GS-1 Preliminary results of bedrock mapping at southern Knee Lake, northwestern Superior province, Manitoba (parts of NTS 53L14, 15)

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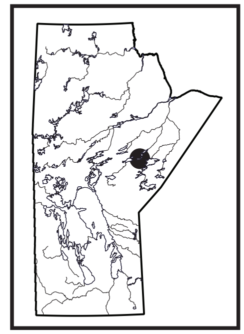

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Summary

In 2015, the Manitoba Geological Survey (MGS) continued its study of the Oxford Lake–Knee Lake belt by extending new 1:20 000 scale bedrock mapping into the southern Knee Lake area, with the objective of better understanding the stratigraphy, tectonic evolution and economic potential of one of the more prospective yet underexplored greenstone belts in the western Superior craton. Building on results of MGS bedrock mapping in 1997–1998, salient results of the 2015 mapping are as follows: 1) definition of three volcanic facies associations in the Oxford Lake group, based on bulk composition (ultramafic, basaltic andesite and andesitic–dacitic) and geochemical affinity (lamprophyric, shoshonitic and calcalkalic, respectively); 2) better understanding of the structural geology and deformation history of the supracrustal succession, including identification of three generations of ductile deformation structure; and 3) improved stratigraphic and structural context for known mineral occurrences, including specific favourable areas for volcanogenic Cu-Zn-Pb-Ag-Au, magmatic Ni-Cu-PGE, alkaline-intrusion–related rare metals, and orogenic Au deposits. These results represent important progress toward a comprehensive geological synthesis of the Oxford Lake–Knee Lake belt and an up-to-date assessment of its economic potential.

Introduction

In 2012, the Manitoba Geological Survey began a renewed study of the Oxford Lake–Knee Lake belt, the largest contiguous greenstone belt in the northwestern Superior province. An improved understanding of the stratigraphy, tectonic evolution and metallogeny of this belt is critical to promoting the resource potential of a vast and geologically diverse region that includes some of the most prospective yet underexplored greenstone belts in the Superior craton. New bedrock mapping, augmented by modern structural, lithogeochemical, Sm-Nd isotopic, U-Pb geochronological and high-resolution aeromagnetic datasets, is being utilized to upgrade published and unpublished maps, with the goal of a comprehensive regional synthesis and seamless geological compilation for the entire Oxford Lake–Knee Lake belt.

Early work in the belt included route surveys of the Hayes River (Bell, 1879, 1881; Brock, 1911; McInnes, 1913; Bruce, 1920) and reconnaissance mapping of Oxford Lake and Knee Lake by the Geological Survey of Canada (Wright, 1926, 1932; Quinn, 1955). Subsequent work by the MGS involved systematic mapping of supracrustal rocks and surrounding plutonic complexes at 1:31 680 scale (Barry, 1959, 1960, 1964; Gilbert, 1985; Hubregtse, 1985)—the latter two studies as part of the 'Greenstone Project' (1970–1973), with the objective of improving the geological context for mineral exploration. Follow-up studies described shoshonitic volcanic rocks at Oxford Lake (Hubregtse, 1978; Brooks et al., 1982). After initial discoveries of base-metal and gold mineralization in the early 1920s, exploration activity has been intermittent; mineral occurrences were described by Wright (1926, 1932), Barry (1959, 1960), Southard (1977) and Richardson and Ostry (1996).

In 1997–1998, shoreline exposures on Knee Lake were remapped at 1:20 000 scale by the MGS under the auspices of the Western Superior NATMAP Project. New lithological, geochemical, structural and geochronological data collected during this project provided important new insights into the complex stratigraphy, structure and tectonic evolution of the belt (Syme et al., 1997, 1998; Lin et al., 1998; Corkery et al., 2000). However, with the exception of a new method of using variations in strain geometry and kinematics to define the movement direction of curved transpressional shear zones (Lin and Jiang, 2001), results of these studies were not formally published. Subsequent work in the area focused on the alkaline intrusive complex at Cinder Lake (Chakhmouradian et al., 2008; Kressall et al., 2010; Kressall, 2012), as well as regional multimedia geochemical surveys (Fedikow et al., 2000) and surficial geology mapping (Trommelen, 2014a, b).

Shoreline mapping (1:20 000 scale) for the present study took place at Oxford Lake in 2012 and 2013 (Anderson et al., 2012a, b, c; 2013a, b, c, d), and continued at

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the south basin of Knee Lake (south of Opischikona Narrows) in 2015 (Figure GS-1-1; see also Figure GS-1-2). The goal of the 2015 fieldwork was to examine key localities identified during the Western Superior NATMAP Project and to remap areas of incomplete data coverage. Results of the new shoreline mapping were augmented by data from inland mapping (Gilbert, 1985) and industry high-resolution aeromagnetic survey data to generate a new 1:20 000 scale map (PMAP2015-1; Anderson et al., 2015) that covers an area of 405 km^2, centred on the south basin of Knee Lake.

Regional setting

Knee Lake is situated in the central portion of the regionally extensive Oxford Lake–Knee Lake greenstone belt (Figure GS-1-1) in the Oxford–Stull domain of the western Superior province (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; Barry, 1960; Gilbert, 1985; Hubregtse, 1985). The HRG consists of pillowed and massive tholeiitic basalt flows and gabbro, with minor intermediate to felsic volcanic rocks and fine-grained sedimentary rocks (Hubregtse, 1978, 1985; Gilbert, 1985). Felsic volcanism in the HRG at Knee Lake is constrained to ca. 2835–2825 Ma (Corkery et al., 2000; Syme et al., unpublished data). At Knee Lake the entire HRG section is estimated to be 9.7 km

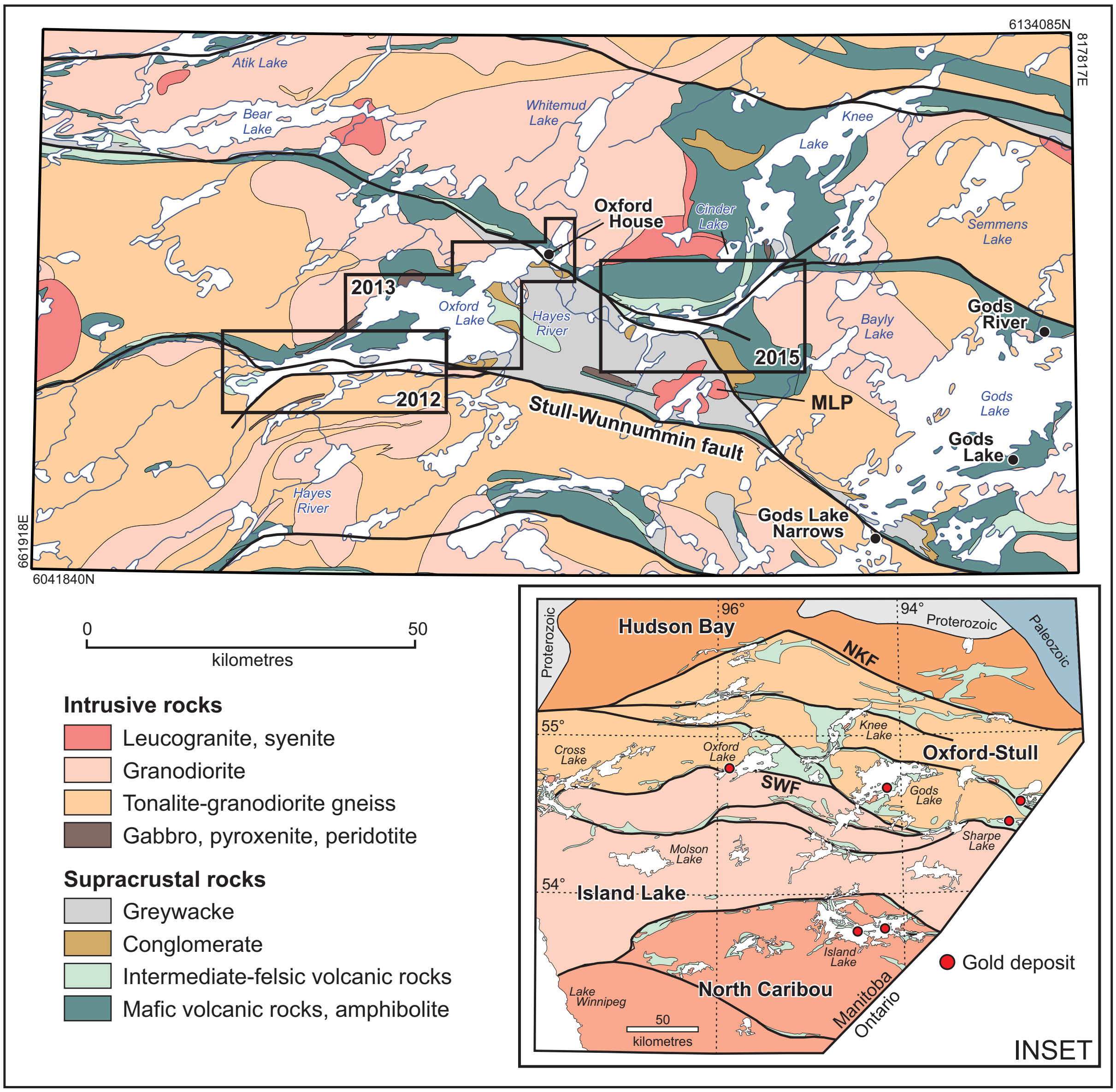

Figure GS-1-1: Regional geological setting of the Oxford Lake–Knee Lake belt, showing the locations of the 2012, 2013 and 2015 study areas. Abbreviation: MLP, Magill Lake pluton. Inset map shows the major geological domains, greenstone belts and shear zones in the northwestern Superior province. Abbreviations: NKF, North Knife fault; SWF, Stull-Wunnummin fault.

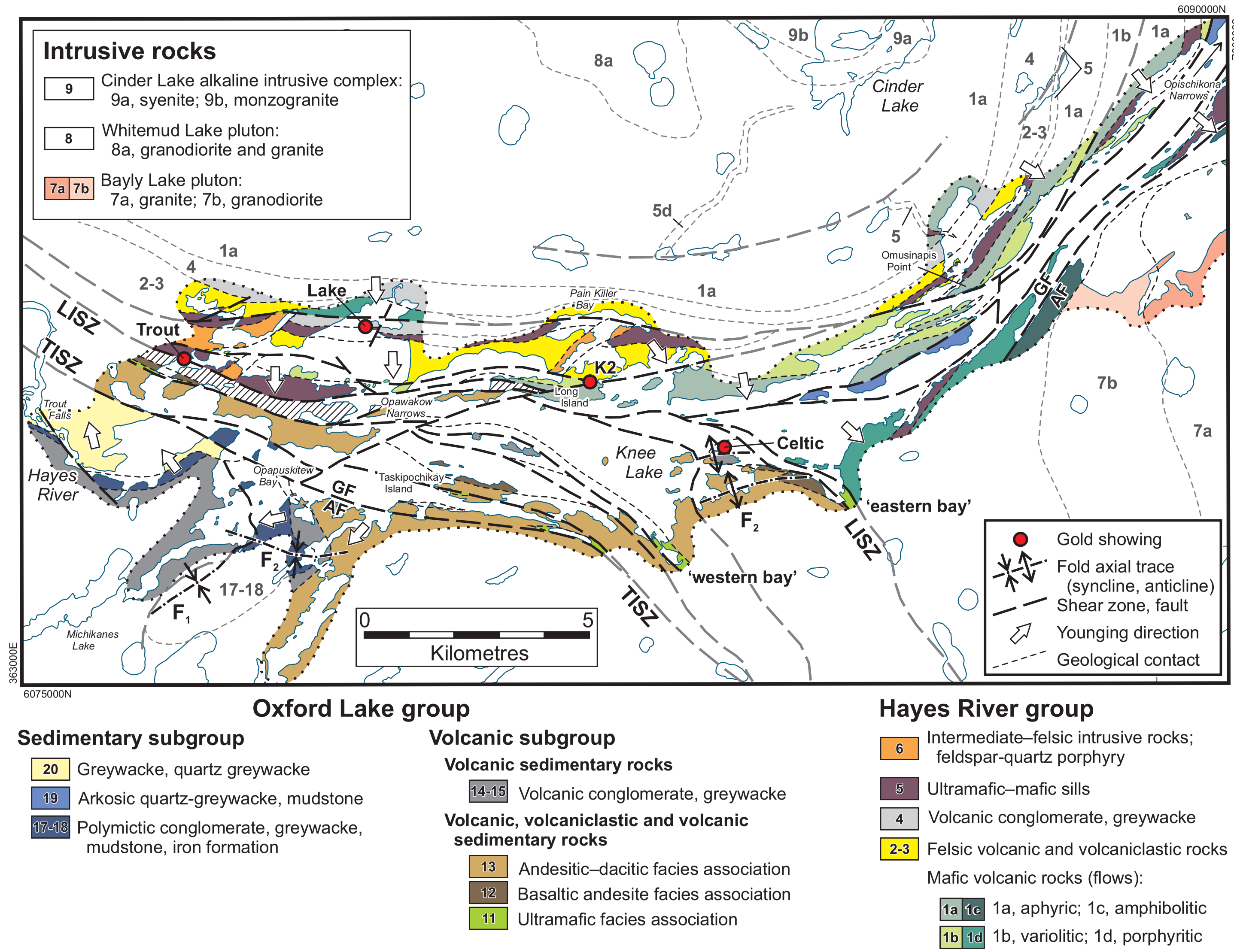

Figure GS-1-2: *Simplified geology of the southern Knee Lake area (after PMAP2015-1; Anderson et al., 2015), including named gold showings and geographic features mentioned in the text. Geology outside the mapping limit is simplified from Gilbert (1985) and high-resolution aeromagnetic data (unit codes correspond to those of PMAP2015-1). Map units 10, 16 and 22 comprise intrusions too small to depict at the scale of this figure. Hachure pattern indicates undivided tectonite (unit 21). Abbreviations: AF and GF indicate structural boundaries between amphibolite facies and greenschist facies rocks; LISZ, Long Island shear zone; TISZ, Taskipochikay Island shear zone.*

thick (Gilbert, 1985). Neither the base nor top is exposed: the base is everywhere defined by granitoid intrusions of the Bayly Lake complex (BLC; Gilbert, 1985), whereas the top is defined by faults or the erosional unconformity at the base of the OLG.

Unconformably overlying rocks of the OLG are subdivided into volcanic and sedimentary subgroups, the latter including polymictic conglomerate that contains clasts derived from the HRG and BLC (Gilbert, 1985). The volcanic subgroup consists of porphyritic volcanic rocks of calcalkalic to shoshonitic (high-K) 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 assigned to the volcanic subgroup of the OLG have reported ages of 2722 ±3 Ma at Knee Lake (Corkery et al., 2000) and 2705 ±2 Ma at Oxford Lake (Lin et al., 2006). The sedimentary subgroup consists of feldspathic greywacke-mudstone turbidite, iron formation, crossbedded quartz-lithic greywacke and polymictic conglomerate deposited in shallow-marine to subaerial settings. At Knee Lake, these rocks have maximum depositional ages of ca. 2715–2705 Ma (Corkery et al., 2000; Syme et al., unpublished data). A minimum age is provided by the Magill Lake pluton, which intrudes the OLG south of Knee Lake and yielded a U-Pb monazite age of 2668 ±1 Ma (Lin et al., 2006).

Supracrustal rocks in the Oxford Lake–Knee Lake belt were overprinted by at least two generations of tight to isoclinal folds, intruded by granitoid plutons and then tectonically segmented by shear zones and faults; consequently, stratigraphic relationships of adjacent and often disparate map units are generally equivocal. The discordant structures are part of an anastomosed array that appears to merge toward the east into the crustal-scale Stull-Wunnummin fault, which defines the southern margin of the Oxford–Stull domain and is thought to represent a fundamental tectonic boundary in the northwestern 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.

Local geology

Major supracrustal and intrusive units exposed in the south basin of Knee Lake are described below in order of decreasing known or apparent age. Unit codes in the text correspond to those on PMAP2015-1 (Anderson et al., 2015). The general arrangement of map units in the legend is based on rock type (volcanic to volcaniclastic to sedimentary to intrusive), grain size (coarse to fine) and composition (mafic to felsic), and is not intended to indicate stratigraphic order. As most of the key map units were described in some detail by Syme et al. (1997, 1998), this report is focused mainly on describing PMAP2015-1 and new results of fieldwork in 2015 by the first author.

Greenschist-facies metamorphic assemblages (chlorite, biotite, actinolite, sericite) characterize most rocks in the study area. However, along the southern and eastern shorelines of Knee Lake, these assemblages change abruptly to those of amphibolite facies (garnet, hornblende, cordierite) across a series of closely spaced shear zones. In the interest of brevity, the prefix ‘meta’ is not used in this report and the rocks are described in terms of protoliths.

Hayes River group

The HRG is exposed along the northern and eastern shorelines of southern Knee Lake, and defines a series of extensive, mostly monoclinal, panels that wrap broadly around large elliptical plutons of the BLC. The panels are often bounded and internally disrupted by semiconcordant faults, such that their stratigraphic relationships are ambiguous. The northern and eastern sections of the HRG are separated by faults, which locally bound a younger (<2713 Ma; Syme et al., unpublished data) panel of sedimentary rocks that appears, on the basis of aeromagnetic data, to underlie the entire northeast arm of southern Knee Lake up to Opischikona Narrows (Figure GS-1-2). Younging directions in the HRG are mostly toward the south or southeast, such that it becomes younger away from the Whitemud Lake pluton, and toward the Bayly Lake pluton (Figure GS-1-2). To the southwest, the HRG is truncated by the Long Island shear zone, along which it is juxtaposed against markedly different rocks of the OLG. This shear zone trends west-northwest through Long Island, and cuts progressively downsection through the HRG toward the northwest.

Mafic volcanic rocks (unit 1)

Pillowed and massive flows of basalt and basaltic andesite dominate the HRG in the Oxford Lake–Knee Lake belt. As described by previous workers, distinct stratigraphic units have been identified in seemingly monotonous sections of subaqueous basaltic flows on the basis of field characteristics such as weathering colour, phenocryst or variole content, pillow morphology and flow organization (Gilbert, 1985; Hubregtse, 1985; Syme et al., 1997; Anderson, 2013d). Based on the dominant textural types of flow, four basaltic map units have been identified in the HRG at southern Knee Lake (Syme et al., 1997).

Aphyric flows (subunit 1a) are composed of basalt and basaltic andesite, and consist mostly of pillowed flows, with subordinate composite and massive flows, and minor flow breccia. Also included are rare lenses of bedded hyaloclastite or iron formation. The pillows tend to be small to medium sized (<1 m) and are bun shaped to irregular, with thin dark green selvages and interpillow hyaloclastite. Aphyric flows dominate in sparse inland exposures north of Knee Lake (Gilbert, 1985) and in the map area define lenticular units that extend eastward from Long Island, through Omusinapis Point, northward to the central basin of Knee Lake. Variolitic flows (subunit 1b) are also composed of basalt and basaltic andesite, but consist almost entirely of pillowed flows, with minor massive flows and almost no flow breccia; good examples of the latter flow types are found on the northern shoreline of the large island north of Opapuskitew Bay. The pillows tend to be very large and bulbous, with thick selvages, and are characterized by centimetre-scale varioles that coalesce to dense masses in pillow cores. Variolitic flows define a semicontinuous map unit along the north shoreline of Knee Lake that is spatially associated with aphyric flows along its entire length. Identical major and trace element signatures (primitive arc-tholeiite; Syme et al., unpublished data) suggest a common magma source, with the differences in flow texture and morphology perhaps related to transient changes in eruption temperature. The varioles, which are thought to form by spherulitic crystallization of plagioclase from severely under-cooled basaltic melts (Sandstå et al., 2011), lend support to this hypothesis.

Aphyric basalt is also exposed on the eastern shoreline of Knee Lake, where it defines a map unit (subunit 1c) that is fault bounded to the northwest and is intruded to the east by the Bayly Lake pluton. This unit consists of dark green weathering pillowed and massive flows, with minor gabbro sills, and differs from basaltic units northwest of the fault in that it contains amphibolite-facies metamorphic assemblages (as opposed to greenschist facies) and is very strongly foliated. In the absence of evidence to the contrary, this unit is tentatively included in the HRG; however, it is possible that these rocks are unrelated.

Plagioclase-phyric flows (subunit 1d) are composed of basalt and consist mostly of pillowed flows, with minor massive flows and flow breccia, and characteristically contain sparse (<10%) plagioclase phenocrysts up to 5 mm. These flows define a major fault-bounded panel along the eastern shoreline of Knee Lake, northwest of the fault that bounds unit 1c, and are also exposed in scattered outcrops along the northern shoreline of Knee Lake and in the large bay in the far northeastern portion of the map area (Figure GS-1-2); the extent of the latter units is unknown. Plagioclase-phyric flows within the fault-bounded panel display distinct geochemical signatures (N-MORB; Syme et al., unpublished data), which distinguishes them from other basaltic rocks in the map area.

Felsic volcanic rocks (unit 2), intermediate–felsic volcaniclastic rocks (unit 3) and volcanic conglomerate (unit 4)

Felsic volcanic rocks and associated volcaniclastic and epiclastic rocks define an internally complex, fault-bounded and structurally disrupted panel that is up to 1.5 km in thickness. This panel is discontinuously exposed along the northern shoreline of southern Knee Lake (Figure GS-1-2), and has been traced inland, northward to the central basin (Gilbert, 1985; Syme et al., 1997, 1998); it is bounded by thick successions of subaqueous basaltic flows. Lithological and stratigraphic aspects of this unit were described in some detail by Syme et al. (1997, see Figure GS-5-5), and are not repeated here. For mapping purposes, this panel is subdivided into three units: felsic volcanic rocks (unit 2), intermediate–felsic volcaniclastic rocks (unit 3), and volcanic conglomerate with minor fine-grained volcanic sedimentary rocks (unit 4).

Felsic volcanic rocks of unit 2 consist of coherent and fragmental rhyolite flows, which typically have buff- to cream-weathered surfaces and sparse plagioclase and/or quartz phenocrysts in an aphanitic groundmass. These flows characteristically show subtle internal gradations from coherent to fragmental textures, which distinguish these rocks from superficially similar hypabyssal felsic intrusions (unit 6; see below). Rhyolite flows are best exposed in shoreline outcrops approximately 1 km east of Pain Killer Bay, but also appear to form an extensive, albeit poorly exposed, unit that extends west from the northwestern arm of Pain Killer Bay. Associated volcaniclastic rocks include heterolithic (subunit 3a) and rhyolitic (subunit 3b) breccia, tuff breccia and lapilli tuff that vary from massive to stratified and are characterized by angular to subangular clasts. These rocks are interlayered with rhyolite flows in the locations described above and in the bay north of Omusinapis Point, and also appear to form a very thick unit in the far western portion of the panel, although exposures are very sparse. Also included in this unit are rare outcrops of monomict breccia and tuff breccia of andesitic–dacitic composition (subunit 3c), which together with the heterolithic breccias points toward minor chemical diversity in the associated volcanism.

Volcanic sedimentary rocks (unit 4) are interlayered at various scales with the volcaniclastic rocks of unit 3, and include crudely stratified to well-bedded volcanic conglomerate, with subordinate intervals of bedded volcanic greywacke and mudstone. Clast populations vary from heterolithic (subunit 4a) to mostly intermediate–felsic (subunit 4b) and are exclusively of volcanic or subvolcanic intrusive origin; minor clasts of basaltic scoria suggest coeval mafic volcanism. Well-rounded clasts indicate significant transport in a subaerial or shallow marine setting, whereas minor interlayers of laminated oxide-facies iron formation and chert (subunit 4c), particularly near the base of the panel, indicate periodic quiescence, likely in a marine setting. The best exposures of unit 4 are found in the bay north of Omusinapis Point (Figure GS-1-2), where they conformably overlie pillowed basalt (unit 1a) and represent the base of a coarsening-upward stratigraphic sequence (~800 m in thickness) capped by coherent and fragmental rhyolite flows (Syme et al., 1997).

Ultramafic–mafic sills (unit 5)

The HRG contains numerous ultramafic–mafic intrusions, most of which are not mappable at 1:20 000 scale. Sills appear to greatly outnumber dikes, perhaps indicating that the coeval tectonic setting was not strongly extensional; alternatively, this could simply be a function of structural transposition. These intrusions are typically fine to medium grained and equigranular, and are subdivided on the basis of bulk composition into four subunits: leucogabbro, quartz gabbro and diorite (subunit 5a); mesogabbro (subunit 5b); pyroxenite and melagabbro (subunit 5c); and peridotite (subunit 5d).

The thickest and most extensive sills at southern Knee Lake occur within or along the contacts of the felsic volcanic-volcaniclastic-epiclastic panel described above (units 2–4). Serpentinized peridotite is exposed north of Omusinapis Point, in the western arm of Pain Killer Bay and in the northwestern-most bay of southern Knee Lake, and has also been intersected in three drillholes north of Opawakow Narrows (Assessment Files 91190, 91192, 93566; Manitoba Mineral Resources, Winnipeg). Although poorly exposed, and possibly transposed, the arrangement of subunits in these locations nevertheless shows a consistent southward progression from ultramafic to mafic, suggestive of layered sills that underwent in-situ differentiation within the southward-younging volcanic section. The best example of this progression is north of Omusinapis Point, where an approximately 300 m thick sill includes basal peridotite overlain by gabbro and capped by quartz diorite. Associated magnetic anomalies indicate that these layered differentiated bodies form part of a laterally extensive string of intrusions that, from west to east, trend across the structural/stratigraphic panel defined by units 2 to 4, indicating that the primary contact relationship was intrusive and slightly discordant (Figure GS-1-2). Two highly discordant magnetic anomalies in the stratigraphic footwall of these intrusions are inferred to represent feeder dikes; diamond drilling of the western anomaly returned 88 m of serpentinized peridotite, constituting the entire core length (Assessment File 91191).

Intermediate–felsic intrusive rocks (unit 6)

High-level porphyritic intrusive rocks of intermediate–felsic composition are abundant in both the area of Pain Killer Bay and in the northwestern portion of the lake. Larger intrusions of this type appear to form discordant multicomponent bodies (Figure GS-1-2). Smaller intrusions include dikes that cut mafic volcanic rocks (unit 1) and layered ultramafic–mafic intrusions (unit 5); hence, the felsic porphyry intrusions are likely not directly related to felsic volcanic rocks of unit 2, despite their close spatial association, and similar textural and compositional characteristics (cf., Syme et al., 1997).

The porphyritic intrusive rocks are characterized by a pale pink to grey to green, aphanitic to very fine grained groundmass, and are subdivided on the basis of phenocryst content as follows: quartz ±feldspar porphyry (subunit 6a); K-feldspar megacrystic quartz-feldspar porphyry (subunit 6b); and feldspar ±quartz porphyry (subunit 6c). Quartz and feldspar phenocrysts are typically less than 5 mm in size and account for less than 20% of these rocks. Subunit 6c makes up most of the large intrusion underlying Pain Killer Bay; as described by Syme et al. (1997), variations in the size and abundance of phenocrysts indicate a multicomponent body, whereas the presence of miarolitic cavities (gas exsolution features) indicates hypabyssal emplacement. Subunit 6b is a very distinctive phase of porphyry that contains euhedral, pale mauve K-feldspar megacrysts (up to 2.5 cm) that often contain oscillatory zoning. The largest intrusion of this type is a 300 m thick dike that intrudes variolitic basalt and a thick gabbro sill in the northwestern part of the lake.

Intrusive rocks

Bayly Lake pluton (unit 7)

Felsic intrusive rocks of the Bayly Lake pluton were examined at widely spaced outcrops in the far northeastern portion of the map area. In this area, the pluton includes porphyritic granite (subunit 7a) and granodiorite (subunit 7b); contact relationships were not observed. The granodiorite is medium grained, equigranular and contains 10–15% hornblende and biotite. It is generally weakly foliated and contains minor inclusions of gabbro and amphibolite, but is otherwise homogeneous. To the west, the granodiorite clearly intrudes amphibolite-facies basalt flows of subunit 1c. The granite is also homogeneous and medium grained, but contains K-feldspar phenocrysts (<2.5 cm) and less than 10% fine-grained biotite, epidote and hornblende; in contrast to the granodiorite, the granite tends to be moderately to strongly foliated.

Whitemud Lake pluton (unit 8)

This pluton does not outcrop in the 2015 map area, but is interpreted to underlie the area west of Cinder Lake based on the homogeneous and subdued magnetic signature in this area, which is comparable to, and continuous with, that of the pluton interior farther north. As described by Gilbert (1985), this pluton mostly consists of granodiorite, with minor granite and porphyritic granite (subunit 8a).

Cinder Lake alkaline intrusive complex (unit 9)

The Cinder Lake alkaline intrusive complex was not examined as part of this study but has recently been studied in considerable detail (Chakhmouradian et al., 2008; Kressall et al., 2010; Kressall, 2012). Due to scarce outcrop, the extent of the complex is poorly defined. It is mainly exposed on islands and the southeastern shoreline of Cinder Lake, where it intrudes mafic and felsic volcanic rocks of the HRG (Gilbert, 1985). The few exposures of this complex consist of fine-grained syenite (including cancrinite-nepheline syenite, vishnevite syenite and porphyritic cancrinite syenite; Kressall et al., 2010), as well as alkali-feldspar syenitic pegmatite and monzogranite. High-resolution aeromagnetic data indicate that the alkaline rocks coincide with the southeastern rim of an elliptical, concentrically zoned pluton with a maximum diameter of approximately 10 km. The syenite exposures correspond to a zone of mottled magnetic intensity, whereas exposures of syenitic pegmatite and monzogranite correspond with magnetic lows. For mapping purposes, the pluton was subdivided into an outer zone of syenite and syenitic pegmatite (subunit 9a) and an inner zone of monzogranite (subunit 9b). Available U-Pb zircon and titanite ages indicate emplacement ages of ca. 2720–2705 Ma (Chakhmouradian et al., 2008; Kressall et al., 2010), coeval with high-K volcanism in the OLG (ca. 2720–2705 Ma; Corkery et al., 2000; Lin et al., 2006).

Mafic–intermediate dikes (unit 10)

Mafic–intermediate dikes of map unit 10 cut the porphyry intrusion (subunit 6c) in Pain Killer Bay and also cut the Bayly Lake pluton (subunits 7a, 7b). These dikes are a distinctive bright green on weathered surfaces and include equigranular (subunit 10a) and porphyritic (subunit 10b) subtypes. The latter subtype contains 10–20% dark brown-black biotite phenocrysts up to 2.5 cm in size in a fine-grained groundmass, whereas the former contains fine-grained biotite in the groundmass. The dikes range up to 2 m in thickness and are characterized by sharp planar contacts and thick (3–5 cm) chilled margins. They trend roughly east and are only weakly deformed; they appear to postdate at least some of the deformation recorded by their hostrocks. Although whole-rock geochemical results are pending, the evidently K-rich composition of these dikes suggests a possible association with high-K volcanism in the OLG.

Oxford Lake group

The OLG underlies the southern and western portions of southern Knee Lake (Figure GS-1-2), and defines a complex series of monoclinal to tightly folded, fault-bounded structural panels. Major shear zones that trend west-northwest through Long Island (LISZ) and Taskipochikay Island (TISZ) bound greenschist-facies rocks of the OLG, whereas amphibolite-facies rocks occur south of the TISZ. Internally, the various structural panels contain tight to isoclinal folds of at least two generations and were subsequently disrupted by subsidiary shear zones and minor faults, such that their internal stratigraphy remains uncertain. Following the terminology of previous workers (Gilbert, 1985; Syme et al., 1997), the OLG at southern Knee Lake is divided for mapping purposes into two subgroups: the 'volcanic subgroup', consisting mostly of volcanic-derived sedimentary rocks, with minor associated volcanic and volcaniclastic rocks; and the 'sedimentary subgroup', consisting exclusively of sedimentary rocks, which show evidence of 'mixed' provenance, such as diverse age populations of detrital zircons (Syme et al., unpublished data) and the presence of granitoid clasts. The stratigraphic relationship between these subgroups also remains unclear—it is likely that they are lateral equivalents, at least in part.

Volcanic subgroup

The volcanic subgroup is subdivided herein to include three volcanic 'facies associations', based on compositional and textural differences of characteristic volcanic and/or volcaniclastic rocks, and corresponding clast populations in derived volcanic sedimentary rocks. These facies associations include: ultramafic (lamprophyric; unit 11); basaltic andesite (shoshonitic; unit 12); and andesitic–dacitic (high-K calcalkalic–calcalkalic; unit 13). Each of these facies associations includes two or three subunits, some of which are only locally mappable at 1:20 000 scale; this applies particularly to volcanic and volcaniclastic rocks, which in many cases form discrete, lenticular units. Each facies association is dominated by coarse epiclastic rocks interpreted as debris and grain-flow deposits in channelized subaqueous fans, proximal to subaerial or shallow-marine volcanic sources (Syme et al., 1997). Local stratigraphic interlayering indicates that ultramafic–dacitic volcanism was broadly coeval, perhaps within a volcanic field composed of multiple eruptive centres. All manner of gradations exist between these three end-member facies associations. Hence, polymictic rocks that could not obviously be assigned to one of these facies associations are subdivided into two additional units based on grain size: volcanic conglomerate (unit 14), and volcanic greywacke and mudstone (unit 15). Minor mafic intrusions not found in the sedimentary subgroup constitute unit 16.

Ultramafic facies association (unit 11)

The ultramafic facies association contains some of the most distinctive rocks in the entire Oxford Lake–Knee Lake belt, due in part to their actinolite-chlorite mineralogy, and resulting bright olive-green and smoothly sculpted weathered surfaces. This facies association is exposed in widely separated locations, mostly between the LISZ and TISZ, and invariably coincides with zones of particularly intense ductile strain. The best exposures are found in two small bays in the southeast corner of the lake (the 'eastern' and 'western' bays; Figure GS-1-2); paradoxically (given their association with high-strain zones), these rocks often display spectacular preservation of primary sedimentary features.

The ultramafic facies association is divided into two subunits: lapilli tuff and tuff (subunit 11a); and volcanic conglomerate, sandstone and mudstone (subunit 11b). Like the other facies associations, volcanic conglomerate and sandstone dominate and are typically interstratified at various scales; bedforms include normal and reverse size-grading, deep erosional scours and local crossbeds. Interbeds of fine-grained sandstone and mudstone often contain delicate primary features, such as rip-up clasts and load structures. Lapilli tuff and tuff of subunit 11a are exposed at three locations in the 'western bay' and form massive, poorly graded layers up to 3 m in thickness. Very angular to subrounded, close-packed lapilli in these rocks consist of dull green, fine-grained, aphyric to sparsely porphyritic (pyroxene?), ultramafic–mafic rock. Some clasts have ragged cuspate margins or densely packed vesicles indicative of scoria (Figure GS-1-3a); whole-rock geochemical results are pending. Subunit 11a is interlayered with very thick (20–30 m), massive layers of ultra-coarse volcanic conglomerate, suggesting that the exposures in the western bay represent a more proximal depositional setting, perhaps explaining the local preservation of primary volcaniclastic deposits.

The volcanic sandstone is bright olive green and pebbly, with a felted matrix of fine-grained actinolite and chlorite. Massive beds range up to several metres thick, particularly in the 'eastern bay', with deeply scoured bases and normally graded tops suggestive of grain-flow deposits; some beds are capped by thin layers of mudstone or crossbedded sandstone (Figure GS-1-3b). Whole-rock geochemical data from one such bed (Syme et al., unpublished data) indicate ultramafic bulk composition (17.6 wt. % MgO; 1200 ppm Cr; 1020 ppm Ni) and strong K-enrichment (3.1 wt. % K_2O), similar to ultramafic lamprophyre (e.g., Lefebvre et al., 2005), possibly indicating that these unusual sandstones derive from lamprophyric volcanism. Angular to well-rounded clasts in the volcanic conglomerate include a wide variety of ultramafic, mafic and intermediate rocks of volcanic and plutonic derivation, including conspicuous clasts of peridotite and pyroxenite. Also present are distinctly spherical pebbles that consist of a lithic (typically ultramafic–mafic plutonic) core mantled by very fine grained lithic material, perhaps representing accretionary lapilli (Figure GS-1-3b, inset). Syme et al. (1997) proposed that the ultramafic–mafic clasts may derive from erosion of a subaerial massif (ophiolite). However, in the context of the observations above, these clasts may alternatively represent basement (oceanic crust or mantle wedge) that was entrained in lamprophyric magmas on their ascent to surface, and subsequently liberated from the matrix during eruptive or post-eruptive processes, and then concentrated as lag deposits during sedimentary reworking. Detailed analysis of the cored lapilli will be key to resolving the origins of these truly unusual rocks.

As noted above, this facies association also presents an interesting structural paradox: on the one hand it is only found within or adjacent to high-strain zones characterized by intense deformation fabrics and corresponding topographic and magnetic lineaments, but on the other hand it often displays remarkable preservation of primary features. Given the mineralogy (actinolite-chlorite), it seems unreasonable to suggest that this paradox might relate solely to structural competence. Indeed, for this reason it could be argued that strain-localization was controlled, at least in part, by the distribution of the ultramafic facies association. Alternatively, it could be argued that structure controlled the distribution: for example, if the lamprophyric volcanism was controlled by synvolcanic faults that were subsequently reactivated as loci for ductile strain. The common proximity of megaclast conglomerate or 'slump deposits' (Syme et al., 1997) may lend support to the latter hypothesis (e.g., talus-slope deposits along synvolcanic faults); however, resolving these relationships requires additional detailed mapping.

Basaltic andesite facies association (unit 12)

The basaltic andesite facies association also contains highly distinctive rocks, only observed between the LISZ and TISZ. The best exposures are found on Taskipochikay Island and the small islands to the north, but several small exposures also occur at the western end of Knee Lake, and on islands and shoreline in the southeastern corner of the lake. This facies association consists of pillowed and massive basaltic andesite flows of shoshonitic affinity (subunit 12a; Figure GS-1-3c), and volcanic conglomerate, sandstone and mudstone (subunit 12b; Figure GS-1-3d); volcaniclastic facies are rare, perhaps owing to efficient removal by erosion shortly after volcanism. The shoshonite (54.2–57.7 wt. % SiO_2; 3.3–4.4 wt. % K_2O; Syme et al., unpublished data) is abundantly and coarsely plagioclase-phyric (20–50%; 0.5–1 cm), with a dark grey, fine-grained, biotitic groundmass; some varieties also include pyroxene phenocrysts. Associated coarse volcanic sedimentary rocks contain abundant shoshonite clasts and coarse plagioclase crystals in a distinctive matrix of dark grey biotitic sandstone.

Andesitic–dacitic facies association (unit 13)

The andesitic–dacitic facies association is much more widespread in the map area: it underlies most of the area between the LISZ and TISZ, and represents the dominant unit south of the TISZ, where it includes thick successions of volcaniclastic material. This facies association

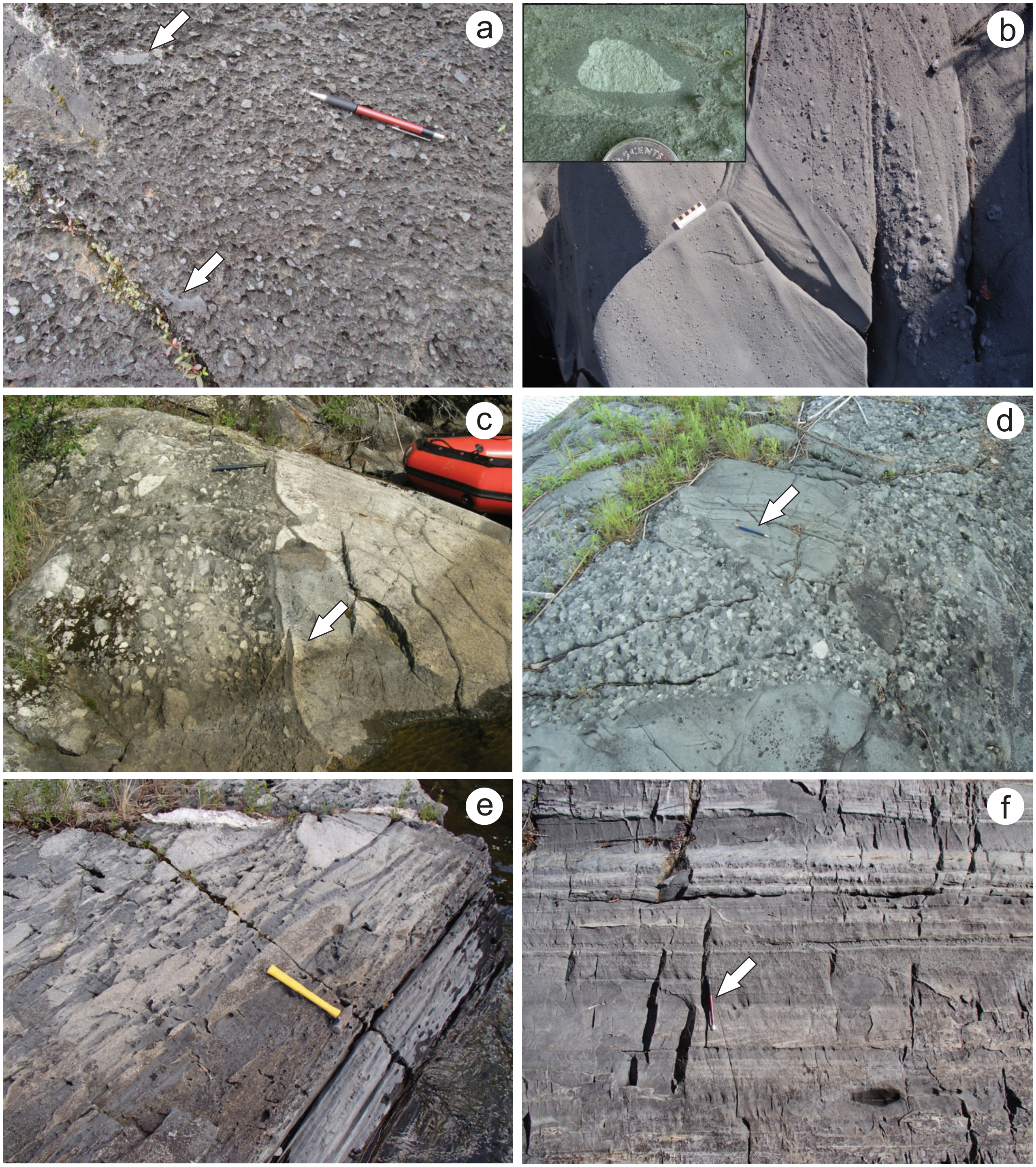

Figure GS-1-3: *Outcrop photographs of characteristic rock types of the volcanic facies associations (units 11–13) in the volcanic subgroup of the Oxford Lake group:* ***a)*** *massive lapilli tuff (subunit 11a), showing examples of ragged cuspate lapilli, indicative of scoria (arrows);* ***b)*** *pebbly volcanic sandstone and conglomerate, showing diffuse stratification and a thin bed of crossbedded sandstone (subunit 11b; inset photo shows serpentinite clast in the centre of a nearly spherical 'cored lapillus'; coin for scale is 2 cm in diameter);* ***c)*** *vaguely pillowed flow of coarsely and densely plagioclase-phyric shoshonite (subunit 12a; arrow indicates the amygdaloidal flow top), overlain by heterolithic breccia;* ***d)*** *polymictic volcanic conglomerate (subunit 12b) overlying the shoshonite flow shown in Figure GS-1-3c, containing large resedimented boulders (arrow indicates pencil for scale);* ***e)*** *plagioclase-phyric andesitic–dacitic breccia and bedded tuff (subunit 13b);* ***f)*** *thin-bedded volcanic sandstone and mudstone (subunit 13c; arrow indicates pencil for scale).*

includes: minor massive to pillowed, aphyric to sparsely porphyritic, andesite–dacite flows of calcalkalic affinity (subunit 13a; 57.9–69.4 wt. % SiO_2; 1.2–1.9 wt. % K_2O; Syme et al., unpublished data); associated breccia, tuff breccia, lapilli tuff and crystal tuff (subunit 13b; Figure GS-1-3e); and derived volcanic conglomerate, sandstone and mudstone (subunit 13c; Figure GS-1-3f). The andesite–dacite flows contain phenocrysts of plagioclase (<30%; <5 mm) and minor quartz (<5%; <3 mm) in a light grey to green, aphanitic groundmass. Associated epiclastic rocks contain abundant plagioclase crystals (1–3 mm) in a light green-grey, variably biotitic matrix. Southeast of Taskipochikay Island (south of the TISZ), monolithic (dacitic) breccia and conglomerate, massive crystal tuff, and turbiditic volcanic sandstone dominate. Although these rocks were previously considered part of the sedimentary subgroup (Gilbert, 1985; Syme et al., 1997), they are herein included in the volcanic subgroup based on their volcanic provenance.

Volcanic conglomerate (unit 14); volcanic greywacke, mudstone (unit 15)

Volcanic sedimentary rocks of units 14 and 15 occur in several areas of southern Knee Lake, but are only extensively exposed in Opapuskitew Bay, extending southwest to Michikanes Lake (Figure GS-1-2). Volcanic conglomerate of map unit 14 is polymictic, matrix to clast supported and varies from bedded (subunit 14a) to massive (subunit 14b); the contained clasts are subangular to well rounded and exclusively of volcanic provenance. Associated finer grained volcanic sedimentary rocks include planar-bedded feldspathic greywacke and mudstone (subunit 15a) with rare interbeds of oxide-facies iron formation and chert (subunit 15b), and very thick intervals of dark grey-black mafic wacke that contains thin interbeds of sulphidic chert (subunit 15c). Turbiditic bedforms, coupled with the presence of iron formation and chert, suggest a deeper water depositional setting.

Mafic dikes and sills (unit 16)

The volcanic subgroup of the OLG contains a variety of mafic dikes and sills that are not observed in the presumably younger rocks of the sedimentary subgroup. These intrusions are nowhere abundant and are rarely mappable at 1:20 000 scale. They are subdivided on the basis of texture and apparent composition into four subunits: equigranular diorite–quartz diorite (subunit 16a); porphyritic (plagioclase ±pyroxene) gabbro–diorite (subunit 16b); equigranular gabbro (subunit 16c); and plagioclase-phyric gabbro (subunit 16d). Whole-rock geochemical data (Syme et al., unpublished data) indicate at least some of these intrusions are subvolcanic, related to OLG volcanism; however, there are insufficient data to resolve these relationships in detail. Of note is the fact that texturally similar dikes are observed in the HRG, consistent with these rocks forming the local basement during OLG volcanism.

Sedimentary subgroup

The sedimentary subgroup of the OLG is subdivided on the basis of grain size, composition and bedforms (turbiditic vs. fluvial) into four map units: polymictic conglomerate (unit 17); feldspathic greywacke and mudstone (unit 18); arkosic quartz greywacke and mudstone (unit 19); and greywacke and quartz greywacke (unit 20). In the western part of the map area, these rocks are only found south of the TISZ. Unlike superficially similar rocks in the volcanic subgroup, the dominant rock type in each of these units contains a significant (>5%) component of coarse detrital quartz. The primary stratigraphic relationships of the various units are unknown; however, units 17 and 18 appear to be interstratified in Opapuskitew Bay, where they define the eastern limb of a dismembered macroscopic F_1 fold (see below).

Polymictic conglomerate (unit 17)

Polymictic conglomerate of unit 17 is only exposed on islands and along shorelines in Opapuskitew Bay; its contacts with surrounding rocks of the volcanic subgroup are not exposed. This conglomerate is generally matrix supported and well bedded, with subangular to well-rounded clasts (<50 cm) that include various types of plutonic rock (tonalite, granodiorite, gabbro), as well as vein quartz (Figure GS-1-4a). Beds show normal and reverse size-grading, erosional scours, and are locally separated by intervals of bedded greywacke; rare trough crossbeds indicate a shallow-water depositional setting.

Feldspathic greywacke, mudstone (unit 18)

Interbedded feldspathic greywacke and mudstone occur in several locations in the southwestern portion of the lake; contact relationships are not exposed. At the outlet of the Hayes River, and on the peninsula west of Opapuskitew Bay, each subunit is locally exposed: planar-bedded greywacke and mudstone (subunit 18a), locally including rhythmic interbeds of oxide-facies iron formation and chert (subunit 18b), or lenses of polymictic conglomerate (subunit 18c). Well-developed turbidite bedforms, coupled with the presence of iron formation and chert, indicate a marine depositional setting. Map patterns and younging criteria suggest that subunits 18b and 18c overlie volcanic conglomerate of unit 14 and underlie the thick sequence of fluvial sandstones (unit 20) that extend to the west along the Hayes River, perhaps recording a depositional hiatus prior to fluvial sedimentation. A similar relationship is apparent just east of Opapuskitew Bay, on the eastern limb of the macroscopic F_1 fold, where subunit 18a separates mafic volcanic wacke (subunit 15c) and polymictic conglomerate (unit 17). In both areas, unit 18 is locally characterized by spectacular development

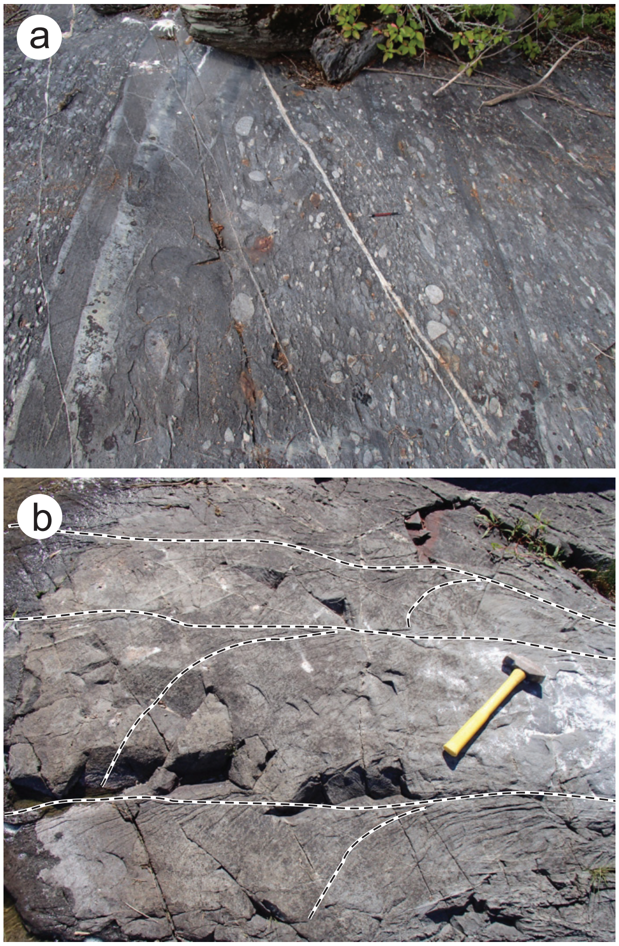

Figure GS-1-4: *Outcrop photographs of key rock types in the sedimentary subgroup of the Oxford Lake group:* ***a)*** *bedded polymictic conglomerate containing well-rounded granitoid clasts (unit 17);* ***b)*** *trough crossbedded greywacke (subunit 20a), showing thick unidirectional crossbeds (dashed lines).*

of garnet or cordierite porphyroblasts, suggesting a comparatively unique, Fe-Mg–rich composition.

Arkosic quartz-greywacke, mudstone (unit 19)

Arkosic quartz-greywacke and mudstone of unit 19 is only exposed in the northeast arm of southern Knee Lake (on the southeastern side of the large island immediately south of Omusinapis Point; Figure GS-1-2), where it forms a fault panel, bounded on either side by basaltic rocks of the HRG. Two subunits are recognized: thin- to medium-bedded arkosic quartz greywacke and mudstone (subunit 19a) and thick-bedded to massive arkosic quartz greywacke, with minor pebble conglomerate (subunit 19b). The greywacke weathers a distinctive reddish-pink to brown and contains abundant pebbles and granules of quartz and feldspar. Locally abundant tight to isoclinal folds, in places showing opposed facing directions, indicate that this unit is strongly transposed. On the basis of aeromagnetic data, unit 19 is interpreted to underlie the entire northeast arm of southern Knee Lake up to Opischikona Narrows.

Greywacke, quartz greywacke (unit 20)

Greywacke of unit 20 is exposed near the outlet of the Hayes River, where it is at least 800 m thick, and extends upstream past Trout Falls. The greywacke is light grey, fine grained and feldspathic, and generally contains well-developed trough crossbeds (subunit 20a) indicative of a fluvial depositional setting (Figure GS-1-4b). Toward Trout Falls, some outcrops lack crossbedding, instead consisting of planar-bedded greywacke (subunit 20b), although this may simply be a result of local transposition. Based on map patterns, it is possible that the base of this unit represents an angular unconformity, which perhaps postdates F_1 folding.

Tectonite

Tectonite (unit 21)

Tectonite in southern Knee Lake is characterized by penetrative, intense, planar fabric, corresponding to zones of mylonite and phyllonite, and is subdivided into two different types: homogeneous (subunit 21a) and layered (subunit 21b). The term tectonite is typically only assigned to outcrops in which all primary textures and structures have been obliterated by deformation, such that the protolith is uncertain; nevertheless, the composition of the tectonite typically mimics that of the local wallrock. Thick zones of tectonite delineate most of the major shear zones in the map area, including the LISZ and TISZ, which broadly correspond to the margins of the 'Southern Knee Lake shear zone' of Lin et al. (1998).

Late-tectonic intrusions

Granitic pegmatite dikes (unit 22)

Minor dikes of granitic pegmatite are common in the area south of Knee Lake and up to the southern margin of the TISZ, but are not observed north of this structure. These dikes are homogeneous to weakly zoned and consist mostly of K-feldspar and quartz (subunit 22b), in some cases with minor plagioclase and accessory biotite and/or tourmaline (subunit 22a). Contacts are planar to slightly irregular, and sharply truncate deformation fabrics in the wallrocks, including those of the TISZ. Some dikes are also weakly foliated or folded, indicating that they were emplaced in the late stages of deformation.

Structural geology

Map patterns, mesoscopic deformation structures and overprinting relationships indicate that supracrustal rocks at southern Knee Lake have been affected by at least three generations of ductile deformation structures. The earliest ductile structures are rare isoclinal symmetric F_1 folds and associated axial-plane S_1 foliations observed in bedded greywacke and iron formation in the OLG, particularly unit 18 (Figure GS-1-5a). Macroscopic isoclinal F_1 folds are inferred from bedding-cleavage relationships in several locations and from aeromagnetic patterns southwest of Knee Lake and in Opapuskitew Bay. The latter structure is defined by iron formation of subunit 18b and is interpreted to be dismembered along its western limb; this fold may also be truncated by the basal contact of unit 20.

Mesoscopic F_1 folds are overprinted by upright, open to isoclinal, steeply plunging F_2 folds that are parasitic to macroscopic F_2 folds that appear to control map patterns in the major structural panels. The F_2 folds are associated with a penetrative and pervasive, subvertical, axial-planar S_2 foliation that trends northeast to east-southeast, and is the main fabric observed in most outcrops outside of late shear zones. The S_2 fabric is defined by flattened primary features and aligned minerals, and locally intensifies into a penetrative transposition fabric. South of the TISZ, sigmoidal inclusion trails in garnet and cordierite porphyroclasts on the limbs of F_2 folds (Figure GS-1-5b) indicate that the F_2-S_2 structures likely formed during peak metamorphism.

Macroscopic F_2 folds are disrupted by a very complex series of subvertical ductile shear zones that bound major and minor structural panels. The principal examples are the LISZ and TISZ (Figure GS-1-2), which mostly delimit the 'Southern Knee Lake shear zone' of Lin et al. (1998). In the western portion of the map area, the LISZ defines the contact between the HRG and OLG, whereas the TISZ marks the northern limit of the sedimentary subgroup of the OLG. The shear zones vary in trend from northeast to southeast; at present it is unknown whether they all represent a single generation of structure. The penetrative, often mylonitic, S_3 foliation is defined by aligned minerals and attenuated primary features; in some outcrops the shear zones include wide zones of layered tectonite formed via intense transposition of bedding or

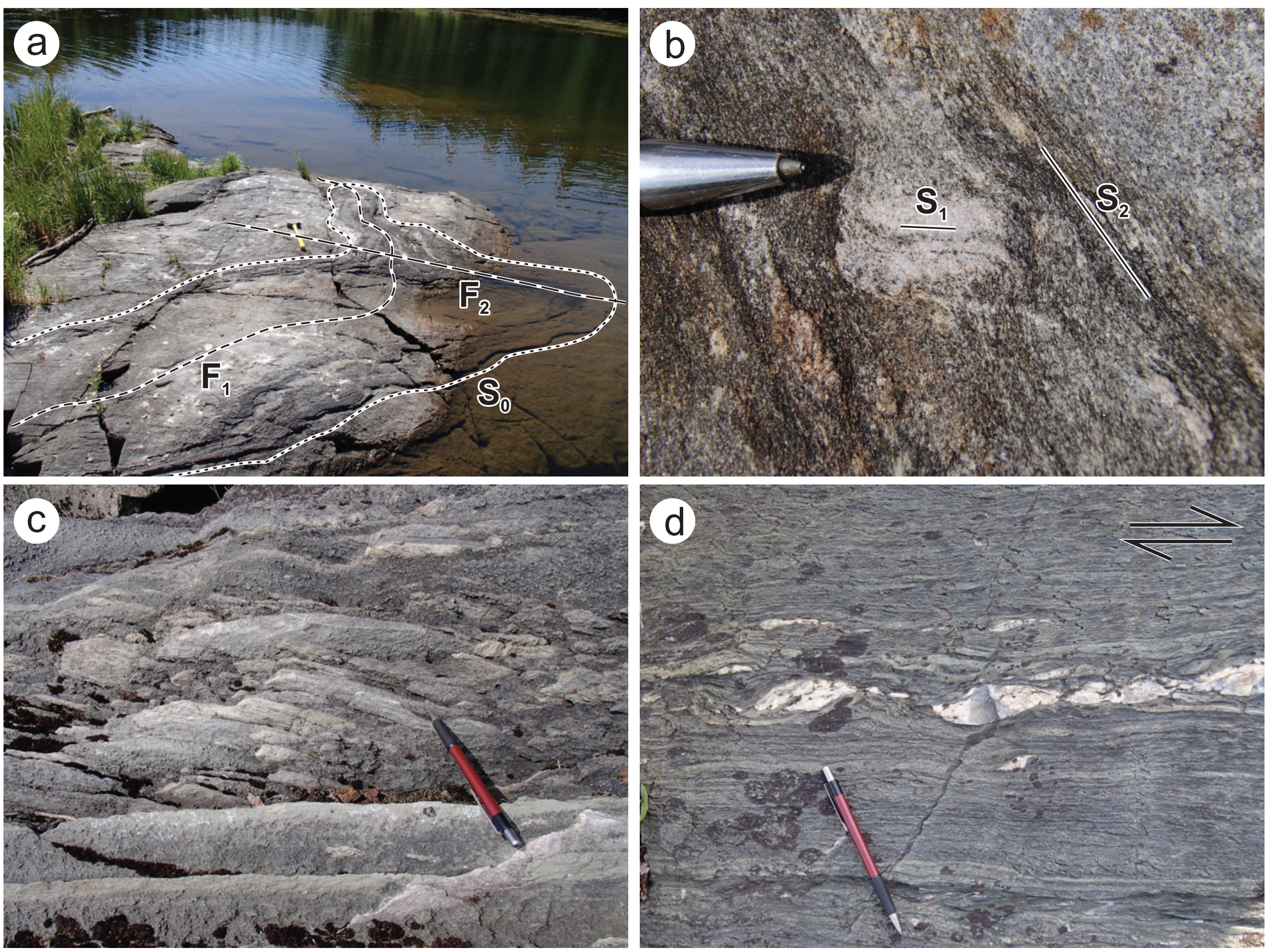

***Figure GS-1-5:** Outcrop photographs of deformation structures at southern Knee Lake: **a)** isoclinal F_1 fold, defined by iron formation in greywacke (unit 18; 'S_o' indicates bedding), overprinted by open to tight F_2 folds (axial planes are indicated by dashed lines); **b)** sigmoidal inclusion trails in a cordierite porphyroblast, representing S_1 fabric overgrown during development of S_2 foliation on the limb of an isoclinal F_2 fold; **c)** shallow-plunging L_3 stretching lineation defined by the long axis of deformed clasts in volcanic conglomerate; **d)** mylonitic S_3 foliation and F_3 Z-folds in the Long Island shear zone (asymmetric quartz boudins indicate dextral shear).*

attenuation of large clasts. The L_3 stretching lineation is typically defined by the long axis of elongate clasts and shows systematic patterns of orientation (Lin et al., 1998): it plunges steeply on the margins of shear zones, or within discrete domains of constrictional strain bounded by shear zones, and progressively becomes more shallowly plunging toward the centres of shear zones, where it is locally subhorizontal (Figure GS-1-5c). Shear-sense indicators (e.g., S-C fabrics, shear bands, asymmetric boudins) are typically well developed on horizontal surfaces and indicate dextral shear (Figure GS-1-5d); rare vertical surfaces show south-side-up kinematics. Open to isoclinal Z-folds, locally associated with a weak to moderate axial-planar crenulation cleavage, variably overprint the S_3 foliation and appear to result from progressive deformation. As described by Lin and Jiang (2001), the overall strain geometry is indicative of deformation-path partitioning within a kinematic regime of dextral transpression.

Later structures include concordant to highly discordant, brittle-ductile or brittle faults, some of which are associated with narrow (<1 m) zones of cataclasite or pseudotachylite. A possible major structure of this type, which is defined by sharply truncated magnetic lineaments in the central portion of southern Knee Lake, trends east-northeast from Opapuskitew Bay to just south of Omusinapis Point. Although not observed in outcrop, this structure appears to account for the map patterns south of Pain Killer Bay, where several units (most notably 1a and 1b) show evidence of significant offset.

Economic considerations

Based on what is presently known about its geology, coupled with results of previous exploration, the southern Knee Lake area has strong potential for a number of important deposit types, including volcanogenic Cu-Zn-Pb-Au-Ag, magmatic Ni-Cu-PGE, intrusion-related rare metals, and orogenic Au. Results from this study provide for an improved understanding of the stratigraphic and structural framework of the Knee Lake area and can therefore be used to formulate exploration strategies. Specific areas of favourable potential include the following:

- **Felsic volcanic rocks (HRG) south of Cinder Lake:** these have been explored in the past for volcanogenic massive sulphide (VMS) deposits and exhibit several indicators of VMS potential, including: calcalkalic (arc type) rhyolite flows and proximal volcaniclastic rocks; drill intercepts of solid sulphide (massive pyrite-pyrrhotite over core lengths of 20–33 m); weakly anomalous Zn (0.86%) and Cu (0.31%); layers of siliceous exhalite; and stringer-style chlorite-garnet alteration (e.g., Assessment Files 72612, 94730).
- **Layered ultramafic–mafic intrusions at Knee Lake:** several bodies of serpentinized peridotite have been tested by diamond drilling, presumably as targets for magmatic Ni deposits, but assay results for Ni were not reported (e.g., Assessment Files 91190, 91191, 91192); these remain interesting exploration targets, in particular the inferred feeder dikes in the footwall, which have not been systematically evaluated.
- **The Cinder Lake alkaline intrusive complex:** although it has not been explored for rare metal deposits, this intrusion exhibits several favourable attributes (Kressel et al., 2010), including: numerous species of REE-bearing minerals in fine-grained and pegmatitic syenite; potentially complex internal zoning, as indicated by aeromagnetic data; and a possible association with carbonatite (a major host of REE deposits worldwide), based on geochemical attributes and common magmatic associations elsewhere.
- **The Long Island shear zone:** marking the boundary between the HRG and OLG, this shear zone is one of the principal structures in southern Knee Lake, and is spatially associated with several significant Au occurrences, including the Celtic, K2, Lake and Trout showings (Assessment Files 93139, 93183, 94459, 94891; Figure GS-1-2). Significant results from previous drilling include 1.45 g/t Au over 13.7 m at the Celtic showing, with individual assays up to 5.1 g/t Au and 18 000 ppm As (Assessment File 93184). In addition to the shear zone and its associated splays, key guides to mineralization appear to be sericite alteration and arsenic enrichment, in keeping with numerous other orogenic gold systems in the Superior craton and elsewhere. On a regional scale, shear zones at or near the contact between the HRG and OLG host significant deposits, as seen at Oxford Lake (Rusty Zone) and Twin Lakes (Monument Bay), suggesting that this contact represents a key regional metallotect for orogenic Au deposits.

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