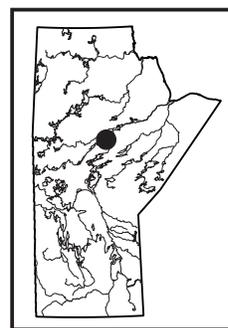


# GS-1 Preliminary results from bedrock mapping in the Armstrong Lake area, Pikwitonei granulite domain, central Manitoba (parts of NTS 63P10, 11)

by C.G. Couëslan



Couëslan, C.G. 2014: Preliminary results from bedrock mapping in the Armstrong Lake area, Pikwitonei granulite domain, central Manitoba (parts of NTS 63P10, 11); in Report of Activities 2014, Manitoba Mineral Resources, Manitoba Geological Survey, p. 7–17.

## Summary

A project to remap portions of the Archean Pikwitonei granulite domain in central Manitoba, with emphasis on protolith interpretation, was extended to the Armstrong Lake area in 2014. The mapped area has been subjected to relatively uniform, high-grade Neoproterozoic metamorphism and deformation. Rocks in the Armstrong Lake area can be divided into three main groups based on structural observations: Archean pre- $D_1$  gneissic rocks, Archean post- $D_1$ –pre- $D_2$  rocks and Proterozoic post- $D_2$  rocks. Pre- $D_1$  gneissic rocks include mafic volcanic rocks, a sedimentary package (including pelite, quartzite, iron formation and wacke), ultramafic rock, tonalite, diorite, anorthosite and mafic dikes. Post- $D_1$ –pre- $D_2$  rocks include diorite, tonalite–granodiorite, granodiorite–monzogranite, enderbite (orthopyroxene tonalite of primary igneous origin) and pegmatitic granite. Proterozoic post- $D_2$  rocks consist of gabbro dikes. The oldest group of rocks in the Armstrong Lake area displays an  $S_1$  gneissosity. This early gneissosity was cut by leucosome that formed during a granulite-facies metamorphic event, which affected all Archean rocks in the area. Metamorphic textures suggest a clockwise P–T–t path for the granulite-facies event. The rocks were then isoclinally folded and transposed during  $D_2$  deformation, which generated  $S_2$  fabrics in all Archean phases.

The supracrustal rocks exposed at Armstrong Lake bear many similarities to those observed in greenstone belts in the adjacent Superior Province, where they include numerous occurrences of gold and base metals. The presence of ultramafic rocks may indicate potential for magmatic Ni–Cu–platinum-group element mineralization.

## Introduction

A project was initiated in 2012 to map portions of the Pikwitonei granulite domain (PGD; Couëslan et al., 2012, 2013a, 2013b). The objective is to remap the mafic, intermediate and enderbite (orthopyroxene-bearing tonalite) gneisses, with an emphasis on protolith interpretation rather than descriptive petrography. It is also hoped that information gathered in the course of mapping will provide further insight into the tectonic significance of the PGD (e.g., Weber, 1983) and a more robust assessment of the mineral potential. Due to the high metamorphic grade and apparent lack of supracrustal rocks, the PGD has

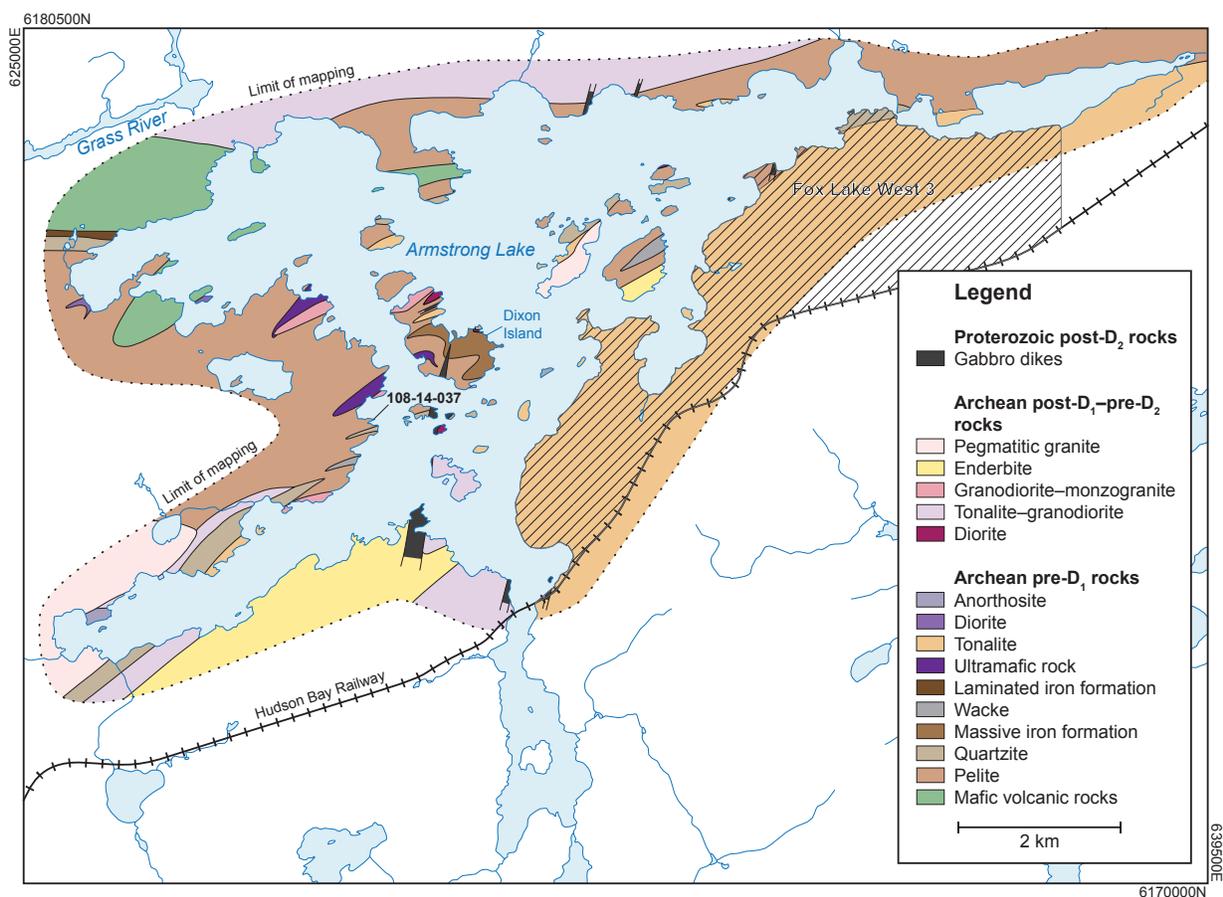
traditionally been considered to have insignificant or lower mineral potential compared to adjacent, lower-grade metamorphic domains.

Mapping in 2014 focused on the Armstrong Lake area (Couëslan, 2014; Figure GS-1-1) and the completion of mapping in the Partridge Crop area (Couëslan, GS-2, this volume). The Armstrong Lake area was selected for a two-week mapping program because of the mapping of Weber (1978a) indicating the potential for widespread supracrustal rocks.

## Regional geology

The PGD is a Neoproterozoic high-grade metamorphic domain along the northwestern margin of the Superior province. It is exposed over a length of approximately 200 km, with a maximum width of 75 km in the Split Lake area (Hubregtse, 1980; Böhm et al., 1999). A regional orthopyroxene-in isograd, which is oblique to the generally east–west fabrics of the Superior province, marks the southeastern boundary of the domain (Hubregtse, 1980; Heaman et al., 2011). The northwestern boundary is defined by the eastern extent of Paleoproterozoic Hudsonian (ca. 1.83–1.75 Ga) north-northeast-trending deformational fabrics, which truncate the east–west Neoproterozoic fabrics of the PGD (Hubregtse, 1980; Heaman et al., 2011; Kuiper et al., 2011; Couëslan et al., 2013).

The PGD dominantly consists of felsic to intermediate metaplutonic rocks (orthopyroxene-bearing granodiorite, tonalite and diorite), and mafic granulite (metagabbro, metapyroxenite and metabasalt; Hubregtse, 1978, 1980; Heaman et al., 2011). Supracrustal rocks were previously considered rare in the PGD. The PGD has experienced two main generations of tectonometamorphism. The  $D_1$ – $M_1$  generation (ca. 2695 Ma) resulted in well-defined, northwest-trending metamorphic layering ( $S_1$ ) accompanied by isoclinal folding (Hubregtse, 1980; Heaman et al., 2011). The accompanying  $M_1$  metamorphism is interpreted to have attained amphibolite- to locally hornblende-granulite-facies conditions (Hubregtse, 1978, 1980). The  $D_2$ – $M_2$  generation (ca. 2680 Ma) resulted in the development of  $S_2$  fabrics and transposition of  $S_1$  into west-southwest-trending shear folds, accompanied by granulite-facies metamorphism (Hubregtse, 1980; Heaman et al., 2011). Peak metamorphism in the PGD is interpreted to have been followed by isobaric cooling



**Figure GS-1-1:** Simplified geology of the Armstrong Lake area, indicating the location of sample 108-14-037 (modified from Couëslan, 2014). Geology underlying the Fox Lake West 3 Reserve (area with hatch pattern) is from Weber (1978a).

resulting in a counter-clockwise cooling path (Mezger et al., 1990); however, textures observed at Partridge Crop Lake in 2013 are more suggestive of isothermal decompression, which would necessitate a clockwise cooling path (Couëslan, 2013a).

### **Armstrong Lake area—previous work**

The Armstrong Lake area was last mapped by Weber (1978a, 1978b), whose work is the source of the geological information outlined in this subsection. The Armstrong Lake area is underlain to the southeast by enderbite and enderbite gneiss, which were interpreted to be metaplutonic, and to the northwest by gneisses, which were interpreted to be derived from supracrustal rocks. The supracrustal rocks include massive to weakly layered noritic rocks underlying the northwestern shore of the lake, interpreted as metamorphosed mafic flows; siliceous and pelitic garnet-bearing gneisses underlying the western shore and central islands, interpreted as basaltic rocks that were hydrothermally altered prior to metamorphism; and exposures of quartzite occurring in the northeastern portions of the lake. A small intrusion of anorthosite occurs in the southwestern arm of the lake and several Proterozoic mafic to ultramafic dikes, interpreted to be related to

the Molson swarm, are exposed in the central islands of the lake. Metamorphic conditions are estimated to have reached 800–860 °C and 6.9–8.3 kbar in the Natawahunan Lake area, immediately west of Armstrong Lake (Paktunç and Baer, 1986; Mezger et al., 1990).

### **Lithological units**

Similar to the Cauchon Lake area (Couëslan, 2013b), the units observed in the Armstrong Lake area are subdivided into three main groups: Archean rocks that predate the  $D_1$  generation of deformation, Archean rocks that postdate  $D_1$  and predate  $D_2$ , and Proterozoic post- $D_2$  rocks. Although the majority of rocks in the Armstrong Lake area have been subjected to granulite-facies metamorphic conditions, the ‘meta-’ prefix has been omitted to improve the readability of the text.

### **Archean pre- $D_1$ gneissic rocks**

Pre- $D_1$  rocks are characterized by a pervasive and well-developed  $S_1$  gneissosity. The stratigraphic/intrusive order of these units is poorly constrained and where no age relationships were observed, the order of Weber (1978b) was retained.

### **Mafic volcanic rocks**

Exposures of variably banded mafic rocks, interpreted as metavolcanic rocks, occur in the northwestern portion of the lake. The mafic volcanic rocks are brown-green to dark green, medium to coarse grained, foliated, and feature weak to well-developed banding (Figure GS-1-2a). This unit is plagioclase-rich and typically contains 40–50% mafic minerals, the content of which varies from 10 to 40% orthopyroxene, trace to 20% biotite, trace to 30% clinopyroxene, and trace to 30% hornblende. Rare lenses up to 5 cm thick contain roughly 50:50 garnet and hornblende. Banding is typically diffuse and on the order of 5–15 mm. Outcrops contain anywhere from 5 to 7% leucosome as small incipient pods 2–3 cm thick or up to 20% leucosome as networks of interconnected pods and veins 3–30 cm thick. The leucosome is coarse grained, foliated and plagioclase-rich, with 2–10% quartz, 2–10% clinopyroxene and 10–20% orthopyroxene. Both the leucosome and mesosome are locally garnet-bearing. Gossanous patches, 2–20 cm across, suggest local accumulations of sulphide.

### **Sedimentary rock package**

Sedimentary rocks consisting dominantly of pelite and quartzite, with subordinate iron formation and wacke, occur over much of the western and northern shores, and the central islands of the lake. The stratigraphic order is unconstrained and the subunits are listed in order of decreasing abundance.

Exposures of pelite, quartzite and wacke can form discrete outcrops, but are more typically interlayered on a scale of up to 5 m, with one phase predominating over the others. Pods of garnet-bearing leucosome are ubiquitous and occur in all outcrops. The leucosome is typically white, coarse grained and foliated. It is likely granitic or monzogranitic, but the prevalence of white feldspar(s) makes the determination of the composition difficult in outcrop and hand sample. The leucosome typically contains 1–3% biotite and 2–5% garnet, and rare cordierite. The rocks are also locally interbanded with 1.5 m bands of garnet monzogranite.

Outcrops of pelite and quartzite also contain local boudinaged bands and isolated boudins of calcsilicate up to 30 cm thick. The calcsilicate is green-brown, medium grained and massive. It typically contains 10–20% quartz, 30–40% diopside and plagioclase. Calcsilicate boudins are rarely mantled by thick rims of garnet. The calcsilicate layers and boudins are interpreted as calcareous layers and/or concretions.

### ***Pelite***

The pelite typically forms a diatexite with 50–60% garnet-bearing leucosome and 5–20% wacke and/or quartzite schollen up to 1 m thick, with the remainder of the exposure consisting of pelitic mesosome and melanosome

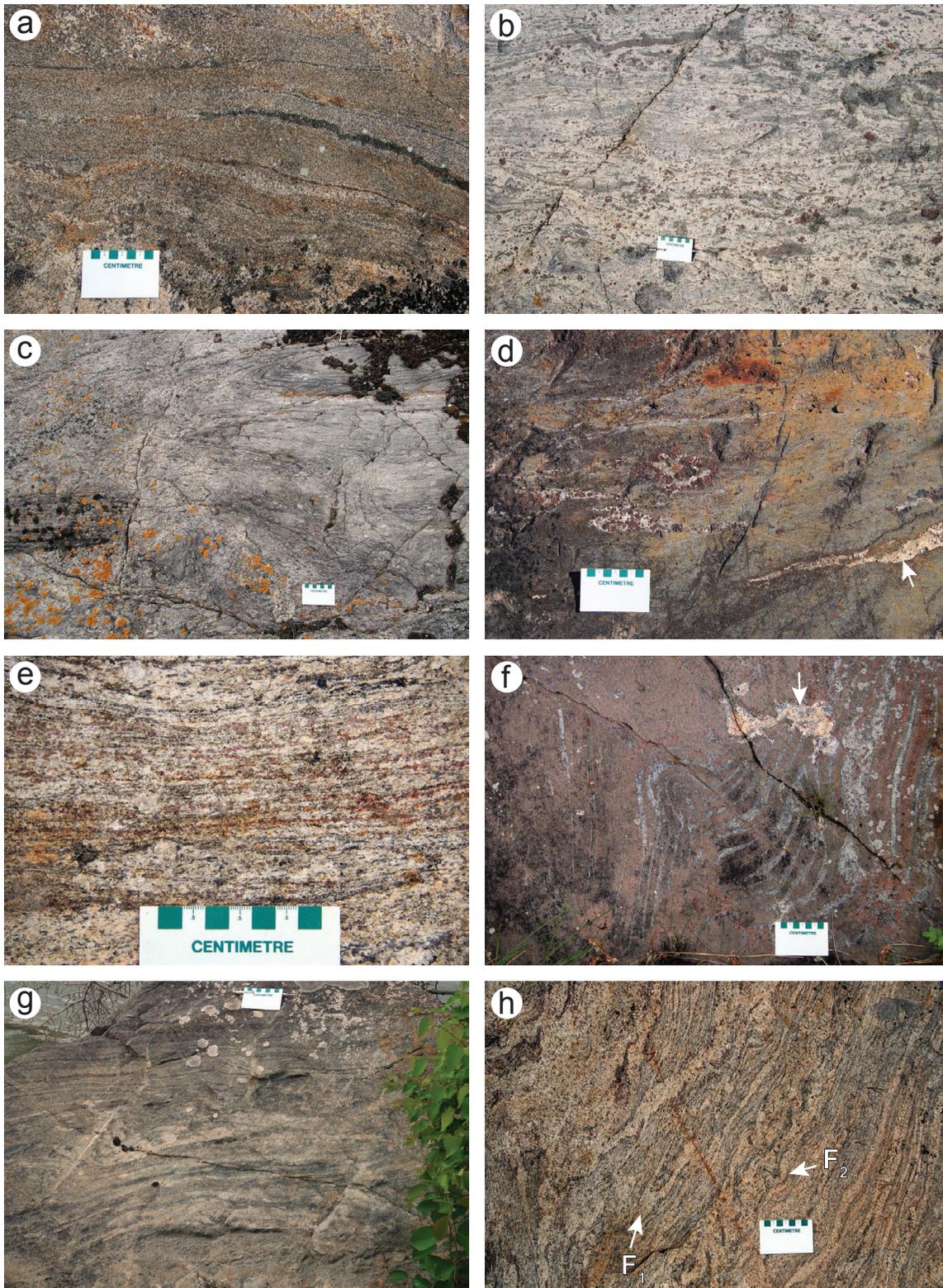
(Figure GS-1-2b). The pelite is white to light grey, coarse to very coarse grained, moderately to strongly foliated, and compositionally banded. The composition of the pelite varies from 2–3% spinel, 3–5% cordierite, 10–20% biotite, 10–20% sillimanite, 10–20% garnet, 20–30% quartz and white feldspar(s), to 7–10% garnet, 10–20% sillimanite, 10–20% cordierite, 10–20% quartz and white feldspar(s). The cordierite and sillimanite are typically found intergrown and large garnet porphyroblasts, or aggregates of porphyroblasts up to 10 cm across, are commonly rimmed by cordierite. Minor spinel is commonly associated with schlieric bands of sillimanite- and cordierite-rich melanosome. Rare garnet-rich melanosome (up to 40% garnet) can also contain up to 7% graphite. Leucosome locally contains orthopyroxene up to 2 cm in size. Small, local patches of light gossan staining suggest the presence of minor sulphide.

Local bands of low-Al pelite are sillimanite- and cordierite-free, with a greater proportion of quartz and feldspar, and locally up to 7% orthopyroxene and 30% biotite. The orthopyroxene and garnet form porphyroblasts up to 1 cm in size. These bands typically have less leucosome (20–40%), which contains 5–7% garnet, 10–12% biotite and locally up to 20% orthopyroxene. The biotite and orthopyroxene locally appear to enclose the garnet. Discontinuous bands and schollen of the less aluminous rocks occur locally within the diatexite of the typical pelite. The low-Al pelite is coarser grained with less well-defined banding than the wacke.

The association of pelite with layered to laminated quartzite, and the common inclusion of quartzite and wacke in pelitic diatexite, suggest a siliciclastic sedimentary protolith, rather than hydrothermally altered basalt as proposed by Weber (1978b). Samples were collected for thin-section and bulk-rock geochemical analysis to further investigate the origins of this unit.

### ***Quartzite***

The quartzite is grey to blue-grey, medium to coarse grained, moderately to strongly foliated, and compositionally banded (Figure GS-1-2c). In addition to quartz, it typically contains 1–5% biotite, 2–7% garnet and  $\leq 20\%$  feldspar. It is locally more feldspathic, with up to 35% feldspar, and can contain up to 3% orthopyroxene. The compositional banding varies from laminated (1–3 mm) to layered (5–15 mm) and generally consists of quartz-rich layers separated by more biotite-enriched laminations rarely exceeding 3 mm. These more aluminous laminations locally contain garnet and thin segregations of leucosome. More substantial bands of pelite up to at least 1 m thick are locally present. Outcrops also typically contain 15–30% leucosome as larger centimetre-scale pods. The leucosome is rarely orthopyroxene-bearing, or may have orthopyroxene-rich selvages. Locally the quartzite has been recrystallized to a coarse-grained rock



**Figure GS-1-2:** Outcrop images of pre- $D_1$  gneissic rocks from the Armstrong Lake area: **a)** banding within mafic volcanic rocks; **b)** pelitic diatexite consisting of white, granitic leucosome, and garnet-, cordierite- and sillimanite-rich melanosome; **c)** quartzite, with isoclinal minor folds; **d)** massive iron formation, with garnet- and quartz-rich stringer (above scale card), and calcrete (calcium carbonate crust, arrow); **e)** detail of diffuse banding in wacke; **f)** garnet- and Fe-orthopyroxene-rich groundmass of laminated iron formation with interlayered chert laminations folded by  $F_1$  and crosscut by a pod of leucosome (arrow); **g)** hornblende-rich laminations in ultramafic rock; **h)** tonalite gneiss with isoclinal  $F_1$  folds developed in the gneissosity and leucosome with open  $F_2$  folds.

with more diffuse banding on a 5–20 mm-scale. Because of its quartz-rich composition, the quartzite locally forms high-strain zones.

### ***Massive iron formation***

Extensive exposures of massive iron formation occur along the eastern shore of Dixon Island. The iron formation is dark green to heavily gossan stained, medium to very coarse grained, weakly foliated, and strongly magnetic in places. It is orthopyroxene-rich and contains trace to 5% biotite, trace to 10% garnet, trace to 10% plagioclase, 5–10% quartz and trace to 15% magnetite. Local bands may contain up to 50% garnet. Outcrops are characterized by discrete zones of intense gossan staining up to 1.5 m wide and minor, discontinuous stringers of quartz with 30–40% garnet (Figure GS-1-2d). Deposits of calcrite (calcium carbonate crusts) commonly obscure gossanous zones. Local bands of mafic rock at least 2 m thick may represent mafic dikes or possibly flows. It is unclear if this unit is derived from an exhalative sedimentary rock, or if it is the product of intense premetamorphic Fe-metasomatism. Samples were collected for thin-section and bulk-rock geochemical analysis to further investigate the origins of this rock.

### ***Wacke***

The wacke appears to be subordinate to both the pelite and quartzite; however, it does dominate in some exposures. It is light grey to brown, medium grained, foliated and compositionally banded. It typically contains 7–10% biotite, 7–10% orthopyroxene, 10–12% garnet, 30–40% quartz, and white feldspar(s). White K-feldspar locally forms coarse porphyroblasts up to 2 cm across. The wacke is compositionally banded on a scale of 5–30 cm. Banding is relatively diffuse with bands being more enriched in garnet or orthopyroxene, but seldom exceeding 15% of either phase (Figure GS-1-2e). Quartz-rich tonalitic leucosome typically makes up 20–30% of exposures. Rare exposures of the wacke are relatively quartz poor and contain trace to 5% biotite, 5–15% garnet, 10–20% orthopyroxene, 10–20% quartz and white feldspar(s).

### ***Laminated iron formation***

A single exposure of laminated to layered, garnet-rich iron formation occurs in the northwestern bay of the lake. It is reddish purple, medium to coarse grained, and foliated. In addition to garnet, the iron formation contains trace to 3% nonmagnetic oxides and 30–40% Fe-orthopyroxene. The Fe-minerals define massive bands up to 40 cm thick, or more commonly, are interlayered with chert layers 2–20 mm thick (Figure GS-1-2f). Patches of gossan staining up to 20 cm across suggest local accumulations of sulphide. Immediately southwest of this exposure is a vertical face of highly strained quartzite that

contains no readily visible feldspar or mafic minerals and could represent a band of massive chert.

### **Ultramafic rock**

The ultramafic rock forms relatively poor exposures along the western shore of Dixon Island and the western shoreline of the lake. It is grey-green to dark green, medium to coarse grained, weakly foliated, and massive to banded (Figure GS-1-2g). The composition of the rock is variable but typically clinopyroxene-rich, and can contain up to 30% orthopyroxene and 30% hornblende. Hornblende commonly occurs as hornblende-rich laminations 2–5 mm thick. The hornblende-rich laminations locally contain up to 7% plagioclase, whereas bands of more massive clinopyroxene can be up to several metres thick. Sulphide is typically present in trace amounts, but can make up as much as 3% of the rock. Local pods of leucosome up to 10 cm thick make up less than 10% of outcrops and are plagioclase-rich, with 20–30% pyroxene. The presence of well-laminated zones within the ultramafic rock could suggest a volcanogenic origin; however, igneous layering within a differentiated intrusion or metamorphic layering are also possibilities.

### **Tonalite**

Gneissic tonalite occurs mostly in the southern portion of the lake and along the eastern shore of the lake, as mapped by Weber (1978a). It is grey-brown, medium to coarse grained, and foliated (Figure GS-1-2h). The tonalite typically contains 10–30% mafic minerals, which consist of varying proportions of orthopyroxene and hornblende, and locally biotite. Orthopyroxene is typically the dominant mafic mineral. Up to 3% magnetite is locally present. Although plagioclase is typically the dominant feldspar, the gneiss locally contains up to 30% pink feldspar grains, which could indicate a more granodioritic to granitic composition; however, the pink feldspar could be antiperthitic plagioclase, as observed in rocks from both Sipiwesk and Cauchon lakes (Couëslan et al., 2012). The gneiss is characterized by 20–40% quartz-rich tonalitic to granodioritic, stromatic leucosome that locally contains up to 3% orthopyroxene and rarely contains up to 3% garnet. In rare instances, garnet also occurs as a discrete selvage lining the contact between leucosome and mesosome. It is unclear if the garnet is a product of a melting reaction, or if it represents a retrograde reaction between the melt and surrounding gneiss during cooling and crystallization. The relatively uniform composition and texture of mesosome in outcrop suggest that the unit is an orthogneiss. Because the orthopyroxene helps define the  $S_1$  gneissosity, it is probably of metamorphic origin and therefore this unit is likely a metatonalite, rather than a primary igneous enderbite. The gneissic tonalite commonly contains continuous mafic bands and boudins up to at least 1.5 m thick, which could represent mafic dikes.

### **Diorite**

Two isolated occurrences of gneissic diorite were observed in the northwestern bay of the lake. One occurrence is beige to brown-green, medium to coarse grained, and foliated. In addition to plagioclase, the gneiss contains 3–5% quartz, 10–15% orthopyroxene and 20–30% clinopyroxene. The gneiss is interbanded with discontinuous plagioclase-rich layers on a scale of 2–20 mm. Tonalitic leucosome forms stromatic bands up to 10 cm thick and makes up 10–20% of the outcrop. The outcrop also contains 30–40% mafic rafts up to 1 m thick, which are texturally and compositionally similar to the mafic volcanic rocks. Leucosome adjacent to the mafic rafts typically contain 5–15% quartz and 10–20% orthopyroxene. The presence of one 5 cm raft of garnet-rich quartzite was noted.

The other occurrence of gneissic diorite is white to light green, medium grained and foliated. It is compositionally banded on a 5–25 mm scale with alternating bands of almost massive plagioclase and plagioclase-rich bands, which contain 10–20% orthopyroxene and 10–20% clinopyroxene. The outcrop contains 30–40% tonalitic to granodioritic leucosome as diffuse veins and pods up to 20 cm thick.

### **Anorthosite**

An isolated outcrop of interlayered anorthosite and leucogabbro occurs at the end of the southwestern arm of the lake. The anorthosite is white to light grey, medium to coarse grained, foliated, weakly gneissic, and weakly magnetic. It is compositionally and texturally variable, ranging from hornblende- and/or clinopyroxene-bearing anorthosite to leucogabbro, and ranging from relatively uniform in grain size to porphyritic, with plagioclase phenocrysts up to 2.5 cm across (Figure GS-1-3a). Plagioclase phenocrysts are commonly recrystallized to flattened granular aggregates of plagioclase. Hornblende locally forms poikiloblasts (possibly pseudomorphs of poikocrysts). Quartz is locally present in minor amounts (<5%). Primary igneous layering has been disrupted and/or boudinaged into blocks 20–200 cm across and rotated, giving the outcrop a chaotic appearance. Local folded and boudinaged mafic bands up to 15 cm thick could represent either more melanocratic phases of the original layered complex or mafic dikes, as they are compositionally similar to mafic bands and boudins in the tonalite gneiss. Local pods of quartz-rich tonalitic leucosome typically contain no mafic minerals.

### **Mafic dikes**

Continuous and boudinaged mafic bands up to at least 2 m thick, which occur within the gneissic tonalite (Figure GS-1-3b) and massive iron formation, and rare bands up to 10 cm thick, within the quartzite and pelite, may represent mafic dikes. The bands are dark green-grey to dark

brown, medium grained, foliated and homogeneous. The composition varies from ultramafic, with varying proportions of orthopyroxene, clinopyroxene, hornblende, and minor biotite and plagioclase, to mafic, with up to 15% plagioclase. The bands locally contain foliated pods of orthopyroxene-rich leucosome. Bands within the massive iron formation contain local porphyroblasts of orthopyroxene (possibly relict phenocrysts) and could represent dikes or flows. Mafic bands within the tonalite gneiss are transposed subparallel to, and typically wrapped by, the  $S_1$  gneissosity, which suggests they predate, or are synchronous with,  $D_1$ . However, mafic dikes of more than one age could exist.

### ***Archean post- $D_1$ -pre- $D_2$ rocks***

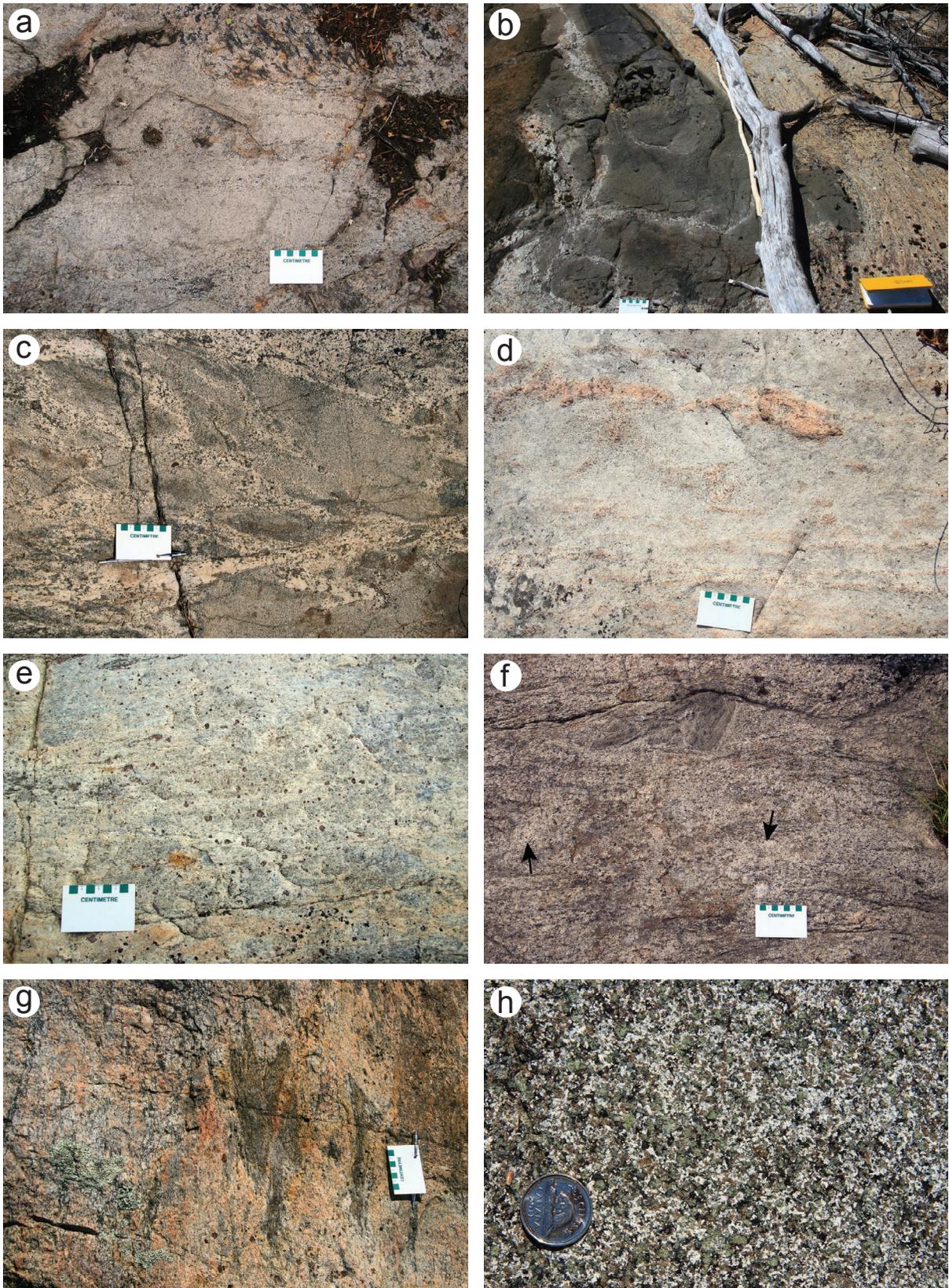
All post- $D_1$ -pre- $D_2$  rocks are interpreted as meta-plutonic rocks. Many phases contain xenoliths of pre- $D_1$  units. The relative timing of intrusion is essentially unconstrained; however, xenoliths of the diorite occur within the massive to weakly gneissic tonalite-granodiorite and no leucosome was observed in the pegmatitic granite, suggesting that it is coincident with, or postdates, the regional melting event ( $M_2$ ).

### **Diorite**

The diorite occurs as isolated exposures on islands in the central portion of the lake. It is green-grey, medium grained and foliated. The diorite is plagioclase-rich with 15–20% orthopyroxene and 15–20% clinopyroxene. Outcrops contain 20–30% coarse-grained plagioclase-rich leucosome as diffuse pods and veins, which consist of 3–5% clinopyroxene and 10–20% orthopyroxene (Figure GS-1-3c). The mesosome is relatively uniform in both composition and texture and suggests an igneous, possibly plutonic protolith for this unit. It appears to be hosted by pelite, perhaps suggesting an intrusive relationship. Alternatively, the diorite could represent tectonic slivers, or syndepositional flows, of mafic volcanic rock in the sedimentary rock package.

### **Tonalite–granodiorite, massive to weakly gneissic**

The massive to weakly gneissic tonalite–granodiorite is most common in the southern portion and along the northern shore of the lake. It is white to light grey-pink, medium to coarse grained, foliated, and locally magnetic. The unit is dominantly tonalitic, but locally grades to granodioritic, with 10–20% K-feldspar. The unit is leucocratic, with typically <5% mafic minerals consisting of varying proportions of biotite and orthopyroxene, with local magnetite. Two varieties of foliated leucosome can be present and locally occur in the same exposure. The more common is white leucosome, which is compositionally similar to the mesosome but slightly more enriched in quartz and typically coarser grained. White leucosome typically makes up 10–20% of the exposure. Less common



**Figure GS-1-3:** Outcrop images of rocks from the Armstrong Lake area: **a)** anorthosite with band of leucogabbro (top right of image); **b)** possible mafic dike hosted in tonalite gneiss; **c)** diorite with abundant plagioclase-rich leucosome; **d)** weakly gneissic granodiorite with granitic leucosome; **e)** garnet-bearing monzogranite; **f)** enderbite with xenolith of mafic rock (top of image) and diffuse leucosome (arrows); **g)** pegmatitic granite with pelitic rafts; **h)** groundmass of unmetamorphosed gabbro dike.

is pink, granitic leucosome containing rare garnet and making up 5–20% of the exposure (Figure GS-1-3d). In exposures where both varieties of leucosome are present, the pink leucosome appears to be younger than the white leucosome. Both varieties of leucosome occur as diffuse veins and pods. The tonalite–granodiorite contains local boudins or xenoliths of mafic rock up to 1 m thick, calc-silicate or ultramafic rock up to 20 cm thick and xenoliths of gneissic tonalite up to 2 m thick. The presence of rare xenoliths of the diorite and rare schlieric bands of garnet and orthopyroxene±biotite, likely derived from pelitic rocks, was also noted. The local weak gneissosity appears to be related to zones of higher strain and greater transposition of leucosome and xenoliths. One outcrop of tonalite in the southern arm of the lake is characterized by reddish brown spots on lightly weathered surfaces. The spotted appearance results from weathering of very fine-grained aggregates of sulphide.

#### **Granodiorite–monzogranite**

The granodiorite–monzogranite forms relatively small intrusions closely associated with, and likely derived from, the partial melting of the sedimentary rock package. It is white to pale pink, medium to coarse grained, and foliated. It is leucocratic, containing only trace to 3% biotite and trace to 5% garnet (Figure GS-1-3e). The garnet locally forms aggregates of grains up to 1.5 cm across. Orthopyroxene is locally present in trace amounts. Exposures contain abundant pelitic schlieren, and local schollen of quartzite and wacke up to 1.5 m thick. Pelitic schlieren locally consist of garnet–sillimanite–orthopyroxene assemblages. The granodiorite–monzogranite also contains abundant diffuse veins and pods of leucosome.

#### **Enderbite**

Enderbite occurs along the southern shore of the lake. It is beige, coarse grained and foliated, and contains 1–2% biotite and 5–15% orthopyroxene. The orthopyroxene occurs as uniformly distributed, 2–5 mm, equant grains, which could indicate they originated as primary magmatic phenocrysts in a relatively anhydrous melt. Similar to the enderbite described at Cauchon Lake (Couëslan, 2013b), this unit contains up to 15% rounded mafic, intermediate and tonalitic xenoliths (Figure GS-1-3f). The enderbite also contains abundant diffuse veins and pods of leucosome.

#### **Pegmatitic granite**

The pegmatitic granite is most abundant in the southwestern arm of the lake. It is pink to white, coarse to very coarse grained, and moderately to strongly foliated. It contains trace to 3% garnet and 2–3% biotite, with the garnet content typically being a function of the abundance of metasedimentary xenoliths (Figure GS-1-3g).

Outcrops locally contain up to 20% xenolithic rafts (up to 1.5 m) consisting of quartzite, pelite, gneissic tonalite and mafic rock. At one location xenoliths of the gneissic tonalite contain trace amounts of molybdenite, which was not observed in outcrop.

### ***Proterozoic post-D<sub>2</sub> rocks***

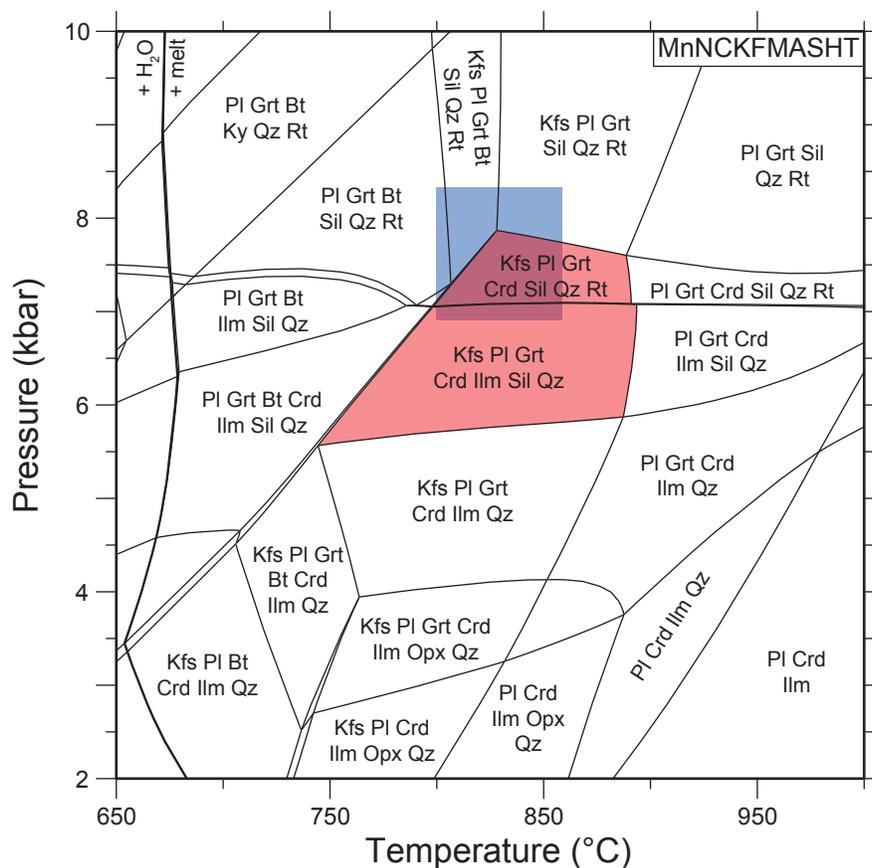
#### **Gabbro**

Gabbro occurs as unmetamorphosed dikes up to 200 m thick, which are present throughout the Armstrong Lake area. Although no contacts were observed, map patterns suggest trends of 010–020°. The gabbro is dark green-grey, coarse grained and massive. The gabbro consists of varying proportions of orthopyroxene, clinopyroxene, hornblende and plagioclase, and can be gradationally zoned. The plagioclase content is typically 30–40%, but is locally as high as 60% and as low as 10% (Figure GS-1-3h). The gabbro contains local pegmatitic segregations up to 15 cm thick, which consist dominantly of plagioclase with 30–40% hornblende. Related diabase dikes, ranging from 5 cm to 5 m thick, occur sporadically throughout the map area. The apparent trend of the dikes suggests they could be related to the ca. 1880 Ma Molson dike swarm (Heaman et al., 1986, 2009).

### **Structural and metamorphic geology**

The structural and metamorphic history of the Armstrong Lake area appears to be very similar to the Cauchon Lake area, as outlined by Couëslan (2013b). The earliest structures recognized in the Armstrong Lake area consist of an S<sub>1</sub> gneissosity in the Archean pre-D<sub>1</sub> gneissic rocks. The metamorphic conditions that accompanied D<sub>1</sub> (M<sub>1</sub>) could not be constrained from observations in the field; however, a relatively high metamorphic grade (likely at least upper-amphibolite facies) would be required for gneissosity development.

Veins and irregular pods of leucosome occur in all pre-D<sub>1</sub> and post-D<sub>1</sub>–pre-D<sub>2</sub> rocks. The leucosome clearly cuts the S<sub>1</sub> gneissosity in older rocks and is therefore younger than D<sub>1</sub> (Figure GS-1-2f, h). The leucosome is locally orthopyroxene-bearing and, in pelitic rocks, contains garnet, cordierite and locally orthopyroxene. The occurrence of these minerals suggests that the leucosome-forming metamorphic event (M<sub>2</sub>) attained granulite-facies conditions. An equilibrium-assemblage diagram was calculated for pelite sample 108-14-037 (Figure GS-1-1). The mineral assemblage observed in outcrop, which consists of garnet–sillimanite–cordierite–quartz–plagioclase–K–feldspar, suggests a possible pressure range of 5.5–8.0 kbar and temperatures likely in the range of 750–900 °C (Figure GS-1-4). Although broad, these P–T conditions are in good agreement with previous estimates for the Natawahunan Lake area (6.9–8.3 kbar, 800–860 °C; Paktunc and Baer, 1986; Mezger et al., 1990). Ongoing



**Figure GS-1-4:** Equilibrium-assemblage diagram for pelite sample 108-14-037 in the system  $\text{MnO-Na}_2\text{O-CaO-FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O-TiO}_2$  (MnNCKFMASHT). The peak metamorphic assemblage observed in outcrop is indicated by the red field. The limits of previous P-T estimates from Paktunç and Baer (1986) and Mezger et al. (1990) are indicated by the blue field. The diagram was calculated using the Theriak–Domino software package (de Capitani and Petrakakis, 2010) with the updated 2003 ds5.5 thermodynamic dataset of Holland and Powell (1998), based on activity models outlined in Tinkham and Ghent (2005), Pattison and Tinkham (2009), and Couëslan et al. (2011). Abbreviations: Bt, biotite; Crd, cordierite; Grt, garnet; Ilm, ilmenite; Kfs, K-feldspar; Ky, kyanite; Opx, orthopyroxene; Pl, plagioclase; Qz, quartz; Rt, rutile; Sil, sillimanite.

petrographic studies will further refine the peak metamorphic conditions. The widespread observation of cordierite rimming garnet in pelitic rocks on Armstrong Lake is in agreement with textures indicating isothermal decompression noted in the Partridge Crop Lake area (Couëslan, 2013a). Garnet rimmed by cordierite is also common in thin sections of pelite from the northeastern arm of Cauchon Lake. These observations strengthen the argument for a regional, clockwise P-T-t path associated with peak metamorphism in the PGD.

In all instances, the locally orthopyroxene-bearing leucosome displays a well-developed  $S_2$  fabric and leucosome veins are commonly folded by  $F_2$ . This suggests that the  $M_2$  event predates some or all of the  $D_2$  generation of deformation, which is manifested as a well-developed  $S_2$  quartz fabric in all Archean rocks. This fabric typically strikes  $230\text{--}250^\circ$ , with a subvertical to steep dip to the northwest. The  $S_2$  fabric typically intersects  $S_1$  at a small counter-clockwise angle ( $10\text{--}20^\circ$ ) and is axial planar to

minor isoclinal folds. Minor fold hinges plunge toward the northwest and southeast at shallow to moderate angles ( $20\text{--}60^\circ$ ). High-strain zones in the southwestern arm of the lake are subparallel to, and possibly coeval with,  $S_2$ ; however, the mylonite zone along the northern shore trends closer to  $270^\circ$  and a relationship to  $S_2$  is not clear. The occurrence of asymmetric porphyroclasts in the mylonite zone indicates a dextral sense of movement and a stretching lineation plunging  $70^\circ$  toward the east was noted in one outcrop along the northern shore.

Small zones ( $<5$  m) of brittle fractures striking northwest, with subvertical dips, occur along the northern shore of the lake. One example displays minor sinistral offset along the fracture zone. Rocks in close proximity to the fractures are chloritized, uralitized and sericitized. A similar zone of fractured and altered rocks was observed in the southern arm of the lake and appeared to affect the Proterozoic gabbro dikes; however, field relationships were obscured by poor exposure.

## Economic considerations

Iron formation and possible massive chert in close spatial association with mafic volcanic rocks indicate exhalative sedimentation may have been temporally associated with volcanism, perhaps suggesting potential for exhalative base- or precious-metal sulphide mineralization. In addition, iron formations are known to have acted as structural and chemical traps for Au-bearing fluids in many Archean and Paleoproterozoic greenstone belts (Kerswill, 1995). This association is also found in greenstone belts in the northwestern Superior province (including at Bear, Utik and Oxford lakes), where gold and base metals are associated with altered volcanic rocks and exhalative deposits (Hartlaub and Böhm, 2006; Böhm et al., 2007; Anderson et al., 2012). A sample of the iron formation was collected for assay and results are pending.

Ultramafic rocks along the western shore of Armstrong Lake could represent ultramafic flows or differentiated ultramafic intrusions. The ultramafic rocks are in close proximity to both sulphidic and siliceous sedimentary rocks (quartzite and massive iron formation), the assimilation of which by an ultramafic magma could have resulted in sulphur saturation and precipitation of a sulphide melt. Nickel, copper and some platinum-group elements (PGEs) are known to partition preferentially into sulphide melts from silicate melts leading to a metal-enriched sulphide phase. Chemical analyses of the ultramafic rocks have returned Cr and Ni values as high as 2890 and 1270 ppm, respectively, suggesting potential for Cr, Ni and possibly PGE mineralization.

Pelitic and siliceous garnet gneisses were interpreted by Weber (1978b) to be hydrothermally altered mafic rocks. Aluminous and iron-magnesium hydrothermally altered rocks occur extensively in the Partridge Crop Lake area (Couëslan, 2013a; Couëslan, GS-2, this volume); however, on Armstrong Lake the close association of the garnet-rich pelitic rocks with laminated to layered quartzite and banded wacke favours a sedimentary origin rather than a premetamorphic hydrothermal origin. Samples have been submitted for bulk-rock geochemistry, which may provide additional information on the protolith of these pelitic rocks.

Although anorthositic rocks underlie a relatively small portion of western Armstrong Lake, their occurrence nevertheless indicates potential for anorthosite-hosted Fe-Ti-V-P deposits.

## Acknowledgments

The author thanks K. Hjorth for providing assistance in the field, Wings Over Kississing for providing reliable air support, and N. Brandson for his attention to detail and for providing thorough logistical support.

## References

- Anderson, S.D., Kremer, P.D. and Martins, T. 2012: Preliminary results of bedrock mapping at Oxford Lake, northwestern Superior Province, Manitoba (parts of NTS 53L12, 13, 63I9, 16); *in* Report of Activities 2012, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 6–22.
- Böhm, C.O., Heaman, L.M. and Corkery, M.T. 1999: Archean crustal evolution of the northwestern Superior Province margin: U-Pb zircon results from the Split Lake Block; *Canadian Journal of Earth Sciences*, v. 36, p. 1973–1987.
- Böhm, C.O., Kremer, P.D. and Syme, E.C. 2007: Nature, evolution and gold potential of the Utik Lake greenstone belt, Manitoba (parts of NTS 53M4, 5, 63P1, 8); *in* Report of Activities 2007, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 98–113.
- Couëslan, C.G. 2013a: Preliminary results from bedrock mapping in the Partridge Crop Lake area, eastern margin of the Thompson nickel belt, central Manitoba (parts of NTS 63P11, 12); *in* Report of Activities 2013, Manitoba Mineral Resources, Manitoba Geological Survey, p. 34–45.
- Couëslan, C.G. 2013b: Preliminary results from bedrock mapping in the northeastern Cauchon Lake area, eastern margin of the Pikwitonei granulite domain, central Manitoba (parts of NTS 63P9, 10); *in* Report of Activities 2013, Manitoba Mineral Resources, Manitoba Geological Survey, p. 23–33.
- Couëslan, C.G. 2014: Bedrock geology of the Armstrong Lake area, central Manitoba (parts of NTS 63P10, 11); Manitoba Mineral Resources, Manitoba Geological Survey, Preliminary Map PMAP2014-1, scale 1:20 000.
- Couëslan, C.G., Böhm, C.O. and Martins, T. 2012: Preliminary results from geological mapping in the central Sipiwesk Lake area, Pikwitonei Granulite Domain, central Manitoba (part of NTS 63P4); *in* Report of Activities 2012, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 79–86.
- Couëslan, C.G., Pattison, D.R.M. and Dufrane, S.A. 2013: Paleoproterozoic metamorphic and deformation history of the Thompson Nickel Belt, Superior Boundary Zone, Canada, from in situ U–Pb analysis of monazite; *Precambrian Research*, v. 237, p. 13–35.
- Couëslan, C.G., Pattison, D.R.M. and Tinkham, D.K. 2011: Regional low-pressure amphibolite-facies metamorphism at the Pipe II mine, Thompson Nickel Belt, Manitoba, and comparison of metamorphic isograds in metapelites and meta-iron formations; *Canadian Mineralogist*, v. 49, p. 721–747.
- de Capitani, C. and Petrakakis, K. 2010: The computation of equilibrium assemblage diagrams with Theriak/Domino software; *The American Mineralogist*, v. 95, p. 1006–1016.
- Hartlaub, R.P. and Böhm, C.O. 2006: Preliminary results from geological mapping of the Bear Lake greenstone belt, Manitoba (parts of NTS 53M4 and 63P1); *in* Report of Activities 2006, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 65–73.
- Heaman, L.M., Peck, D. and Toope, K. 2009: Timing and geochemistry of 1.88 Ga Molson Igneous Events, Manitoba: insights into the formation of a craton-scale magmatic and metallogenic province; *Precambrian Research*, v. 172, p. 143–162.

- Heaman, L.M., Machado, N., Krogh, T.E. and Weber, W. 1986: Precise U–Pb zircon ages for the Molson dyke swarm and the Fox River sill: constraints for Early Proterozoic crustal evolution in northeastern Manitoba, Canada; *Contributions to Mineralogy and Petrology*, v. 94, p. 82–89.
- Heaman, L.M., Böhm, Ch.O., Machado, N., Krogh, T.E., Weber, W. and Corkery, M.T. 2011: The Pikwitonei Granulite Domain, Manitoba: a giant Neoproterozoic high-grade terrane in the northwest Superior Province; *Canadian Journal of Earth Sciences*, v. 48, p. 205–245.
- Holland, T.J.B. and Powell, R. 1998: An internally-consistent thermodynamic dataset for phases of petrological interest; *Journal of Metamorphic Geology*, v. 16, p. 309–343.
- Hubregtse, J.J.M.W. 1978: Sipiwesk Lake–Landing Lake–Wintering Lake area (parts of NTS 63P3, 4, 5, 6, 63J16 and 63I13 and 14); *in* Report of Field Activities 1978, Manitoba Department of Mines, Resources and Environmental Management, Mineral Resources Division, p. 54–62.
- Hubregtse, J.J.M.W. 1980: The Archean Pikwitonei Granulite Domain and its position at the margin of the northwestern Superior Province; Manitoba Energy and Mines, Mineral Resources Division, Geological Paper, GP80-3, 16 p.
- Kerswill, J. A. 1995: Iron formation-hosted stratabound gold; *in* Chapter 15 of *Geology of Canadian Ore Deposit Types*, O.R. Eckstrand, W.D. Sinclair and R.I. Thorpe (ed.), Geological Survey of Canada, Geology of Canada, no. 8, p. 367–382 (*also* Geological Society of America, *The Geology of North America*, v. P-1).
- Kuiper, Y.D., Lin, S. and Böhm, C.O. 2011: Himalayan-type escape tectonics along the Superior Boundary Zone in Manitoba, Canada; *Precambrian Research*, v. 187, p. 248–262.
- Mezger, K., Bohlen, S.R. and Hanson, G.N. 1990: Metamorphic history of the Archean Pikwitonei Granulite Domain and the Cross Lake Subprovince, Superior Province, Manitoba, Canada; *Journal of Petrology*, v. 31, p. 483–517.
- Paktunç, A.D. and Baer, A.J. 1986: Geothermobarometry of the northwestern margin of the Superior province: implications for its tectonic evolution; *Journal of Geology*, v. 94, p. 381–394.
- Pattison, D.R.M. and Tinkham, D.K. 2009: Interplay between equilibrium and kinetics in prograde metamorphism of pelites: an example from the Nelson aureole, British Columbia; *Journal of Metamorphic Geology*, v. 27, p. 249–279.
- Tinkham, D.K. and Ghent, E.D. 2005: Estimating P–T conditions of garnet growth with isochemical phase diagram sections and the problem of effective bulk-composition; *Canadian Mineralogist*, v. 43, p. 35–50.
- Weber, W. 1978a: Armstrong Lake (NTS 63P10); Manitoba Department of Mines, Resources and Environmental Management, Mineral Resources Division, Preliminary Map 1978U-1, scale 1:50 000.
- Weber, W. 1978b: Natawahunan Lake (NTS 63P10, 11, 15 and parts of 64P12, 14, and 64A2); *in* Report of Field Activities 1978, Manitoba Department of Mines, Resources and Environmental Management, Mineral Resources Division, p. 47–53.
- Weber, W. 1983: The Pikwitonei granulite domain: A lower crustal level along the Churchill-Superior boundary in central Manitoba; *in* A Cross Section of Archean Crust, L.D. Ashwal and K.D. Card (ed.), Lunar and Planetary Institute, Houston, Texas, Technical Report 83-03, p. 95–97.