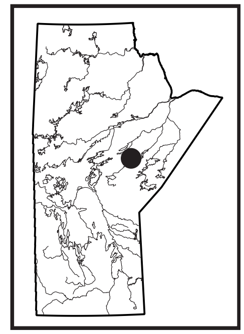
# GS-1 Preliminary results of bedrock mapping at Oxford Lake, northwestern Superior province, Manitoba (parts of NTS 53L13, 14)

by S.D. Anderson, P.D. Kremer and T. Martins



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## Summary

In 2012, the Manitoba Geological Survey began a multiyear project to remap the supracrustal succession at Oxford Lake. The purpose of this project is to better understand the stratigraphy, tectonic evolution and economic potential of the Oxford Lake–Knee Lake belt, which is one of the more prospective yet underexplored greenstone belts in the western Superior craton. Based on preliminary results from the 2012 field season, the supracrustal succession was divided into four tectonostratigraphic assemblages (Hyers, Cat Eye Bay, Carghill and Thomsen), each characterized by distinct associations of lithofacies, and three major structural panels (north, central and south) bounded by ductile shear zones. In 2013, the new mapping was extended into the northern and eastern portions of the lake and focused mainly on the eastern extensions of the Carghill and Thomsen assemblages, corresponding to the north and central structural panels, respectively. Salient results of the 2013 mapping include: 1) a revised stratigraphy for the seemingly monotonous mafic-flow–dominated lower section of the Carghill assemblage, which is now defined to include three distinct units or flow complexes (Bjornson Island, Bleak Island and Kanawastiwiwin Island units) based on distinctive field-characteristics of subaqueous mafic flows; 2) a better understanding of volcanic and volcaniclastic lithofacies of shoshonitic affinity in the upper section of the Carghill assemblage; 3) the collection of a comprehensive sample suite to constrain the petrogenesis, tectonic setting and age of volcanism in the Carghill assemblage using high-precision lithogeochemistry and U-Pb geochronology; and 4) improved understanding of the depositional setting, contact relationships and structural geometry of overlying coarse-clastic sedimentary rocks of the Thomsen assemblage. These results will be utilized to further constrain the stratigraphic and structural setting of base- and precious-metal occurrences at Oxford Lake, and to provide an up-to-date assessment of the economic potential.

## Introduction

In 2012, the Manitoba Geological Survey initiated a program of bedrock geological mapping at Oxford Lake, located 170 km southeast of Thompson, Manitoba, in the western portion of the Oxford Lake–Knee Lake greenstone belt. This project includes new 1:20 000 scale bedrock mapping coupled with structural analysis, lithogeochemistry, Nd-Sm isotope geochemistry, U-Pb geochronology and mineral occurrence studies, and was designed to complement and expand upon investigations done in the Knee Lake portion of the belt during the Western Superior NATMAP Project (Syme et al., 1997, 1998; Corkery et al., 2000). The objective is to better understand the stratigraphy, tectonic evolution and economic potential of the Oxford Lake–Knee Lake belt—the largest continuous greenstone belt in the northwest Superior craton—and to provide up-to-date geoscience data for local stakeholders and the mineral-exploration industry.

Previous work at Oxford Lake included route surveys and reconnaissance mapping by the Geological Survey of Canada (e.g., Bell, 1879, 1881; Brock, 1911; McInnes, 1913; Bruce, 1920; Wright, 1926, 1932), systematic quadrangle mapping by the Manitoba Geological Survey (Barry, 1959, 1960; Gilbert, 1985; Hubregtse, 1985), and detailed geochemical studies of shoshonitic volcanic rocks (e.g., Hubregtse, 1978; Brooks et al., 1982). Significant mineral occurrences were described by Wright (1926, 1932), Barry (1959, 1960), Haskins and Stephenson (1974), Haskins and Evans (1977), Southard (1977) and Richardson and Ostry (1996).

Renewed study of the Oxford Lake–Knee Lake belt began in 2012 with bedrock mapping of extensive shoreline exposures in western and central Oxford Lake (Anderson et al., 2012a, b, c). In July and August 2013, the mapping was extended into the northern and eastern portions of the lake and now covers an area of approximately 480 $km^2$. During this fieldwork, a comprehensive suite of lithogeochemical samples (n = 114) was collected for analysis by high-precision, inductively coupled plasma–mass spectrometry (ICP-MS). Also collected were 8 samples of key supracrustal and intrusive rocks for U-Pb geochronology; these will be analyzed by laser-ablation ICP-MS (detrital zircons) or thermal ionization mass spectrometry at the University of Alberta Radiogenic Isotope Facility. This report describes the preliminary results of the 2013 mapping in the context of results from the 2012 field season and follow-up analytical work.

## Regional context

Oxford Lake is situated in the southwestern portion of the regionally extensive Oxford Lake–Knee Lake greenstone belt (Figure GS-1-1) in the Oxford–Stull domain

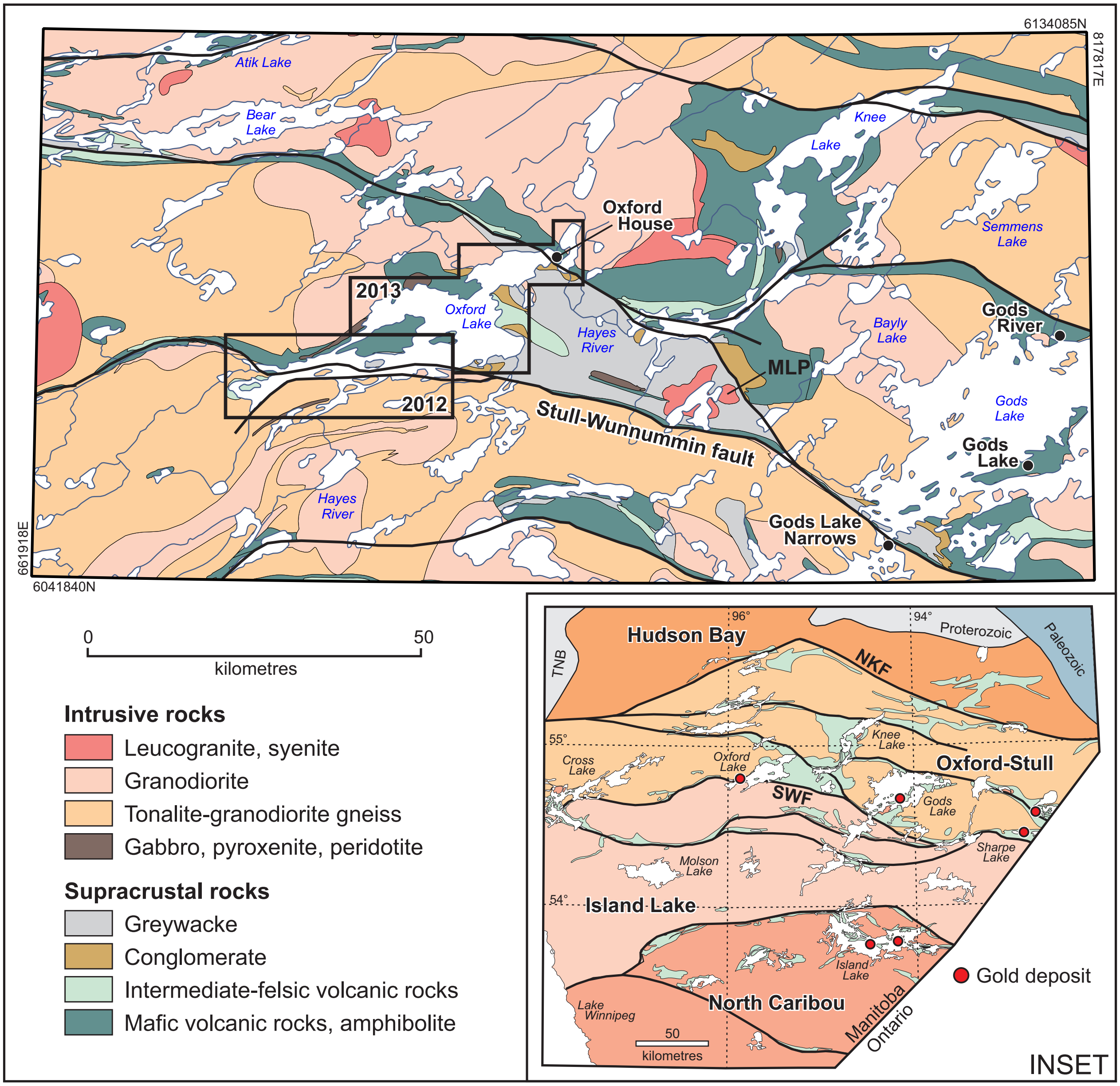



***Figure GS-1-1:*** *Regional geological setting of the Oxford Lake–Knee Lake greenstone belt, showing the location of the 2012 and 2013 study areas. Abbreviation: MLP, Magill Lake pluton. Inset map shows the major geological domains, greenstone belts and shear zones in the Manitoba segment of the northwestern Superior province. Abbreviations: NKF, North Knife fault; SWF, Stull-Wunnummin fault; TNB, Thompson nickel belt.*

of the western Superior province[1] (Stott et al., 2010). Following the original scheme of Wright (1932), supracrustal rocks in the Manitoba segment of the Oxford–Stull domain have traditionally been divided into two stratigraphic units: the older, basalt-dominated Hayes River group (HRG) and the younger, more diverse Oxford Lake group (OLG; e.g., Barry, 1960; Gilbert, 1985; Hubregtse, 1985).

The HRG consists of pillowed and massive basalt flows and gabbro, with minor intermediate to felsic volcanic rocks and fine-grained sedimentary rocks (Hubregtse, 1978, 1985; Gilbert, 1985). At Oxford Lake, the HRG is described as consisting of three volcanic cycles, each of which consists of a thick mafic lower section with or without a thinner felsic upper section (Hubregtse, 1978). Felsic volcanic rocks in the HRG at Knee Lake vary in

[1] For the sake of consistency, the Manitoba Geological Survey has opted to make a universal change from capitalized to noncapitalized for the generic part of lithostructural feature names (formal stratigraphic and biostratigraphic nomenclature being the exceptions).

age from ca. 2827 to ca. 2834 Ma (Corkery et al., 2000); however, the HRG at Oxford Lake has not been dated. On a regional scale, the HRG is disrupted by tonalite–granodiorite plutons, gabbro intrusions and tonalitic gneiss of the Bayly Lake complex, which is inferred to predate OLG volcanism (Gilbert, 1985).

Unconformably overlying rocks of the OLG are subdivided into lower volcanic and upper sedimentary subgroups, and locally include polymictic conglomerate that contains clasts derived from the HRG and tonalite–granodiorite intrusions of the Bayly Lake complex (Gilbert, 1985). The volcanic subgroup includes porphyritic volcanic rocks of high-K calcalkalic to shoshonitic affinity that range in composition from basalt to rhyolite and are intercalated with locally derived, coarse epiclastic rocks (Hubregtse, 1978, 1985; Brooks et al., 1982; Gilbert, 1985). Felsic volcaniclastic rocks of the volcanic subgroup have yielded U-Pb ages of 2722 ±3 Ma at Knee Lake (Corkery et al., 2000) and 2705 ±2 Ma at Oxford Lake (Lin et al., 2006). The more extensive sedimentary subgroup consists of a thick succession of feldspathic greywacke-mudstone turbidite, iron formation, crossbedded quartz-lithic greywacke and polymictic conglomerate deposited in shallow-marine to subaerial settings. In southern Knee Lake, these rocks have a maximum depositional age of ca. 2707 Ma (Corkery et al., 2000). The OLG is intruded by widespread tonalite–granodiorite–granite plutons; its minimum age is constrained by the Magill Lake pluton, which intrudes the OLG south of Knee Lake (Figure GS-1-1) and yielded a U-Pb monazite age of 2668 ±1 Ma (Lin et al., 2006).

Supracrustal rocks at Oxford Lake were overprinted by at least two generations of upright folds, intruded by granitoid plutons and tectonically segmented by greenschist-facies dextral shear zones. The latter structures are part of an anastomosed array of regional-scale shear zones that appear to merge toward the east into the crustal-scale Stull-Wunnummin fault, which is thought to represent a fundamental tectonic boundary in the western Superior province (e.g., Skulski et al., 2000; Stott et al., 2010). In Manitoba, the main strand of this fault trends in a westerly direction through Sharpe Lake (Beaumont-Smith et al., 2003) and bifurcates toward the west into a series of second-order splays (Figure GS-1-1, inset). The northernmost of these splays trends through the narrows in Gods Lake, where it is referred to as the 'Gods Lake Narrows shear zone' (Lin et al., 2006), and continues along strike to Oxford Lake, where it roughly coincides with the southern boundary of the Oxford Lake–Knee Lake belt.

## Revised tectonostratigraphic framework

Based on the preliminary results of the 2012 field season, supracrustal rocks in western Oxford Lake were divided into four tectonostratigraphic assemblages (Cat Eye Bay, Hyers, Carghill and Thomsen), each characterized by distinctive associations of rock types (Anderson et al., 2012a, b, c). To avoid implied correlations with adjacent belts, the assemblages were assigned provisional names from geographic features at their local type-localities. The map area was also divided into three main structural panels (north, central and south) bounded by greenschist-facies shear zones (Figure GS-1-2). As described by Anderson et al. (2012c), crosscutting relationships of intrusions suggest different depositional ages and/or geological histories for the constituent supracrustal rocks of each panel. Fieldwork in 2013 was mainly focused on the eastern extensions of the north and central panels, containing the Carghill and Thomsen assemblages, respectively. Nevertheless, the geology of each whole panel is summarized briefly below.

Supracrustal and intrusive rocks at Oxford Lake are metamorphosed and deformed. Metamorphic grade varies from amphibolite facies (hornblende±garnet, cordierite) along the margins of the belt to greenschist facies (chlorite±biotite, actinolite, sericite) in the interior. In the interest of brevity, however, the prefix 'meta' is not used in this report and the rocks are described in terms of their protoliths. Primary features are, in general, exceptionally well preserved in the 2013 map area.

At the west end of Oxford Lake, the panels and bounding shear zones are stitched by post-tectonic gabbro dikes that are presumed, on the basis of orientation, to be parts of the Molson (1883 Ma; Heaman et al., 1986) and Mackenzie (1267 Ma; LeCheminant and Heaman, 1989) swarms.

### *South panel*

The south panel of the Oxford Lake belt is bounded to the north by the Hyers shear zone and to the south by strongly deformed tonalite of the Bayly Lake complex. This panel contains two distinct assemblages of supracrustal rocks: the mafic-flow–dominated Cat Eye Bay assemblage and the felsic-volcaniclastic–dominated Hyers assemblage (Figure GS-1-2). Based on the widespread occurrence of intratectonic dikes (i.e., dikes that crosscut ductile deformation fabrics and were later deformed, thereby indicating relatively complex and protracted magmatism and deformation), these assemblages are interpreted to contain the oldest supracrustal rocks in the belt. The intratectonic intrusions include diabase, plagioclase-phyric biotite tonalite and syenogranite dikes, most of which are too small to depict at 1:20 000 scale, as well as equigranular biotite tonalite of the Cat Eye Bay pluton, all of which are only observed in the south panel.

The Hyers assemblage crops out on Hyers Island and along the southwestern shoreline of Lynx Bay (Figure GS-1-2), and consists mostly of intermediate to felsic volcaniclastic rocks, with minor subvolcanic porphyry intrusions and derived epiclastic rocks. Coarse volcaniclastic

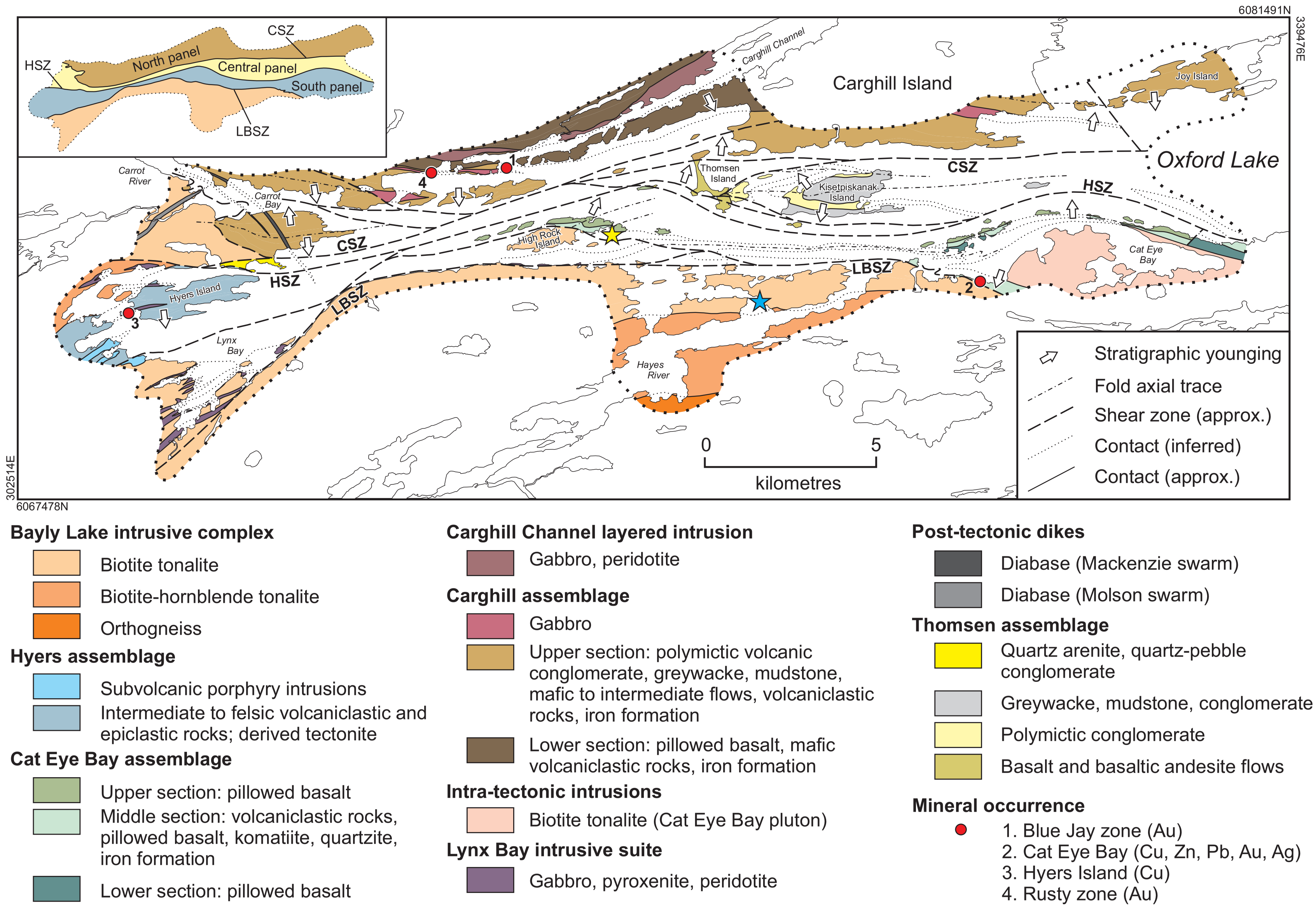



***Figure GS-1-2:*** *Simplified geology of western Oxford Lake (after Anderson et al., 2012a, b), showing the main components of the various supracrustal assemblages, major structural features and significant mineral occurrences. Inset diagram shows the three main structural panels. Yellow and blue stars indicate the locations of komatiite and carbonatite occurrences, respectively. Abbreviations: CSZ, Carghill shear zone; HSZ, Hyers shear zone; LBSZ, Lynx Bay shear zone.*

rocks in this assemblage are characterized by widespread volcanogenic alteration and host the Hyers Island copper-rich massive-sulphide deposit, consistent with a sub-aqueous-arc depositional setting. Results are pending for samples of felsic volcanic sandstone and intrusive quartz-porphyry from the Hyers assemblage, which were submitted for U-Pb dating in 2012, to provide upper and lower age constraints on deposition.

The Hyers assemblage is intruded by biotite tonalite–granodiorite of the Bayly Lake complex and both are cut by gabbro dikes of the Lynx Bay intrusive suite, which also includes minor peridotite and pyroxenite. As defined by Gilbert (1985) and Hubregtse (1985), the Bayly Lake complex south of Oxford Lake includes tonalitic gneiss and strongly lineated biotite-hornblende tonalite, which are part of a regionally extensive belt of tonalite gneiss that bounds the southern margin of the Oxford–Stull domain (Figure GS-1-1). This belt includes the 'Michikinabish Lake–Brown Lake gneiss complex' at Gods Lake (Corkery et al., 2000) and the 'Richardson Arm gneiss complex' at Sharpe Lake (Beaumont-Smith et al., 2003). Four multigrain fractions of zircon from the tonalite gneiss at Gods Lake yielded near-concordant data with $^{207}Pb/^{206}Pb$ ages ranging from 2880 to 2834 Ma, which were interpreted to represent a mixture of older and younger components (Lin et al., 2006). Farther east along strike in Ontario, the tonalite gneiss yielded more precise U-Pb zircon ages of 2855 ±5 Ma and 2848 ±7 Ma (Skulski et al., 2000). Based on the intrusive relationship observed at Oxford Lake, these dates suggest a minimum age of ca. 2850 Ma for the Hyers assemblage. In 2013, two samples of the tonalite (one lineated, the other gneissic) south of Oxford Lake were collected for U-Pb dating to further constrain the age relationships.

The Cat Eye Bay assemblage crops out along the southern shoreline of Oxford Lake and consists mostly of pillowed basalt flows, with minor komatiite and komatiitic-basalt flows, volcaniclastic rocks, iron formation and quartzite—an association that is suggestive of continental-rift sequences documented elsewhere in the Superior province. At the type locality in Cat Eye Bay, these rocks define a macroscopic anticline that trends parallel and adjacent to the southern shoreline of Oxford Lake, and is intruded along its axis by the intratectonic Cat Eye Bay pluton (Figure GS-1-2). The contact between the Cat Eye Bay assemblage and Bayly Lake complex appears to be wholly tectonic across the Lynx Bay shear zone. A sample of fuchsitic quartzite from western Cat Eye Bay was submitted for U-Pb dating in 2012, but did not yield any zircon; an additional sample of garnetiferous quartzite was collected in 2013 from farther west along strike, in the hope of obtaining detrital zircon to constrain the maximum depositional age of the possible rift-sequence.

### *North panel*

The north panel of the Oxford Lake belt is bounded to the south by the Carghill shear zone and lies in tectonically modified intrusive contact to the north with massive to weakly foliated granodiorite of the Semple River pluton (Hubregtse, 1985). This panel appears to continue along strike to the west, beyond the limits of the 2012 map area, and may be contiguous with the narrow septa of supracrustal rocks that define the Carrot River belt west of Oxford Lake (Figure GS-1-1; Hubregtse, 1985; Peck et al., 1997). This panel thickens considerably toward the east and was the main focus of the 2013 mapping program. Intratectonic dikes are absent in the north panel, indicating that the Carghill assemblage may have been deposited after an orogenic cycle recorded by the south panel.

As described by Anderson et al. (2012c), the Carghill assemblage crops out along the northern shoreline of Oxford Lake and adjacent islands, and is interpreted to underlie all of Carghill Island (Figure GS-1-2). The assemblage includes a monotonous lower section dominated by subaqueous mafic flows and a more diverse upper section dominated by epiclastic rocks. The lower section consists mostly of pillowed and massive basalt flows, with minor subvolcanic intrusions, volcaniclastic rocks and iron formation, and is intruded by the Carghill Channel layered ultramafic–mafic intrusion, which consists mostly of gabbro with minor peridotite, pyroxenite and pegmatitic phases. The upper section—mainly volcanic conglomerate and turbiditic greywacke—also includes minor coherent mafic to felsic flows, associated subvolcanic intrusions, and iron formation. Barry (1960) assigned these sections to lower and upper 'units' of the HRG, and described the contact as "conformable or gradational", whereas Hubregtse (1985) assigned the lower section to the HRG and the upper section to the volcanic subgroup of the OLG and argued, on the basis of map patterns and structural trends, for an unconformable contact relationship. Except where obviously folded, bedding orientations above and below the contact are concordant and younging indicators are consistently south-younging.

Observations made during the 2012 and 2013 field seasons did not shed substantial new light on the nature of this contact. However, preliminary geochemical results indicate the presence of basalt, basaltic andesite, andesite and dacite flows of high-K calcalkalic to shoshonitic affinity in the upper section, which strongly supports its correlation with the type locality of the OLG in eastern Oxford Lake, as suggested by Hubregtse (1985). Preliminary results of U-Pb dating of detrital zircons, in turbiditic feldspathic greywacke of the upper section, define a unimodal distribution dominated by ca. 2740–2720 Ma detritus. These results also indicate a maximum depositional age of ca. 2715 Ma (Anderson et al., 2013, unpublished data), which is also in keeping with its correlation to the OLG.

### *Central panel*

The central panel of the Oxford Lake belt contains the Thomsen assemblage and is bounded to the north and south by the Carghill and Hyers shear zones, respectively (Figure GS-1-2). The Thomsen assemblage crops out on islands in western and central Oxford Lake and mostly consists of turbiditic greywacke and mudstone, with minor lenses of polymictic conglomerate, assigned to the OLG by both Barry (1960) and Hubregtse (1985). Abundant granitoid clasts in polymictic conglomerate and the near absence of intrusions indicates a relatively young depositional age. As described by Anderson et al. (2012c), the assemblage includes a thick succession of pillowed basalt flows that was previously assigned to the HRG (Barry, 1960; Hubregtse, 1985), but was found to depositionally overlie polymictic conglomerate in one location on Thomsen Island. Preliminary results of U-Pb dating of detrital zircons, in the conglomerate immediately beneath the basalt, define an essentially unimodal distribution dominated by ca. 2720–2700 Ma detritus and indicate a maximum depositional age of ca. 2695 Ma (Anderson et al., 2013, unpublished data); hence the basalt flows and associated sedimentary rocks must be younger than the HRG and are among the youngest supracrustal rocks identified to date in the region.

Also included in the Thomsen assemblage is a distinctive unit of trough-crossbedded quartz arenite and quartz-pebble conglomerate of fluvial-alluvial origin, which crops out northeast of Hyers Island and was previously assigned to the OLG (Barry, 1960) or the ‘Lynx Bay assemblage’ of the Bayly Lake complex (Hubregtse, 1985), the latter of which is equivalent to the Hyers assemblage of Anderson et al. (2012c). Preliminary results of U-Pb dating of detrital zircons in the quartz arenite define a mostly bimodal distribution that includes a dominant mode at ca. 2890–2870 Ma and a lesser mode at ca. 2730–2700 Ma (Anderson et al., 2013, unpublished data), indicating a similar maximum depositional age to the sample from Thomsen Island, but a distinctly older source area. The close proximity of the fluvial-alluvial rocks to the Hyers assemblage (Figure GS-1-2) may implicate the latter as the main source of ca. 2890–2870 Ma detritus.

## Results from the 2013 field season

As noted above, fieldwork in 2013 was focused on the eastern extensions of the Carghill and Thomsen assemblages in the northern and eastern portions of Oxford Lake. The general characteristics of these units are described briefly below, in order of decreasing apparent age. Unit codes in the text correspond to those of Anderson et al. (2013a, b, c); a simplified version of these maps is included herein as Figure GS-1-3. The authors emphasize that the arrangement of map units in the legend is based on composition (mafic to felsic), grain size (coarse to fine) and rock type (volcanic to volcaniclastic to sedimentary to intrusive), and is not intended to indicate stratigraphic order.

### *Carghill assemblage*

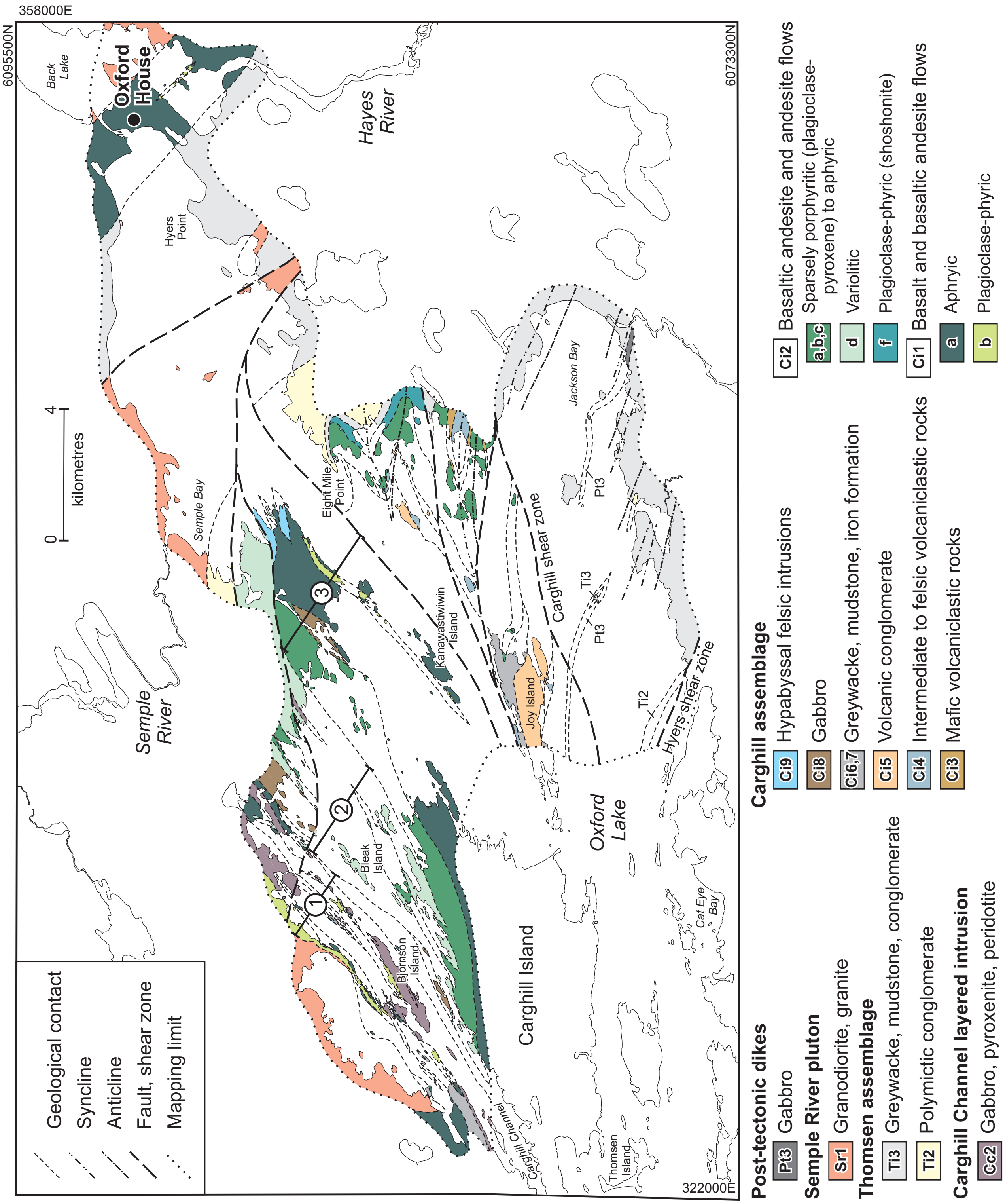
The Carghill assemblage widens considerably and is exceptionally well exposed in the northern and eastern portions of Oxford Lake. It includes perhaps the thickest, most complete and best exposed section of ‘HRG’ stratigraphy in the western portion of the Oxford–Stull domain. As described above, the assemblage includes a monotonous lower section dominated by subaqueous mafic flows and a more diverse upper section dominated by epiclastic rocks.

#### Lower section, Cargill assemblage

The lower section of the Carghill assemblage is at least 9 km thick in the area northeast of Carghill Island. Primary layers strike southwest and dip steeply to moderately northwest; ubiquitous younging indicators show that the rocks consistently young toward the southeast and are thus overturned. The stratigraphic base is not exposed. Instead, the section is bounded to the northwest by biotite granodiorite of the Semple River pluton (unit Sr1) along a discordant intrusive contact. The upper contact is also not exposed, but map patterns suggest it is concordant and probably fault modified, if not wholly tectonic (see below). Along strike to the northeast, the lower section is truncated by an east-trending panel of strongly transposed sedimentary rocks of the Thomsen assemblage (units Ti2, 3). Although the contact is not exposed, it is inferred on the basis of map patterns to be a tectonically modified angular unconformity.

The lower section is provisionally subdivided into stratigraphic units, mostly on the basis of the field characteristics of associated subaqueous lava flows; flows in each unit were also sampled for lithogeochemistry (results pending) to determine if they are chemically distinct. The most useful field characteristics for distinguishing the lava flows included 1) weathering colour; 2) phenocryst type and abundance; 3) vesicularity; 4) presence or absence of varioles; 5) pillow morphology; and 6) flow organization, including the proportion of primary volcaniclastic deposits (e.g., pillow-fragment breccia or hyaloclastite). Based on these criteria, three distinct units (or flow complexes) were identified. From oldest to youngest, these units include the Bjornson Island, Bleak Island and Kanawastiwiwin Island units, which are respectively characterized

***Figure GS-1-3 (facing page)**: Simplified geology of northern and eastern Oxford Lake (after Anderson et al., 2013a, b, c), showing the main components of the various supracrustal assemblages and major structural features. Abbreviations: CSZ, Carghill shear zone; HSZ, Hyers shear zone.*


Geological contact
Syncline
Anticline
Fault, shear zone
Mapping limit
358000E
609550N
607330N
322000E
0
4
kilometres
Oxford House
Back Lake
Hayes River
Hyers Point
Semple River
Semple Bay
Eight Mile Point
Jackson Bay
Kanawastiwiwin Island
Carghill shear zone
Carghill Island
Bleak Island
Bjornson Island
Joy Island
Oxford Lake
Cat Eye Bay
Thomsen Island
Carghill Channel
Hyers shear zone
Pt3
Ti3
Ti2
Post-tectonic dikes
Pt3 Gabbro
Semple River pluton
Sr1 Granodiorite, granite
Thomsen assemblage
Ti3 Greywacke, mudstone, conglomerate
Ti2 Polymictic conglomerate
Carghill Channel layered intrusion
Cc2 Gabbro, pyroxenite, peridotite
Carghill assemblage
Ci9 Hypabyssal felsic intrusions
Ci8 Gabbro
Ci6,7 Greywacke, mudstone, iron formation
Ci5 Volcanic conglomerate
Ci4 Intermediate to felsic volcaniclastic rocks
Ci3 Mafic volcaniclastic rocks
Ci2 Basaltic andesite and andesite flows
a,b,c Sparsely porphyritic (plagioclase-pyroxene) to aphyric
d Variolitic
f Plagioclase-phyric (shoshonite)
Ci1 Basalt and basaltic andesite flows
a Aphyric
b Plagioclase-phyric

by plagioclase-phyric, variolitic and aphyric lava flows. Similar textural subdivisions were proposed by Syme et al. (1997) for mafic flows of the HRG at Knee Lake, suggesting it may be possible to correlate units on a regional scale.

Pillowed and massive basalt flows exposed near the community of Oxford House and downstream along the Hayes River at Back Lake (Figure GS-1-3) are tentatively included in the Carghill assemblage on the basis of the criteria outlined above, but are not further subdivided because of their limited exposure and uncertain stratigraphic context. Basalt flows at Back Lake are bound to the south by strongly sheared sedimentary rocks of the Thomsen assemblage, and are intruded by tonalite of the Semple River pluton to the north.

### *Bjornson Island unit (plagioclase-phyric flows)*

The Bjornson Island unit defines the base of the Carghill assemblage and is the most diverse of the three units that make up the lower section. It is cut out by the Semple River pluton, but is at least 2.5 km in thickness. The Bjornson Island unit consists of pillowed and massive basalt flows, associated mafic volcaniclastic rocks, and subordinate feldspathic greywacke, heterolithic volcanic conglomerate, felsic volcaniclastic rocks and iron formation. It is pervasively intruded by basalt dikes and thick gabbro sills, which are rare in the overlying Bleak Island unit and are tentatively correlated with the Carghill Channel layered intrusion (units Cc1, 2). Minor felsic porphyry dikes in this unit are presumed to be related to the Semple River pluton (unit Sr1). The Bjornson Island unit also tends to be more strongly deformed than overlying units, perhaps due to its location on the margin of the belt.

The basalt flows weather buff to green-grey and are dark green on fresh surfaces. They are typically amygdaloidal and vary from aphyric to plagioclase-phyric (5–10%; <5 mm); some flows contain sparse varioles in pillow cores. The characteristic flow type is seriate-porphyritic and contains up to 25% coarse (0.5–1.5 cm) tabular plagioclase phenocrysts (unit Ci1b; Figure GS-1-4a). Pillowed flows consist of bun-shaped to amoeboid pillows that range up to 2 m across, but are generally less than 50 cm. The pillows are closely packed and contain only minor (<5%) interpillow hyaloclastite. They are locally intercalated with pillow-fragment breccia, crystal-rich hyaloclastite and mafic or felsic volcaniclastic rocks (units Ci3, 4), or thin intervals of thin-bedded epiclastic rocks and iron formation (units Ci6, 7; Figure GS-1-4b). Two samples of feldspathic greywacke in this unit were collected for detrital zircon U-Pb geochronology to constrain the maximum age of deposition. Also collected was a sample of pegmatitic gabbro from the Carghill Channel layered intrusion, which would provide a minimum age constraint for the lower section of the assemblage.

### *Bleak Island unit (variolitic flows)*

The Bleak Island unit is approximately 3 km in thickness and is remarkably homogeneous: it consists almost exclusively of pillowed basalt (and/or basaltic andesite) flows, with only minor massive flows and very rare flow-breccia; epiclastic rocks are absent. The characteristic basalt weathers pale grey-green to buff and is aphyric, nonamygdaloidal and strongly variolitic (unit Ci2d). The varioles are typically light grey, round and less than 1 cm in diameter, with an internal structure that varies from concentric to radial. They are locally arranged in concentric bands along the inner side of pillow margins, and increase in size and abundance toward the pillow cores, where they commonly coalesce into dense masses (Figure GS-1-5a). Pillowed flows consist of particularly large (1–3 m) bulbous to bun-shaped pillows, with relatively thick (3–10 cm) selvages (Figure GS-1-5b). Some pillows have sparse amygdules on the inner margin of the selvage. Drain-out structures are common and, together with pillow cusps, provide unambiguous younging directions

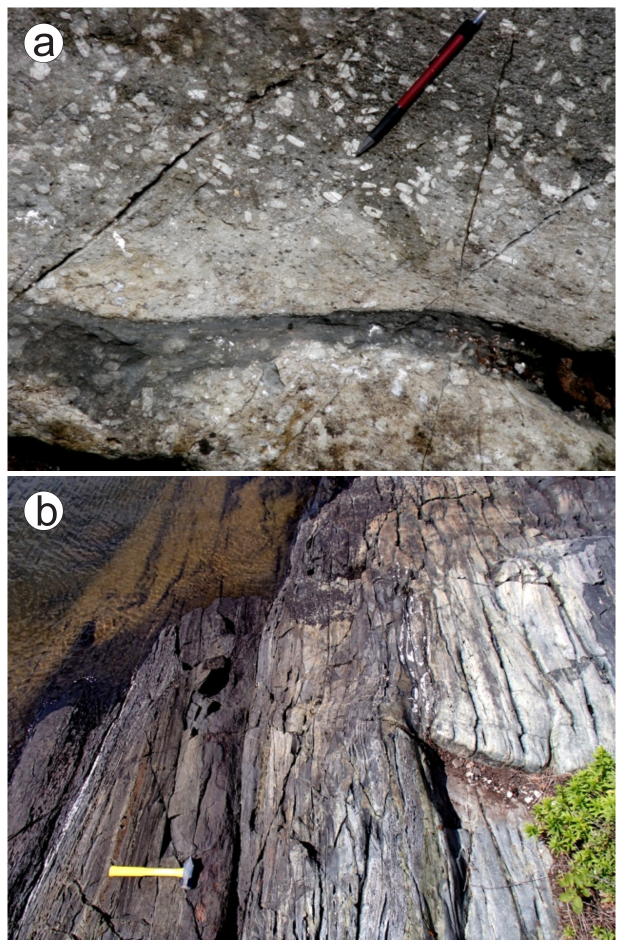



***Figure GS-1-4:*** *Outcrop photographs of rocks in the Bjornson Island unit of the lower Carghill assemblage:* ***a)*** *plagioclase-phyric pillowed basalt, showing seriate-porphyritic texture;* ***b)*** *thin-bedded oxide-facies iron formation and feldspathic greywacke (left) overlain by strongly deformed pillowed flow of plagioclase-phyric basalt (right).*

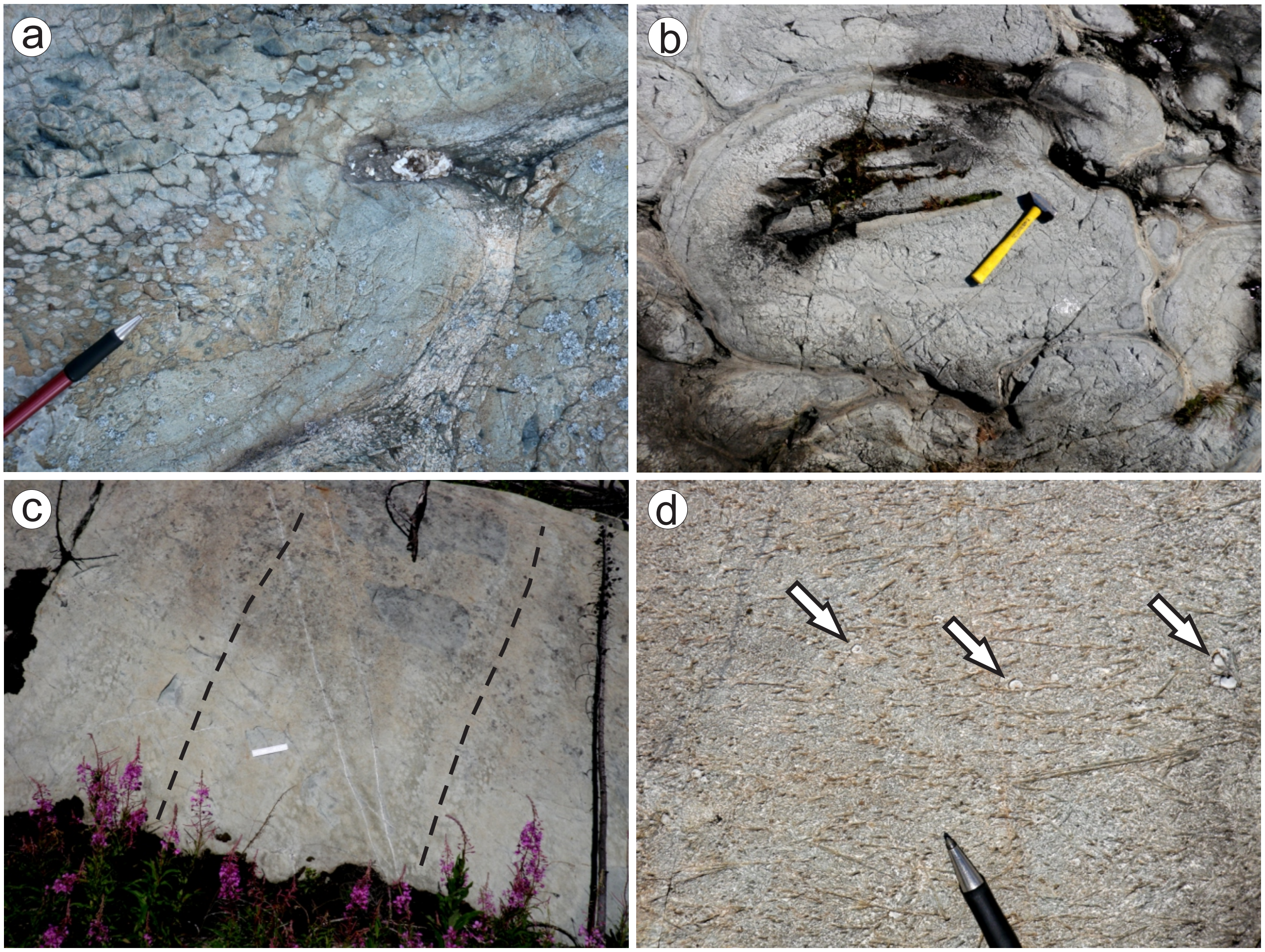



***Figure GS-1-5:*** *Outcrop photographs of rocks in the Bleak Island unit of the lower Carghill assemblage:* ***a)*** *detail of pillowed variolitic basalt, showing a decrease in size and abundance of varioles toward a thick selvage;* ***b)*** *large bulbous pillow of variolitic basalt, showing drain-out structures (above hammer);* ***c)*** *faintly layered leucogabbro in the thick, sill-like intrusion near the base of the Bleak Island unit (dashed lines indicate trend of layers; ruler for scale is 15 cm in length);* ***d)*** *detail of a leucogabbro layer showing quartz-carbonate amygdules (arrows) and plumose spinifex texture.*

(Figure GS-1-5b). Many outcrops also contain mega-pillows or coherent flow-lobes up to 15 m across. Flow breccia is virtually absent and most flows contain less than 10% hyaloclastite in pillow interstices. Massive flows range up to 15 m in thickness and are characterized by thick (10–30 cm) basal chilled-margins, upward transition into pillowed flows, and variolitic, sparsely amygdaloidal flow-tops. The large size and bulbous shapes of the pillows, coupled with the scarcity of massive flows and near-absence of flow breccias, indicate a rather unique combination of eruption parameters (e.g., flow rate, temperature and viscosity), which also favoured the widespread development of variolites.

Near its base, the Bleak Island unit contains a thick (~500 m) sill that shows an upward variation from fairly homogeneous equigranular mesogabbro (unit Ci8a), in the lower portion, to heterogeneous, faintly layered leucogabbro, in the upper portion (unit Ci8d; Figure GS-1-5c). Some layers in the upper portion contain well-developed quench-crystallization textures (bow-tie, plumose and radiating spinifex) and abundant (up to 10%) quartz or carbonate amygdules (Figure GS-1-5d), suggesting the sill represents very high-level intrusion or cryptoflow; neither the base nor top is exposed.

#### *Kanawastiwiwin Island unit (aphyric flows)*

The Kanawastiwiwin Island unit is approximately 4 km in thickness and defines the top of the lower section of the Carghill assemblage. It consists of massive, pillowed and brecciated basalt flows that are interstratified on meso- to macroscopic scales and thus display well-developed flow organization. The basalt is amygdaloidal, nonvariolitic and typically aphyric; flows show systematic textural variation toward the top of the unit, perhaps related to a change in composition. Near the base, the basalt is light green, sparsely amygdaloidal and massive to pillowed, with only minor flow breccia; pillows are relatively large (0.5–1.5 m) and bulbous (unit Ci2c; Figure GS-1-6a). Near the top, the basalt weathers dark green-grey and contains abundant round amygdules or radial pipe-amygdules, concentrated along the inner margins of pillow selvages (<40%; <1.5 cm; unit Ci1a; Figure GS-1-6b). The pillows are smaller (generally <50 cm) and more amoeboid in shape, and the upper parts of flows exhibit a much higher proportion (up to 50% in places) of pillow-fragment breccia (Figure GS-1-6c). Pillow selvages throughout the unit are dark green, chloritic and relatively thin (<1.5 cm). Interpillow hyaloclastite is relatively minor (<10%) and is strongly altered to chlorite, carbonate or epidote. Massive and pillowed flows range up to approximately 40 m in thickness, and are demonstrably compound in most locations. Thicker massive flows include a basal cumulate zone up to several metres in thickness that contains abundant (up to 30%), coarse (1–6 cm) phenocrysts and glomerocrysts of plagioclase; these phenocrysts are also locally present in the cores or cusps of scattered pillows in overlying flows (similar rocks are exposed along the chain of islands in the Hayes River at Back Lake, suggesting a possible correlation). Near the very top of this unit, particularly thick (5–10 m), normally graded layers of pillow-fragment breccia are capped by crudely stratified layers of hyaloclastite up to 50 cm thick.

Along strike to the northeast, the Kanawastiwiwin unit is intruded by two large bodies of feldspar-phyric dacite (unit Ci9d) that are unique to this unit. This rock weathers buff to light grey and is dark grey on fresh surfaces, with a fine-grained, seriate-porphyritic texture defined by blocky phenocrysts of plagioclase (5–10%; 0.5–5 mm) in an aphanitic, siliceous groundmass. Some outcrops contain a false-fragmental texture produced by fracture-controlled sericite alteration (Figure GS-1-6d), although most are homogeneous and strongly foliated. The external contact is exposed in one location and is

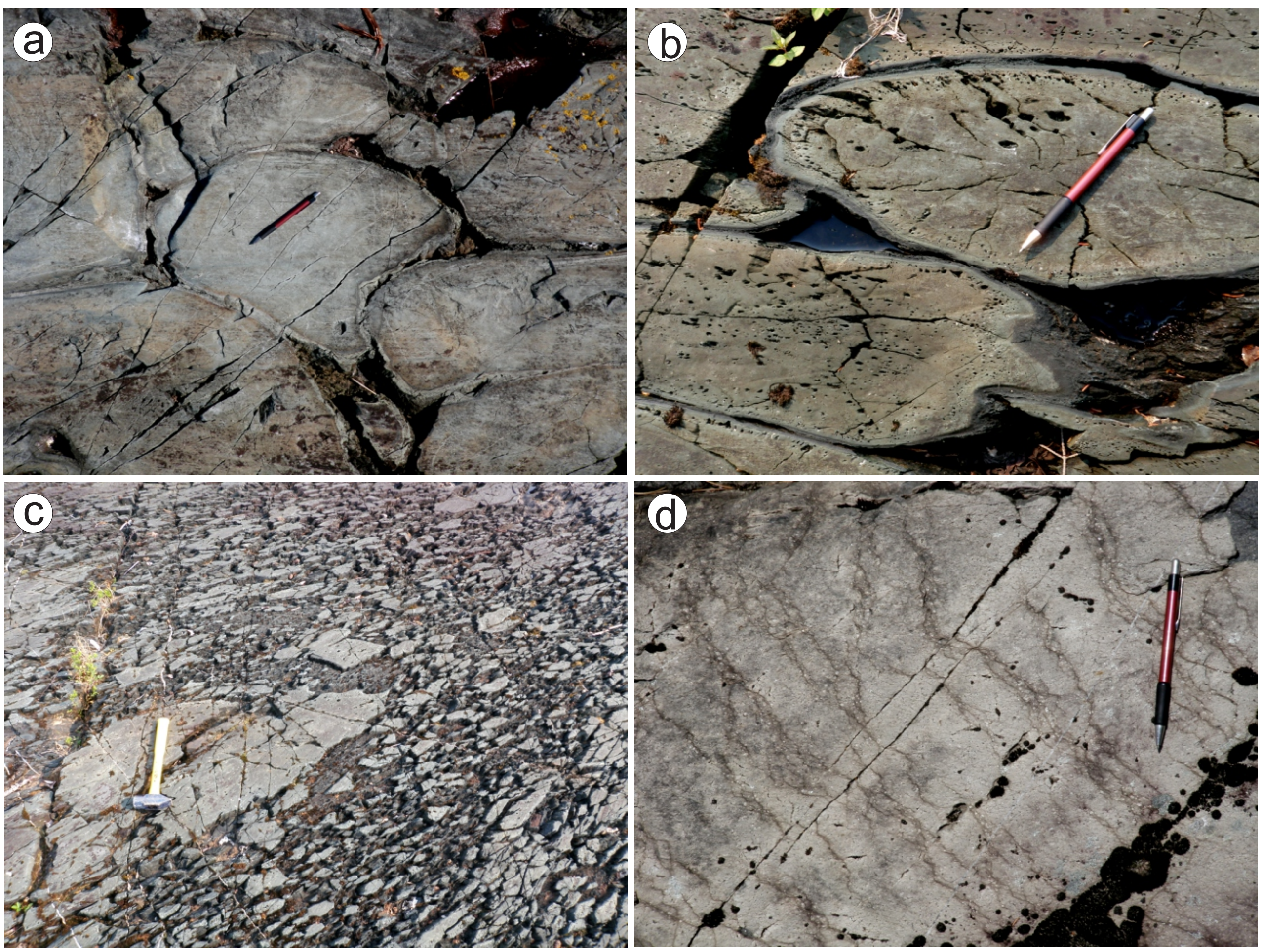



***Figure GS-1-6:*** *Outcrop photographs of rocks in the Kanawastiwiwin unit of the lower Carghill assemblage:* ***a)*** *bulbous to bun-shaped pillows of light green-grey, sparsely amygdaloidal basalt near the base of the unit;* ***b)*** *bun-shaped to amoeboid pillows of dark green, highly amygdaloidal basalt near the top of the unit;* ***c)*** *pillow-fragment breccia near the top of the unit; outside the frame of this photo, the breccia grades downward (to the upper left) into pillowed basalt and is sharply overlain (to the lower right) by massive basalt;* ***d)*** *false-fragmental texture defined by sericitized fractures in porphyritic dacite.*

sharp, somewhat irregular and clearly discordant to the adjacent pillowed flow. A sample of this body was collected for U-Pb geochronology to provide a minimum age constraint on mafic volcanism in the lower section of the Carghill assemblage.

### Upper section, Cargill assemblage

The upper section of the Carghill assemblage is at least 2 km thick and shows a systematic progression from dominantly epiclastic lithofacies (mostly units Ci5, 6) in the west to dominantly volcanic and volcaniclastic lithofacies (mostly units Ci2, 4) in the east. The epiclastic lithofacies is not extensively exposed in the 2013 map area, but was examined at the western end of Joy Island, where it consists mostly of thick-bedded feldspathic greywacke and heterolithic volcanic conglomerate, with minor coherent flows of pyroxene (±plagioclase)–phyric andesite and associated volcaniclastic rocks. This lithofacies continues along strike to the west for over 30 km and is fairly uniform in terms of the character and proportion of the constituent rock types. As noted above, analytical results from samples collected in 2012 indicate that the coherent flows are high-K calcalkalic–shoshonitic andesite and dacite, and have a maximum age of ca. 2715 Ma, based on U-Pb dating of the youngest detrital zircons in intercalated feldspathic greywacke (Anderson et al., 2013, unpublished data). Although structural data indicate the presence of macroscopic tight to isoclinal, east-trending folds, most of the epiclastic lithofacies tops toward the south and is overturned. In western Oxford Lake, the basal contact is concordant with lava flows in the lower section of the Carghill assemblage, which is also overturned to the south, consistent with a depositional contact relationship. However, the absence of macroscopic folds in the underlying rocks suggests décollement along the contact.

Additional evidence of décollement is found along strike to the northeast, where the volcanic and volcaniclastic lithofacies of the upper section are exposed along the shoreline and on islands in the area between Eight Mile Point and Jackson Bay, which represents the type locality of the volcanic subgroup of the OLG (Gilbert, 1985; Hubregtse, 1985). Bedforms in this area define a series of tight to isoclinal macroscopic folds that trend northeast or east, and plunge steeply. The authors found no evidence to support the existence of an earlier generation of isoclinal folds in this area, as proposed by Hubregtse (1985). As in the western portion of Oxford Lake, the folds do not carry across the basal contact of the upper section, indicating that it is fault-modified, if not wholly tectonic. Toward the northeast, the upper section is truncated by sedimentary rocks of the Thomsen assemblage; complex map patterns of the Carghill and Thomsen assemblages appear to require a folded angular unconformity in this location.

Primary features are exceptionally well-preserved in the area between Eight Mile Point and Jackson Bay, allowing for detailed interpretation of eruptive processes and settings, despite the effects of isoclinal folding indicated by structural data, as noted above. Field observations (summarized here) will be augmented by petrographic and geochemical data from a comprehensive new sample suite collected in 2013. Field data from this study, coupled with results from previous geochemical and petrographic studies (Hubregtse, 1978, 1985; Brooks et al., 1982), indicate that the volcanic rocks range in composition from basalt to rhyolite, and show a systematic progression from shoshonitic or high-K calcalkalic affinity in mafic end-members (~51–56 wt. % $SiO_2$) to low-K calcalkalic affinity in felsic end-members (~73–74 wt. % $SiO_2$). The volcanic rocks are typically plagioclase-phyric; mafic end-members also contain pseudomorphs (chlorite-biotite) after primary pyroxene or amphibole, whereas felsic end-members locally contain quartz phenocrysts.

Coherent, brecciated and pillowed flows of the volcanic lithofacies are intercalated with thick volcaniclastic deposits that include spectacular examples of primary autoclastic (±hyaloclastic) and pyroclastic material (unit Ci2a; Figure GS-1-7a, b). The eruptive setting was clearly subaqueous, and interlayers of crossbedded volcanic sandstone (Figure GS-1-7c) and heterolithic volcanic conglomerate (units Ci4, 5) indicate a setting that was likely transitional from subaerial to shallow-marine; the conglomerate locally contains well-rounded boulders up to 2.5 m in diameter (Figure GS-1-7d), indicating at least some detritus underwent subaerial transport. This lithofacies includes distinctive flows of coherent, brecciated and locally pillowed basaltic andesite (unit Ci2f) that are densely packed with coarse tabular phenocrysts of plagioclase (40–60%; 0.5–1.5 cm). In most locations, these flows contain round to amoeboid quartz amygdules and a diffuse to well-developed flow foliation defined by aligned phenocrysts (Figure GS-1-8a). Clasts of this textural type are readily identifiable in associated coarse autoclastic or epiclastic deposits (the internal flow-foliation commonly parallels the clast margins, indicating fragmentation by spalling of highly viscous flow-lobes; Figure GS-1-8b); as noted by Hubregtse (1985), these clasts are also common in polymictic conglomerate of the Thomsen assemblage north of Eight Mile Point, indicating its younger relative age.

## *Thomsen assemblage*

The Thomsen assemblage is exposed along the shoreline of Jackson Bay and northeast of Eight Mile Point, and also in widely scattered outcrops in the northern basin of Oxford Lake. This distribution appears to define two major panels, both of which preserve evidence of intense transposition and at least one generation of tight to isoclinal folds. The exposures in Jackson Bay and at Eight Mile Point respectively correspond to the eastern portions of

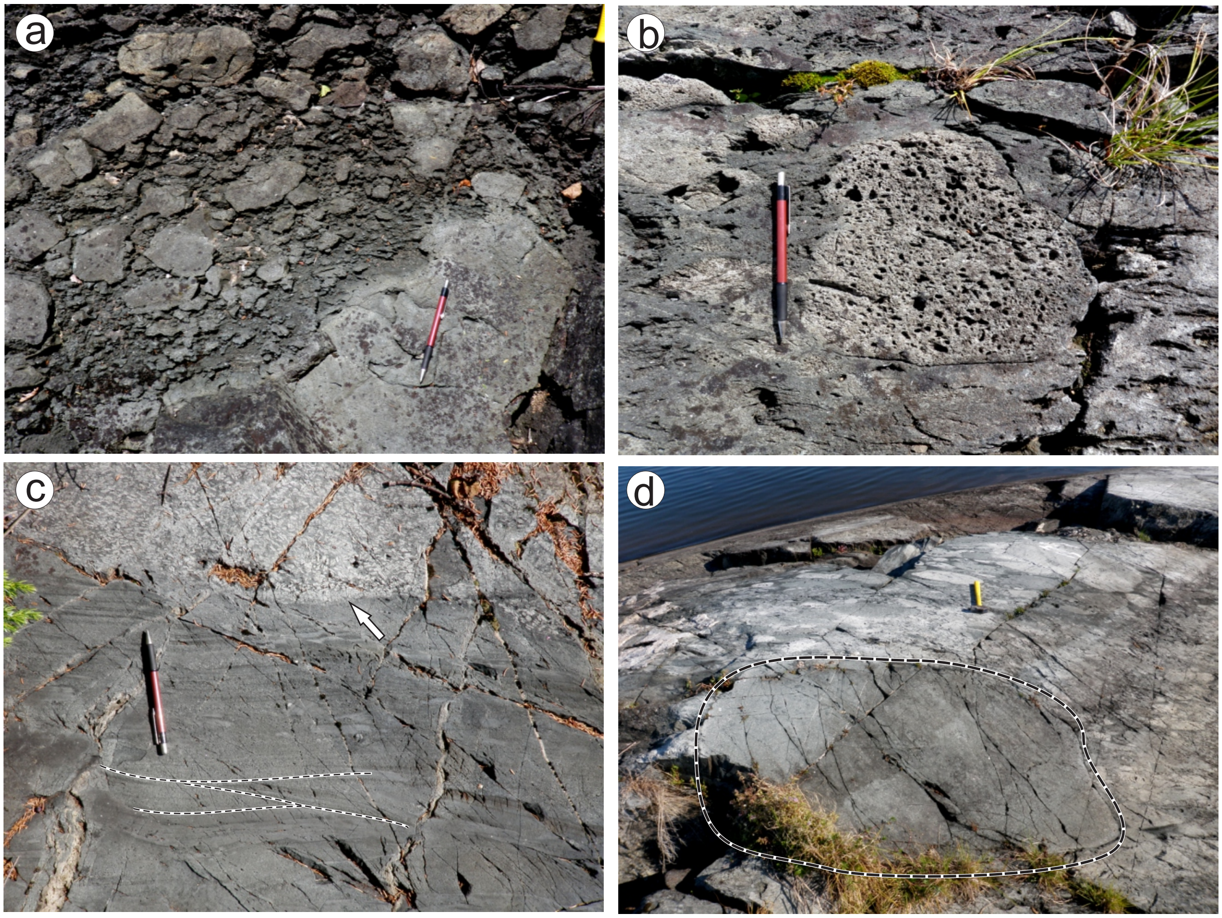



***Figure GS-1-7:*** *Outcrop photographs of rocks in the upper Carghill assemblage at type locality of the Oxford Lake group (Gilbert, 1985; Hubregtse, 1985) southeast of Eight Mile Point:* ***a)*** *autoclastic breccia composed of angular blocks of plagioclase-phyric andesite; note the broken selvage on the largest block (under pen);* ***b)*** *intact block of andesitic scoria in monolithic, crudely stratified, poorly sorted tuff breccia; possibly representing a proximal scoria-fall deposit;* ***c)*** *crossbeds (dashed lines) in medium-grained pebbly volcanic sandstone; the thin-bedded volcanic sandstone, pebble conglomerate and mudstone section is approximately 10 m thick at this location, and is bounded above and below by coherent to brecciated flows of densely porphyritic basaltic-andesite; the sharp, chilled, basal contact of the overlying flow is indicated by the arrow;* ***d)*** *very large rounded boulder (outlined) of plagioclase-phyric andesite in heterolithic volcanic conglomerate (note hammer for scale), indicating subaerial transport of detritus and a proximal, high-energy depositional setting.*

the central and north structural panels defined previously, whereas those in the northern basin of the lake correspond to a different panel, referred to here as the northeast panel. The northeast panel is intruded and disrupted by foliated biotite granodiorite of the Semple River pluton (unit Sr1), whereas the central and north panels are intruded by rare, apparently massive, dikes of gabbro (unit Pt3) and possible lamprophyre (unit Pt4). Four widely spaced exposures of gabbro in the area southeast of Carghill Island are provisionally interpreted to represent a single dike, which appears to stitch the northern margin of the central panel (i.e., the Carghill shear zone) south of Joy Island (Figure GS-1-3). Contact relationships with older rocks are nowhere exposed at Oxford Lake, but the high abundance of apparently local detritus strongly suggests a depositional relationship, probably above a deeply eroded, angular unconformity (e.g., Gilbert, 1985; Hubregtse, 1985). The various panels may represent separate, possibly fault-bounded, basins or perhaps a single basin disposed on opposite limbs of a macroscopic fold. Map patterns and younging directions in the area southeast of Eight Mile Point indicate that the basal contact of the Thomsen assemblage at least locally truncates macroscopic folds in the Carghill assemblage, consistent with a pronounced angular unconformity or early low-angle fault in this location, and was subsequently folded, resulting in a complex structural geometry.

In the 2013 map area, the Thomsen assemblage consists mostly of intercalated greywacke and polymictic conglomerate (units Ti3 and Ti2, respectively). The pillowed basalt flows (unit Ti1) and quartz-rich fluvial-alluvial sedimentary rocks (unit Ti4) documented in the western portion of Oxford Lake were not observed in the 2013 map area, perhaps indicating a more distal depositional

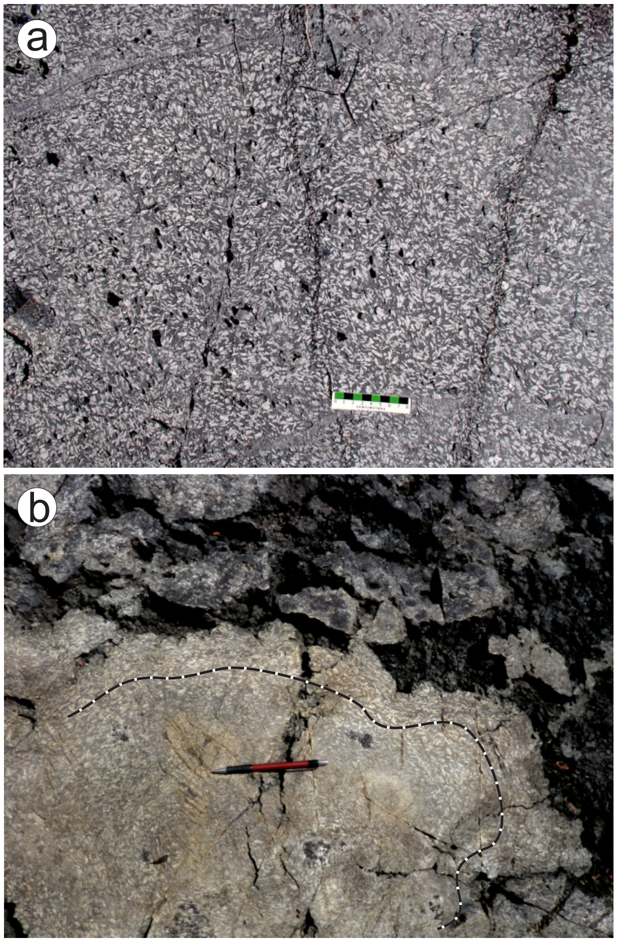



***Figure GS-1-8:*** *Outcrop photographs of plagioclase-phyric basaltic andesite of shoshonitic affinity in the upper Carghill assemblage:* ***a)*** *coherent flow, showing densely packed plagioclase phenocrysts;* ***b)*** *autoclastic breccia, showing flow-foliation (dashed line) of plagioclase phenocrysts that roughly parallels the irregular margin of a basaltic andesite block or lobe.*

setting in the east. The greywacke is feldspathic and forms planar, normally graded beds that range up to several metres in thickness. Thicker beds are deeply scoured and pebbly at the base, contain abundant mudstone rip-ups, and are capped by thin (<10 cm) mudstone beds, or distinct layers of thin-bedded greywacke-mudstone turbidites up to 50 cm thick. The greywacke locally defines thick, monotonous intervals that contain only minor diffuse layers of pebble- to cobble-conglomerate.

Polymictic conglomerate (unit Ti2) is most extensive along the shoreline northeast of Eight Mile Point, but also occurs at Semple Bay and Hyers Point in the northern basin of Oxford Lake, and more sporadically along the northern and southern shorelines of Jackson Bay. In general, the conglomerate is poorly sorted, massive to crudely stratified, and matrix to clast supported (Figure GS-1-9a, b). It contains angular to very well rounded clasts that range in size up to 1.5 m in diameter, and is clearly distinguished from superficially similar rocks in the upper section of the Carghill assemblage by the high proportion of well-rounded clasts of medium to coarse-grained tonalite, granodiorite and granite (unit Ti2b; Figure GS-1-9b).

## Structural geology

Map patterns, mesoscopic deformation structures and overprinting relationships indicate that the supracrustal rocks at Oxford Lake have been affected by at least four phases of ductile deformation. The earliest structures are found in the south panel and include penetrative planar fabrics and tight to isoclinal folds that are discordantly cut by intratectonic dikes of various compositions.

In western Oxford Lake, the upper section of the north panel preserves evidence for two generations of tight to isoclinal folds, which overprint subvolcanic dikes and are thus inferred to postdate the fabrics observed in the south panel. Rare, tight to isoclinal, asymmetric fold closures and associated axial-planar foliation are overprinted by upright, tight to isoclinal, steeply plunging folds that appear to be parasitic to macroscopic folds. The associated axial-planar foliation is penetrative, pervasive and subvertical, and is the main fabric observed in most outcrops, except those in late shear zones. It is defined most prominently by flattened primary features and locally intensifies into a penetrative transposition fabric. Aligned metamorphic minerals and elongate primary features define down-dip mineral and stretching lineations, respectively, in the foliation plane. Variations in the aspect ratios of deformed clasts, from markedly prolate (cigar shaped) to oblate (pancake shaped), define distinct structural domains within and between the shear-bounded panels, and may reflect strain variations within the macroscopic fold structures; however, overprinting deformations may also have played a role in these variations.

In general, finite strain is considerably lower in eastern Oxford Lake, and rocks in the north panel preserve evidence for only a single generation of tight to isoclinal folds, indicating that the deformation is markedly heterogeneous on a regional scale. The lower section of the Carghill assemblage typically contains a weak to moderate shape-fabric (most prominently defined by flattened pillows) that is consistently oriented slightly clockwise to layering, indicating that the section is located on the north limb of a tight macroscopic syncline that is overturned to the southeast. As noted above, the upper section of the assemblage defines a series of tight to isoclinal overturned folds southeast of Eight Mile Point that perhaps represent the hinge of the same macroscopic fold structure. Stretching lineations are not well developed in either section. Due to poor exposure, locally sparse younging indicators and intense transposition, the macroscopic structural geometry of the Thomsen assemblage remains poorly resolved.

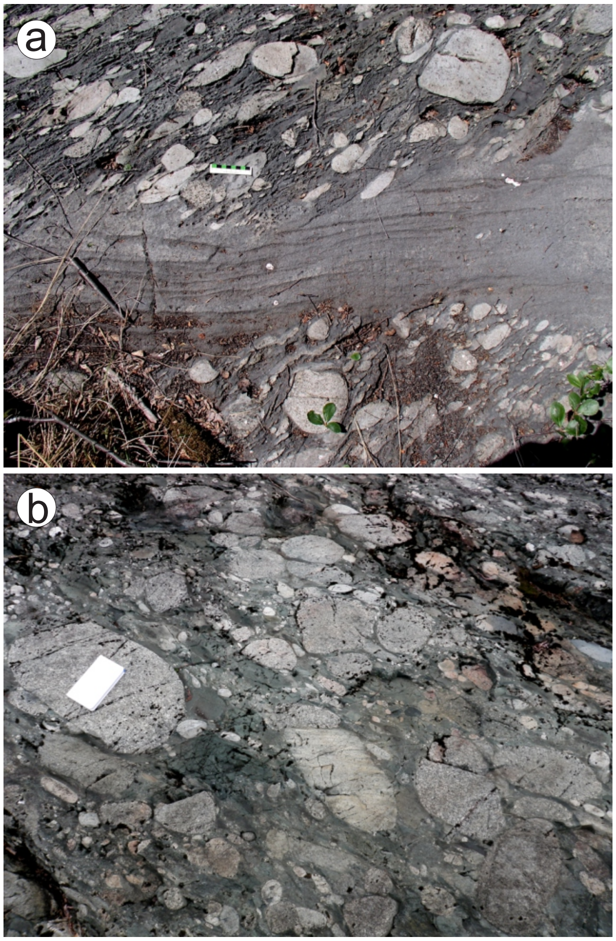



***Figure GS-1-9:*** *Outcrop photographs of rocks in the Thomsen assemblage:* ***a)*** *interbedded greywacke and cobble-conglomerate;* ***b)*** *polymictic cobble- and boulder-conglomerate containing abundant, well-rounded, granitoid clasts (beneath notebook)—a characteristic feature of conglomerate in the Thomsen assemblage.*

Throughout Oxford Lake, the macroscopic folds are disrupted by an anastomosed network of subvertical ductile shear zones that bound the major structural panels and vary from northwest to southwest in trend. The shear zones are characterized by penetrative mylonitic foliation and contain well-developed shear-sense indicators on horizontal outcrop surfaces. In northwest- or west-trending shear zones, the shear-sense indicators generally indicate dextral movement, whereas those in southwest-trending segments indicate sinistral movement. Stretching lineations are steep everywhere, but the shear zones locally contain mineral or slickenline lineations that plunge shallowly in the plane of the mylonitic foliation; these features can be interpreted in terms of overprinting deformations or progressive transpression (e.g., Lin and Jiang, 2001; Lin et al., 2006). Asymmetric Z-folds are developed throughout the western portion of the Oxford Lake belt and are associated with a weak to moderate axial-planar crenulation cleavage that overprints both the regional foliation and isoclinal folds at a shallow counter-clockwise angle.

## Economic considerations

Previous mineral exploration at Oxford Lake has resulted in the discovery of several base- and precious-metal occurrences in the western portion of the lake, thus demonstrating significant exploration potential. Exhalative base-metal sulphide occurrences are restricted to the south panel and include the Hyers Island Cu deposit (Assessment File 72236, Manitoba Mineral Resources, Winnipeg) and the Cat Eye Bay Cu-Zn-Pb-Au-Ag occurrence (A.F. 93258) in the Hyers and Cat Eye Bay assemblages, respectively. Results from the 2012 mapping program provided a much improved understanding of the stratigraphic and structural context of these occurrences, and indicate unrecognized potential for magmatic Ni-Cu-PGE deposits associated with komatiite and iron formation in the Cat Eye Bay assemblage at High Rock Island (Figure GS-1-2).

Iron-formation–hosted, orogenic Au mineralization occurs in the north panel, at the interface between the lower and upper sections of the Carghill assemblage (i.e., the Rusty zone; A.F. 72085) in the western portion of Oxford Lake. Preliminary results from detailed structural analysis of folds and shear zones in 2012 provided important new constraints on the possible structural settings and controls of gold mineralization. In addition, results from the 2013 field season indicate that, rather than extending west through Carghill Island (i.e., along the contact between the upper and lower sections of the Carghill assemblage), the favourable stratigraphy (including iron formations) may trend northeast along Carghill Channel, where its presence is obscured by the Carghill Channel layered intrusion, and may correlate with the Bjornson Island unit near the base of the assemblage. If correct, this correlation would provide a much-improved understanding of the stratigraphic setting of the Rusty zone and may indicate significant economic potential in a seemingly overlooked portion of the belt.

Fieldwork in 2013 also included a detailed examination of the carbonatite occurrence reported in 2012, consisting of a single recessively weathered dike approximately 1.5 m thick, hosted by biotite tonalite of the Bayly Lake complex south of Oxford Lake on the Hayes River (Figure GS-1-2). Preliminary petrographic and whole-rock geochemical results from 2012 indicated that the mineralogy and chemistry of this calcite-dominated dike were similar to those for known carbonatite intrusions in the northwestern Superior Province. Hence additional fieldwork was conducted in 2013 to obtain a suite of samples for detailed petrographic and geochemical analysis; an attempt to identify additional occurrences was unsuccessful.

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