) to extend for about 1 km around the Kaminis Lake pluton (1856 ±2 Ma; Stern and Lucas, 1994) in the western part of the Athapapuskow Lake area (Figure GS2017-10-2a). The aureole is less well defined compared to the Lynx Lake, Mink Narrows, Neso Lake and Mistik Creek plutons. Rocks immediately adjacent to the Kaminis Lake pluton in the northern and northwestern parts of the aureole are characterized by pale green to grey weathered surfaces and are dark grey to black on fresh surfaces. Local porphyritic basalt contains pseudomorphs of pyroxene and/or plagioclase phenocrysts. A metamorphic-mineral assemblage consisting of Hbl+Act+Pl+Bt+Chl+Qtz±Opq±Ap is commonly observed in this part of the aureole. Domains in the eastern and southeastern parts of the aureole show a strong foliation oriented approximately 150°/80°. Up-grade of the hornblende-in isograd, it becomes difficult to differentiate between a regional and a contact metamorphic origin for the mineral assemblages.

A region of amphibolite-facies rocks approximately 5 km wide is present southeast of the Kaminis Lake pluton (Mystic lake assemblage; Figure GS2017-10-2b). Rocks in this area consist of strongly foliated amphibolite interlayered with fine-grained granitic layers, consistently oriented 130°/90°. These relatively fine-grained amphibolite bands, usually 5–20 cm wide, are grey to green on weathered surfaces and dark green on fresh surfaces. The characteristic mineral assemblage for metabasic rocks of this area is Hbl+Pl+Bt+Chl+Qtz±Opq±Ap. The granitic layers vary between a few millimetres and several centimetres in thickness, and consist of fine-grained quartz and feldspar. No contact aureole on the southeastern side of the Kaminis Lake pluton could be distinguished.

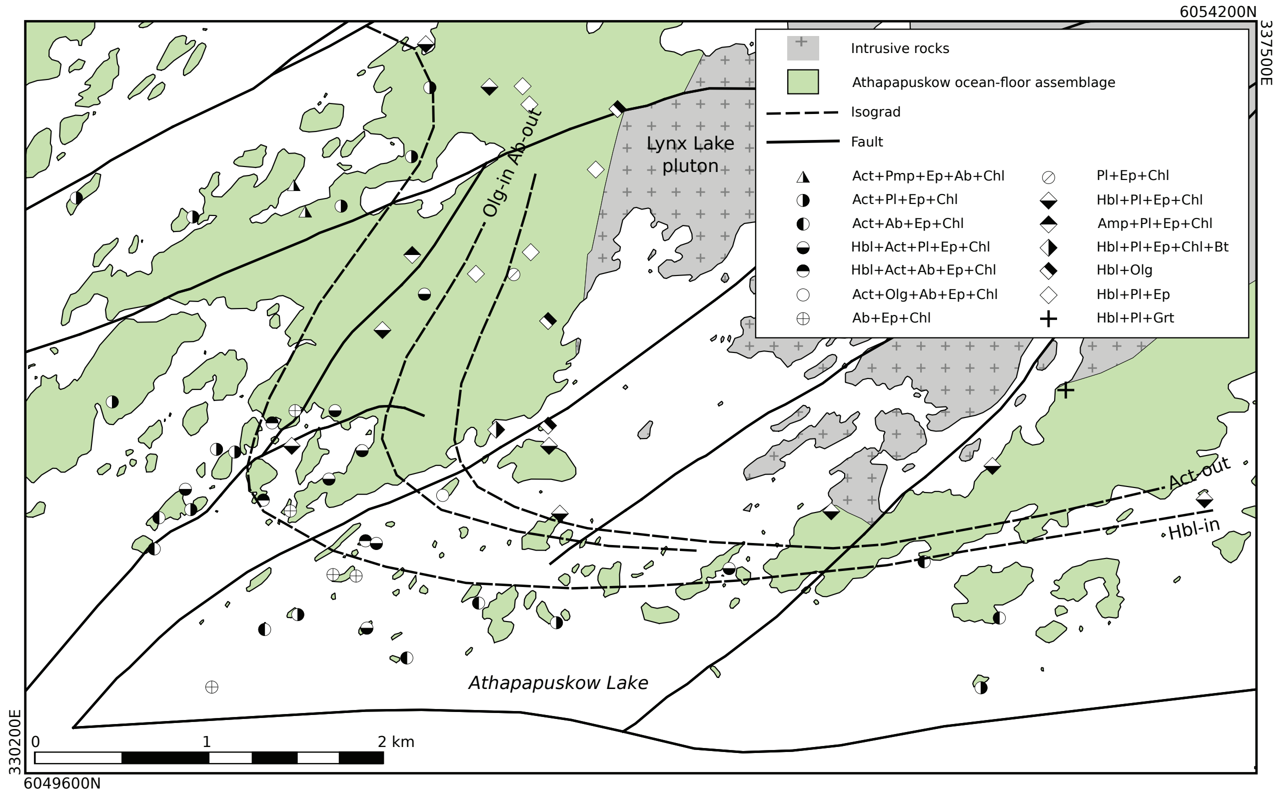

Figure GS2017-10-4: *Map of the metamorphic-mineral assemblages and isograds for the Lynx Lake contact aureole. Abbreviations: Ab, albite; Act, actinolite; Amp, amphibole (undefined); Bt, biotite; Chl, chlorite; Ep, epidote; Grt, garnet; Hbl, hornblende; Olg, oligoclase; Pl, plagioclase; Pmp, pumpellyite.*

Thermodynamic modelling

Phase-equilibria diagram sections were calculated for representative average bulk compositions of the juvenile-arc rocks and the ocean-floor–assemblage rocks (Table GS2017-10-1), in order to estimate pressure and temperature conditions at the peak of metamorphism. The Gibbs energy minimization software Theriak-Domino (de Capitani and Brown, 1987; de Capitani and Petrakakis, 2010) was used, together with the thermodynamic dataset of Holland and Powell (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 integrated. The phase-equilibria modelling was 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 was selected because it is a good approximation of the analyzed composition of the rocks. Iron oxide (Fe_2O_3) was estimated as 15% of the total FeO^T, based on the presence of accessory Fe-bearing phases, wet titration of selected samples, and iterative T-XFe^{3+} and pressure-temperature(P-T) equilibrium modelling for different iron contents and pressures. Manganese was not considered as a component due to its low abundance (usually MnO <0.1 wt. %) and to avoid overstabilization of garnet, which is the main mineral thermodynamically incorporating Mn. Phosphorous is assumed to be completely incorporated in apatite. Hydrogen was set at a large value to obtain H_2O in excess over the whole calculated P-T range.

Figure GS2017-10-5 shows the isochemical phase diagrams for the average juvenile-arc bulk composition (Figure GS2017-10-5a) and the average ocean-floor bulk composition (Figure GS2017-10-5b) in the NCKFMASHTO chemical system. The same colour scheme used in the map of metamorphic-mineral assemblages and isograds (see legend of Figure GS2017-10-2b) is applied to facilitate comparison.

The calculated diagrams for the two different bulk compositions show a number of similar features. In both sections, a large field containing the assemblage Act+Ab+Chl+Ep+Bt+Qtz+Ttn is present below 450°C. Just up-grade of this field are two successive, relatively narrow fields (<20°C) containing coexisting albite and plagioclase, followed by coexisting hornblende and actinolite. The overlap in pressure between the two fields varies between bulk compositions. In the case of the average juvenile-arc assemblage, the overlap spans over a pressure range of 3.7–4.2 kbar, whereas for the average ocean-floor assemblage, the overlap range is 2.7–4.4 kbar. The stability fields, where hornblende coexists with epidote, become narrower and eventually disappear with decreasing pressure. For the juvenile-arc rocks,

Table GS2017-10-1: Whole-rock geochemical data used to calculate phase-equilibria diagrams of figure GS2017-10-5. Average calculated based on selected data from Bailes and Syme (1989), Gilbert (2012), Syme (2015) and Starr (2016), and samples collected by the authors.

wt. % oxides	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Average juvenile-arc assemblage	53.84	0.617	14.94	1.911	9.745	4.98	7.8	2.692	0.699	0.126	2.619	99.97
Average ocean-floor assemblage	48.92	1.193	14.09	2.266	11.56	7.147	8.722	2.513	0.214	0.137	3.524	100.3
mol% cations	**Si**	**Ti**	**Al**	**Fe3+**	**Fe2+**	**Mg**	**Ca**	**Na**	**K**	**P**	**H**	**Total**
Average juvenile-arc assemblage	52.16	0.449	17.06	1.393	7.896	7.193	7.926	5.057	0.864	0	100	200
Average ocean-floor assemblage	47.61	0.873	16.17	1.66	9.405	10.37	8.906	4.742	0.266	0	100	200

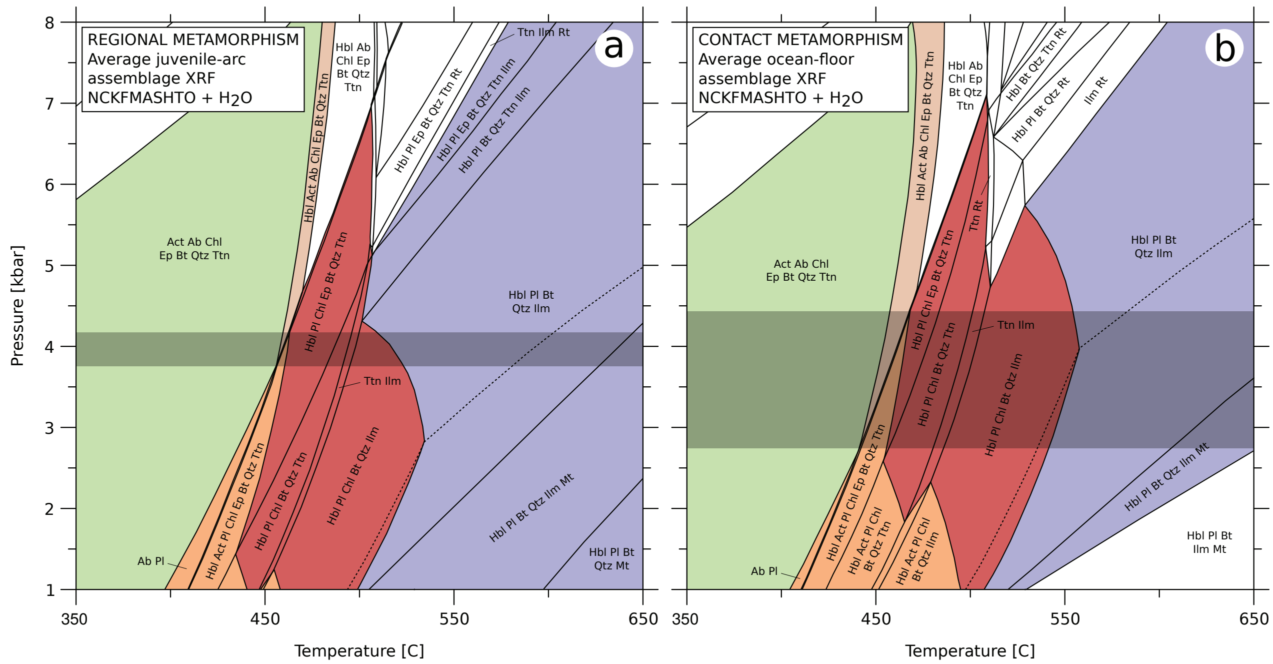

Figure GS2017-10-5: *Pressure-temperature–equilibrium phase diagram constructed for **a)** the average juvenile-arc assemblage, and **b)** the ocean-floor assemblages in the NCKFMASHTO chemical system. Fields use the same colour scheme as in Figure GS2017-10-2b to facilitate comparison. The grey overlay indicates the estimated equilibration-pressure range, based on the sequence of isograds observed (regional metamorphic gradient for the juvenile-arc assemblage and Lynx Lake pluton contact aureole for the ocean-floor assemblage). Abbreviations: Ab, albite; Act, actinolite; Bt, biotite; Chl, chlorite; Ep, epidote; Hbl, hornblende; Ilm, ilmenite; Mt, magnetite; Pl, plagioclase; Qtz, quartz; Rt, rutile; Ttn, titanite; XRF, X-ray fluorescence.*

this occurs at about 0.5 kbar, whereas for the ocean-floor rocks, it happens at 1.5 kbar. Up-grade of the hornblende-oligoclase zone, the chlorite-out reaction occurs at slightly lower temperatures in the juvenile-arc assemblage, compared to the ocean-floor assemblage (525°C in the juvenile-arc assemblage, 550°C in the ocean-floor assemblage). Up-grade of the chlorite-out reaction, an amphibole phase is predicted to be stable (upgrade of dashed line). This phase is a calculated amphibole, created to handle order-disorder of Fe, Mg and Al within the crystal structure for minerals, where the partitioning between these elements is unknown (camo1 and camo2; see Diener et al., 2007, Holland and Powell, 2006). In the natural sequences analyzed in this study, no additional amphibole other than actinolite and hornblende was observed, neither through optical microscopy nor through microprobe analysis. The calculated amphibole stability field up-grade of the dashed line is therefore interpreted as hornblende. At relatively low pressures (<3.5 kbar) and temperatures >500°C magnetite is stable. Biotite is stable over the entire P-T range.

Comparison of the calculated phase diagrams, with the sequence of isograds observed in the field (Hbl-in, Olg-in, Ab-out, Act-out and Chl-out), allows an approximation of the pressure during metamorphism, assuming the models provide a reasonable representation of the natural reactions. The grey band on each diagram represents the range of possible pressures. According to the calculated models, rocks from the regional metamorphic juvenile-arc assemblage equilibrated at pressures between 3.7–4.2 kbar, whereas rocks from the contact metamorphic ocean-floor assemblages experienced pressures of 2.7–4.4 kbar. Within the estimated pressure range, for both the regional metamorphic juvenile-arc assemblage and the contact metamorphic ocean-floor assemblage, the hornblende-in isograd occurs around 440–450°C, followed by the oligoclase-in at 450°C and actinolite-out at 450–460°C. The chlorite-out isograd is situated at approximately 525°C for the juvenile-arc assemblage and at 550°C for the ocean-floor assemblage.

Discussion and conclusion

The new map of metamorphic-mineral assemblages, together with the phase-equilibria modelling, confirms the general increase in metamorphic grade from south to north within the studied part of the Flin Flon greenstone belt. The offset of metamorphic zones by faults and shear zones suggests at least one episode of late tectonic activity (i.e., post-peak regional metamorphism?).

Within the study area, two major metamorphic-facies transitions in metamorphosed basic rocks are observed: the prehnite-pumpellyite– to greenschist-facies transition-and the greenschist- to amphibolite-facies transition. The first is characterized by the first appearance of actinolite, and the last appearence of prehnite and pumpellyite, resulting in a zone where the three minerals coexist. The second is a domain where hornblende coexists with actinolite, located between the hornblende-in isograd and the actinolite-out isograd.

Based on the sequence of isograds observed in the field within the regional metamorphic sequence of the juvenile-arc rocks and the contact metamorphic sequence of the ocean-floor rocks, thermodynamic phase-diagram modelling suggests that the greenschist- to amphibolite-facies transition within the Athapapuskow Lake area is situated at pressures of 3.7–4.2 kbar and temperatures close to 450°C.

Isochemical phase diagrams were calculated using an estimated amount of Fe_2O_3 of 15% of the total FeO^T. Investigation of the influence of ferric iron on the topology of the calculated phase-diagram sections shows that by increasing the amount of Fe_2O_3 to 20%, the equilibration-pressure range of the observed sequence is lowered by more than 1 kbar. In contrast, decreasing the amount of Fe_2O_3 to 10% yields pressures in excess of 1 kbar. This indicates that care should be taken when interpreting results obtained from phase-equilibria modelling of rocks containing ferric iron.

Previous work has demonstrated that important dehydration reactions, which release significant volumes of fluid, are associated with the greenschist- to amphibolite-facies transition. Identifying this transition and the controlling reactions related to the hornblende-in and chlorite-out isograds carries implications for orogenic gold exploration and targeting (e.g., Phillips and Powell, 1993; Starr, 2016). Further work will be directed toward estimating the volume of the fluids released.

Economic considerations

The Flin Flon greenstone belt is host to a variety of mineral deposits and occurrences, including VMS and orogenic gold deposits. Volcanogenic massive sulphide deposits form by seafloor venting of metalliferous hydrothermal fluids in active volcanic settings (e.g., Galley et al., 2007). The Athapapuskow Lake area contains bimodal volcanic successions of mafic and felsic rocks that are characteristic of extensional tectonic regimes and are similar to the volcanic sequence that hosted the Flin Flon and Callinan VMS deposits (e.g., Bailes and Syme, 1989; Syme and Bailes, 1993), indicating excellent exploration potential. Because they formed early in the tectonic evolution of the region, these deposits are overprinted, and in some cases strongly remobilized, via metamorphic and deformational processes. Recognizing the effects of metamorphism on these deposits and their alteration haloes (e.g., Starr, 2016) is important for exploration.

Orogenic-Au 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. Dehydration reactions, for example at the transition from greenschist to amphibolite facies in metabasites, has been interpreted to provide fluids for the transport of gold (e.g., Phillips and Powell, 1993). Identifying these transitions therefore has implications for gold exploration. In addition, crustal-scale shear zones can create pathways and/or traps for the transport and deposition of base metals and gold in solution (e.g, Dubé and Gosselin, 2007). Constraining the magmatic, tectonic and metamorphic framework of the region, combined with a better understanding of the mechanisms and processes involved in mineral alteration and transport, may therefore help focus base- and precious-metals exploration in the Flin Flon belt.

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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): back-arc origin and collisional inversion; Geology, v. 23, p. 1039–1043.

Ashton, K.E., Lewry, J.F., Heaman, L.M., Hartlaub, R.P., Stauffer, M.R. and Tran, H.T. 2005: The Pelican Thrust Zone: basal detachment between the Archean Sask Craton and Paleoproterozoic Flin Flon–Glennie Complex, western Trans-Hudson Orogen; Canadian Journal of Earth Sciences, v. 42, p. 685–706.

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.

Bleeker, W. 1990: New structural-metamorphic constraints on Early Proterozoic oblique collision along the Thompson Nickel Belt, Manitoba, Canada; *in* The Early Proterozoic Trans-Hudson Orogen of North America, J.F. Lewry and M.R. Stauffer (ed.), Geological Association of Canada, Special Paper 37, p. 57–73.

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.

Digel, S. and Gordon, T.M. 1995: Phase relations in metabasites and pressure-temperature conditions at the prehnite-pumpellyite to greenschist facies transition, Flin Flon, Manitoba, Canada; *in* Low-Grade Metamorphism of Mafic Rocks, P. Schiffman and H.W. Day (ed.), Geological Society of America, Special Paper 296, p. 67–80.

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.

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.

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.

Ellis, S., Beaumont, C. and Pfiffner, O.A. 1999: Geodynamic models of crustal-scale episodic tectonic accretion and underplating in subduction zones; Journal of Geophysical Research, v. 15, p. 169–184.

Fedorowich, J.S., Kerrich, R. and Stauffer, M.R. 1995: Geodynamic evolution and thermal history of the central Flin Flon Domain, Trans-Hudson Orogen: constraints from structural development, $^{40}Ar/^{39}Ar$, and stable isotope geothermometry; Tectonics, v. 14, no. 2, p. 472–503.

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.

Gilbert, H.P. 2012: Geology and geochemistry of arc and ocean-floor volcanic rocks in the northern Flin Flon Belt, Embury–Wabishkok–Naosap lakes area, Manitoba (parts of NTS 63K13, 14); Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Geoscientific Report GR2011-1, 46 p., 1 DVD.

Gordon, T.M., Hunt, P.A., Bailes, A.H. and Syme, E.C. 1990: U-Pb zircon ages from the Flin Flon and Kisseynew belts, Manitoba: chronology of crust formation at an Early Proterozoic accretionary margin; *in* The Early Proterozoic Trans-Hudson Orogen of North America, J.F. Lewry and M.R. Stauffer (ed.), Geological Association of Canada, Special Paper 37, p. 177–199.

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.

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.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.

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, 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.

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

Schneider, D.A., Heizler, M.T., Bickford, M.E., Wortman, G.L., Condie, K.C. and Perilli, S. 2007: Timing constraints of orogeny to cratonization: thermochronology of the Paleoproterozoic Trans-Hudson orogen, Manitoba and Saskatchewan, Canada; Precambrian Research, v. 153, no. 1, p. 65–95.

Starr, P.G. 2016: Sub-greenschist to lower amphibolite facies metamorphism of basalts: examples from Flin Flon, Manitoba and Rossland, British Columbia; Ph.D. thesis, University of Calgary, Calgary, AB, 511 p.

Stern, R.A. and Lucas, S.B. 1994: U-Pb zircon age constraints on the early tectonic history of the Flin Flon accretionary collage, Saskatchewan; *in* Radiogenic Age and Isotopic Studies: Report 8, Geological Survey of Canada, Current Research 1994-F, p. 75–86.

Stern, R.A., Machado, N., Syme, E.C., Lucas, S.B. and David, J. 1999: Chronology of crustal growth and recycling in the Paleoproterozoic Amisk Collage (Flin Flon belt), Trans-Hudson Orogen, Canada; Canadian Journal of Earth Sciences, v. 36, p. 1807–1827.

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, 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, 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 volcanogenic massive sulfide deposits, Flin Flon, Manitoba; Economic Geology, v. 88, p. 566–589.

Syme, E.C., Hunt, P.A. and Gordon, T.M. 1991: Two U-Pb zircon crystallization ages from the western Flin Flon belt, Trans-Hudson orogen, Manitoba; *in* Radiogenic Age and Isotopic Studies: Report 4, Geological Survey of Canada, Paper 90-2, p. 25–34.

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.

Thomas, D.J. 1991: Revision bedrock geological mapping: Bootleg Lake–Birch Lake area (parts of NTS 63K-12 and 63L-9); in Summary of Investigations 1991, Saskatchewan Geological Survey, Saskatchewan Energy Mines, Miscellaneous Report 91-4, p. 2–8

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.

Whitney, D.L. and Evans, B.W. 2010: Abbreviations for names of rock-forming minerals; American Mineralogist, v. 95, no. 1, p. 185–187.