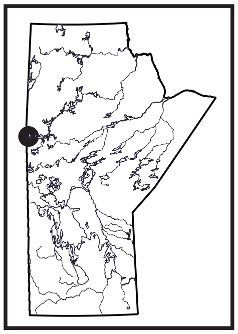
# GS-8 Tectonometamorphic investigations in the Athapapuskow Lake area, west-central Manitoba (part of NTS 63K12)

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



Lazzarotto, M., Gagné, S. and Pattison, D.R.M. 2016: Tectonometamorphic 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.

## 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 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 belt from prehnite-pumpellyite–facies rocks in the south through to amphibolite-facies rocks in the north, but this general pattern is locally disrupted by faults and plutons. Rocks in contact metamorphic aureoles around plutons record proximal amphibolite-facies conditions. Late shear zones overprint the margins of the plutons and the contact aureoles. A preliminary metamorphic map of the area is presented, together with new isograd maps for the contact aureole of the Lynx Lake pluton and for fault-bounded blocks in the Schist Lake region. Displacement of isograds along faults, kinematic indicators and relative timing of movement on the shear zones indicate that vertical and strike-slip movements played an important role in the tectonometamorphic evolution of the region. Relationships and timing of metamorphism and structures suggest that peak metamorphic conditions may have been attained during an early stage in the tectonometamorphic evolution of the Schist Lake area.

## Introduction

In 2015, the University of Calgary, in collaboration with the Manitoba Geological Survey, started a new project involving the tectonic and metamorphic study of parts of the Flin Flon–Snow Lake greenstone belt. In addition to providing insight into tectonic and metamorphic processes, such as behaviour of rocks at the transition from low-grade (prehnite-pumpellyite facies) to medium high-grade (greenschist- to amphibolite-facies) metamorphism, an improved understanding of the tectonometamorphic evolution of this area provides information to constrain exploration models for volcanogenic massive sulphide (VMS) and orogenic gold deposits in the region. For example, orogenic gold deposits are often situated in brittle-ductile shear zones near transitions from greenschist- to amphibolite-facies rocks, where fluids released during metamorphic reactions transport and concentrate precious metals. Identifying these transitions therefore has implications for gold exploration.

The objective of the project is to refine the metamorphic and tectonic history of the Athapapuskow Lake area established by previous workers (e.g., Syme and Bailes, 1989; Syme, 2015) based on field mapping and petrography.

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. Results of these investigations 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), with implications for base- and precious-metals exploration.

During two field seasons (summer 2015 and 2016), targeted mapping and sampling was completed in the Athapapuskow Lake area and in the nearby North Star Lake and File Lake areas. This report focuses on results from the Athapapuskow Lake area. A preliminary new metamorphic map of the Athapapuskow Lake area, including newly defined isograds for an area around Schist Lake and the contact aureole of the Lynx Lake pluton, is presented. Relationships and timing of metamorphism and structures are discussed. Future research will focus on the investigation of relationships along a north–south transect in the File and North Star lakes areas.

## Regional geology

The Athapapuskow Lake area is situated in the western Flin Flon belt, Manitoba (part of NTS 63K12) and is part of the juvenile Reindeer zone of the Trans-Hudson Orogen (Figure GS-8-1; Hoffmann, 1988). Convergence between the Hearne and Superior cratons resulted in a geological setting characterized mainly by the juxtaposition

---

[1] Department of Geosciences, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4

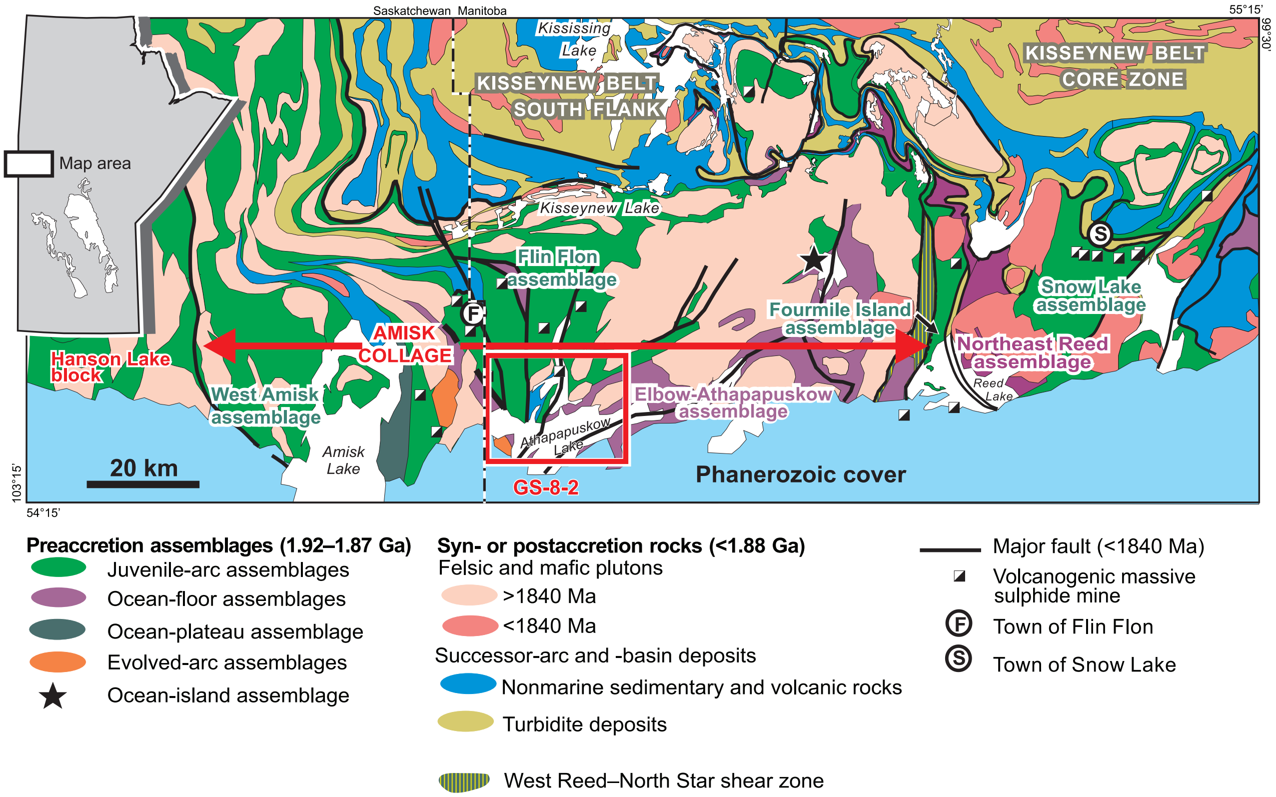


***Figure GS-8-1:*** *Generalized geology of the Flin Flon–Snow Lake greenstone belt (modified from NATMAP Shield Margin Project Working Group, 1998). The box outlined in red indicates the Athapapuskow Lake area (Figure GS-8-2).*

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 group 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, which resulted in what is known as the 'Amisk collage' (Lucas et al., 1996). The first event involved the Sask craton at 1840–1830 Ma and the second, immediately afterwards, involved the Superior craton at 1830–1800 Ma (Bleeker, 1990; Ellis et al., 1999; Ashton et al., 2005).

Today the Athapapuskow Lake area of the Flin Flon belt consists of imbricated juvenile-arc, ocean-floor and sedimentary rocks, characterized by internally complex patterns of faults and folds (Figure GS-8-2a; 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.

The rocks show a metamorphic overprint ranging from sub-greenschist facies to amphibolite facies (Figure GS-8-2b; Digel and Gordon, 1995; Syme, 2015). A northward increase in metamorphic grade within single blocks is observed. In general, the grade changes northward from prehnite-pumpellyite, through greenschist, to amphibolite facies starting at the unconformable contact with overlying Paleozoic sediments in the southern part of Athapapuskow Lake (Bailes, 1979; Digel and Gordon, 1995).

## Structures

Faults and shear zones that separate distinct stratigraphic packages in the Athapapuskow Lake area were termed 'block-bounding structures' by Bailes and Syme (1989). These structures vary from abrupt faults (e.g.,

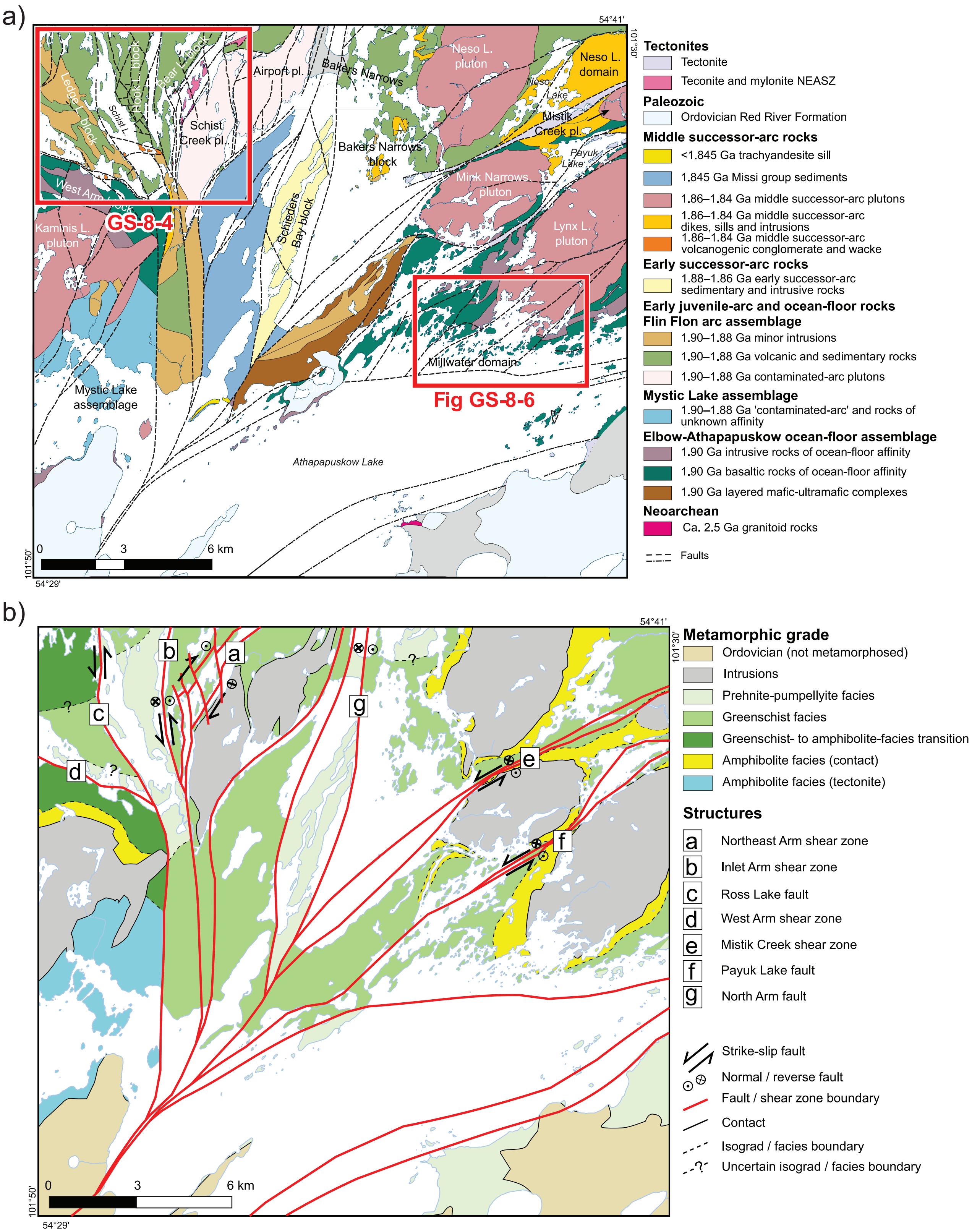


***Figure GS-8-2: a)** Generalized geology of the Athapapuskow Lake area (modified from Syme, 2015). Boxes outlined in red indicate locations of Figures GS-8-4 and GS-8-6. **b)** Preliminary map of metamorphic facies in the Athapapuskow Lake area. Abbreviations: NEASZ, Northeast Arm shear zone; pl., pluton.*

Ross Lake fault, labelled ‘c’ in Figure GS-8-2b) to wide zones of intensely sheared rocks (e.g., Northeast Arm shear zone, labelled ‘a’ in Figure GS-8-2b). Some of these structures were re-investigated in the course of this project and are briefly described here.

### *Northeast Arm shear zone*

The Northeast Arm shear zone (Figure GS-8-2b) is a north-northeast-trending structure characterized by a zone of mylonite and tectonite up to 1000 m wide. In the study area, it juxtaposes substantially different assemblages, namely mafic extrusive rocks of the Bear Lake block to the west with intrusive rocks of the Airport and Schist Creek plutons to the east (Figure GS-8-2a).

Two different units are recognized in the shear zone. A series of deformed mafic extrusive and intrusive rocks (mostly basalt and diabase) are found on the western side of the shear zone. They are typically interlayered with volcaniclastic rocks (lapilli tuff?) and mylonitized toward the margins of the shear zone. In contrast, a succession of strongly tectonized mafic and felsic sheets of unknown precursor, usually showing brittle deformation, is observed on the eastern side of the shear zone. The strongly foliated rocks on either side of the shear zone define the main foliation oriented approximately 010°/90°. Shear-sense indicators in the form of sigma-clasts (Figure GS-8-3a) and shear bands suggest dextral movement with an east-side–down component.

A syncline is present just outside of the shear zone along the western shore of the northeastern arm of Schist Lake. This structure folded a gabbroic sill and caused thickening of nearby tuffaceous units in the hinge. Parasitic Z-asymmetric isoclinal folds of the same structure fold the main foliation (Figure GS-8-3b) and can be followed south along the shear zone for several kilometres. Axial planes of the parasitic folds are oriented at a low angle to the foliation, with fold axes plunging between 40° and 60° to the south-southwest.

In the southwestern part of the Northeast Arm shear zone, Syme (2015) reported a series of late, north-northwest-trending brittle faults with a significant vertical component of movement. No direct evidence of these structures was found, but they would explain the stepwise narrowing (and eventual disappearance) to the south of the tectonized rocks (Figure GS-8-2b).

The plutons to the east of the shear zone show little evidence of shearing, suggesting that the main phase of movement of the shear zone was in an early stage of the tectonic evolution, prior to the emplacement of the intrusions. In some domains within the shear zone, the mylonitic foliation is folded into tight, asymmetric folds. These folds may be the result of shearing (drag folds?) or parasitic folds of the syncline described further to the north. An unperturbed axial-planar feature is developed as a result of the folding. This new foliation does not seem to be affected by the movements along the shear zone, suggesting that the displacement along the fault ceased once the folding took place. These observations do not exclude the possibility of some degree of younger reactivation in other parts of the shear zone.

### *Inlet Arm shear zone*

The Inlet Arm shear zone (Figure GS-8-2b) consists of a main discrete fault surrounded by a broad (800 m) zone of ductile deformation. The shear zone trends north and separates mainly mafic volcaniclastic rocks of the Hook Lake block to the west from mafic extrusive rocks of the Bear Lake block to the east. It juxtaposes prehnite-pumpellyite–facies assemblages in the Hook Lake block with greenschist-facies assemblages in the Bear Lake block, suggesting that considerable displacement occurred along this structure following regional metamorphism.

Primary textures are well preserved in rocks on the western side of the fault, whereas those on the eastern side record a considerable amount of ductile deformation, causing the obliteration of original textures. Abundant epidotized domains lacking relict primary textures and minerals are present within the zone of deformation. Foliation along the eastern shore of Inlet Arm is usually vertical, and kinematic indicators suggest a sinistral sense of shear coupled with an east-side–up movement.

### *Ross Lake fault*

The Ross Lake fault (Figure GS-8-2b) is a predominantly narrow fault found in the northwestern arm of Schist Lake. It separates mainly prehnite-pumpellyite–facies volcaniclastic rocks of the Hook Lake block to the east from a series of greenschist– (to lower–amphibolite–) facies mafic and intermediate rocks of the Ledge Lake block to the west.

A sequence of strongly foliated chlorite±actinolite schist makes up a 200 m wide, high-strain band adjacent to the fault in the northern and southern parts of the northwestern arm of Schist Lake. Stretched pillows and pillow fragments with elongate quartz-amygdules and aligned plagioclase phenocrysts are recognized in some domains. The Ross Lake fault is defined by a series of steep cliffs up to 30 m high found along the west-central shoreline of the northwestern arm of Schist Lake. This escarpment consists of apparently undeformed pillowed and flow basalt, with minor gabbroic and tuffaceous units sharply cut by the fault. The foliation is usually close to vertical and strikes between 000° and 020° along the northern and central parts, and between 320° and 340° along the southern part of the shear zone. Poorly developed kinematic indicators suggest a sinistral sense of shear. The sharp nature of the Ross Lake fault may suggest that it is a relatively late structure.

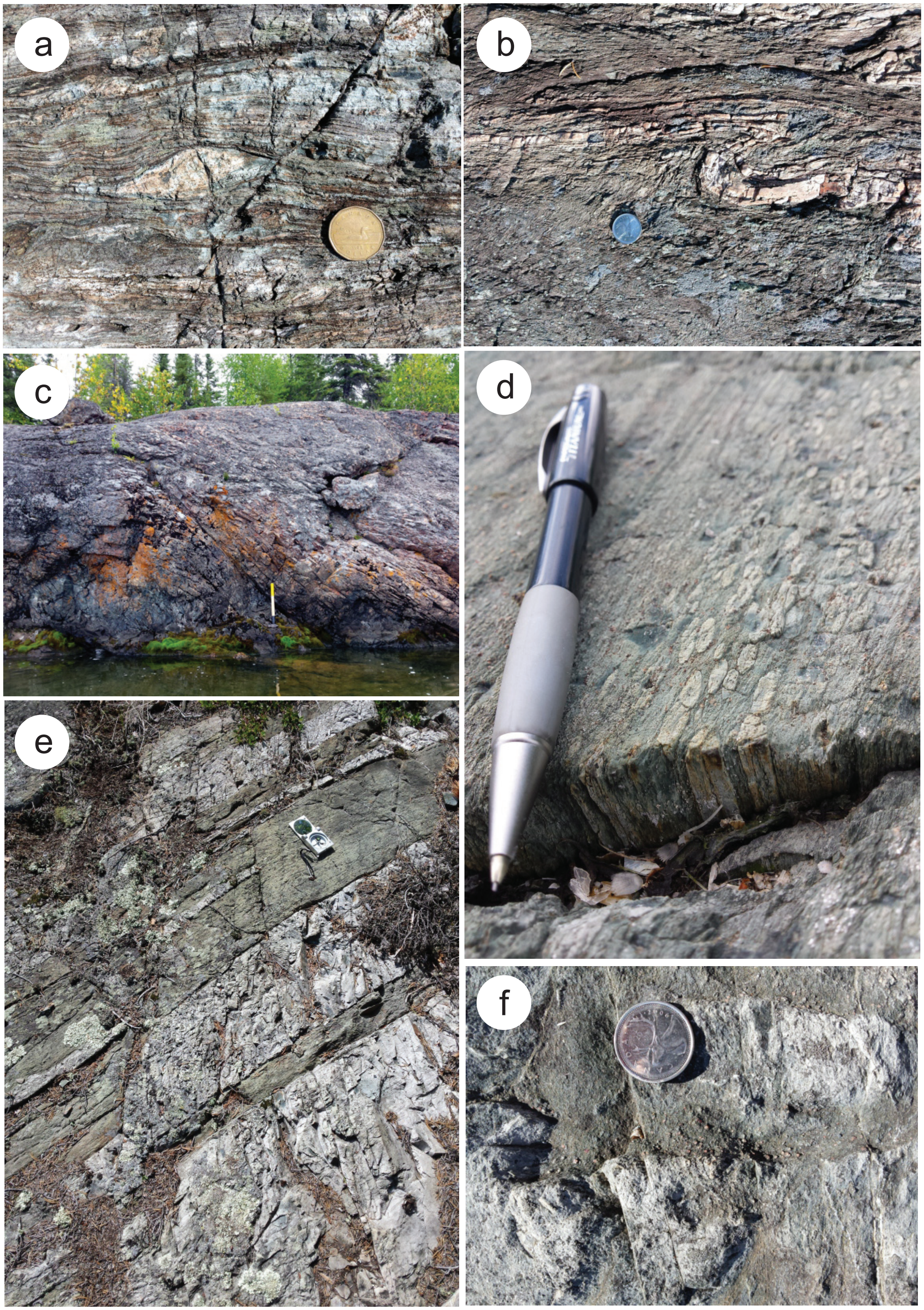


***Figure GS-8-3:*** *Field photographs of the study area:* ***a)*** *$\sigma$-type porphyroclast indicating dextral strike-slip movement in mylonite of the Northeast Arm shear zone;* ***b)*** *parasitic Z-fold with axial-planar crenulation cleavage in mylonite of the Northeast Arm shear zone;* ***c)*** *evidence of shearing in a granodiorite at the edge of the Lynx Lake pluton;* ***d)*** *vertical stretching lineation defined by quartz amygdules in pillow basalt along the North Arm fault;* ***e)*** *interlayered felsic (light) and mafic (dark) domains in tectonites of the Mystic Lake assemblage;* ***f)*** *garnet porphyroblasts in a mafic domain in rhyolite within the contact aureole of the Mink Narrows pluton.*

### *West Arm shear zone*

The West Arm shear zone (Figure GS-8-2b) occurs in the western arm of Schist Lake. It separates basaltic to andesitic rocks and gabbroic sills of island-arc affinity of the Ledge Lake block to the north, from gabbro and basalt of ocean-floor affinity of the West Arm block to the south (Syme, 2015). Rocks of the West Arm block are relatively high grade (greenschist to amphibolite facies), whereas rocks of the Ledge Lake block are relatively low grade (sub-greenschist facies).

Both the northern and southern shores of the western arm of Schist Lake are characterized by relatively high strain. An abrupt decrease in strain is observed from the shore toward the north and south, respectively, suggesting that the shear zone, which is covered by the lake, is only a couple of hundred metres wide. Within the shear zone, bands of undeformed rocks 10–20 cm wide are typically interlayered with strongly sheared domains of the same thickness. Zones of intense schistosity up to 2 m in width occur in several outcrops along the southern shore of Schist Lake.

Foliations from the western arm of Schist Lake vary from parallel to the fault (120°/80°) to oblique (180°/80°) to it. Two distinct foliations were observed at one location: the first ($S_1$) is oriented subparallel to the trend of the shear zone, whereas the second ($S_2$) is a crenulation cleavage oriented at an angle of approximately 30° to the shear zone.

A sliver of sedimentary rocks that contained detrital zircons yielding a U-Pb age of 1863 ±3 Ma is found within the shear zone (Stern et al., 1999), providing a maximum age for the deformation.

### *Mistic Creek shear zone*

The Mistic Creek shear zone (Figure GS-8-2b) is a northeast-trending structure 200–400 m wide situated south of Neso Lake. The shear zone is characterized by strongly foliated chlorite±actinolite schist interlayered with minor strongly flattened pillowed basalt, deformed quartz-feldspar veins and granitoid dikes.

Ductile deformation features are common within the shear zone. These are sometimes overprinted by brittle deformation features such as brecciated domains. The ductile foliation dips steeply to the northwest (235°/85°) and contains lineations that plunge steeply to the east. Shear bands and other kinematic indicators are consistent with northwest-side–down movement coupled with sinistral shear.

The strongly foliated schist lies in sharp contact with virtually undeformed mafic rocks to the southeast. These gabbro and diabase intrusions display shear fabrics only in the immediate vicinity of the shear zone. The northwestern limit of the shear zone is less well defined. A decrease in strain to the northwest is observed in a rhyolite package (and partially in some of the mafic flows). Undeformed pillow basalt is found within about 150 m northwest of the deformed assemblages.

The shear zone forms the boundary between arc-assemblage rocks to the northwest and ocean-floor rocks to the southeast, and is therefore interpreted as an early accretionary structure (Syme, 2015). Deformed quartz-feldspar veins within the shear zone close to the Mink Narrows pluton suggests that the structure was active after the intrusion of the pluton. Furthermore, a lens of Missi group sedimentary rocks contained in the southwestern part of the shear zone suggests that some of the deformation must have occurred after ca. 1847–1842 Ma, the depositional age of the sediments (Syme, 2015).

### *Payuk Lake fault*

The Payuk Lake fault (Figure GS-8-2b) is characterized by brittle-ductile deformation. A major brittle fault is recognized on the southwestern edge of the fault zone, whereas a zone of high strain extends for up to 800 m to the northeast. The fault cuts through the margin of the Lynx Lake pluton on Payuk Lake (Figure GS-8-3c).

The southwestern portion of the Payuk Lake fault juxtaposes gabbro and pyroxenite of a mafic–ultramafic complex with undeformed pillowed basalt. Farther north, the same pillowed-basalt flow is cut by the shear zone. Massive basalt is transected by the shear zone along the central and northeastern portion of the fault, which then widens to several hundred metres at Payuk Lake.

Kinematic indicators suggest movements along the shear zone are a combination of north-side–down normal and sinistral strike slip. The average foliation is oriented 220°/90°, which is slightly rotated compared to the trend of the shear zone. A limited dataset of lineation measurements shows that they trend southwest and plunge relatively steeply. The fact that the shear zone cuts across all the units in a brittle-ductile manner suggests that it is a relatively young structure.

### *North Arm fault*

The North Arm fault (Figure GS-8-2b) is a north-northeast–striking feature that extends through the northern arm of Athapapuskow Lake. It juxtaposes two packages of rocks containing felsic to mafic intrusive and extrusive units belonging to the Schieders Bay block to the west and Bakers Narrows block to the east.

The shear zone cuts a prehnite-pumpellyite–facies domain close to Bakers Narrows, whereas further north it separates prehnite-pumpellyite–facies rocks to the west from greenschist-facies rocks to the east. A mineral assemblage consisting of prehnite-chlorite-epidote-albite was found east of the fault in an outcrop 2.5 km north of the east channel of Bakers Narrows. The prehnite most commonly occurs as amygdules. Further to the north, the typical assemblage is albite-actinolite-chlorite-epidote (lacking prehnite). Prehnite and pumpellyite were observed in amygdules and in the matrix of basalt flows and pillowed basalt as far north as Sourdough Bay on the western side of the fault.

Foliations dip steeply to the east and strike 020°. Elongate quartz amygdules define a strong vertical stretching lineation (Figure GS-8-3d). The partially contrasting metamorphic grade, and steep foliation and lineation, suggest that the structure is a reverse fault.

## Metamorphism

With the exception of the Phanerozoic sedimentary cover in the south of Athapapuskow Lake, most rocks in the Athapapuskow Lake area are metamorphosed. Two distinct types of metamorphism are recognized in the area: regional metamorphism and contact metamorphism.

### *Regional metamorphism*

The regional metamorphic grade in the Flin Flon belt broadly increases from south to north (e.g., Bailes and Syme, 1989; Digel and Gordon, 1995). In the Athapapuskow Lake area, the general pattern is the same, although abrupt changes are observed across some block-bounding faults.

In the northwestern Athapapuskow Lake area, the metamorphic grade varies across the various fault-bounded blocks from prehnite-pumpellyite to greenschist facies. Digel and Gordon (1995) and Digel and Ghent (1994) mapped metamorphic mineral isograds based on the first appearance and disappearance of prehnite, pumpellyite, actinolite, hornblende, epidote and chlorite in the Ledge Lake, Hook Lake and Bear Lake blocks.

Typical mineral assemblage for mafic rocks in the Bear Lake block is albite-actinolite-chlorite-epidote-quartz, characteristic of greenschist-facies conditions (Figure GS-8-4). A mineral assemblage consisting of garnet-biotite-plagioclase-chlorite was observed on two islands along the eastern edge of the Bear Lake block, within the Northeast Arm shear zone (Figure GS-8-5a). Biotite and chlorite define a strong foliation, which is overgrown by <0.1 mm garnet porphyroblasts. The garnet-grade metamorphic conditions implied by the observed mineral assemblage may result from contact metamorphism due to the nearby Schist Creek pluton.

Rocks in the Hook Lake block in the Schist Lake area are characterized by the presence of prehnite-pumpellyite-albite-quartz±actinolite±chlorite±epidote±relict pyroxene (Figure GS-8-4). Prehnite, together with chlorite and quartz, occurs in amygdules, veins and in the matrix. Bow-tie textures are characteristic of prehnite in the area. Pumpellyite is sometimes found as fine-grained green needles in amygdules or in the matrix. Plagioclase phenocrysts are typically replaced by albite. Actinolite was observed in the northernmost part of the block, possibly marking the transition to greenschist facies.

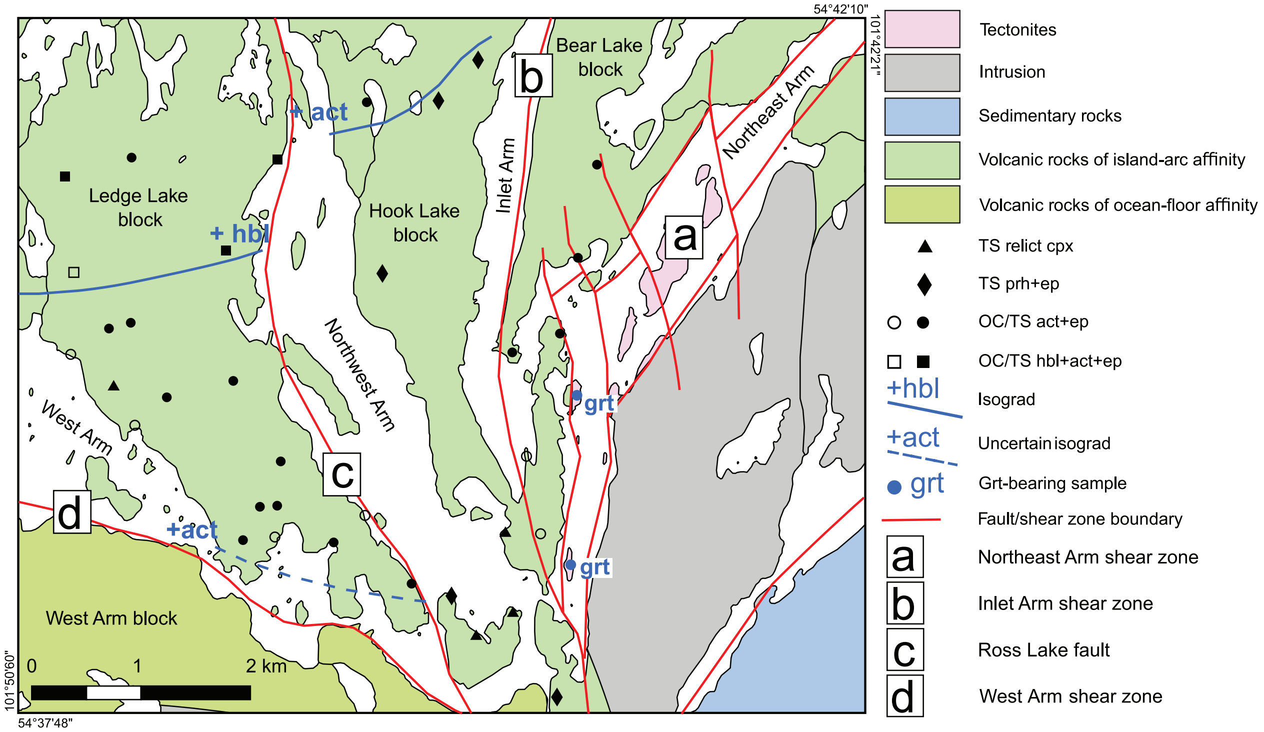


***Figure GS-8-4:*** *Partial mineral assemblage and isograd map depicting the regional metamorphic overprint around Schist Lake, based on outcrop (OC) and thin section (TS) observations. Abbreviations: act, actinolite; cpx, clinopyroxene; ep, epidote; grt, garnet; hbl, hornblende; prh, prehnite; +, mineral-in isograd.*

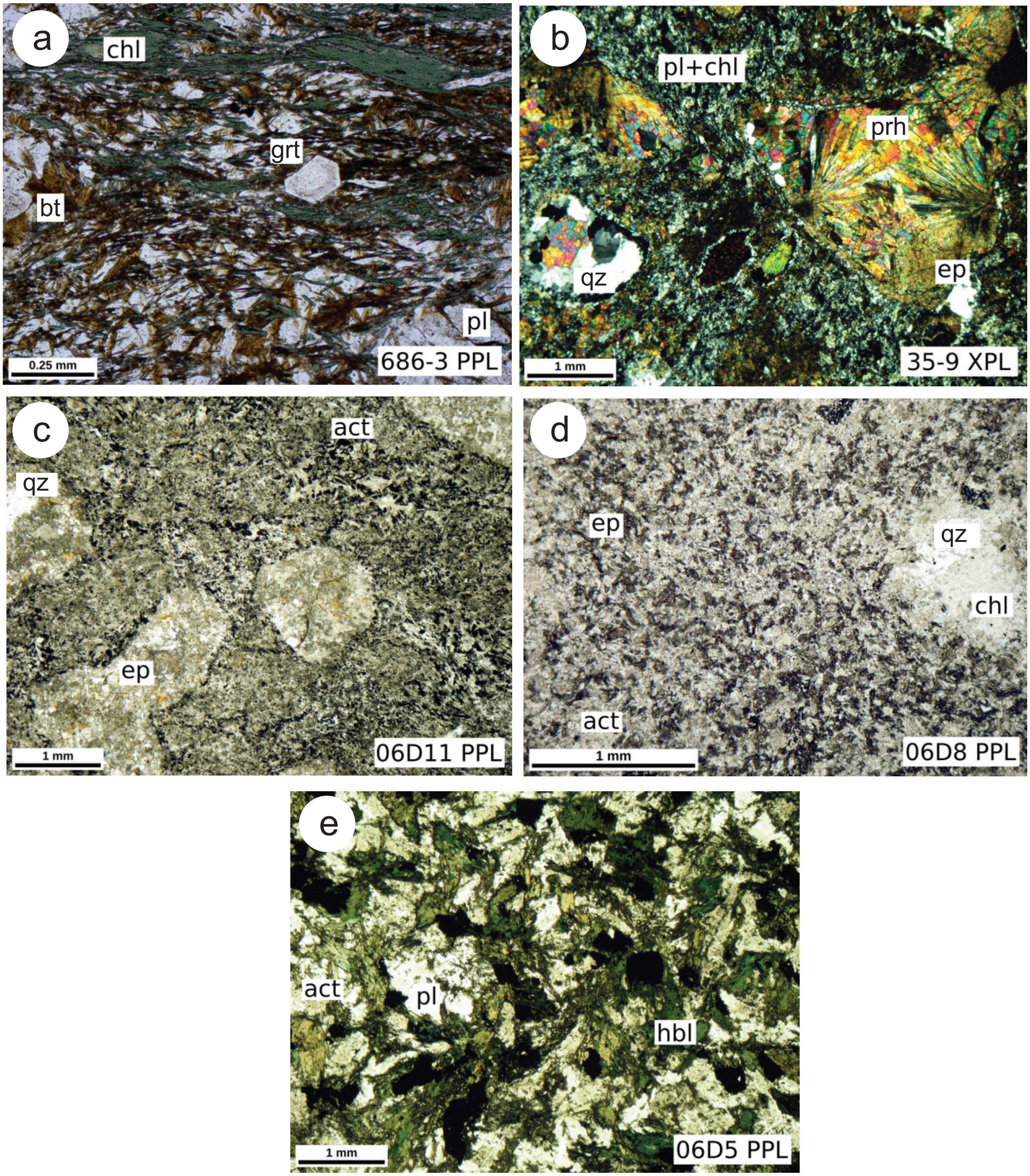


***Figure GS-8-5:*** *Thin-section micrographs of metamorphic assemblages in the study area:* ***a)*** *garnet-biotite-plagioclase-chlorite schist from the Northeast Arm shear zone;* ***b)*** *prehnite-epidote-chlorite–bearing sample (35-9) from south of the Lynx Lake pluton;* ***c)*** *chlorite-actinolite-epidote-plagioclase-quartz–bearing sample (06D11) from inside the Lynx Lake pluton contact aureole;* ***d)*** *epidote-actinolite–bearing sample (06D8) from inside the Lynx Lake contact aureole;* ***e)*** *actinolite-hornblende–bearing sample (06D5) from inside the Lynx Lake pluton contact aureole. The locations of the samples are plotted in Figure GS-8-6. Abbreviations: act, actinolite; bt, biotite; chl, chlorite; ep, epidote; grt, garnet; hbl, hornblende; pl, plagioclase; prh, prehnite; qz, quartz; PPL, plane-polarized light; XPL, cross-polarized light.*

West of the Ross Lake fault, rocks of the Ledge Lake block contain an albite-actinolite-quartz±chlorite±epidote ±hornblende mineral assemblage (Figure GS-8-4). Relict pyroxene phenocrysts occur in the southern portion of the Ledge Lake block, approximately 100 m from the West Arm shear zone. Hornblende is part of the stable assemblage in the northernmost portion of the block, implying a transition from greenschist facies to amphibolite facies. Neither prehnite nor pumpellyite were observed anywhere in the Ledge Lake block.

An abrupt change in metamorphic grade occurs across the West Arm shear zone. The most common mineral assemblage south of the shear zone is actinolite-chlorite-epidote-albite±plagioclase±quartz±hornblende; these greenschist– to lower-amphibolite–facies assemblages contrast with prehnite-pumpellyite–facies assemblages north of the fault. An observed increase in hornblende grain size toward the Kaminis Lake pluton may indicate that the amphibolite-facies conditions are the consequence of contact metamorphism (Figure GS-8-2b).

Rocks containing actinolite-chlorite-epidote-albite-quartz, in which magmatic textures, such as phenocrysts, are rarely preserved, occur east of the Kaminis Lake pluton. These assemblages are typical of greenschist facies in metabasalt and metadiabase. Epidote, chlorite and quartz are part of the matrix assemblage, and also occur as fracture-fills and in amygdules (where preserved).

Further to the south, this greenschist-facies assemblage is gradually replaced by hornblende-plagioclase-chlorite±actinolite±epidote, indicating the transition into the amphibolite facies (Figure GS-8-2b). This transition is accompanied by an increase in strain toward the south. The typical foliation (120°/90°) is defined by the alignment of relatively fine-grained (ferro-) hornblende crystals, which display an increase in grain size toward the Kaminis Lake pluton. Amphibolite-facies rocks in the western arm of Athapapuskow Lake weather pale green to green and are dark green to black on fresh surfaces. Mafic units are interlayered with tiny slivers of strongly deformed, and in some cases tightly folded, felsic material (pegmatite?) oriented parallel to the foliation (Figure GS-8-3e). Garnet was observed in a metabasalt band interlayered with felsic material in an outcrop of the Mystic Lake assemblage.

The eastern part of the study area is characterized by an increase in metamorphic grade from prehnite-pumpellyite facies in the south to greenschist facies in the north. Dull-weathering pillowed and flow basalt south of Lynx Lake pluton contains prehnite±epidote±chlorite–filled amygdules. Prehnite is also present in the matrix of these rocks, together with albite, quartz and rare actinolite (Figure GS-8-5b). Rocks from the Millwater domain, Bakers Narrows block and Neso Lake domain typically contain assemblages of actinolite-chlorite-epidote-albite-quartz, indicative of the greenschist facies.

These relatively fine-grained, aphyric to plagioclase-phyric mafic rocks are green to grey on weathered surfaces and green to dark grey on fresh surfaces. A series of felsic packages (mainly rhyolite?) are found north of the Mistic Creek shear zone. These rocks are generally fine grained and consist of quartz-feldspar-mica; they show no distinctive metamorphic characteristics as no diagnostic mineral assemblage is present.

A mineral assemblage consisting of prehnite-chlorite-epidote-albite-quartz was found in one outcrop 2.5 km north of the eastern channel of Bakers Narrows, where prehnite was mainly recognized in amygdules. This suggests that the prehnite-pumpellyite– to greenschist–facies boundary does not coincide with the North Arm fault (Figure GS-8-2b), as proposed by Syme (2015).

### *Contact metamorphism*

Contact metamorphic aureoles around plutons are difficult to recognize in the field, but become evident through petrographic analysis of thin sections. For the purpose of this study, a contact aureole is defined as the area around a pluton where mafic rocks contain hornblende as a result of thermal metamorphism due to the intrusion, and is accompanied by an increase in grain size toward the pluton.

In the eastern part of Athapapuskow Lake area, contact aureoles extend for approximately 1 km outward from the margins of the Lynx Lake and Mink Narrows plutons, and a narrower aureole surrounds the Mistic Creek pluton (Figure GS-8-2b). Rocks found in the contact aureole of the intrusions consist of (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. Magmatic textures are typically preserved; however, igneous minerals are replaced (e.g., pyroxene is usually replaced by amphibole). The typical mineral assemblage observed in thin section is hornblende-plagioclase-quartz-biotite±epidote±chlorite. Hornblende can be intergrown with discrete grains of actinolite. Epidote, chlorite and quartz occur in veins and amygdules.

Several observations indicate the presence of a contact aureole around the Lynx Lake pluton: 1) a general increase in grain size is observed with proximity to the pluton, 2) the mineralogy changes from plagioclase-chlorite-epidote-quartz±actinolite±prehnite outside the aureole, to hornblende-actinolite-chlorite-plagioclase±epidote 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 the northeastern end of the Mink Narrows pluton. The garnet occurs in mafic domains, within rhyolitic rocks (Figure GS-8-3f). The mafic domains are interpreted as zones of premetamorphic alteration. The aureole is narrower south of the Lynx Lake pluton, where prehnite-pumpellyite–facies assemblages occur 800 m from the pluton (Figure GS-8-6). These assemblages are the result of regional metamorphism and are therefore outside of the interpreted contact aureole.

Figure GS-8-6 shows a partial mineral assemblage and isograd map for the aureole of the Lynx Lake pluton. Samples 06D11, 06D8 and 06D5 were collected along a transect from outside the aureole to the contact with the pluton (Figure GS-8-5c-e). Sample 35-9 is from an outcrop on the southern side of the pluton, outside the contact aureole (Figure GS-8-5b).

A contact aureole was interpreted by Syme (2015) to extend for about 1 km around the Kaminis Lake pluton in the western part of the Athapapuskow Lake area (Figure GS-8-2b). The aureole is less well defined compared to the Lynx Lake, Mink Narrows and Mistic 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. Assemblages of hornblende-plagioclase-biotite-quartz±chlorite±actinolite are commonly observed in this part of the aureole. Domains in the eastern part of the aureole show a strong foliation oriented 150°/80°.

A region of amphibolite-facies rocks approximately 5 km wide is present southeast of the intrusion (Figure GS-8-2b). Rocks in this area consist of amphibolite interlayered with fine-grained granitic layers, consistently oriented 130°/90°. The amphibolite bands are usually 5–20 cm wide, relatively fine grained, and are gray to green on weathered surfaces and dark green on fresh surfaces. The mineral assemblage is typically (ferro-)hornblende-quartz-plagioclase-biotite-chlorite. The felsic 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.

## Discussion and conclusion

The trend of south-to-north increasing metamorphic grade described by several authors for the Flin Flon belt (e.g., Bailes and Syme, 1989; Digel and Gordon, 1995) is complicated in the Athapapuskow Lake area by the presence of major tectonic structures. Some of the major discontinuities (e.g., Ross Lake fault, West Arm shear zone, North Arm fault) juxtapose rocks of relatively low metamorphic grade against units containing higher grade assemblages, suggesting considerable displacement (Figure GS-8-2b). Steeply dipping foliations and steeply dipping stretching lineations (e.g., Figure GS-8-3d) suggest that a substantial part of the observed displacement may have been vertical, with a minor strike-slip component.

Structures can be broadly separated into two groups in the Athapapuskow Lake area: early structures and late structures. In general, early structures are those that do not displace regional metamorphic isograds and were active prior to the regional metamorphic peak at ca. 1812 Ma (Lucas et al., 1996). These structures are usually characterized by ductile fabrics. In contrast, late structures are those that displace regional metamorphic isograds and were active after the regional metamorphic peak. These structures are characterized by brittle-ductile deformation.

According to Lucas et al. (1996) the Northeast Arm shear zone is one of the earliest structures in the area.

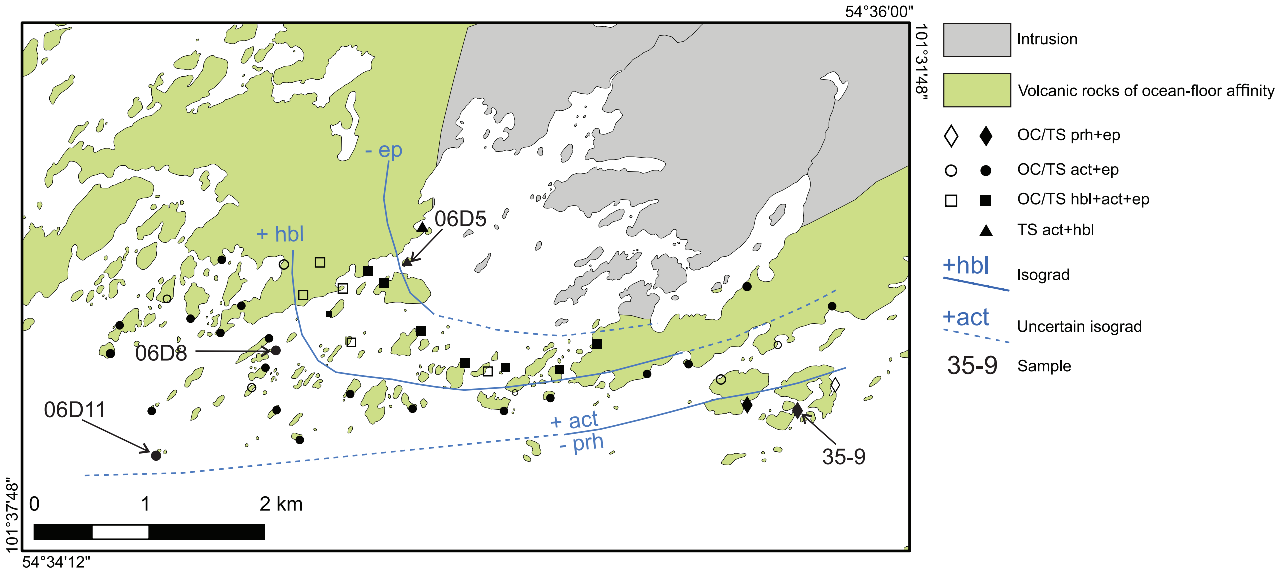


***Figure GS-8-6:** Partial mineral assemblage and isograd map for the Lynx Lake pluton contact aureole, based on outcrop (OC) and thin section (TS) observations. Abbreviations: act, actinolite; ep, epidote; hbl, hornblende; prh, prehnite; +, mineral-in isograd; -, mineral-out isograd.*

Garnet-biotite-chlorite schist is found within the mylonite of the shear zone. Chlorite and biotite define a strong foliation wrapping around deformed plagioclase porphyroblasts, and the foliation is overgrown by garnet. This implies that the growth of garnet, and therefore the associated metamorphic overprint, occurred during or after shearing. The observed mineral assemblage is indicative of lower-amphibolite–facies conditions (Spear, 1993). It is not yet clear if the observed assemblage is the result of regional metamorphism or contact metamorphism due to the nearby Schist Creek pluton. The Northeast Arm shear zone is cut to the south by the Inlet Arm shear zone, another relatively early structure. Stern et al. (1999) dated a felsic dike cutting the tectonite fabric of the Inlet Arm shear zone and concluded that intense deformation along this structure ceased by ca. 1840 Ma. Another early structure is the West Arm shear zone, which is crosscut by the undeformed Boot-Phantom pluton (Thomas, 1989). The pluton was dated by Heaman et al. (1992) at ca. 1838 Ma, giving a minimum age for the West arm shear zone. Both the Inlet Arm shear zone and the West Arm shear zone juxtapose greenschist-facies rocks against prehnite-pumpellyite–facies rocks (Figure GS-8-4), suggesting that peak metamorphic conditions in the Schist Lake area might have been attained relatively early in the tectonometamorphic evolution, compared to the age of ca. 1810 Ma suggested, for example, by Ansdell (2005).

One of the youngest structures in the Schist Lake area is the Ross Lake fault (Bailes and Syme, 1989; Lafrance et al., 2016). It is characterized by sinistral strike-slip movement, which displaces greenschist-facies rocks of the Ledge Lake block toward the south, with respect to the Hook Lake and West Arm blocks.

Preliminary actinolite-in and hornblende-in isograds were determined in the Hook Lake and Ledge Lake blocks, respectively (Figure GS-8-4), which differ from the observations of Digel and Gordon (1995). In the Hook Lake block, the first appearance of actinolite occurs 3 km further south than suggested by these authors.

Isograds for prehnite-out, actinolite-in, hornblende-in and epidote-out were defined for the Lynx Lake pluton contact aureole (Figure GS-8-6). The observed decrease (and disappearance) of epidote and the development of hornblende toward the intrusion suggest peak metamorphic conditions above the greenschist- to amphibolite-facies transition.

Phase-equilibria modelling was attempted for these rocks; inconsistencies between models and observations were observed. More work is required before reliable results can be presented.

## 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 form early in the tectonic evolution of their host volcanic terranes, these deposits are overprinted, and in some cases strongly remobilized, via metamorphic and deformational processes.

Orogenic-Au deposits form later, during regional deformation and metamorphism, from hydrothermal fluids sourced from magmas or metamorphic reactions. The controls on orogenic gold deposits are thus strongly related to metamorphic and tectonic processes. For example, dehydration reactions (e.g., greenschist- to amphibolite-facies transition in metabasites) can provide fluids for the transport of gold (Phillips and Powell, 1993) and crustal-scale shear zones can create a pathway or trap for the transport, and concentration, of base metals and gold (e.g., Dubé and Gosselin, 2007). Understanding the stratigraphic and tectonic framework, and improving the understanding of the mechanisms and processes involved in mineral alteration and transport, will therefore help constrain models for base- and precious-metals exploration in the Flin Flon belt.

## Acknowledgments

The authors thank J. MacDonald and R. Ponto for providing enthusiastic field assistance, as well as all the staff at Midland Rock Preparation Laboratory for thorough logistical support and sample preparation. The authors also thank C. Coueslan and S. Anderson for reviewing earlier versions of this manuscript.

## 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.

Ansdell, K.M., 2005: Tectonic evolution of the Manitoba-Saskatchewan segment of the Paleoproterozoic Trans-Hudson Orogen, Canada; Canadian Journal of Earth Sciences, v. 42, no. 4, p. 741–759.

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. 1979: Sedimentology and metamorphism of a Proterozoic volcaniclastic turbidite suite that crosses the boundary between the Flin Flon and Kisseynew belts, File Lake, Manitoba, Canada; Ph.D. thesis, University of Manitoba, Winnipeg, MB, 154 p.

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.

Digel, S. and Ghent, E.D. 1994: Fluid-mineral equilibria in prehnite-pumpellyite to greenschist facies metabasites near Flin Flon, Manitoba, Canada: implications for petrogenetic grids; Journal of Metamorphic Geology, v. 12, no. 4, p. 467–477.

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.

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.

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.

Heaman, L.M., Kamo, S.L., Ashton, K.E., Reilly, B.A., Slimmon, W.L. and Thomas, D.J. 1992: U-Pb geochronological investigations in the Trans-Hudson Orogen, Saskatchewan; *in* Summary of Investigations, 1992, Saskatchewan Geological Survey, Saskatchewan Energy Mines, Miscellaneous Report 92-4, p. 120–123.

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.

Lafrance, B., Gibson, H.L., Pehrsson, S., Schetselaar, E., DeWolfe, Y.M. and Lewis, D., 2016: Structural reconstruction of the Flin Flon volcanogenic massive sulfide mining district, Saskatchewan and Manitoba, Canada; Economic Geology, v. 111, no. 4, p. 849–875.

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 100 000.

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

Spear, F.S., 1993: Metamorphic phase equilibria and pressure-temperature-time paths; Mineralogical Society of America, Washington, D.C., 799 p.

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., 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.

Syme, E.C., Lucas, S.B., Zwanzig, H.V., Bailes, A.H., Ashton, K.E. and Haidl, F.M. 1998: Geology, NATMAP Shield Margin Project area (Flin Flon Belt), Manitoba/Saskatchewan; Geological Survey of Canada, Map 1968A, Manitoba Energy and Mines, Map A-98-2, Saskatchewan Energy and Mines, Map 258A, 54 p., scale 1:100 000.

Thomas, D.J. 1989: Geology of the Douglas Lake–Phantom Lake area (part of NTS 63K-12 and -13); *in* Summary of Investigations 1989, Saskatchewan Geological Survey, Saskatchewan Energy and Mines, Miscellaneous Report 89-4, p. 44–54.

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