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# Operation Superior: multimedia geochemical survey results northeast of the Knee Lake greenstone belt, northern Superior Province, Manitoba (NTS 53M, 53N)

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## INTRODUCTION

In 1996, the Manitoba Geological Services Branch (now the Manitoba Geological Survey) embarked upon a six-year program of helicopter- and fixed wing-assisted multimedia geochemical and mineralogical sampling. The program, called Operation Superior, was designed to assist in the definition of exploration targets and the assessment of mineral resource potential in the greenstone belts of the northern Superior Province using current and innovative technologies. Preliminary results for the areas surveyed in 1996, 1997, 1998, 1999 and 2000 were released in Fedikow and Nielsen (1997) and Fedikow et al. (1997a, b, 1998, 1999, 2000, 2001, 2002).

The application of belt-scale and regional geochemical surveys to relatively underexplored terrain has been extensively documented. Usually, these surveys have utilized one or two sampling media, such as soil or rock, with generally positive results in reducing large tracts of ground to more localized areas of higher exploration potential. Operation Superior belt-scale multimedia geochemical surveys specifically address the relatively underexplored Archean greenstone belts in the Superior Province of northeastern Manitoba by systematically collecting rock, till, b-horizon soil, humus and vegetation samples from sample sites established at 1 km centres, within mapped boundaries of the greenstone belts. The results of surveys conducted in year six of this project are presented in this report, and include geochemical survey results for rock, till, b-horizon soil, humus, and vegetation. Kimberlite indicator-mineral (KIM) survey results for diamonds, based on 25 kg bulk till samples, are also presented from the 2001 survey and for all KIM survey results between the years 1996 and 2000.

One of the nongeochemical benefits of landing a helicopter every 1 km during sampling is the opportunity to make geological observations at outcrop sample sites and in areas of recent burn. Forest fires in 1988 and 1989 have exposed large areas of outcrop in the northern Superior Province that were covered with vegetation and/or soil. An excellent example of this benefit has been described in Fedikow et al. (1997a, b) and Fedikow and Nielsen (1997), where an areally extensive, hydrothermally altered, base- and precious-metal depositional environment was recognized.

A complementary project was initiated by the Geological Survey of Canada (GSC) in 1996. In the GSC survey, which focused on the predominantly intrusive geological terranes separating the greenstone belts, till samples were collected on a 40 km sample spacing to provide a regional framework for interpretation of the more detailed multimedia program. This survey was undertaken by Harvey Thorleifson of the Geological Survey of Canada and Gaywood Matile of the Manitoba Geological Survey, and was released as Open File Report OF97-3 (Matile and Thorleifson, 1997).

Historically, the commodity focus in Manitoba has been on base and precious metals, with lesser interest in the pegmatite-hosted rare-element deposits such as those at Bernic Lake. This multimedia geochemical and mineralogical survey is designed to address base and precious metals, pegmatite- and carbonatite-hosted rare-element deposits, and diamonds. The approach is to collect a variety of sample media at each site and analyze these samples in a multi-element manner using the most advanced instrumentation and innovative digestion techniques available. Instrumental neutron activation (INAA), inductively coupled plasma–atomic emission spectrometry (ICP-AES), and inductively coupled plasma–mass spectrometry (ICP-MS) are the main analytical techniques chosen for this purpose. Additionally, pH and conductivity measurements (converted to $H^+$ and specific conductance, respectively) assess water-extractable components in rock, b-horizon soil and humus samples in this survey. The pH measurements were done using a VWR model 8000 pH meter with a Ross #8165 BN Combination pH electrode. Conductivity was measured with an Orion model 125 conductivity meter with an Orion #011020 glass conductivity cell.

The enzyme-leach^SM selective-extraction process has once again been applied to b-horizon soil samples in this survey. This approach utilizes a phase-specific dissolution that liberates metals adsorbed onto the amorphous Mn-oxide coatings of individual mineral grains in the b-horizon. The leachate is analyzed using ICP-MS, and element concentrations are reported at the parts per billion level. Because of the relative abundance of thick and compositionally variable surficial deposits in this study area and the successful application of this technique in years one, two, three and four of the project, year five and six b-horizon soils were analyzed using only the enzyme-leach^SM–ICP-MS technology. The nature of the surficial sampling environment necessitated the application of innovative analytical approaches for this survey.

A unique opportunity to assess the diamond potential of greenstone belts in the northern Superior Province in Manitoba has been provided by cooperative efforts with DeBeers Canada Exploration Inc. Eleven litre pails of till collected at each sampling site were concentrated, mineralogically picked and analyzed by electron microprobe by DeBeers laboratories to provide mineral chemistry for classification purposes. Sample locations were withheld from DeBeers until release of the open file report to ensure security and equal opportunity for follow-up by all interested parties in the exploration community. This approach permitted diamond potential to be assessed throughout the 1996–2001 Operation Superior survey areas. Under normal circumstances, this assessment would have been too costly for the Manitoba Geological Survey to undertake.

As part of another cooperative arrangement with the Geological Survey of Canada (GSC), crown twig samples collected from black spruce trees were ashed in the GSC laboratories by Colin Dunn. The vegetation geochemical samples were prepared with good control on ashing temperatures and contamination. Analyses were bracketed with vegetation geochemical standards prepared in these same laboratories, resulting in the development of a well-constrained vegetation geochemical database. This marked the sixth year of vegetation sample preparation in the GSC laboratories.

The element Hg was analyzed in outcrop rock-chip, b-horizon soil and humus samples as a specialty element. The analysis was undertaken at Activation Laboratories Ltd. (Ancaster, Ontario) using a flow-injection mercury system (FIMS) designed by Perkin

Elmer Ltd. Till was analyzed for Hg by cold vapour–atomic absorption spectrometry (AAS).

The interpretation of exploration geochemical data often relies upon the recognition of localized patterns of element variation. This approach to data interpretation is strongly recommended for the data presented from the 2001 Operation Superior multimedia geochemical survey. The interpretation of enzyme-leach$^{SM}$ data is premised on the recognition of central lows or zones of low metal concentrations surrounded by, or associated with, elevated metal contents, as well as morphological characteristics of the anomalies. This approach to interpretation is somewhat more difficult with irregularly distributed data, such as those collected during this survey; however, the identification of a geochemical ‘cell’ using the enzyme-leach$^{SM}$ approach is most desirable. Apical or single-point anomalies have been recognized in previous years’ surveys.

A major diamond play was initiated following the release of the 1999 multimedia geochemical and mineralogical data as Open File Report OF2000-2 and the kimberlite indicator-mineral survey results from the northern half of the Knee Lake greenstone belt in Open File Report OF2001-4 and OF2001-5. A total area of 2 440 579 hectares was covered by 50 exploration permits and 15 special permits, primarily for diamond exploration. Permits were taken out by 18 companies, including DeBeers Canada Exploration Inc., Kennecott and BHP. This represents the most significant exploration play in Manitoba since the Thompson nickel rush in the 1950s.

## METHODOLOGY

Multimedia geochemical samples were collected on approximately 1 km centres or as dictated by access to landing sites using a float equipped helicopter (Bell Jet Ranger 206B). The procedure at each site was to establish, by way of hand augering, the location from which a till sample was to be collected. All other samples were collected in and around the immediate area of the till pit. Sample site locations were plotted on airphotos while viewing the sites from the helicopter subsequent to sample collection.

The specifics of sample collection, preparation and analyses, including data and derived products are described individually for each media type.

## DATA DISPLAY

Geochemical data for all sample types are presented in Excel table format with site identification and UTM coordinates (Zone 15, NAD83). GIS shape files are included for each media/method/element and include rank percentile calculations in the attribute table. Percentile values represent the percentage of data points that fall below a certain analytical value. For example, a $25^{th}$ percentile value of 30 ppm Cu indicates that 25% of the data points have values for Cu that are less than 30 ppm. Likewise, at a $95^{th}$ percentile value of 200 ppm Cu, only 5% of the data points would have values in excess of 200 ppm.

This presentation is a preliminary attempt to identify areas of high metal contents and thereby reduce the large areas surveyed to smaller areas for follow-up work. Although, for any given area and sample medium, the number of samples may be low for the calculation of percentiles, the user can still quickly assess geochemical response by examining nontransformed geochemical data. Users can manipulate the geochemical data in a manner appropriate to their needs by using the unreduced data in the Excel tables. Elements consistently below the Lower Limit of Detection (LLD) have been included in the Excel tables but excluded from the shape file dataset. Samples with concentrations below the LLD for any particular element are assumed to have metal contents equivalent to one-half of the stated LLD. This value was also used for all plotting purposes. For brevity and simplicity in the graphical display of geochemical data, only the total rare-earth element (TREE) value is plotted as shape file for rock, humus and vegetation data. Concentrations for individual REE, as well as total REE, are presented in the Appendices.

The UTM coordinates for sample sites are derived from 1:50 000 scale topographic maps.

## BEDROCK GEOLOGY AND MINERAL DEPOSITS OF THE 2001 SURVEY AREA

Multimedia geochemical and mineralogical surveys were conducted northeast of the Knee Lake greenstone belt in 2001 (Fig. 1). The simplified regional geology and sample-site locations in the survey area are presented in Figure 2. The area of the Knee Lake greenstone belt sampled in 2001 extends northward and eastward from the northern tip of Knee Lake.

### Knee Lake greenstone belt (northern half)

#### Introduction

The description of the geological setting of the Knee Lake greenstone belt is taken primarily from Gilbert (1985), Syme et al. (1997, 1998) and Lin et al. (1998). These reports summarize recent geological mapping in the Knee Lake portion of the Superior Province and can be consulted for further details on the geology of the Knee Lake belt, including individual unit descriptions. Additionally, work conducted prior to 1970 by Bruce (1919), Wright (1925, 1931), Springer (1946), Quinn (1955) and Barry (1959, 1964) provides a historical perspective and additional sources of information for the Knee Lake area.

#### Geological setting

Supracrustal rocks in the Oxford Lake–Knee Lake Belt have been assigned to two principal stratigraphic groups, the Hayes River Group and Oxford Lake Group (Gilbert, 1985). Both groups are interpreted to have potential to host gold and base-metal deposits.

The Hayes River Group (HRG) is a predominantly volcanic sequence dominated by pillowed basalt and related gabbro, minor intermediate to felsic volcanic rocks, and minor volcanogenic sedimentary rocks. An age of ca. 2830 Ma has been determined for the HRG at Knee Lake (Syme et al., 1997). Hubregtse (1976) described the volcanic rocks at Knee Lake in terms of five volcanic cycles, each comprising a lower, tholeiitic basalt section and an upper, calc-alkalic, intermediate to felsic portion locally containing sedimentary rocks and iron formation. The HRG section in the Knee Lake area is estimated to be 9.7 km thick (Gilbert, 1985); neither the base nor top is exposed. The section at Knee Lake represents the upper portion of the HRG, the lower portion being that exposed on Oxford Lake (Manitoba Energy and Mines, 1987). The base of the HRG has been intruded by tonalitic to granitic plutons and related gneiss of the Bayly Lake Complex, which have an age of between 2883 and 2730 Ma (Syme et al., 1998).

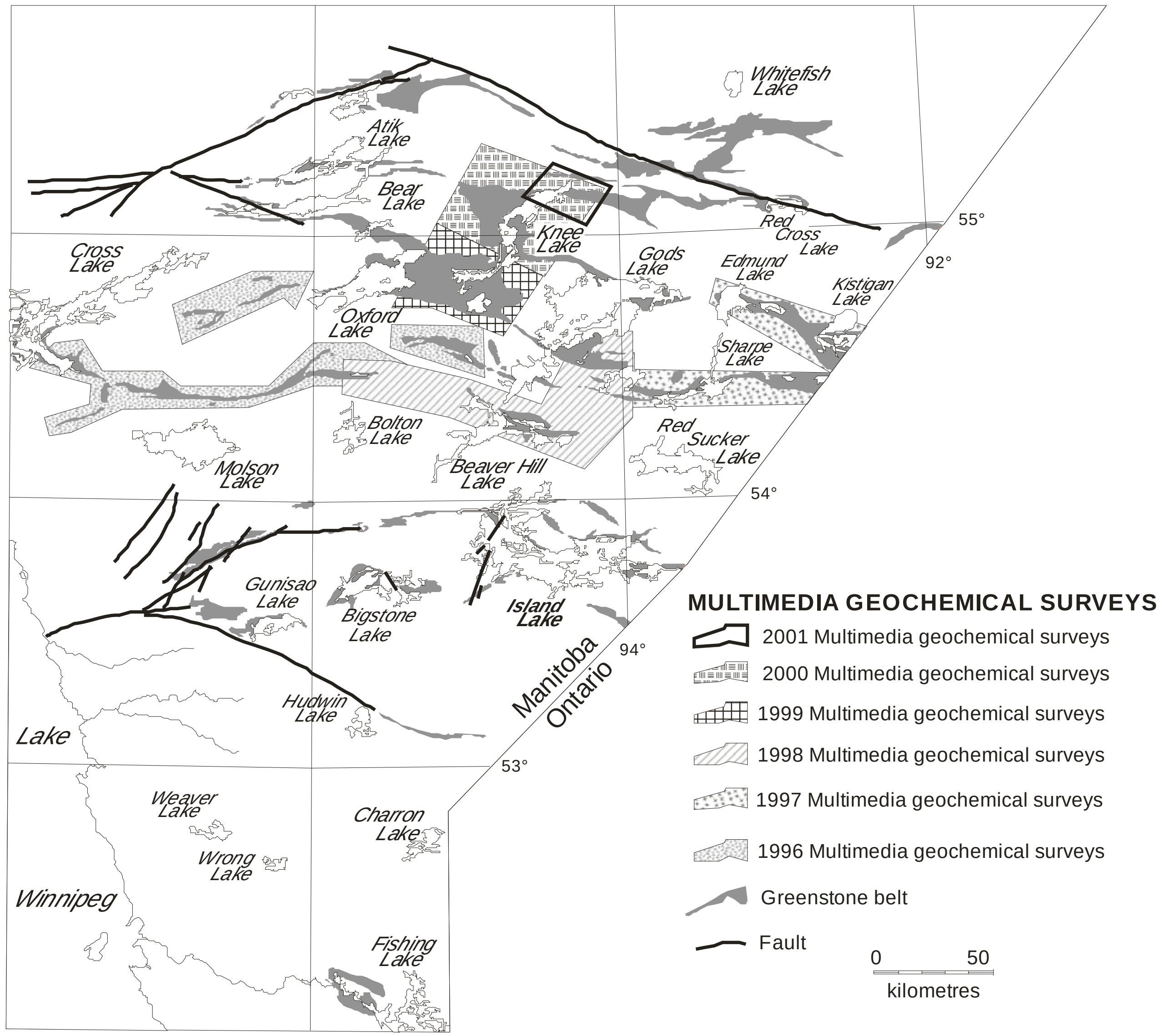


*Figure 1: Location of multimedia geochemical surveys.*

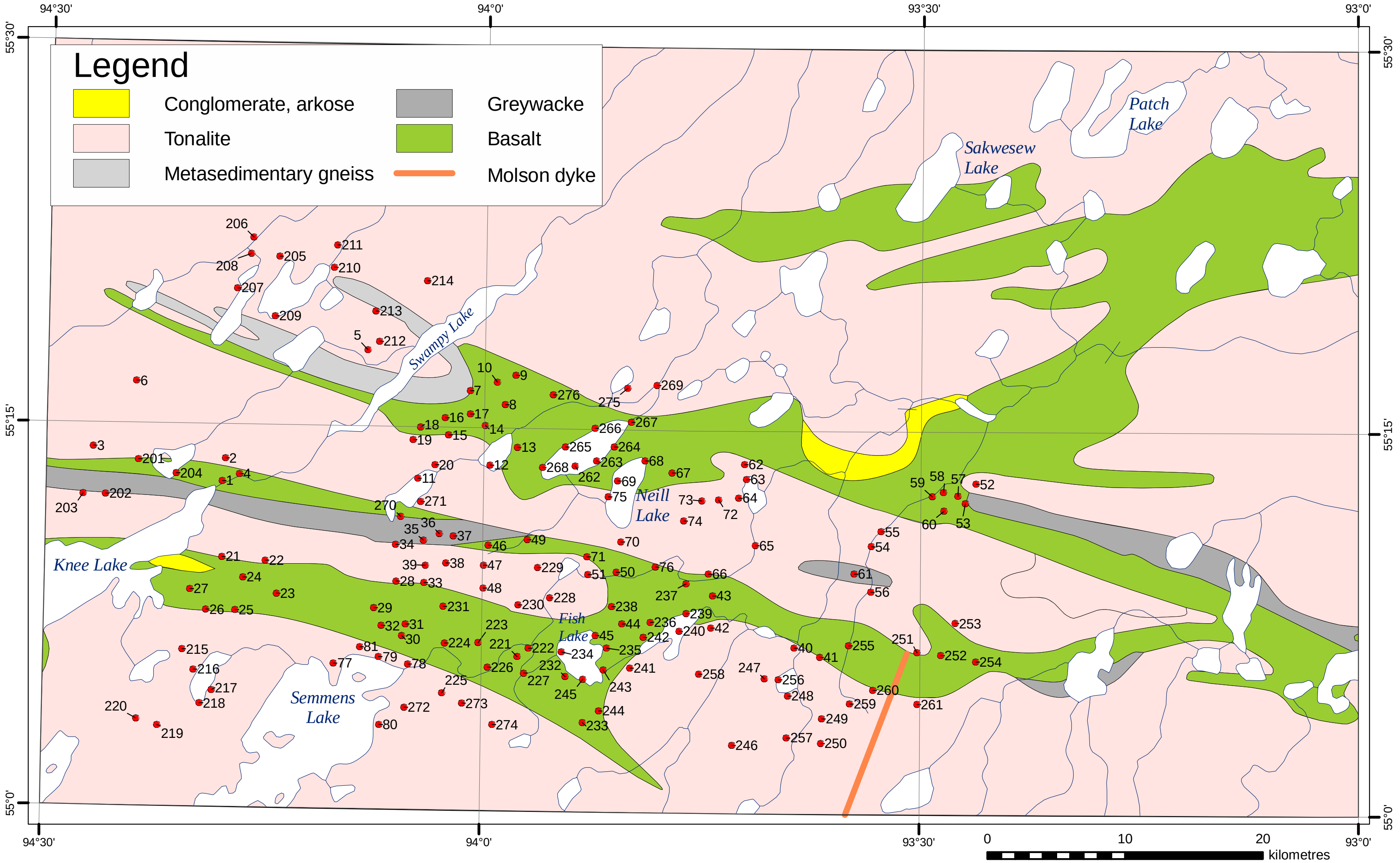


*Figure 2: Regional geology and multimedia sampling sites in the 2001 survey area.*

terms of five volcanic cycles, each comprising a lower, tholeiitic basalt section and an upper, calc-alkalic, intermediate to felsic portion locally containing sedimentary rocks and iron formation. The HRG section in the Knee Lake area is estimated to be 9.7 km thick (Gilbert, 1985); neither the base nor top is exposed. The section at Knee Lake represents the upper portion of the HRG, the lower portion being that exposed on Oxford Lake (Manitoba Energy and Mines, 1987). The base of the HRG has been intruded by tonalitic to granitic plutons and related gneiss of the Bayly Lake Complex, which have an age of between 2883 and 2730 Ma (Syme et al., 1998).

The Oxford Lake Group (OLG) is a younger (2706 Ma at Oxford Lake, Syme et al., 1998), predominantly sedimentary succession that lies unconformably on HRG volcanic rocks at Gods Lake (Gilbert, 1985). It consists of a lower, dominantly 'volcanic' subgroup of limited extent, overlain by more extensive sedimentary rocks extending 40 km from Oxford Lake to Magill Lake in a 12 km wide belt (Gilbert, 1985; Manitoba Energy and Mines, 1987). Volcanic rocks in the lower subgroup are shoshonitic to calc-alkalic in character (Hubregtse, 1976; Brooks et al., 1982; Gilbert, 1985) and include fragmental and flow rocks. Syme et al. (1998) interpreted the fragmental rocks to be epiclastic (conglomerate) rather than volcanogenic (reworked pyroclastic rocks; Gilbert, 1985). The Opischikona Narrows sedimentary rocks occur within a structural basin in southern and central Knee Lake. Greywacke, pebbly sandstone and conglomerate characterize these rocks at Opischikona Narrows (Syme et al., 1997). These rocks were previously interpreted to be part of the HRG (Gilbert, 1985) but were reinterpreted by Syme et al. (1998) as OLG. Stratigraphic relations within the OLG suggest that the sedimentary rocks were deposited in shallow- to deep-water basinal environments (Manitoba Energy and Mines, 1987).

### Structure

Preliminary structural analysis of the Knee Lake greenstone belt suggests that it has been affected by multiple generations of folding (Gilbert, 1985). The earliest folds recognized ($F_1$) are very tight to isoclinal with a locally developed axial-planar cleavage ($S_1$). They are overprinted by $F_2$ folds that are also very tight to isoclinal but have a generally well-developed axial-planar cleavage ($S_2$). The $S_2$ cleavage is locally refolded by open $F_3$ folds. Very tight to isoclinal folds ($F_1$ or $F_2$) are also recognized at the mesoscopic scale, in many parts of the Knee Lake Belt, based on younging direction reversal, fold asymmetry change and repetition of lithological units. At several localities, clasts in the conglomerate of the OLG contain a predepositional foliation, indicating that rocks of the HRG had probably been deformed before deposition of the OLG. It is interesting and yet to be explained that, although deformation in the HRG is mainly concentrated in localized shear zones and many parts of the group are only very weakly deformed, rocks of the OLG are generally very strongly deformed.

Major west-northwest- and northeast-trending faults and shear zones occur in the area of southern Knee Lake (Lin et al., 1998). Rocks in these faults and shear zones are intensely deformed with well developed, steeply plunging stretching lineations.

The contact between the HRG and the OLG is defined by west-northwest-trending structures. Northeast-trending faults crosscut the HRG and the Opischikona Narrows sedimentary rocks, resulting in a fault-bounded panel of sedimentary rocks extending through the centre of southern Knee Lake. The ages of the west-northwest- and northeast-trending faults and shear zones have not been precisely established, although dating of the ‘volcanic’ subgroup of the OLG and Opischikona Narrows sedimentary rocks is proceeding.

The most significant shear zone in the northern Knee Lake area has been identified by Syme et al. (1998) as a northeast-trending structure that extends the entire length of northern Knee Lake. This structure separates OLG sedimentary rocks from HRG volcanic rocks in the south. The horizontal sense of movement along this structure has been determined to be sinistral. Secondary structures parallel to this feature have been identified in northeastern Knee Lake.

Lin et al. (1998) described a zone of strong deformation that occurs in the southern portion of the Oxford Lake–Knee Lake greenstone belt. This zone, referred to as the Southern Knee Lake Shear Zone (SKLSZ), strikes east-southeast, has an indicated dextral shear sense, and is characterized as a dextral transpressional zone of shear. Transpressional shear zones are significant in terms of gold mineralization, as evidenced by the Kirkland Lake–Larder Lake–Cadillac Break (Robert, 1989; Robin and Cruden, 1994).

### Metamorphism

Two distinct metamorphic zones are observed within the supracrustal assemblages in the Knee Lake greenstone belt. Lower to middle greenschist-facies metamorphic mineral assemblages characterize the HRG and 'volcanic' subgroup of the OLG throughout the area. An exception occurs to the east of the northeast-trending fault through Omusinapis Point, where HRG basalt contains amphibolite-facies mineral assemblages. Rocks crosscut by the Seller Lake Shear Zone also contain amphibolite-facies mineral assemblages. These rocks are abruptly truncated at a northeast-trending fault zone across which there is a change to greenschist grade. A second major break occurs between the 'volcanic' subgroup and the 'sedimentary' subgroup of the OLG on the south side of Knee Lake. The change from greenschist to amphibolite grade is abrupt; however, there is a stepwise increase in metamorphic grade, recrystallization and regional deformation to the south.

### Mineral deposits

To date, no economic deposits of base and/or precious metals have been discovered in the northern portion of the Knee Lake Belt. A compilation of known mineral occurrences is available in Gale et al. (1980). Southard (1977) also described mineralization and reviewed exploration history for the Knee Lake area.

*Sulphide mineral occurrences*

Despite the absence of production from base-metal deposits, the subaqueous volcanic strata of the HRG are interpreted as having potential to contain volcanogenic massive sulphide (VMS)-type deposits (Gale et al., 1980). These volcanic rocks include tholeiitic basalt as well as calc-alkaline intermediate to felsic flows and volcaniclastic rocks (Hubregtse, 1976). This suggests that at least part of the HRG was emplaced in an arc environment. Specific factors suggesting VMS potential include the presence of a large, proximal felsic volcanic complex (Pain Killer Bay) and identification of hydrothermally altered basalt. The HRG basalt is unusually pale weathering throughout most of the Knee Lake area. This low-grade pervasive alteration locally intensifies such that the basalt weathers white, it is very light grey on fresh surfaces, and primary structures are obliterated. The alteration is manifest as an epidote-clinozoisite-albite-quartz rock, with patchy rusty weathering gossans locally developed in the most intensely altered rocks in the Pain Killer Bay area in the southern portion of the greenstone belt.

Gale et al. (1980), in a study of massive-sulphide depositional environments in the Knee Lake Belt, recognized lithodomain units with high potential to contain massive-sulphide–type deposits (cf. Gale et al., 1980, Map ER79-1-8). The high-potential areas are based upon the presence of favourable geology and/or the presence of known massive-sulphide–type deposits (‘Type 1’). Significant potential is also indicated by favourable geology but without documented evidence of massive-sulphide mineralization (‘Type 2’). In northern Knee Lake, high-potential areas are indicated by the presence of known massive-sulphide-type mineralization with associated alteration zones and stringer sulphide mineralization (cf. Map ER-79-1-11; Gale et al., 1980). The first of these diamond-drill–indicated zones is near-massive pyrrhotite with 2% Cu over 0.3 m hosted by rhyodacite and rhyolite and underlain by chloritic and sericitic rhyolite (occurrence 5 in Table A-10; Gale et al., 1980). The second mineralized zone comprises bands and stringers of sphalerite and pyrite over 0.6 m hosted by andesite and felsic tuff (occurrence 1 in Table A-10; Gale et al., 1980).

Syme et al. (1998), based on recent geological mapping, placed the observed sulphide-mineral occurrences in stratigraphic context in the northern portion of the belt. The majority of the sulphide mineralization and the areas of highest potential occur in the upper part of the HRG. Widespread silicification, comprising feldspar+quartz alteration, is documented from spherulitic basalt (unit 8). Massive-sulphide mineralization occurs at Cinder Lake in the central portion of the belt and comprises pyrite and pyrrhotite with minor chalcopyrite and sphalerite. This mineralized zone is localized at the contact between rhyolitic and andesitic volcanic rocks near the base of the HRG.

*Gold mineralization*

Gold mineralization in the northern Knee Lake belt is demonstrated to be structurally controlled (Southard, 1977; Richardson and Ostry, 1996; Syme et al., 1997; Lin et al., 1998). Archean gold mineralization has generally been recognized in association with regional-scale shear zones; however, the largest gold deposits are controlled by smaller scale structures with limited displacements (Vearncombe, 1998). Syme et al. (1998) have defined numerous shear zones and faults in the north Knee Lake belt that had previously been unrecognized. The structures have variable ages and include brittle north-northeast- and northeast-trending structures as well as numerous other ductile shear zones that have unknown age relationships.

The most significant of the gold occurrences on Knee Lake are the Knee Lake Gold Mines and Johnson Knee Lake Mines gold-silver occurrences. Southard (1977) described the Knee Lake Gold Mines mineralized zone as a sheared and locally silicified, 2 m thick tuff unit that occurs at the contact between pillow basalt and a quartz porphyry dyke. Visible gold occurs in a less than 15 cm thick quartz vein at the contact with the dyke. Southard (1977) reported the highest grades of “2.65 oz/ton Au and 0.45 oz/ton Ag” from samples collected from muck piles. Sphalerite, chalcopyrite and pyrite were documented in trenches and adjacent trench muck from this site during Operation Superior fieldwork undertaken in 2000. Underground exploration of this mineralized zone was hampered by erratic ore shoots and attendant difficulty in correlating with diamond-drill results. This geological scenario was similar for the nearby Johnson Knee Lake Mines mineralization, 350 m to the west.

## QUATERNARY GEOLOGY OF THE 2001 SURVEY AREA

### Introduction

Continued work northeast of Knee Lake in the summer of 2001 resulted in the collection of 148 till and related sediment samples for geochemical and kimberlite indicator-mineral analyses. Glacial striae were measured at a number of sites, and observations on sediment colour, texture, stratigraphy and other field relations were made when the opportunity presented itself. The orientation of drumlinoid ridges was taken from published topographic maps and airphotos.

### Stratigraphy

Conclusions regarding the Quaternary stratigraphy of the northern Knee Lake area are derived from observations made in hand-dug pits. A single till sheet blankets the bedrock throughout most of the area and is, in turn, overlain by glaciolacustrine silt and clay and a variety of wetland deposits. The extensive glaciolacustrine sediments and wetland deposits are the main impediments to till sampling from hand-dug holes. Extensive cryoturbation due to discontinuous permafrost makes sampling difficult in places. Frost action severely mixes the till and the glaciolacustrine clay to the point where it may be almost impossible to collect pristine samples of either material.

Till is very widespread throughout the northern Knee Lake area and occurs primarily as extensive drumlins or drumlinoid ridges on the northwest side of the lake, and primarily as a discontinuous till sheet on the southeast side. Neither of these terrains is mutually exclusive, which is to say that a few drumlins occur on the southeast side of the lake and an extensive area dominated by bedrock outcrops is found to the west of the central Knee Lake area. The till is composed of highly calcareous, beige to grey, fine-textured, allochthonous material derived in large part from the Hudson Bay Lowland. The carbonate content of the silt+clay fraction is relatively uniform across the area, with a mean of about 40%. The single most noticeable difference between the drumlin and nondrumlin terrain is the till thickness. The till in the drumlins is generally thicker, and bedrock outcrops fewer, than in areas where there are no drumlins. Glaciofluvial sand and gravel occur at some drumlin sites on the northwest side of Knee Lake. At several sites, near the northern limit of the 2000 sampling, the drumlins are composed of Sky

Pilot till, a fine-textured, reddish-coloured, silty till that is widely distributed across the Hudson Bay Lowland (Nielsen et al., 1986). Sky Pilot till is the surface till throughout much of the Hudson Bay Lowland and derived its reddish color from similarly coloured Devonian bedrock formations (such as the Williams Island Formation) that subcrop in the bay. The discovery of Sky Pilot till in the Knee Lake area marks the southern occurrence of this till in Manitoba.

The variable internal composition (beige till, Sky Pilot till, sand and gravel) and form suggest that the drumlinoid shape is erosional and not related to the composition or provenance of the enclosing material. The high carbonate content and the presence of carbonate pebbles and other erratics indicate that the till was derived, in large part, from the Hudson Bay Lowland to the north and northeast.

### Ice-flow direction

The presence of erratics from central Keewatin, Hudson Bay and eastern Hudson Bay, as well as westerly, southwesterly and southeasterly striae, found in places throughout the northern Superior province of Manitoba, are evidence of a long and complex ice-flow history (Fedikow et al., 2001). However, depositional evidence for the early events indicated by southeasterly and westerly striae has not been forthcoming outside the Hudson Bay Lowland (the northeastern limit of esker development). While these early ice-flow events are of some interest, they have little relevance to overburden geochemical exploration in most of the northern Superior Province. The 233° striae direction is the only sediment-transport direction that is relevant to geochemical exploration and mineral tracing in the northern Knee Lake area.

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