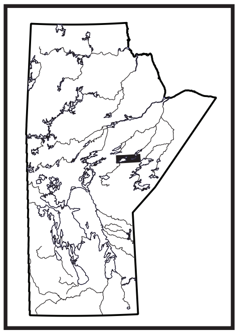
GS-2 Alkaline rocks at Oxford Lake and Knee Lake, northwestern Superior province, Manitoba (NTS 53L13, 14, 15): preliminary results of new bedrock mapping and lithogeochemistry

by S.D. Anderson



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Summary

On the basis of field characteristics and whole-rock geochemistry, alkaline rocks in the Oxford Lake–Knee Lake greenstone belt are defined herein to include six distinct types: 1) syenitic plutons (Cinder Lake alkaline intrusive complex); 2) carbonatite dikes; 3) lamprophyre dikes; 4) shoshonitic lava flows, cryptodomes and subvolcanic sills; 5) ultramafic volcanic conglomerate and sandstone; and 6) ultramafic volcaniclastic rocks. Similar geochemical attributes indicate that the shoshonitic rocks and at least some of the lamprophyre dikes likely share a common petrogenesis, with the ultramafic volcaniclastic and sedimentary rocks representing extrusive and reworked equivalents to ultramafic lamprophyre dikes. Published U-Pb geochronological data indicate that shoshonitic volcanism spanned more than 15 m.y. (>2722 to <2705 Ma) and was broadly coeval with emplacement of the main phases of the Cinder Lake complex (ca. 2723–2705 Ma). Facies relationships of the volcanic, volcaniclastic and sedimentary members, coupled with major- and trace-element geochemical signatures, point toward fault-controlled, synorogenic magmatism in a suprasubduction-zone setting. By analogy with alkaline rock associations worldwide, the Oxford Lake–Knee Lake area is considered to have significant potential for rare-earth element mineralization. These rocks may also have potential for unconventional diamond deposits (i.e., lamprophyre or conglomerate hosted), and may also serve as important guides to crustal-scale structures associated with orogenic gold mineralization.

Introduction

In 2012, the Manitoba Geological Survey began a renewed study of the Oxford Lake–Knee Lake belt in order to improve understanding of the stratigraphy, tectonic evolution and mineral potential of this highly prospective yet underexplored greenstone belt. A key aspect of this work involves documenting the distribution and characteristics of alkaline and high-K calcalkaline volcanic rocks, subvolcanic intrusions and associated volcanic sedimentary rocks at Oxford Lake and Knee Lake. Such rocks are important because they typically represent the latest stages of synorogenic magmatism in Archean greenstone belts and show a close spatial and temporal association with gold mineralization in several major gold districts, such as the prolific Kirkland Lake camp in the Abitibi greenstone belt of Ontario (e.g., Ispolatov et al., 2008). Because alkaline volcanic rocks are derived from low-degree partial melting of the mantle, they also have potential to host mantle-derived xenoliths or xenocrysts, including diamonds (e.g., Lefebvre et al., 2005). Mantle-derived minerals (commonly referred to as 'kimberlite indicator minerals') are widespread in surficial sediments in the Knee Lake area (e.g., Fedikow et al., 2001, 2002), yet their bedrock source has not been identified.

Alkaline and high-K calcalkaline volcanic rocks at Oxford Lake and Knee Lake have been described by Hubregtse (1978, 1985), Brooks et al. (1982) and Gilbert (1985): these studies included aspects of their distribution, field relationships, petrography, geochemistry, petrogenesis and implications with respect to the tectonic setting of magmatism. More recently, the Cinder Lake alkaline intrusive complex has been described by Chakhmouradian et al. (2008), Kressall et al. (2010) and Kressall (2012), and Reimer (2014) described a calcite-dolomite carbonatite dike at Oxford Lake. In this context, the goal of the present study is to examine the alkaline rocks at Oxford Lake and Knee Lake in light of new mapping and geochemical data, to gain insight into their potential economic implications; preliminary findings of this work are presented in this report.

Regional setting

Oxford Lake and Knee Lake are situated in the southwest and northeast portions, respectively, of the regionally extensive Oxford Lake–Knee Lake greenstone belt (Figure GS-2-1) in the Oxford-Stull domain of the western Superior province (Stott et al., 2010). On the basis of isotopic data, this domain is thought to represent a juvenile, ca. 2.83–2.72 Ga, oceanic terrane that was accreted to the margins of two older protocontinental terranes during tectonic amalgamation of the Superior province (e.g., Skulski et al., 2000; Lin et al., 2006; Percival et al., 2006). 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; Wright, 1932; Barry, 1959, 1960; Gilbert, 1985; Hubregtse, 1985). However, recent results from bedrock mapping and U-Pb geochronology point toward a more diverse stratigraphy, particularly for the

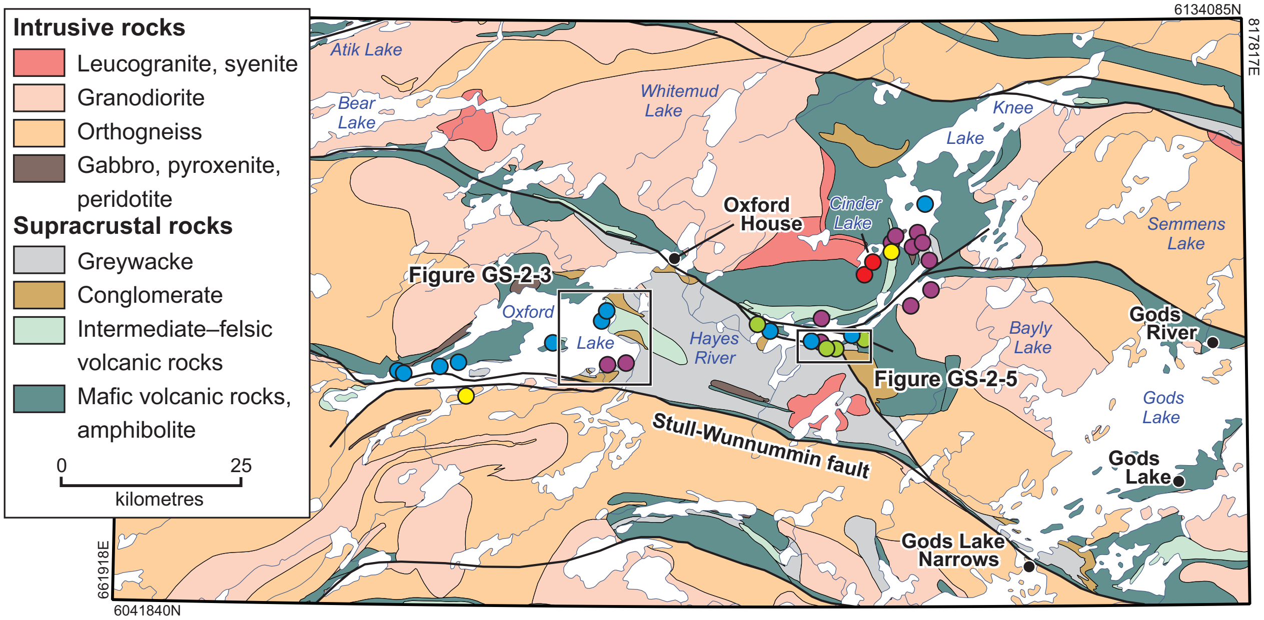

Figure GS-2-1: *Regional geological setting of the Oxford Lake–Knee Lake belt, showing the areas of Figures GS-2-3 and -5. Also indicated are occurrences of alkaline (shoshonitic) to high-K calcalkaline flows and subvolcanic sills (blue) and lamprophyre dikes (purple); alkaline plutonic (red) and volcanic sedimentary and volcaniclastic rocks (green); and carbonatite dikes (yellow); identified at Oxford Lake; interpreted at Knee Lake.*

OLG, that appears to record a complex history of synorogenic volcanism and sedimentation spanning more than 30 million years (e.g., Syme et al., 1997, 1998; Corkery et al., 2000; Lin et al., 2006).

Rocks traditionally assigned to the HRG consist of pillowed and massive tholeiitic basalt flows and gabbro, with minor calcalkaline 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; Lin et al., 2006; Syme et al., unpublished data, 2008). Rocks of the classical OLG are interpreted to unconformably overlie the HRG and have generally been subdivided into volcanic and sedimentary subgroups. Porphyritic volcanic rocks of alkaline to calcalkaline affinity characterize the volcanic subgroup and range in composition from ultramafic to felsic; the felsic volcanic rocks have 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 Cinder Lake alkaline intrusive complex, which intrudes the HRG just west of central Knee Lake, has yielded U-Pb ages of ca. 2720–2705 Ma (Chakhmouradian et al., 2008; Kressall et al., 2010). Collectively, these age data indicate that alkaline magmatism spanned at least 20 million years in the Oxford Lake–Knee Lake belt. The sedimentary subgroup includes greywacke-mudstone turbidite, iron formation, crossbedded sandstone and polymictic conglomerate, deposited in marine to subaerial settings. The most recent mapping at Knee Lake (Anderson, GS-1, this volume) indicates the 'subgroup' locally includes an older marine sequence and younger shallow-marine to subaerial sequence, separated by an angular unconformity. At Knee Lake, the younger rocks have a maximum depositional age of 2707 Ma (Corkery et al., 2000) and are locally cut by alkaline lamprophyre dikes.

Supracrustal rocks in the Oxford Lake–Knee Lake belt are overprinted by at least two generations of tight to isoclinal folds, intruded by granitoid plutons and segmented by shear zones and faults; consequently, stratigraphic relationships are often equivocal. Major discordant structures are part of a regional array that merges into the Stull-Wunnummin fault, which defines the south margin of the belt and is thought to represent a fundamental tectonic boundary and metallotect in the northwestern Superior province (e.g., Skulski et al., 2000; Stott et al., 2010).

Alkaline rocks

Alkaline rocks identified to date are divided into six major types based on field characteristics and bulk-rock geochemistry: 1) syenitic plutons (Cinder Lake alkaline intrusive complex); 2) carbonatite dikes; 3) lamprophyre dikes; 4) shoshonitic lava flows, cryptodomes and subvolcanic sills; 5) ultramafic volcanic conglomerate and sandstone; and 6) ultramafic volcaniclastic rocks. Alkaline volcanic and sedimentary rocks are interstratified with subalkaline intermediate to felsic volcanic and sedimentary rocks at Oxford Lake and Knee Lake.

Cinder Lake alkaline intrusive complex

The Cinder Lake alkaline intrusive complex, located just west of Knee Lake (Figure GS-2-1), 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); a brief description from these studies is provided here for the sake of completeness. High-resolution aeromagnetic data indicate that the complex is elliptical and concentrically zoned, with a maximum diameter of approximately 10 km. It intrudes mafic and felsic volcanic rocks of the HRG and the eastern margin of the Whitemud Lake granodiorite pluton. The only exposures occur on islands and shoreline on Cinder Lake, corresponding to the southeastern rim of the complex, and consist of fine-grained syenite (cancrinite-nepheline syenite, vishnevite syenite and porphyritic cancrinite syenite), alkali-feldspar syenitic pegmatite and monzogranite. On the basis of mineralogical and geochemical evidence, these authors also argued for the presence of unexposed ultramafic and carbonatitic phases, the latter implying significant exploration potential for rare-metal mineralization. Uranium-lead ages of 2723 ±10 Ma and 2705 ±2 Ma from vishnevite syenite, and 2721 ±16 Ma from monzogranite (Chakmouradian et al., 2008; Kressall et al., 2010), indicate a potentially protracted emplacement history.

Carbonatite dikes

Carbonatite dikes, discovered in 2012 during MGS bedrock mapping at Oxford Lake, intrude orthogneiss (biotite-hornblende tonalite) south of Oxford Lake (Figure GS-2-1). The thickest dike is approximately 1.5 m thick, with sharp but irregular contacts, and appears to be hosted by a brittle-ductile fault. It was described in detail by Reimer (2014) and consists of fine-grained dolomite-rich layers alternating with fluorapatite-rich layers, with interstitial calcite. In addition to the carbonate minerals, it also contains tremolite and phlogopite as major ferromagnesian silicate minerals, and accessory allanite, monazite, bastnaesite, parisite, magnetite and uraninite. This dike is slightly enriched in Sr and light rare-earth elements (LREE), and is associated with a thin metasomatic halo, evidenced by replacement textures and alteration of feldspars in the host tonalite.

As described in a companion report (Anderson, GS-1, this volume), a swarm of superficially similar carbonate dikes was discovered during MGS mapping in the westernmost bay of south-central Knee Lake, immediately east of Cinder Lake (Figure GS-2-1). The dikes weather an earthy brown colour and consist mainly of fine-grained carbonate (>80% calcite-dolomite), with lesser silicate, oxide and sulphide mineral phases. They vary from massive to flow layered and are up to 1 m thick, with sharp contacts. The dikes trend generally east, discordantly cutting ductile deformation fabrics in the hostrocks along later faults. Dark green metasomatic haloes extend up to 40 cm outward into the hostrocks (Figure GS-2-2). Whole-rock geochemical analyses reveal highly elevated concentrations of Ba, Sr and LREE, comparable to evolved alkaline intrusions such as carbonatite. Hence, alkaline rocks at Knee Lake also likely include carbonatitic phases, as originally inferred by Chakhmouradian et al. (2008) for the nearby Cinder Lake alkaline intrusive complex.

Lamprophyre dikes

Lamprophyre dikes are most abundant in the area of Opischikona Narrows in central Knee Lake (Figure GS-2-1), where they intrude the HRG, OLG and tonalite-granodiorite plutons. Dikes also intrude greywacke turbidites of the OLG on the south shore of Jackson Bay at Oxford Lake (Figure GS-2-3). These dikes weather dark green to emerald green and typically contain 10–20% dark brown or black phlogopite/biotite phenocrysts up to 2.5 cm in size in a fine-grained groundmass (Figure GS-2-4a, b). The dikes range up to 5 m in thickness and are characterized by sharp planar contacts and thick (3–5 cm) chilled margins; some dikes are flow banded or contain granitoid xenoliths of exotic derivation. Several examples of such dikes intrude the homoclinal younger sequence of the Opischikona Narrows basin (Anderson, GS-1, this volume) and thus demonstrably postdate at least the early stages of regional orogenesis that produced two generations of macroscopic isoclinal folds in underlying rocks. Most dikes also contain ductile deformation fabrics; hence, they are considered to be broadly synorogenic. Uranium-lead ages of detrital zircons in the younger sequence indicate a maximum depositional age of ca. 2710 Ma (Syme et al., unpublished data, 2008), which thus also represents the maximum emplacement age of lamprophyre dikes cutting that sequence.

Figure GS-2-2: *Outcrop photograph of a carbonate dike, tentatively interpreted as carbonatite, at Knee Lake. Note laminated internal structure and dark green metasomatic haloes on both margins.*

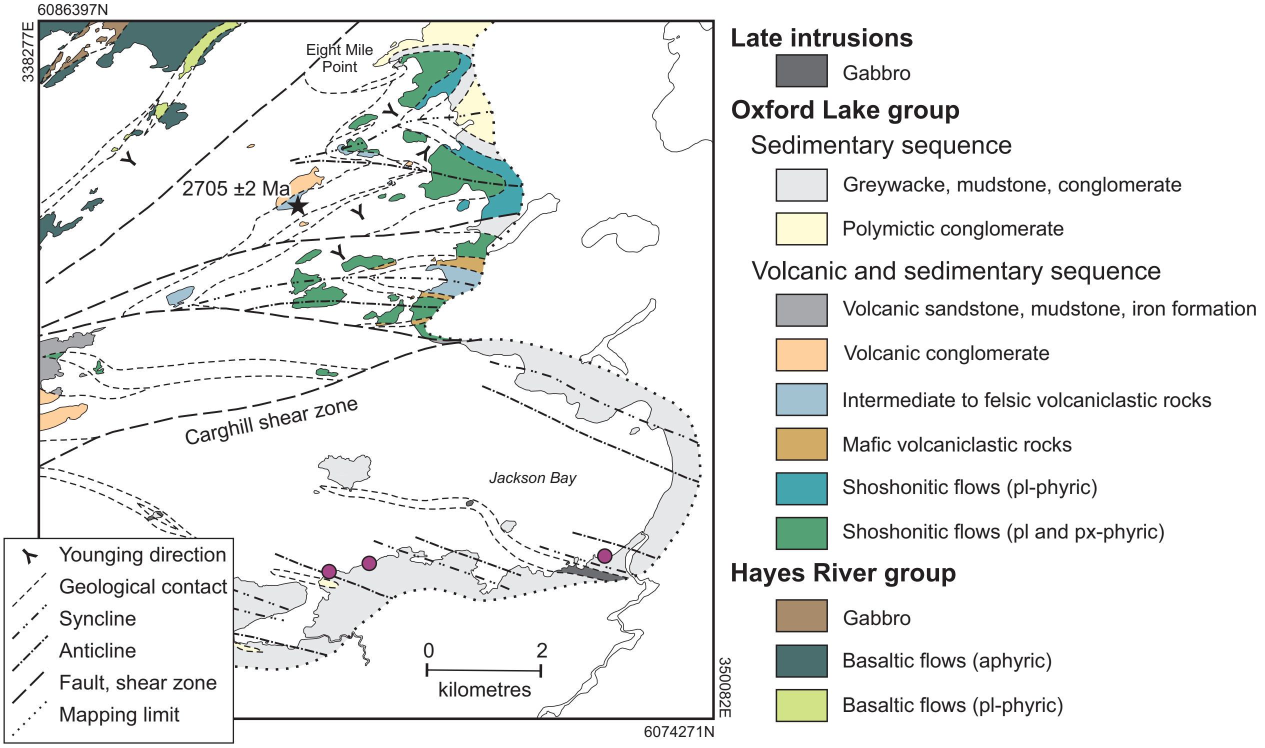

Figure GS-2-3: *Simplified geology of the Jackson Bay area of Oxford Lake (after Anderson et al., 2013a–c), showing the locations of lamprophyre dikes (purple circles) and shoshonitic volcanic rocks. Star indicates the location of the rhyolitic lapilli tuff dated by U-Pb geochronology (Lin et al., 2006). Abbreviations: pl, plagioclase; px, pyroxene.*

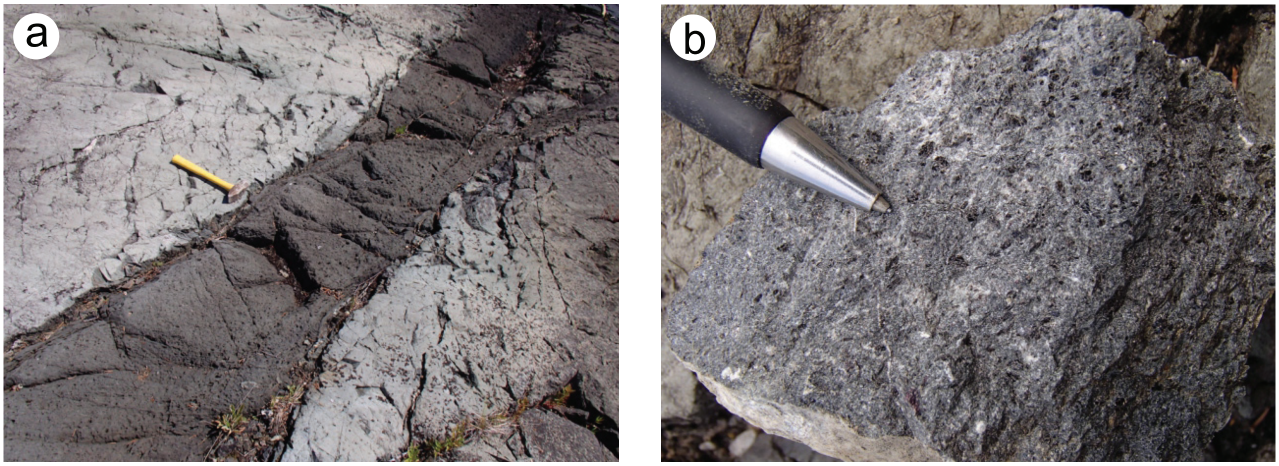

Figure GS-2-4: *Outcrop photographs of lamprophyre dikes from central Knee Lake:* ***a)*** *lamprophyre dike with a deeply pitted central zone due to recessive weathering of coarse phenocrysts and thick chilled margins;* ***b)*** *hand specimen showing phenocrysts of phlogopite/biotite in an aphanitic groundmass.*

Shoshonitic flows, cryptodomes and subvolcanic sills

Rocks of shoshonitic composition form highly distinctive flows, cryptodomes and associated volcaniclastic deposits in the volcanic subgroup of the OLG, and also occur as subvolcanic sills in the OLG and underlying HRG. The type locality, north of Jackson Bay at Oxford Lake (Figure GS-2-3; Gilbert, 1985; Hubregtse, 1985; Anderson et al., 2013d), was described in some detail by Brooks et al. (1982). These rocks are also exposed in fault-bounded panels in the south basin of Knee Lake, where the best exposures are found on Taskipochikay Island and small islands to the northwest (Figure GS-2-5), and correspond to the ‘basaltic andesite facies association’ of Anderson et al. (2015b).

The flows include coherent, breccia and pillow types that consist mostly of basaltic andesite, with lesser andesite and basalt, and often contain abundant and very large

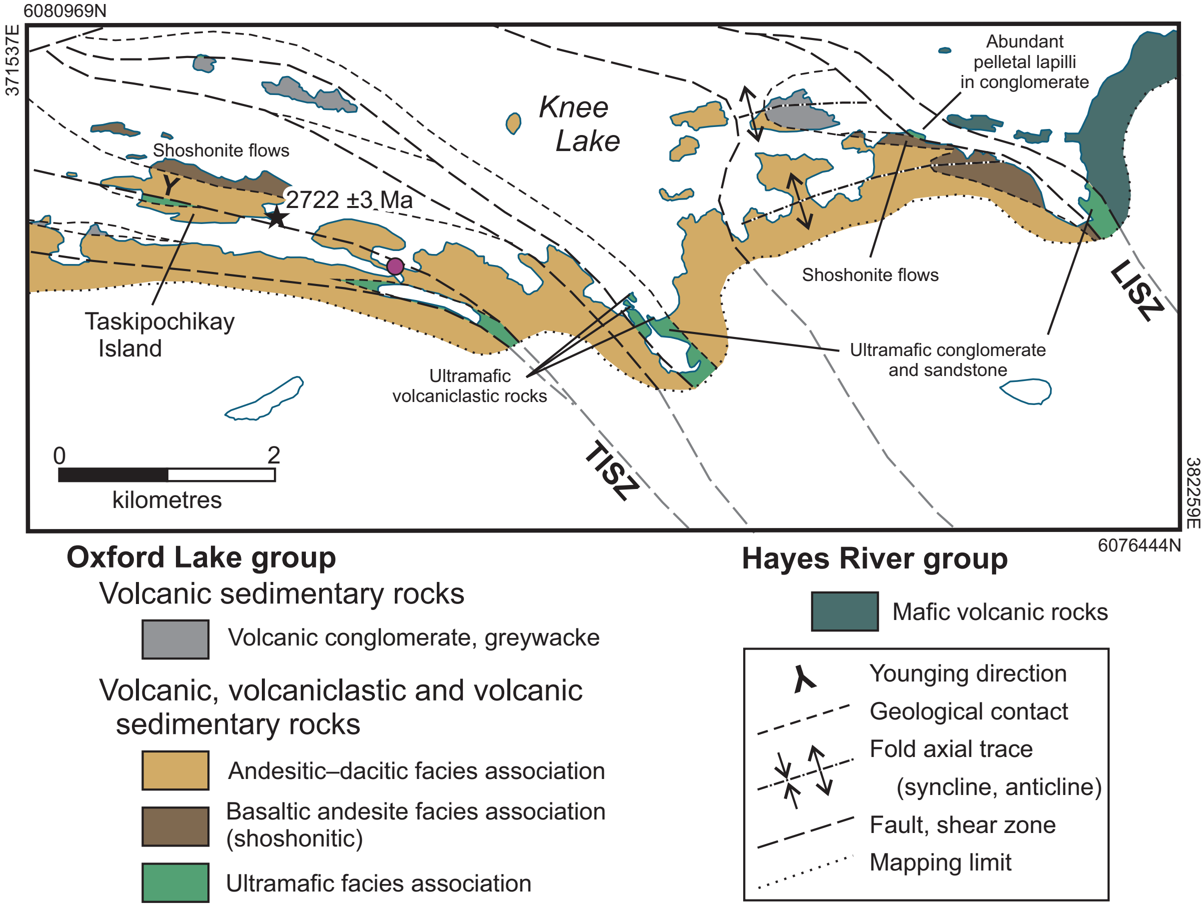

***Figure GS-2-5:** Simplified geology of the southeast portion of southern Knee Lake (after Anderson et al., 2015a), showing the locations of lamprophyre dikes (purple circle), shoshonitic volcanic rocks, and ultramafic volcaniclastic and volcanic sedimentary rocks. Star indicates the location of the dacitic lapilli tuff dated by U-Pb geochronology (Corkery et al., 2000). Abbreviations: LISZ, Long Island shear zone; TISZ, Taskipochikay Island shear zone.*

phenocrysts of plagioclase (20–60%; 0.5–1.5 cm) within a dark grey, fine-grained biotitic groundmass; some varieties also include pseudomorphs (chlorite-biotite) after primary pyroxene or amphibole. Primary features are exceptionally well preserved, allowing for detailed interpretations of eruptive processes and settings despite the effects of later deformation. Quartz amygdules are common, particularly near the margins of pillows, where they vary from round to amoeboid or pipe shaped (Figure GS-2-6a). In some flows, densely packed tabular phenocrysts of plagioclase are aligned to form a prominent flow foliation.

Primary autoclastic (±hyaloclastic) material forms thick, crudely stratified intervals of monolithic, clast-supported breccia and tuff breccia. Fragmentation by spalling of flow lobes is indicated by intact pillows in these deposits or by clasts that contain a concentric internal flow foliation defined by plagioclase phenocrysts. The eruptive setting of these rocks was clearly subaqueous. Interlayers of crossbedded sandstone and boulder conglomerate indicate local shallow-marine settings; rounded boulders up to 2.5 m in diameter in the conglomerate indicate significant subaerial transport of detritus. Associated cryptodomes and subvolcanic sills are texturally similar to the flows but are demonstrably intrusive into underlying rocks of the OLG or HRG. Cryptodomes in the OLG are characterized by sharp contacts and thick chilled margins, with prominent vesicles along the inner selvages and vague pillow-like structures that dissipate downward over several metres (Figure GS-2-6b).

The shoshonitic volcanic rocks at Oxford Lake and Knee Lake have not been directly dated. However, they occur within thick sequences of intermediate to felsic volcaniclastic rocks of calcalkaline affinity that have been dated in two locations. At Knee Lake, the shoshonite flows exposed on Taskipochikay Island are overlain by dacitic volcaniclastic rocks that yielded a U-Pb zircon age of 2722 ±3 Ma (Corkery et al., 2000; Figure GS-2-5), indicating the minimum age of alkaline flows in this location. In contrast, shoshonite flows at the type locality north of Jackson Bay at Oxford Lake are underlain by rhyolitic volcaniclastic rocks that yielded a U-Pb zircon

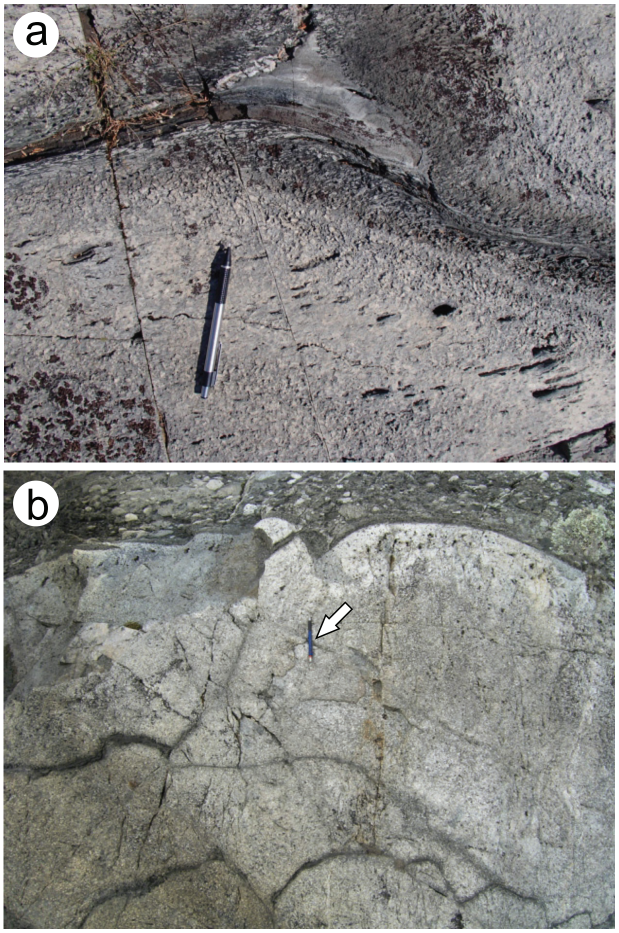

***Figure GS-2-6:** Outcrop photographs of shoshonitic volcanic rocks at southern Knee Lake: **a)** pillowed flow showing densely packed plagioclase phenocrysts and large vesicles along the inner margin of a pillow selvage; **b)** upper contact of a cryptodome emplaced into heterolithic volcanic conglomerate (top); note the smooth chilled contact, vesicular selvage and pillow-like internal structure of the cryptodome (arrow indicates pencil for scale).*

age of 2705 ±2 Ma (Lin et al., 2006; Figure GS-2-3), indicating a maximum age for the alkaline flows in that location. Hence, it appears likely that shoshonitic volcanism within the belt as a whole occurred over a fairly protracted time interval (>15 m.y.), in keeping with the U-Pb ages obtained from the Cinder Lake alkaline intrusive complex.

Ultramafic volcanic conglomerate and sandstone

Ultramafic volcanic conglomerate and sandstone, exposed in the south basin of Knee Lake, are some of the most distinctive rocks in the entire Oxford Lake–Knee Lake belt, primarily due to their bright olive-green, sculpted weathered surfaces. These rocks belong to the 'ultramafic facies association' of Anderson et al. (2015b) and are exposed in several locations, but the best exposures are found in two small bays in the southeast corner of the lake (Figure GS-2-5). Despite a spatial association with major high-strain zones, the rocks at these localities are characterized by spectacular preservation of primary sedimentary features.

The ultramafic volcanic conglomerate is polymictic and forms poorly sorted to unsorted beds that range up to more than 10 m in thickness. Coarser beds are typically clast supported and massive to normally graded, whereas finer beds are matrix supported and often show compound size-grading (reverse to normal); some beds contain very subtle large-scale tabular-planar or trough crossbeds. Bed contacts vary from sharp to diffuse. Many beds have deeply scoured basal contacts with prominent lag deposits. The clasts have highly variable shapes (very angular to well rounded) and include a wide variety of ultramafic, mafic and intermediate rocks of volcanic and plutonic origin (Figure GS-2-7a), including conspicuous clasts of pyroxenite, and abundant examples of resedimented volcaniclastic or sedimentary material of ultramafic composition. The matrix consists of bright green,

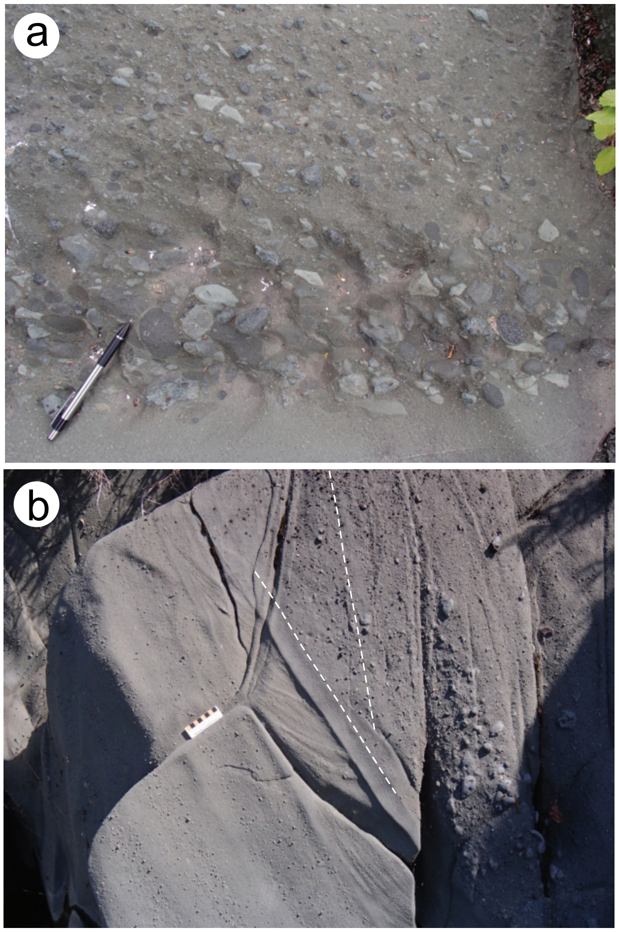

***Figure GS-2-7:** Outcrop photographs of ultramafic volcanic sedimentary rocks in southern Knee Lake: **a)** polymictic, graded, matrix- and clast-supported conglomerate containing ultramafic to mafic clasts; **b)** bedded volcanic sandstone and conglomerate, showing diffuse graded beds and crossbedding (dashed lines).*

pebbly, medium-grained chloritic sandstone of the type described later in this section. Boulder conglomerate beds tend to contain a much higher proportion of intermediate to felsic volcanic material, which includes well-rounded clasts indicative of significant subaerial transport of detritus. Some beds contain angular clasts, up to 2 m across, of resedimented material of similar texture and composition to finer grained facies of the conglomerate, indicating minimal transport, likely via slumping or sliding of weakly consolidated material. Collectively, these features are indicative of proximal channel-fill deposits in an alluvial or shallow-marine fan system, with episodic influxes of more far-travelled detritus. In the easternmost occurrence (Figure GS-2-5), these rocks are underlain by megaclast conglomerate or 'slump deposits' (Syme et al., 1997), suggesting sedimentation was controlled partly by faults, perhaps on the margin of a synorogenic extensional basin.

The conglomerate is interstratified at various scales with volcanic sandstone of similar composition. This 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, with deeply scoured bases and normally graded tops; some beds are capped by thin layers of mudstone or crossbedded sandstone (Figure GS-2-7b), whereas other beds contain abundant, highly contorted rip-up clasts of chloritic green mudstone. These features suggest deposition by grain flow, likely in the channelized portion of a shallow-marine fan.

Of particular note in the volcanic conglomerate is a distinct population of near-spherical pebbles, which consist of a lithic core of highly variable texture and composition mantled by a rim of very fine grained, dark green lithic material. These composite particles vary in abundance from bed to bed but locally account for close to 5% of the clast population and range up to several centimetres in diameter (Figure GS-2-8). Similar particles, referred to as 'pelletal lapilli', are common features of diatreme pipes formed by high-intensity explosive eruptions of volatile-charged melts, including kimberlites and other types of alkaline volcanic rocks. Recent work on pelletal lapilli from kimberlite pipes in South Africa indicates that these particles form when volatile-rich melts are emplaced into unconsolidated volcaniclastic material near the root zones of diatreme pipes and undergo intensive degassing, leading to a process referred to as 'fluidized spray granulation' (Gernon et al., 2012). Coupled with the unusual chemistry of the ultramafic volcanic conglomerate (see below), the pelletal lapilli may indicate an associated alkaline volcanic centre that included one or more diatreme pipes.

Ultramafic volcaniclastic rocks

Ultramafic volcaniclastic rocks are exposed at three locations in a small bay at southern Knee Lake (Figure GS-2-5) and are interpreted to be of pyroclastic origin.

Figure GS-2-8: *Outcrop photograph of ultramafic volcanic conglomerate showing a polymictic clast population that includes numerous spherical cored clasts (arrows), tentatively interpreted as pelletal lapilli.*

These rocks weather dark green to olive green and have smoothly sculpted weathered surfaces similar to the ultramafic volcanic sedimentary rocks with which they are interstratified. They were included in the 'ultramafic facies association' of Anderson et al. (2105b) but are distinctly different from the sedimentary rocks, not only in terms of primary textures and structures but also because they include alkaline and subalkaline geochemical types (see below). The volcaniclastic rocks consist of lapilli tuff and minor lapillistone, which form massive or crudely graded layers up to 3 m in thickness. Lithic lapilli are aphyric or sparsely porphyritic (phlogopite/biotite±pyroxene), with an aphanitic to very fine grained chloritic groundmass, and are supported in a matrix of similar composition (Figure GS-2-9). Lapilli shapes range from very angular and shard like to subrounded, and some have ragged cuspate margins and contain densely packed vesicles indicative of scoria. The layers are essentially monolithic, in marked contrast to the associated volcanic conglomerate, although rare clasts of gabbro or felsic volcanic material occur locally. These rocks likely record periodic influxes of primary volcaniclastic material into the alluvial or shallow-marine fan system, perhaps during major eruptive events.

Whole-rock geochemistry

Representative samples were collected from all major supracrustal map units and subvolcanic intrusions during MGS mapping at Knee Lake (Syme et al., 1997, 1998; Anderson et al., 2015b) and Oxford Lake (Anderson et al., 2012, 2013d), and were submitted for geochemical analysis. Each sample consists of least-altered homogeneous rock that was trimmed to remove weathered surfaces, veins, altered fractures or other inhomogeneities. The clean rock chips were crushed and pulverized at the

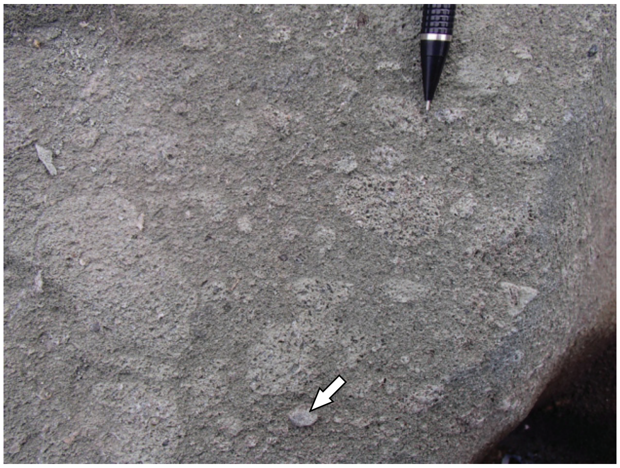

***Figure GS-2-9:** Outcrop photograph of ultramafic lapilli tuff, showing angular to subrounded lithic lapilli and minor accessory clasts of felsic volcanic material (arrow).*

MGS Midland Sample and Core Library, and homogenized powders were submitted to Activation Laboratories Ltd. (Ancaster, Ontario) for analysis. The powders were taken into solution by lithium metaborate-tetraborate fusion followed by nitric-acid digestion, with analysis by inductively coupled plasma–emission spectrometry (ICP-ES) for major elements and some trace elements (Ba, Sc, Sr, V, Y, Zr) and inductively coupled plasma–mass spectrometry (ICP-MS) for trace and rare-earth elements.

Geochemical attributes of the alkaline rocks are described briefly below, focusing on rocks of alkaline as well as high-K calcalkaline affinity, including lamprophyre dikes, shoshonitic volcanic and subvolcanic intrusive rocks, and ultramafic volcanic sedimentary and volcaniclastic rocks. Also included are clasts from the ultramafic conglomerate, which vary from alkaline to subalkaline, and subalkaline ultramafic volcaniclastic rocks. The Cinder Lake alkaline intrusive complex was not examined as part of these mapping programs and is not described below. Also excluded are the documented and inferred carbonatite dikes, the latter of which are currently the subject of detailed study to confirm their genesis.

Lamprophyre dikes and shoshonitic volcanic rocks

Lamprophyre dikes are mostly alkaline but include minor high-K calcalkaline and calcalkaline members (Figure GS-2-10a). Bulk compositions vary from ultrabasic to intermediate, and show evidence of two distinct trends of decreasing MgO with increasing SiO_2 (Figure GS-2-10b). Low SiO_2 end-members define two distinct clusters—one with high MgO, the other with moderate MgO—indicating they may derive from different parental magmas. The high-MgO 'ultramafic' end members (n = 2) contain 2.6–3.4 wt.% K_2O and 16.9–17.7 wt.% MgO, with strongly enriched Cr and Ni (>1160 ppm combined). The lower-MgO members generally have lesser, but still significant, concentrations of Cr and Ni (typically ~300–700 ppm combined). Primitive mantle–normalized trace-element profiles (Figure GS-2-11a) show variably enriched and fractionated light rare-earth elements (LREE), variably fractionated heavy rare-earth elements (HREE) and prominent depletions of Nb, Zr and Ti. The lower-MgO members are strongly enriched in large-ion lithophile elements (LILE), with 1.3–5.1 wt.% K_2O, 555–2581 ppm Ba, 228–2046 ppm Sr and 25–222 ppm Rb, whereas the high-MgO members show lesser concentrations of Ba (<658 ppm), Sr (<273 ppm) and Rb (<144 ppm) but, interestingly, are strongly enriched in Cs (145–174 ppm) in comparison to the other members (<26 ppm Cs).

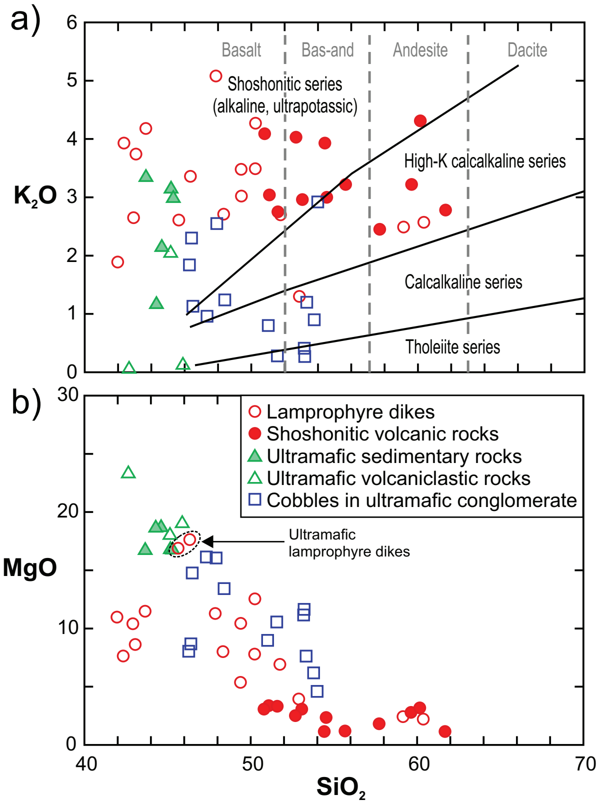

***Figure GS-2-10:** Harker plots of whole-rock geochemical data for alkaline and associated subalkaline rocks: **a)** SiO_2 vs. K_2O; fields for shoshonitic (alkaline, ultrapotassic), calcalkaline and tholeiitic series are from Peccerillo and Taylor (1976); **b)** SiO_2 vs. MgO (symbols legend applies to both diagrams).*

Shoshonitic volcanic rocks show fairly coherent trends on major-element diagrams, from ultrapotassic basalt to high-K calcalkaline andesite (e.g., Figure GS-2-10a, b). These rocks are also strongly enriched in LILE, containing 2.5–4.3 wt.% K_2O, 555–1669 ppm Ba, 428–1881 ppm Sr and 49–124 ppm Rb. Primitive mantle–normalized trace-element profiles (Figure GS-2-11b)

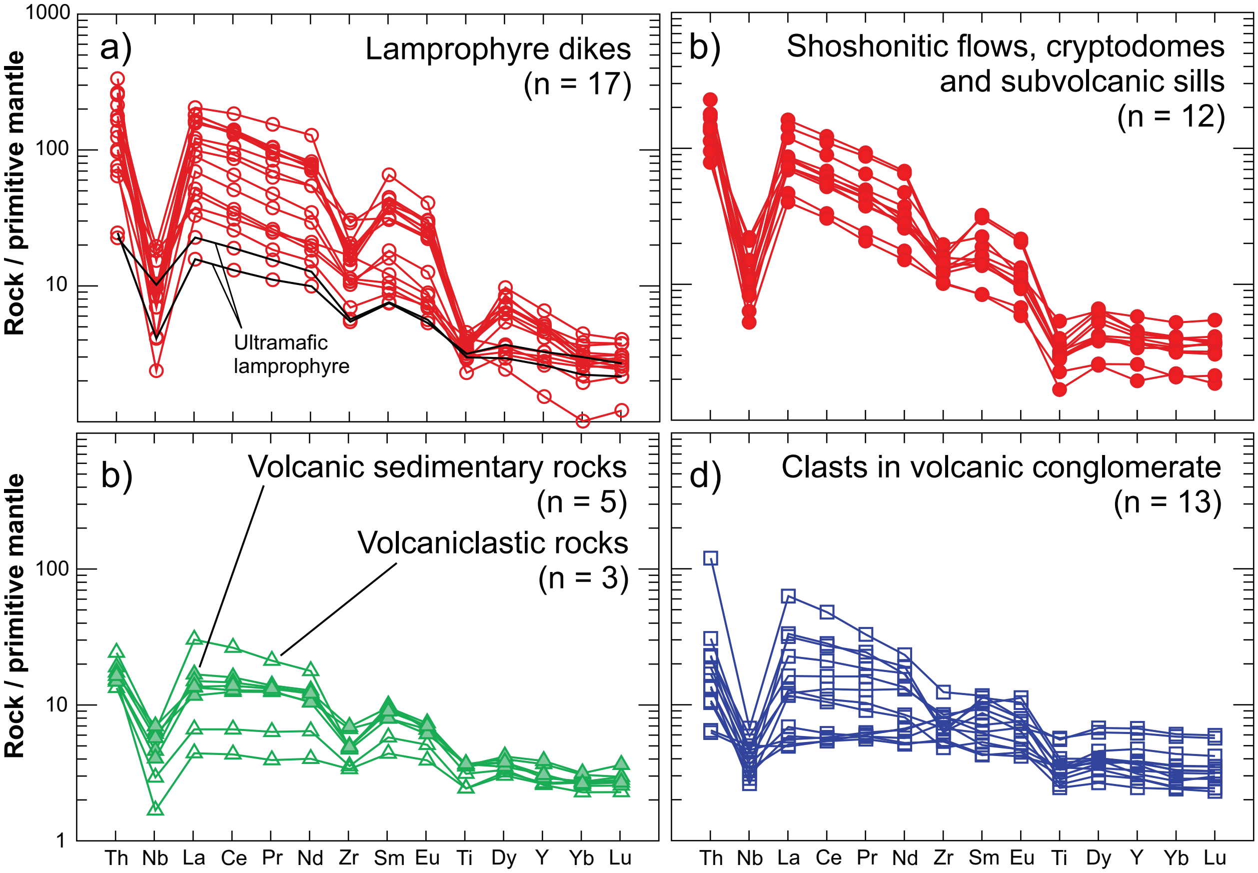

Figure GS-2-11: *Primitive mantle–normalized trace-element diagrams for the alkaline and associated subalkaline rocks (normalizing values and order from Sun and McDonough, 1989):* ***a)*** *lamprophyre dikes;* ***b)*** *shoshonitic flows, cryptodomes and subvolcanic intrusions;* ***c)*** *ultramafic volcanic sedimentary rocks and volcaniclastic rocks;* ***d)*** *clasts in ultramafic volcanic conglomerate.*

are comparable to the more evolved members of the lamprophyre suite, with strongly enriched and fractionated LREE, weakly fractionated HREE and prominent depletions of Nb, Zr and Ti.

Collectively, these features are consistent with the shoshonitic volcanic rocks and the more evolved lamprophyre dikes sharing a common petrogenesis. Both are characterized by the absence of negative Eu anomalies and relatively high $(La/Yb)_n$ ratios (~20–60) that decrease slightly with decreasing silica content (not shown). As described by Brooks et al. (1982), these rocks are comparable to shoshonite and high-K calcalkaline series volcanic rocks in modern suprasubduction settings.

Ultramafic volcanic sedimentary and ultramafic volcaniclastic rocks

The volcanic sedimentary rocks are characterized by primitive compositions, with 43.7–45.3 wt.% SiO_2, 16.7–18.7 wt.% MgO and strongly enriched Cr (500–1200 ppm) and Ni (684–1020 ppm), yet they also show significant enrichments in LILE (1.2–3.3 wt.% K_2O, 332–1255 ppm Ba, 188–548 ppm Sr, 42–132 ppm Rb). Primitive mantle–normalized trace-element profiles (Figure GS-2-11c) show weakly enriched and fractionated LREE, weakly fractionated HREE and depleted Nb, Zr and Ti.

Clasts within the conglomerate show a general trend from ultramafic, ultrapotassic compositions to tholeiitic, mafic compositions, with one sample of mafic material showing a strong alkaline affinity (Figure GS-2-10a). Trace-element profiles are similar to those of the ultramafic sedimentary rocks (Figure GS-2-11d) and some of the less evolved members of the lamprophyre and shoshonite suites. These data likely reflect compositional diversity of the alkaline magmatism, as well as contamination by the local basement, which may have been entrained as xenoliths in alkaline magmas on their ascent to surface.

Associated ultramafic volcaniclastic rocks also have very primitive compositions (42.7–45.9 wt.% SiO_2, 18–23.3 wt.% MgO, 1190–1880 ppm Cr, 480–1090 ppm Ni) and similar trace-element profiles to the ultramafic volcanic sedimentary rocks (Figure GS-2-11c). However, unlike the volcanic sedimentary rocks, some of the volcaniclastic rocks are depleted in LILE (<0.12 wt.% K_2O,

<13 ppm Ba, <115 ppm Sr, <3 ppm Rb), indicating a subalkaline affinity, whereas others are alkaline (2 wt.% K_2O, 303 ppm Ba, 126 ppm Sr, 69 ppm Rb). These features indicate a significantly different source and/or petrogenesis: the alkaline volcaniclastic rocks and volcanic sedimentary rocks are similar in most respects to the ultramafic lamprophyre dikes, suggesting that they likely represent primary extrusive and reworked equivalents of the latter. The subalkaline volcaniclastic rocks may be unrelated to this magmatism or may represent one compositional extreme within a much more diverse magmatic suite than is currently indicated by the limited number of analyses.

Economic considerations

Alkaline intrusive and extrusive rocks are associated with major orogenic gold deposits in several Archean gold districts, most notably the Kirkland Lake–Larder Lake belt in the Abitibi greenstone belt of Ontario (e.g., Poulsen et al., 2000; Ispolatov et al., 2008; Bleeker, 2015), where they serve as an empirical guide for exploration. As described by Bleeker (2015), the association is thought to reflect the fundamental interplay between deep crustal-scale faults, mantle-derived magmatism and the initiation of large-scale hydrothermal-circulation systems, which ultimately produce orogenic gold deposits. Although the dataset for the Oxford Lake–Knee Lake belt remains sparse, the widespread distribution and diversity of the alkaline rocks identified to date is a favourable indicator of potential, which will be evaluated in the context of new MGS mapping to help constrain exploration models.

Syenite-carbonatite complexes host major deposits of rare-earth elements (REE) at Maoniuping, China (Xu et al., 2004) and Mountain Pass, California (Castor, 2008), and both of these complexes show similarities to the Cinder Lake alkaline intrusive complex, located west of Knee Lake. Of particular note, the Cinder Lake complex contains abundant REE minerals in syenitic phases and shows textural and chemical evidence of an association with carbonatite (Chakhmouradian et al., 2008; Kressall et al., 2010). Carbonate dikes discovered in 2016 at central Knee Lake (Anderson, GS-1, this volume), adjacent to the southeastern margin of the Cinder Lake complex, are tentatively interpreted as carbonatite. Although detailed petrographic and geochemical studies are ongoing, confirmation of carbonatite at Knee Lake would represent significant progress toward understanding the REE potential of not only the Cinder Lake complex but also the region in general.

This report sheds considerable new light on the nature, distribution and chemistry of mantle-derived alkaline magmatism in the Oxford Lake–Knee Lake belt, with potential implications for diamond prospectivity. Mantle-derived indicator minerals, commonly referred to as 'kimberlite indicator minerals' due to their usefulness in locating kimberlite pipes (the main worldwide host of conventional diamond deposits), are widespread in surficial sediments in the Oxford Lake–Knee Lake region and appear to define a southwest-trending glacial dispersal train through central Knee Lake (Fedikow et al., 2001, 2002). Despite a brief surge in diamond exploration (1999–2004), a bedrock source of these minerals, some of which are indicative of diamondiferous hostrocks, has yet to be identified. Kimberlite pipes are the most common host of high-value diamond deposits; however, significant deposits also occur in other types of mantle-derived alkaline intrusions, including lamprophyre and associated volcaniclastic or sedimentary deposits. One of the well-documented examples occurs in the Michipicoten greenstone belt near Wawa, Ontario, in the south-central portion of the Superior province, where diamondiferous rocks include calcalkaline lamprophyre intrusions, as well as polymictic volcaniclastic breccia and conglomerate (e.g., Lefebvre et al., 2005; Bruce et al., 2010). The ultramafic sedimentary rocks identified at Knee Lake, which are chemically similar to ultramafic lamprophyre and may contain pelletal lapilli indicative of diatreme volcanism, are potential analogues of these rocks but have yet to be assessed as potential sources of mantle indicator minerals or diamonds.

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