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GEOLOGICAL SETTING AND GENESIS OF HIGH-GRADE IRON-ORE DEPOSITS IN THE EASTERN LABRADOR TROUGH

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ABSTRACT

The Paleoproterozoic Sokoman Formation in the eastern Labrador Trough hosts numerous occurrences of high-grade (>55% Fe) iron ore. These were first reported from the Sawyer Lake area in the 1930s, and recent exploration has identified significant iron-ore resources at the Joyce Lake deposit (24.3 million tonnes at 58.6% Fe) and Houston deposit (30.1 million tonnes at 57.7% Fe). A geological description of the main occurrences as well as results of whole-rock geochemistry and oxygen isotope analysis are presented in this report, and a genetic model for the formation of these deposits is proposed.

High-grade iron-ore deposits in the eastern Labrador Trough differ markedly from the soft direct-shipping ore (DSO) bodies of the Schefferville area. They form stratabound, tabular ore bodies and are composed mainly of hard, massive to laminated hematite-rich ore with lesser pockets of soft friable ore. The high-grade ore bodies are surrounded by altered iron formation with layers of partially leached chert and secondary hematite. A later, low-temperature alteration has variably affected both the high-grade ore bodies and the surrounding altered iron formation. Geochemical analyses show that the high-grade ore and altered iron formation are strongly depleted in Mg, Ca and Na compared to unaltered Sokoman Formation taconites. Enrichment of Fe is not associated with a corresponding enrichment in immobile elements such as Al and Ti, indicating that the formation of these deposits was associated with the addition of Fe rather than simple leaching of silica. Hematite from the high-grade ore bodies is also associated with a strong depletion of $\delta^{18}O_{VSMOW}$ compared to magnetite in unaltered taconites.

The geological and geochemical characteristics of high-grade iron-ore deposits in the eastern Labrador Trough are consistent with a supergene-modified hypogene enrichment model. The main stage of iron enrichment is associated with the flow of large volumes of meteoric and/or formational waters during the deformation of the Sokoman Formation in the New Québec Orogen. These fluids were focussed in structural zones (faults and fold hinges) and silica was leached and secondary hematite was precipitated. Later supergene alteration, which partially transformed hematite to goethite and remobilized Mn, may represent the same pre-Cretaceous supergene alteration recorded in the DSO deposits of the main ore zone or more recent groundwater circulation.

INTRODUCTION

The Labrador Trough is located in western Labrador and northeastern Québec and contains several world-class iron-ore deposits. High-grade (>55% Fe) iron-ore deposits have been intermittently mined in the Schefferville area since 1954, where they are commonly called direct-shipping ore (DSO) deposits. However, all mining to date has been concentrated in a narrow zone (35 km long and 7 km wide) straddling the provincial boundary, and little information has been published on high-grade iron-ore deposits outside of this zone.

The occurrence of high-grade iron-ore deposits in the eastern part of the Labrador Trough was first reported in 1937 by Mathiau Andre, a Montagnais Innu guide, close to Sawyer Lake. Work by Labrador Mining and Exploration Company (LM&E) during the 1940s and 1950s indicated the presence of a significant ore body at Sawyer Lake (Retty and Moss, 1945) and noted many other zones of iron enrichment (Burgess, 1951; Hagen, 1952; Perrault, 1952; Usher, 1953; Figure 1). However, with the exception of the Houston and Malcolm deposits, none of these was considered to represent a major ore deposit, and LM&E focused their activities on developing the large iron-ore deposits in the Schefferville area. In the 2000s, increase in iron-ore prices led to renewed exploration activity, which provided much new information on high-grade iron-ore deposits in the Labrador Trough.

This report presents an overview on the geological setting of selected high-grade iron-ore occurrences, based on

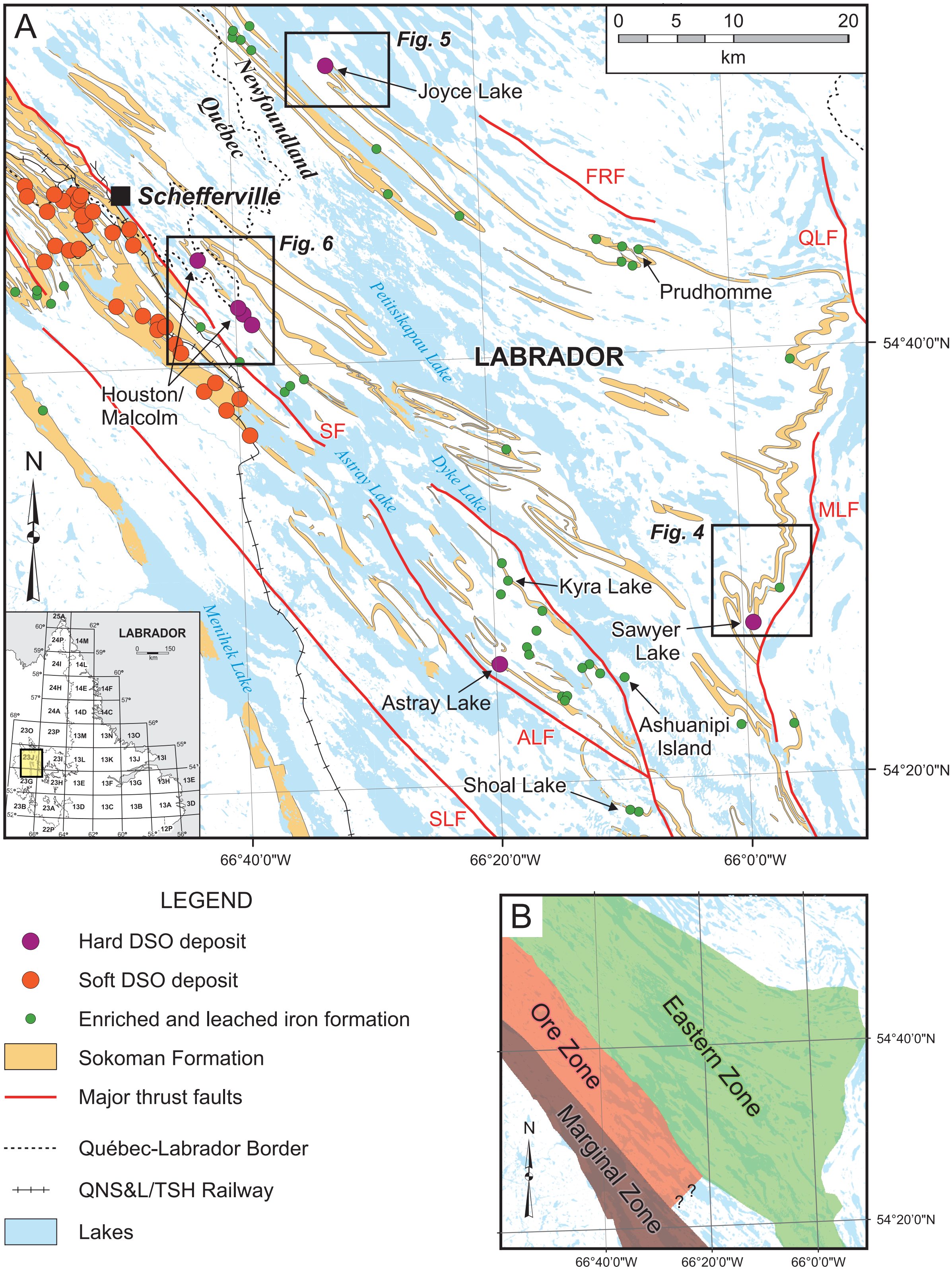

Figure 1. *A) Regional map showing distribution of the Sokoman Iron Formation and location of high-grade DSO ore deposits and occurrences of enriched and leached iron formation (modified after Wardle, 1982a, b). SLF = Stakit Lake Fault; SF = Schefferville Fault; ALF = Astray Lake Fault; FRF = Ferrum River Fault; QLF = Quartzite Lake Fault; MLF = Mina Lake Fault. B) map shows location of Marginal, Ore and Eastern zones of Harrison* et al. *(1972).*

field work from 2012 to 2014, as well as published and unpublished company data. The key geological characteristics of each deposit are outlined, and comparisons between these deposits are discussed, including implications of these comparisons for regional exploration in the Labrador Trough. New lithogeochemical and oxygen isotope data from selected deposits are also presented. These data are used to develop a genetic model for these deposits, and to compare high-grade iron-ore deposits in the eastern Labrador Trough with other major deposits worldwide.

REGIONAL GEOLOGY

STRATIGRAPHY AND ROCK TYPES

The Labrador Trough consists of Paleoproterozoic (2.17 to 1.87 Ga; Rohon *et al.*, 1993; Findlay *et al.*, 1995; Machado *et al.*, 1997) sedimentary and volcanic rocks, collectively known as the Kaniapiskau Supergroup (Zajac, 1974; Wardle and Bailey, 1981; Le Gallais and Lavoie, 1982). The Kaniapiskau Supergroup is subdivided into three sedimentary and volcanic cycles (Figure 2), rocks of which were deposited during the development of a foreland basin on the eastern margin of the Superior Provence (Zajac, 1974; Wardle and Bailey, 1981; Le Gallais and Lavoie, 1982; Clark and Wares, 2005). Cycle 1 (the lower cycle) developed during rifting on the eastern margin of the Superior Craton at least 2.17 billion years ago (Rohon *et al.*, 1993). The immature sandstones and siltstones of the Seaward Formation grade upward into the passive margin sediments of the Attikamagen Group, which includes Le Fer Formation siltstone and shale, Denault Formation dolomite, Fleming Formation chert breccia and Dolly Formation shale and siltstone. Cycle 2 is a transgressive sequence that progresses from shelf-type rocks of the Wishart Formation (sandstone and siltstones) and the Sokoman Formation (iron formation) at the base to deeper water turbidites of the Menihek Formation at the top. The intermediate to mafic volcanic rocks of the Nimish Formation are interbedded with the Sokoman Formation in the Dyke Lake area (Evans, 1978). A syenite cobble from a polymictic conglomerate in the Nimish Formation yielded a U–Pb age of 1877.8 ± 1.3 Ma, which was interpreted as an approximate age for the coeval Sokoman Formation (Findlay *et al.*, 1995). In places, Cycle 2 is unconformably overlain by the Tamarak River Formation arkoses (Cycle 3), which are interpreted as a syn-orogenic molasse.

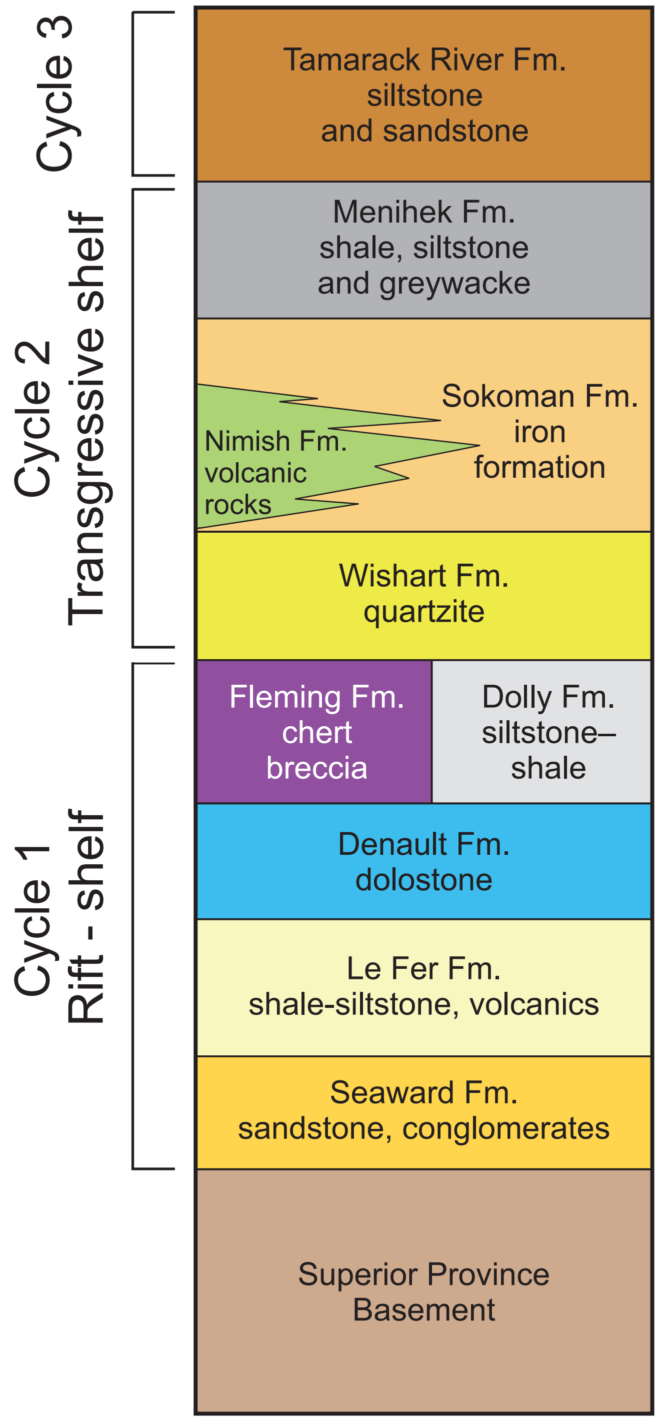

Figure 2. *Simplified stratigraphy of the Kaniapskau Supergroup.*

The iron-ore deposits in the Labrador Trough are hosted in the Sokoman Formation, a 30- to 350-m-thick sequence of cherty iron-rich sedimentary rocks that can be correlated throughout the Labrador Trough. Stratigraphic and sedimentological studies in the Schefferville area have shown that the Sokoman Formation was deposited in a shallow to moderately deep shelf environment (Zajac, 1974; Pufahl *et al.*, 2014), and is characterized by significant lateral and vertical facies variations that represent changes in basin architecture and relative sea levels. The base of the Sokoman Formation is commonly marked by a dark-green to black ferruginous shale containing minor tuffs, sometimes called the Ruth Formation (Zajac, 1974). Above this the Sokoman Formation has traditionally been subdivided

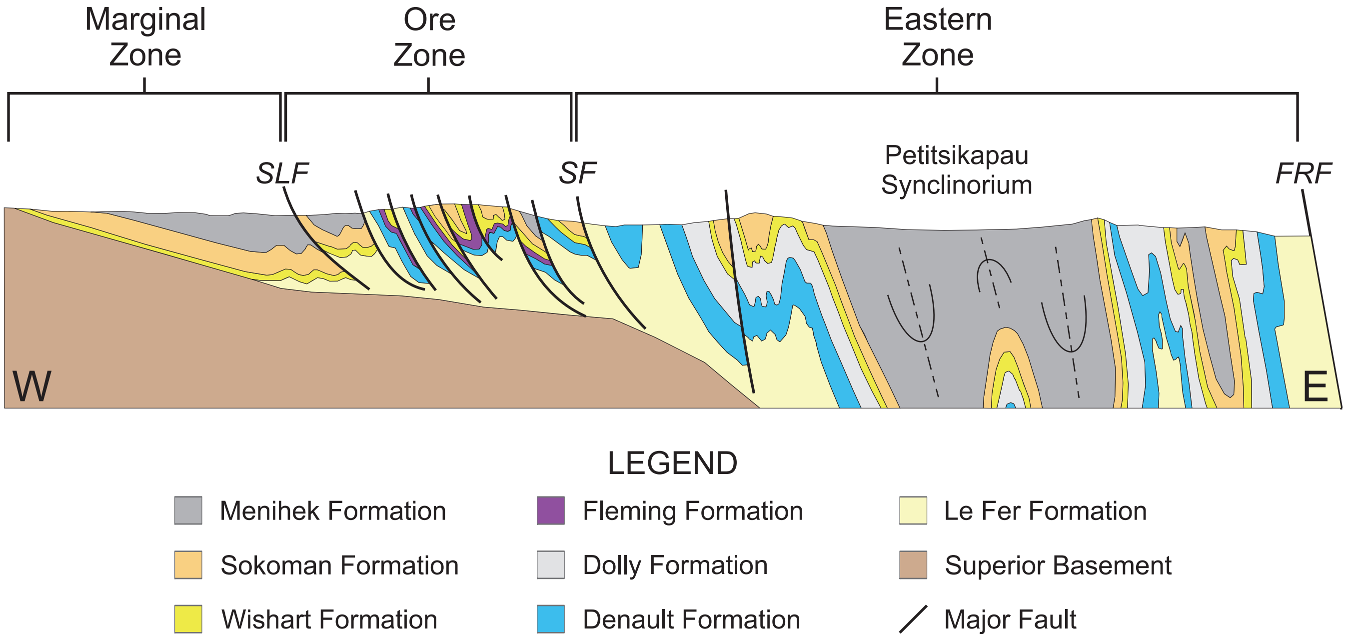

Figure 3. *Schematic cross-section through the Labrador Trough (adapted from Wardle, 1982a, b), showing the structural style of the Marginal, Ore and Eastern zones as defined by Harrison* et al. *(1972). SLF = Stakit Lake Fault; SF = Schefferville Fault; FRF = Ferrum River Fault.*

into three broadly defined units, termed the Upper, Middle and Lower Iron formations. The Lower Iron Formation consists mostly of a magnetite-poor carbonate–silicate facies. This grades upward into the Middle Iron Formation, an oxide facies marked by abundant coarse-grained hematite and/or magnetite and sugary-textured quartz. These oxide-rich beds are the most economically important, and the iron-rich layers and lenses commonly contain more than 50% hematite and magnetite. The Upper Iron Formation is another oxide-poor, carbonate–silicate facies rock.

The stratigraphy on the eastern margin of the Labrador Trough is less well understood because of poor outcrop and less intense exploration activity. Regional-scale government and limited small-scale company mapping have identified the same main units described in the Sokoman Formation of the Schefferville area (Dufresne, 1950; Evans, 1978; Wardle, 1979; Lachance, 2015), although the stratigraphy differs somewhat. The Lower Iron Formation consists of thinly laminated ferruginous cherts and mudstones, both of which contain thin magnetite-rich layers. The Lower Iron Formation is often indistinguishable from the Ruth Formation shales in the field (Lachance, 2015). The Middle Iron Formation consists of blue-grey weathering iron oxide-rich cherts, containing magnetite and hematite as the dominant oxides. The Upper Iron Formation is thin (<20 m) and is absent in many areas; where present it consists of iron silicate or carbonate-rich iron formation with minor magnetite (Wardle, 1979; Lachance, 2015). In the southern part of the study area the Sokoman Formation is interbedded with the intermediate to mafic volcanic rocks of the Nimish Formation (Evans, 1978; Wardle, 1979; Watanabe, 1996). The Nimish Formation consist of a thick (up to 1700 m) sequence of alkali basalts with minor intermediate and felsic differentiates, which are believed to represent the products of localized crustal extension (Watanabe, 1996). In addition, the Wishart and Sokoman formations are intruded by a number of pretectonic gabbro sills, which may relate to the Nimish volcanism or later volcanic events (Evans, 1978; Watanabe, 1996).

TECTONIC AND STRUCTURAL SETTING

The Labrador Trough forms the western part of the larger New Québec Orogenic belt, which records the oblique convergence and collision of the Archean Superior Craton to the west and an Archean core zone to the east at 1.82 to 1.77 Ga (Wardle *et al.*, 1990, 2002). Harrison *et al.* (1972) subdivided the rocks of the Kaniapiskau Supergroup in the Labrador Trough into three zones, based on their structural geology (Figures 1 and 3). The westernmost allochthonous Marginal Zone consists of the Wishart, Sokoman and Menihek formations, which lie on the Superior Province basement rocks (Figure 3). The eastern boundary of the Marginal Zone is marked by a major fault (Stakit Lake Fault; Figures 1 and 3). East of the Stakit Lake Fault the Kaniapiskau Supergroup is repeated by a series of high-angle reverse faults and tight folds (Figure 3). This zone was termed the Ore Zone by Harrison *et al.* (1972) and includes the major soft DSO deposits of the Schefferville area (Figure 1). The characteristic fold and thrust structural style of the Ore Zone is believed to be related to the stratigraphy of the zone (Harrison *et al.*, 1972), with competent layers (Denault, Fleming, Wishart and Sokoman formations) separated by a number of incompetent shale layers (Le Fer, Ruth and Menihek formations), which would act as "decollements" for thrust planes. Although Harrison *et al.* (1972) only described the structural geology of the Schefferville area, it is likely that the fold and thrust geometry of the Ore Zone extends northward at least to the Goodwood–Kivivic zone, ~45 km northwest of Schefferville. The southern extent of the Ore Zone is less well understood due to a lack of outcrop, but is it likely that in the Astray Lake area, the Ore Zone is absent and Marginal and Eastern zones are separated by the Stakit Lake Fault.

The area to the east of the Schefferville and Astray Lake faults (Figure 1), called the Eastern Zone by Harrison *et al.* (1972), is characterized by open to tight folds and more widely spaced faults (Figure 3). The most prominent structures are the Petitsikapau Synclinorium and the Hollinger Lake Anticline, which have a northwestern trend in the northern sector of the Eastern Zone, and have been rotated clockwise due to late-stage sinistral-slip movement on the Mina Lake Fault in the southern sector of the zone (Wardle, 1979). The intricate pattern of folds and faults evident in the Ore Zone was likely inhibited by the greater thicknesses of some units, particularly the Denault, Dolly and Menihek formations (Harrison *et al.*, 1972). In addition, the presence of significant thicknesses of Nimish Formation volcanic rocks (and associated gabbro sills) in the southern part of the Eastern Zone may have contributed to its overall rigidity and reduced small-scale deformation. The eastern margin of the Eastern Zone is marked by a number of major faults (Ferrum River Fault, Quartzite Lake Fault, Mina Lake Fault; Figure 1).

GEOLOGICAL CHARACTERISTICS OF HIGH-GRADE IRON-ORE DEPOSITS IN THE EASTERN LABRADOR TROUGH

A description of some of the main high-grade iron-ore deposits in the Eastern Zone, based on fieldwork carried out by the author in 2012, 2013 and 2014, as well as published and unpublished company data (press releases and assessment files) are presented below. Three main zones have been the focus of much of the recent exploration, the Sawyer Lake, Joyce Lake and Houston–Malcolm areas (Figure 1). Each of these areas are discussed, including results of exploration programs and a description of iron enrichment associated with each deposit. In addition, other important zones of iron enrichment in the Eastern Zone are briefly discussed.

SAWYER LAKE AREA

The Sawyer Lake deposit was described in detail by Conliffe (2014), and will be only briefly considered here. It is located approximately 65 km southeast of Schefferville (Figure 1), where it underlies a small hill ~1.5 km northwest of Sawyer Lake. Exploration by LM&E in the 1930s and 1940s demonstrated that the Sawyer Lake deposit represents a large orebody that is distinct from the soft DSO ores of the Schefferville area. Although no NI-43-101 compliant mineral-resource calculation is available for the Sawyer Lake deposit, estimates by LM&E and Iron Ore Company of Canada (IOC) geologists vary from 3 to 16 million tonnes of high-grade (>65%) iron ore. Recent exploration by Labrador Iron Mines (LIM) included prospecting, mapping, trenching and diamond drilling around the main deposit.

The deposit is hosted in the Lower Sokoman Formation, below a thick sequence of Nimish Formation volcanic rocks (Figure 4). It is located on the crest of a small north-plunging anticline on the eastern limb of the larger syncline, and cross-sections through the orebody show that it forms a stratiform body with a saddle reef-like structure (Conliffe, 2014). Two main rock types have been described from the Sawyer Lake deposit by Conliffe (2014). High-grade hematite ore consists of dark-grey to blue, hard hematite with a metallic lustre (Plate 1A). It is massive to weakly layered and consists of >90% fine-grained (<10 μm) microplaty hematite with minor quartz and magnetite. Layering is subtle and defined by quartz-rich layers, or variations in porosity from 0 to 20% (Plate 1A), and is interpreted to represent original textures (Conliffe, 2014). Locally, the high-grade hematite is brecciated (Plate 1B), which indicates that open space was created during or after the main mineralizing event, due to the dissolution of cherty layers. The main orebody is surrounded by fine-grained iron formation, which consists of alternating blue hematite-rich layers and pink to white cherty layers, ranging in thickness from 1 to 20 mm (Plate 1C).

Recent exploration and drilling by Mamba Minerals Limited have focused on the area north of the Sawyer Lake deposit (Figure 4). A number of drill targets were identified by combined magnetic and ground gravity surveys, the largest of which is the CLC deposit (Lyons and Brown, 2013). The CLC deposit is located along strike from the Sawyer Lake deposit in the same stratigraphic position. In total, altered and enriched iron formation was encountered in nine drillholes along a total strike length of more than 4 km. The altered iron formation has a true width of up to 150 m (Lyons and Brown, 2013), with grades of 52% Fe over 101 m and a number of high-grade intervals of >60% Fe (Mamba Minerals Limited, press release, May 3, 2014).

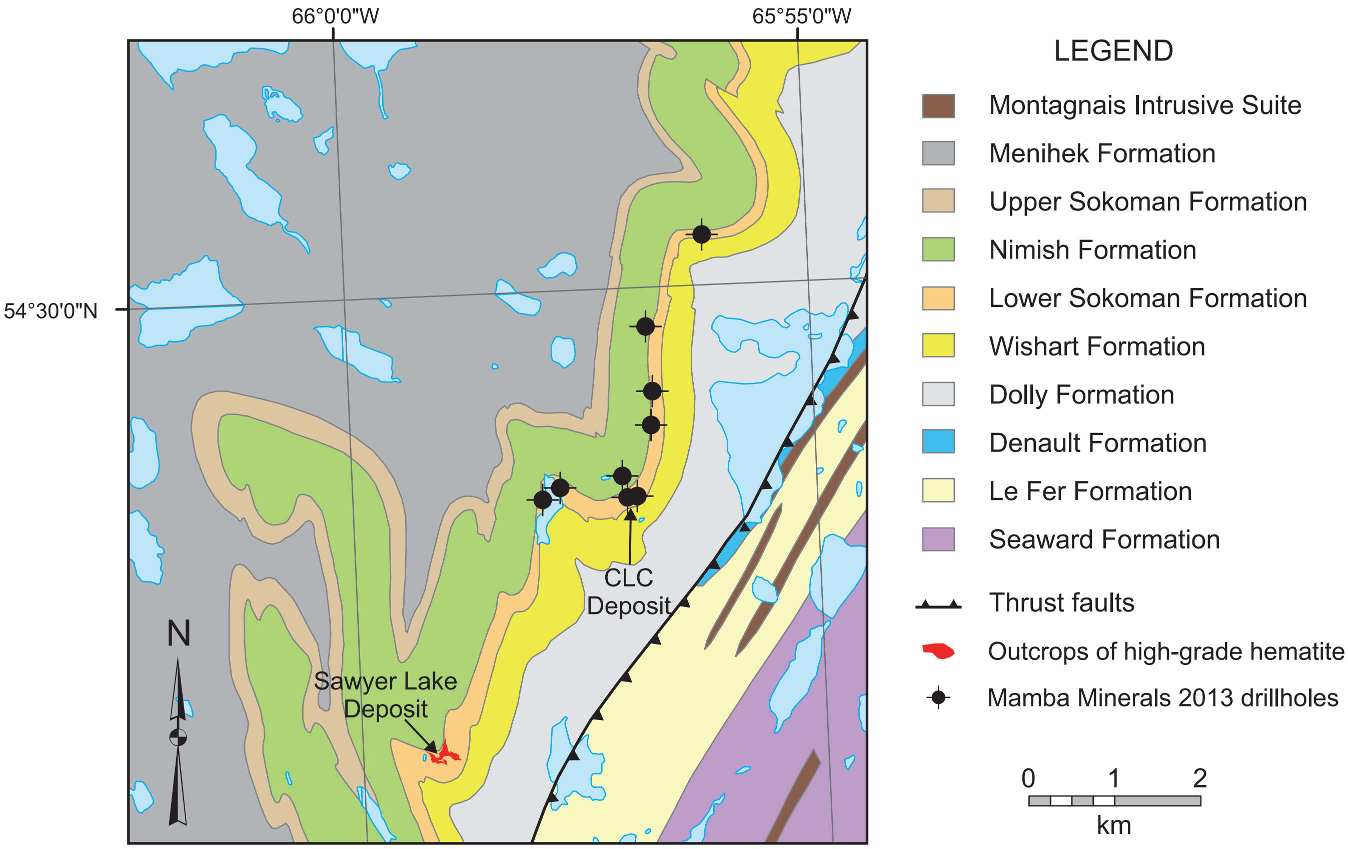

Figure 4. *Simplified geological map of the region around the Sawyer Lake and CLC deposits (modified after Dufresne, 1950, and Gross, 1968).*

Based on geophysics, field mapping and drilling, it is clear that the CLC deposit is structurally complex, with multiple phases of folding and faulting (Lyons and Brown, 2013). Iron enrichment is similar to the Sawyer Lake deposit, with narrow (<5 m) zones of high-grade, hard, blue hematite ore (Plate 1D) surrounded by altered iron formation (Plate 1E). No unaltered iron formation has been reported from any of the drillholes, and the lower contact of the altered iron formation with the pyrite-bearing shales of the Ruth Formation or Nimish Formation volcanics and/or sills is sharp. High-grade hematite consists predominantly of microplaty hematite (locally altered to goethite) with minor quartz and quartz-filled vugs. Minor brecciation is also recorded. The altered iron formation consists of alternating layers of blue hematite and white to pink chert. Evidence of iron remobilization is common, with late-stage hematite veinlets (Plate 1F) and secondary hematite overgrowing chert layers (Plate 1G). The iron formation is also altered by late-stage fluids, with abundant goethite staining (Plate 1H) and goethite-filled vugs. This alteration is most pronounced close to north-northwest-striking faults (Lyons and Brown, 2013), indicating that these structures were conduits for the late influx of groundwater.

JOYCE LAKE DEPOSIT

The Joyce Lake deposit is located 20 km northeast of Schefferville, on a peninsula in Attikamagen Lake (Figure 5). Although exploration by LM&E in the 1940s reported the presence of high-grade (>69% Fe) hard, blue hematite with a strike length of more than 300 m, the Joyce Lake deposit was not considered large enough to meet the one million tonne minimum used to define economic ore deposits in the Schefferville area (Burgess, 1951). Little further work was done on the property until 2008, when detailed geological mapping combined with an airborne magnetic geophysical survey identified a DSO target, which was subsequently confirmed by Labec Century Iron Ore Inc. based on ground gravity data, surface geological mapping and sampling. From 2010 to 2013, Labec Century completed 176 drillholes and 16 trenches on the property and collected three 10-tonne bulk samples for metallurgical test work, which Duplessis (2014) used to calculate a measured and indicated resource for the Joyce Lake deposit of 24.3 million tonnes at 58.6% Fe (50% Fe cut-off).

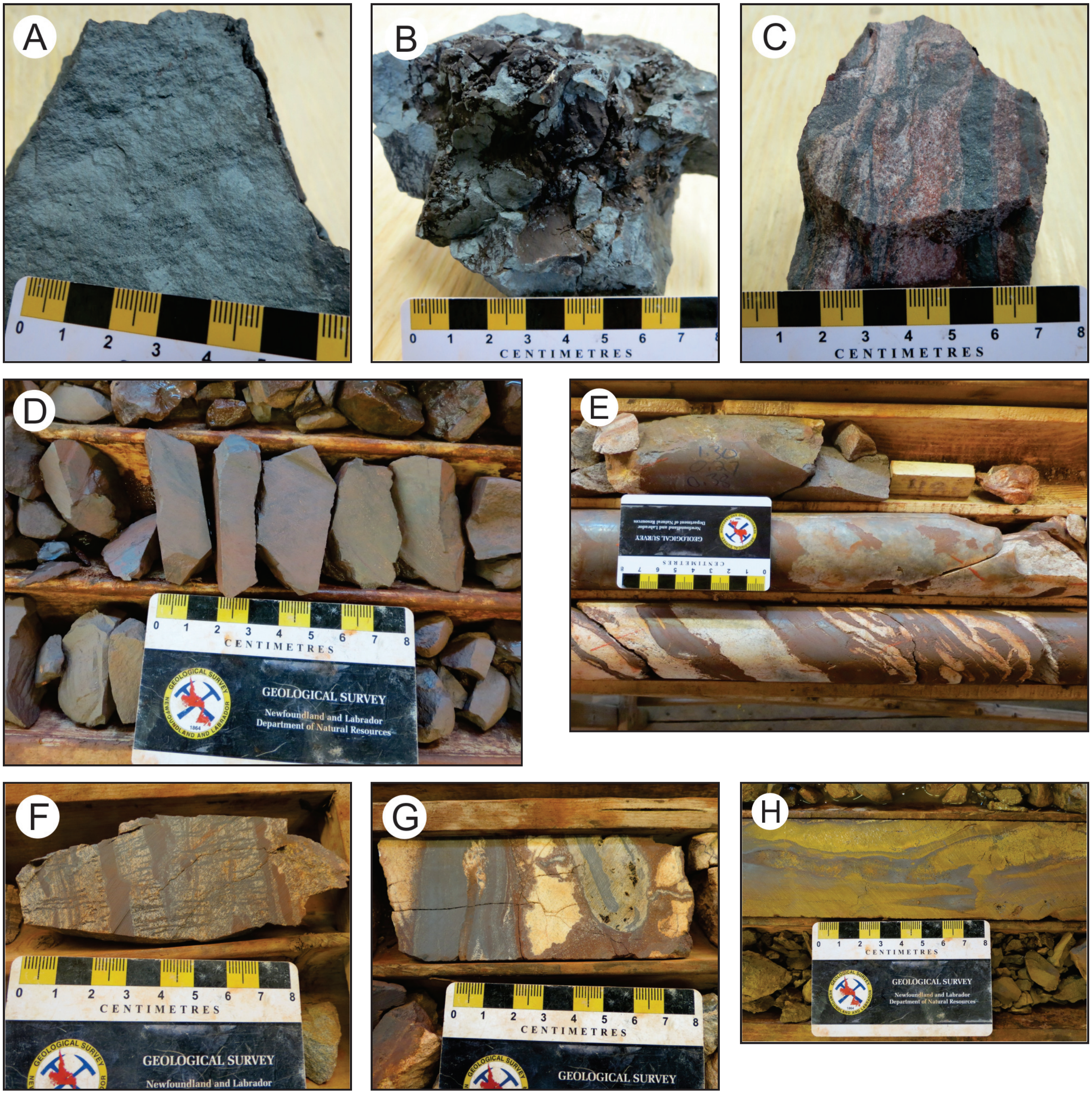

Plate 1. *A) High-grade hematite ore showing subtle layering defined by variations in porosity, Sawyer Lake deposit; B) Brecciated high-grade hematite ore, Sawyer Lake deposit; C) Layered altered iron formation, Sawyer Lake deposit; D) Massive high-grade hematite ore, CLC deposit; E) Altered iron formation with white chert and red/blue hematite layers, CLC deposit; F) Altered iron formation with hematite veinlets crosscutting chert layer, CLC deposit; G) Altered iron formation with secondary hematite overgrowing chert layers, CLC deposit; and H) Late-stage limonite alteration in iron formation, CLC deposit.*

At Joyce Lake, the iron enrichment occurs within the nose of northwest-southeast-trending syncline that plunges to the southeast at approximately 42° (Duplessis, 2014). This folding was accompanied by shorting of the limbs of the fold, with volume change accommodated by numerous hematite- and specularite-filled tension gashes. Two main stratabound zones of high-grade hematite ore have been recorded, a series of discontinuous ore bodies near the top of the Middle Iron Formation and a more continuous and extensive zone at the base (Figure 5). Enrichment to >50%

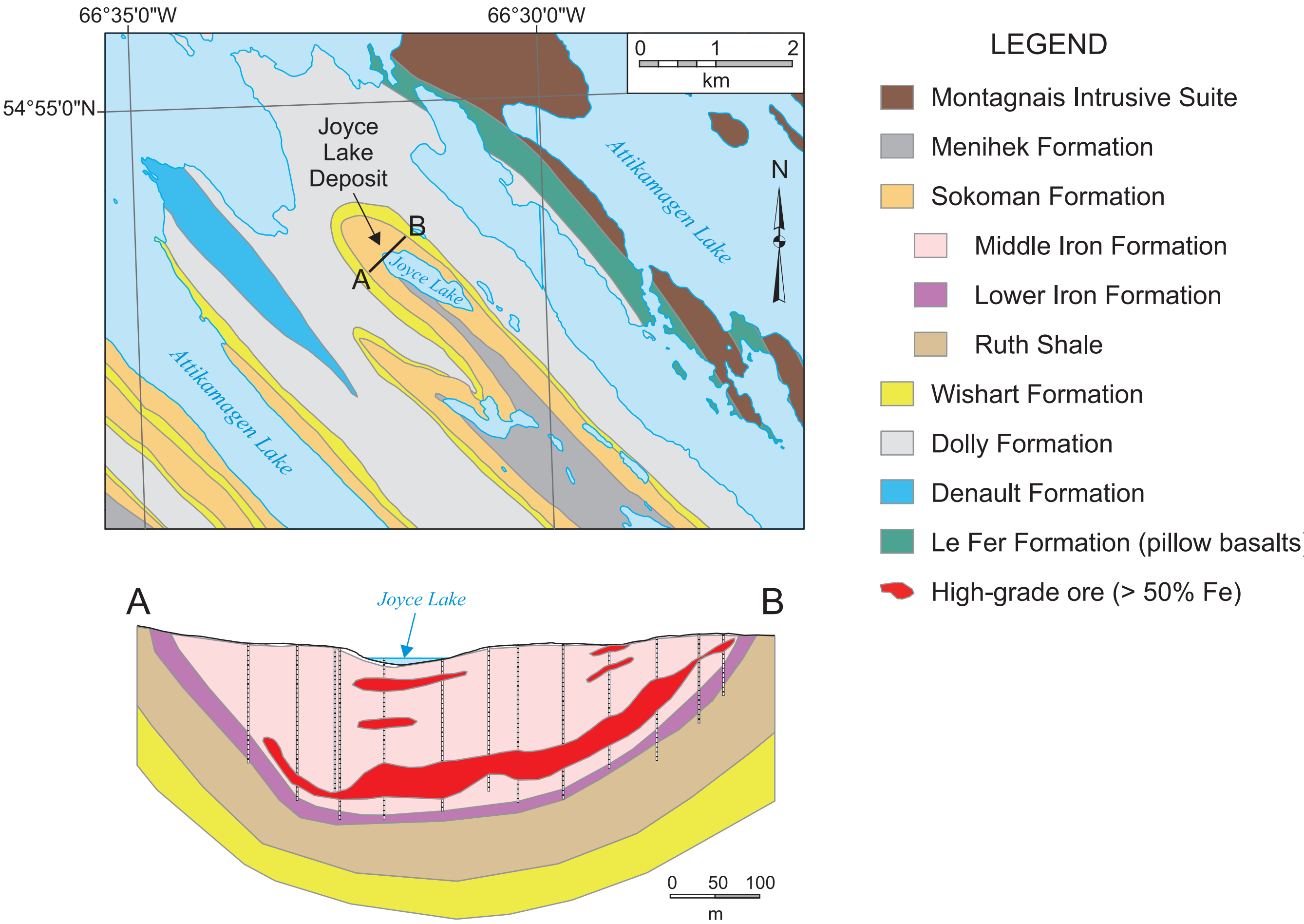

Figure 5. *Simplified geological map of the region around the Joyce Lake deposit (modified after Burgess, 1951, and Wardle, 1982a) and cross-section (A-B) through the deposit subdivision of the Sokoman Formation.*

Fe has been recorded to depths of 190 m, and does not always persist to the surface.

The ore at Joyce Lake consists of massive to weakly laminated, hard, blue ore (Plate 2A), with rare pockets of soft friable hematite. The massive hard ore consists of >90% hematite (locally replaced by goethite) with minor interstitial quartz and goethite and low to moderate porosity. In the laminated ore, the original layering in the iron formation has been preserved during iron enrichment (Plate 2B). The iron-rich layers of the iron formation protolith are completely replaced by patchy to microplaty hematite (Plate 3A), whereas original chert layers are characterized by higher porosity (commonly vuggy) and consist of martite crystals surrounded by fine-grained hematite and goethite (Plate 3B), suggesting at least two phases of iron enrichment. In places, the massive hematite ore is brecciated (Plate 2C), with fragments of massive ore (partially altered to goethite) cemented by microplaty hematite, goethite, quartz and rarely Mn-oxides (Plate 3C).

The iron formation surrounding the high-grade hematite ore is strongly altered and composed of pink to bleached white chert-rich layers and blue to red iron-oxide-rich layers (Plate 2D). The chert-rich layers retain primary sedimentary fabrics (*i.e.*, fabric retentive) and consist of cryptocrystalline (<5 µm) to microcrystalline (<50 µm) quartz and microplaty hematite with rare spongy hematite and iron silicates recorded in the cores of peloids. Secondary hematite is common, where it occurs as fine disseminations in the chert (giving the chert its pink hue), replacing primary fabrics such as peloids (Plate 3D), as irregular patches (likely after iron silicates) and forms pseudomorphs after magnetite grains (martite). The chert-rich layers are commonly strongly leached and vuggy and crosscut by hematite and quartz veinlets (Plate 2E), consistent with silica leaching and iron remobilization during alteration. The iron-oxide-rich layers consist predominantly of microplaty and patchy hematite and martite, with minor interstitial quartz, and have low to moderate porosity. In both the chert-rich and iron-rich layers, goethite partially replaces hematite and infills vugs and secondary pore spaces.

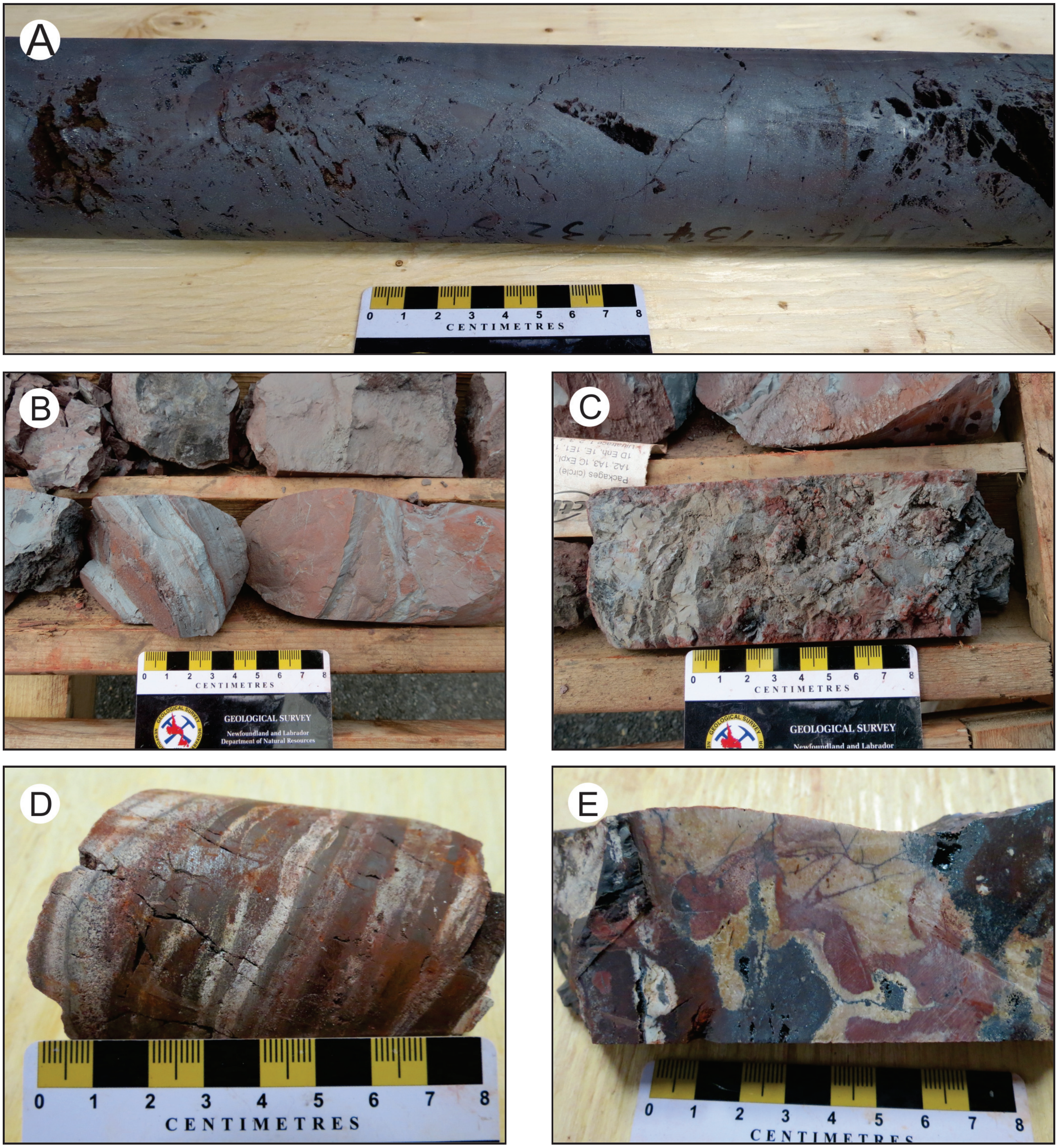

Plate 2. *Photographs of representative rock types from the Joyce Lake deposit. A) Massive to weakly laminated and vuggy high-grade hematite ore; B) Laminated high-grade hematite ore; C) Brecciated high-grade hematite ore; D) Altered iron formation with white chert and red/blue hematite layers; and E) Altered iron formation with secondary hematite overgrowing chert layers and hematite veinlets.*

HOUSTON AND MALCOLM DEPOSITS

A series of at least seven individual DSO deposits are located 10 to 20 km southeast of Schefferville, on the western margin of the Eastern Zone. These deposits are hosted within a 20 km belt of iron formation that crosses the

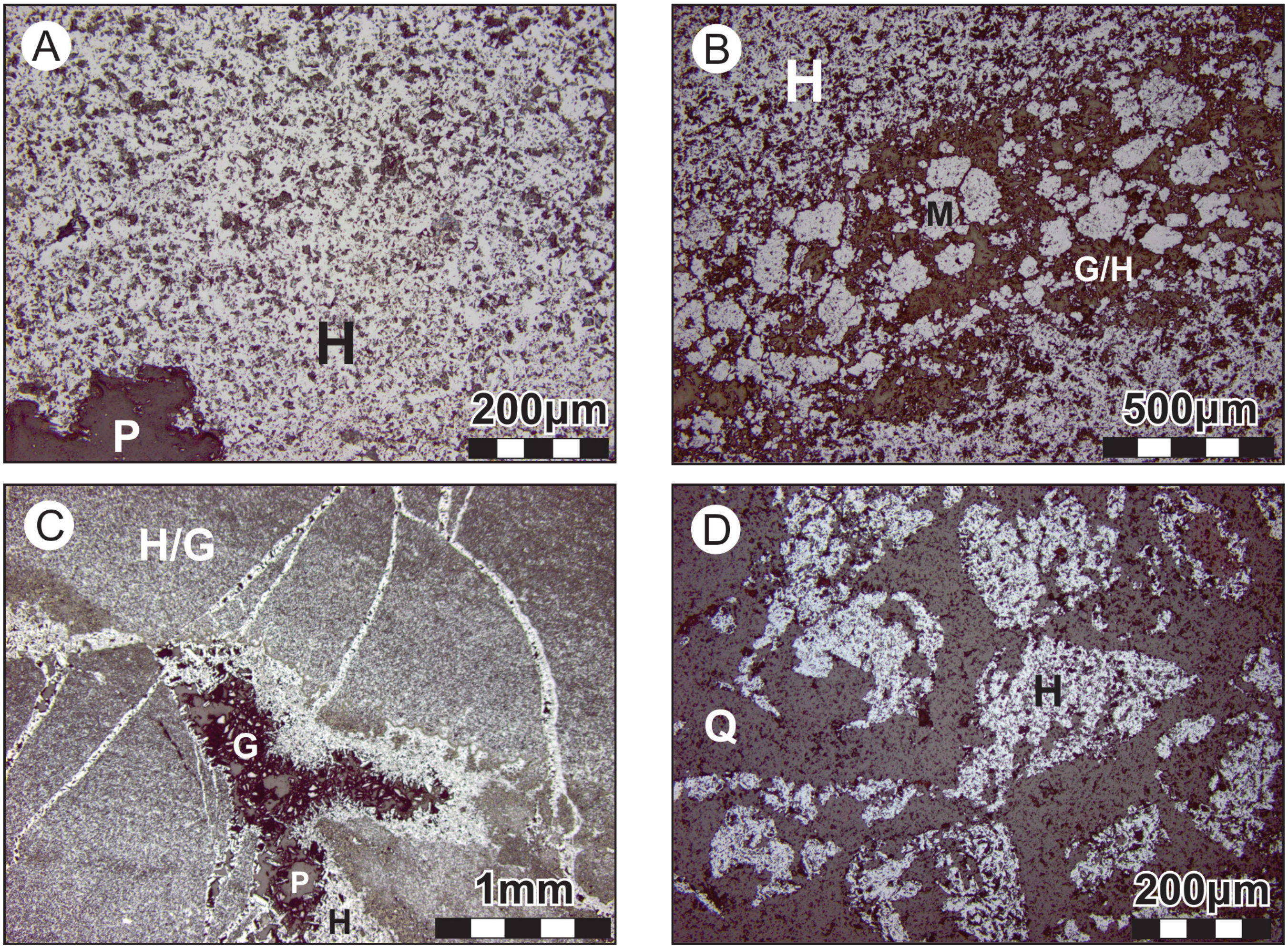

Plate 3. *Photomicrographs of high-grade and altered iron formation samples, Joyce Lake deposit (reflected light). A) Microplaty hematite in massive high-grade hematite ore; B) Martite crystals and hematite and goethite replacing chert layer in laminated high-grade hematite ore; C) Brecciated high-grade hematite ore, showing fragments of hematite and goethite and vug filled with hematite and goethite; and D) Secondary microplaty hematite after peloids in altered iron formation. H = hematite; P = pore space; G = goethite; Q = quartz.*

provincial border between Newfoundland and Labrador and Québec (Figure 6). The deposits in Labrador are called the Houston deposits and the deposits in Québec are called the Malcolm deposits. Detailed mapping and prospecting by LM&E discovered all the known ore bodies by 1950 (Gilman, 1950). Further exploration by LM&E and IOC from 1950 to 1982 included trenching and diamond drilling, and the project was at an advanced exploration stage when the Schefferville mines closed in 1982. Labrador Iron Mines (LIM) began preliminary exploration at the Houston deposit in 2005, and from 2006 to 2012 LIM completed 42 diamond-drill holes and 238 reverse circulation drillholes. In addition, 33 reverse circulation drillholes were drilled at the Malcolm 1 deposit in Québec. Based on this work, NI 43-101 compliant measured and indicated resource estimates of 30.1 million tonnes (57.7% Fe) for the Houston deposit and 9.2 million tonnes (57.8% Fe) for the Malcolm 1 deposit were calculated (Dupéré and Taylor, 2013). The following description is based on the Houston deposit, but the style of mineralization is similar throughout the belt.

The Houston deposit was historically subdivided into three separate deposits (from northwest to southeast: Houston 2, Houston 1 and Houston 3) but exploration by LIM has shown that these deposits form a continuous band of iron enrichment (Figure 6). At Houston 1 and 2, the iron formation forms a northeast-dipping homocline, becoming almost vertical at Houston 3. The deposit is cut by a number of high-angle reverse faults. Iron enrichment and associated alteration are stratigraphically controlled and high-grade ore occurs at the lower part of the iron formation (Figure 7). This altered zone has a sharp upper contact with a green tuff or an intensely weathered and leached clay-rich unit that may represent altered iron formation or tuff. This unit is

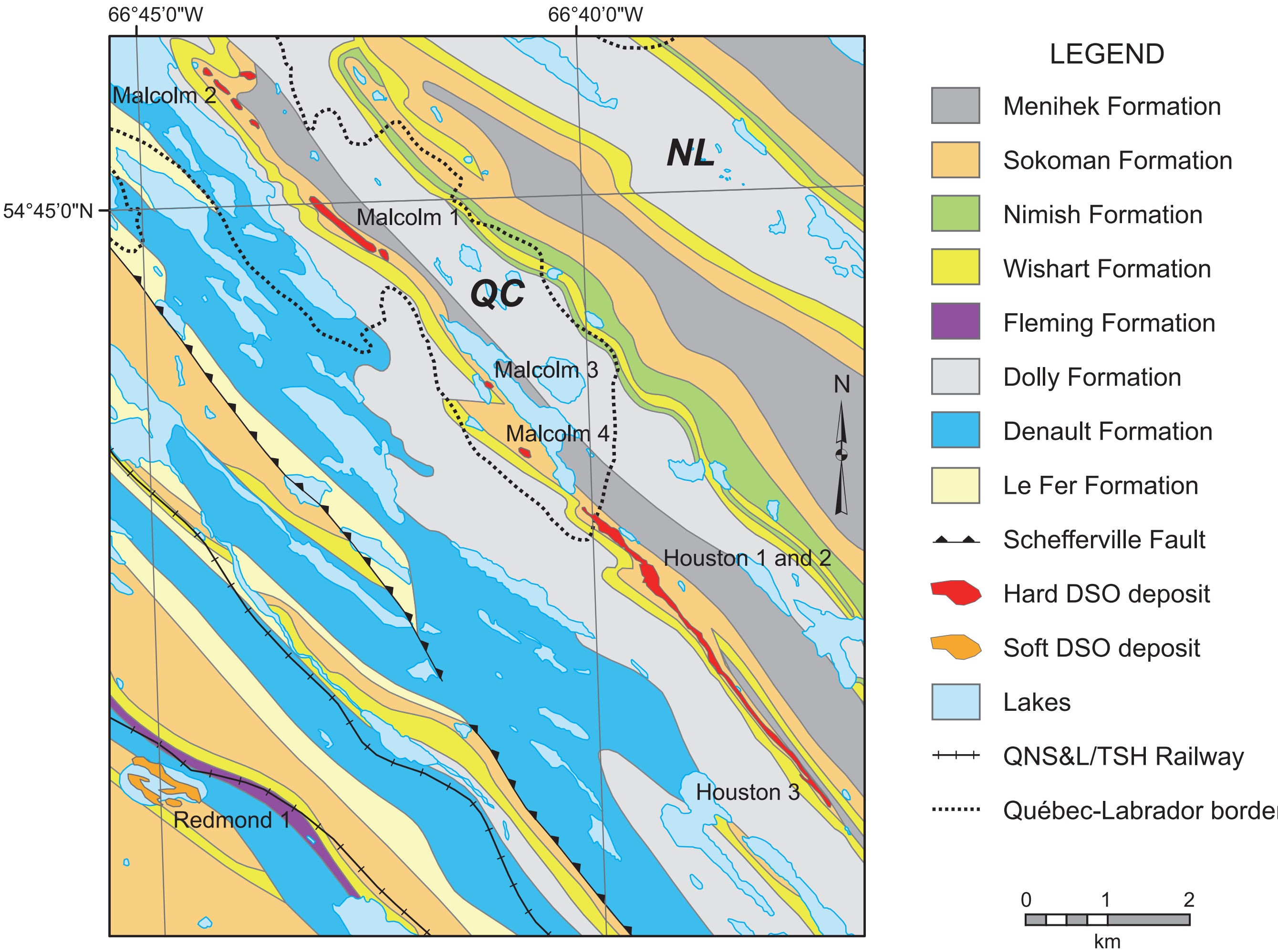

Figure 6. *Simplified geological map of the Malcolm and Houston area, showing the location of the main ore deposits (modified after Wardle, 1982a).*

overlain by essentially unaltered pink to grey, cherty, magnetite-rich iron-oxide formation with minor limonite and pyrolusite staining along fractures. The base of the altered zone is marked by a grey shale with occasional pyritic or graphitic horizons, which may correlate with the Ruth Formation shale or Lower Iron Formation in other deposits.

High-grade ore in the Houston deposit can be subdivided into two main types; 1) hard ore with a massive or semi-massive texture (Plate 4A), and 2) soft, friable ore with lesser fragments of hard ore. The massive to semi-massive hard ore is dominant, and consists of >90% patchy to microplaty hematite (partially altered to goethite) with lesser microcrystalline quartz. Original sedimentary fabrics are preserved, with hematite replacing chert layers in laminated ores and peloids replaced by hematite (Plate 5A). The massive ores are commonly brecciated and vuggy (due to dissolution of silica), with open space filled with specular hematite, goethite and Mn-oxides (Plates 4B and 5B). Soft, friable ore consists of fine-grained hematite and goethite with some larger fragments of hard hematite. This may represent a more porous equivalent of the massive ores that has been subjected to later supergene alteration.

The iron formation outside the main ore body consists of alternating layers of chert and iron oxides (Plate 4C), and is similar to the altered iron formation at Joyce Lake. The chert layers are composed of microcrystalline quartz with disseminated hematite and goethite giving a pink or brown colouration, respectively. Locally the chert is also leached, leaving a sandy quartz-rich residue. The oxide layers are generally more competent and composed dominantly of microplaty to patchy hematite with minor quartz. Secondary alteration of hematite to goethite is common, and in outcrop, strong yellow limonite and red hematite alteration is evident along the boundaries between chert and oxide layers (Plate 4D). In thin section, this is seen as pervasive goethite alteration along the margins of the chert-rich layers (Plate 5C, D).

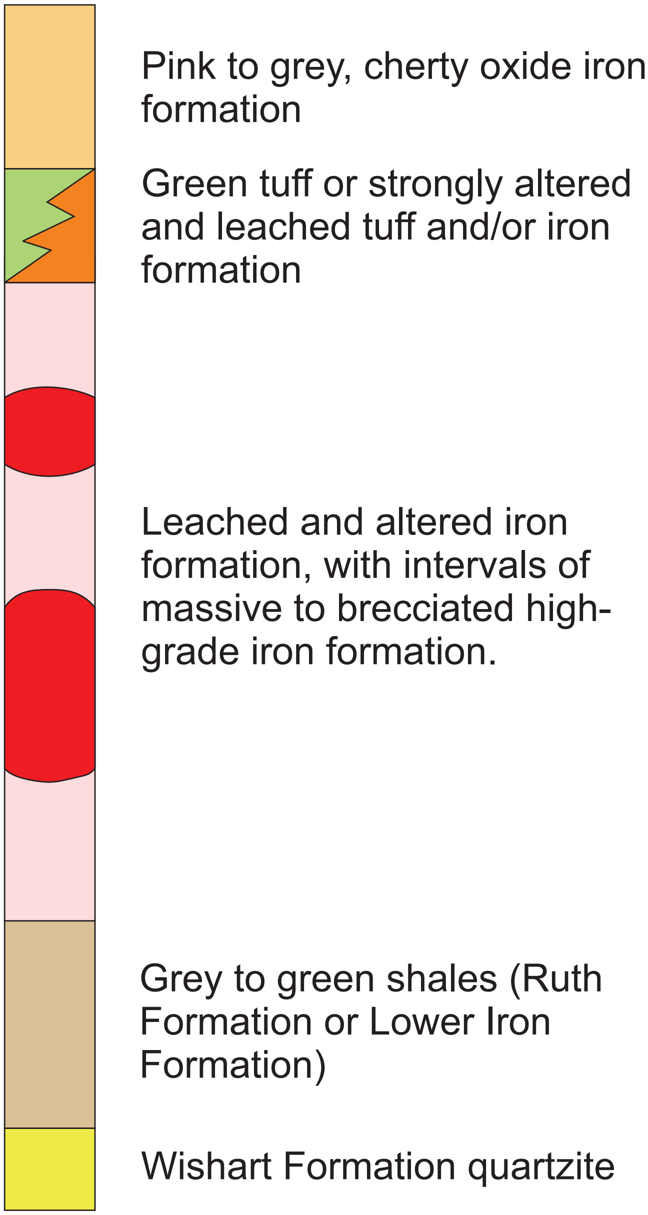

Figure 7. *Simplified stratigraphy of the Sokoman Formation at the Houston deposit.*

In both the high-grade ore zone and the lower grade altered iron formation, fractures and vugs are commonly lined by secondary Mn-oxides (pyrolusite, manganite, manjiroite). Manganese concentrations of up to 24% have been recorded and this enrichment is structurally controlled, with the highest grades associated with folding and faulting along the east-dipping reverse fault system (Dupéré and Taylor, 2013).

OTHER SHOWINGS

Numerous other high-grade iron-ore occurrences have been reported from the Eastern Zone (Figure 1). The most developed of these is the Astray Lake deposit, located on a ridge above the eastern shores of Astray Lake and ~55 km southeast of Schefferville (Figure 1). The deposit was first described by LM&E in 1949, and detailed prospecting and mapping showed that the zone of enrichment extends for the entire peninsula, a strike length of more than 5 km (Usher, 1953). A single reverse circulation hole was drilled on the deposit in 2008 and encountered minor enrichment (Vatcher *et al.*, 2009), but no further work has been carried out on the property. The iron enrichment is located in easterly dipping beds of iron formation below a thick sequence of Nimish Formation basalts. The iron formation consists of jasper iron formation and conglomerate iron formation. It is weakly magnetic and altered, with magnetite partially to completely replaced by hematite (martite) and silica replaced by microplaty hematite. Close to the contact with the overlying basalts, the iron formation is brecciated and cemented by hard, blue hematite.

Other occurrences in the Eastern Zone have not been the focus of detailed exploration, but are broadly similar to other high-grade deposits. The Prudhomme occurrence is located along strike from the Joyce Lake deposit in a similar structural setting (Figure 1). Iron enrichment was reported by LM&E, with assays from two samples indicating enrichment to 50-60% Fe (Hagen, 1952). This occurrence is located in the trough of a southeast-plunging syncline that is crosscut by a steeply dipping northwest-striking fault. Several small zones of iron enrichment have also been reported from the southern part of the Eastern Zone. Iron enrichment at Ashuanipi Island consists of layered hematite and pink chert, with chert layers being partly to completely replaced by secondary hematite and hydrothermal quartz. Similar enrichment has been reported from Shoal Lake, with outcrop samples containing 62.3% Fe (Perrault, 1952). Another belt of occurrences has been reported close to Kyra Lake, where trenching and test pitting by LM&E encountered a broad zone of altered and enriched iron formation (38.7 to 56% Fe; Perrault, 1952).

WHOLE-ROCK GEOCHEMISTRY

METHODS

Samples of high-grade ore and associated altered iron formation (outcrop and drillcore samples) were collected from the Sawyer Lake, CLC, Joyce Lake, Houston and Malcolm deposits in the eastern Labrador Trough. Seventeen high-grade ore samples and 29 samples of altered iron formation were selected for geochemical analysis. In addition, three samples of Mn-rich ores were selected from the Houston and Malcolm deposits. All surface weathering was removed from outcrop samples and a representative slab was prepared for geochemical analysis at the GSNL Geochemistry Laboratory in St. John's. Samples were milled

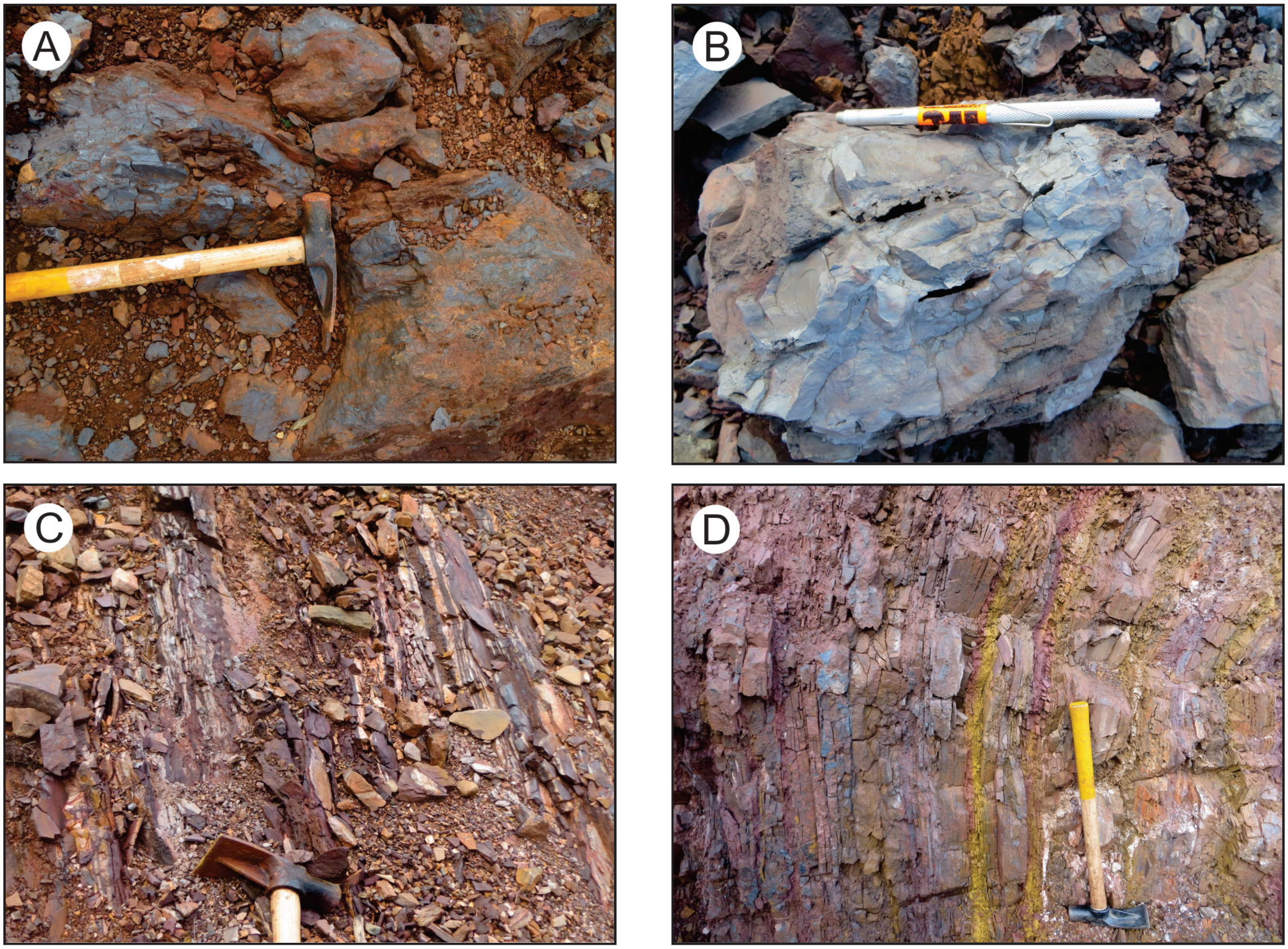

Plate 4. *Photographs of representative rock types from the Houston deposit. A) Massive high-grade hematite ore exposed in trench; B) Brecciated high-grade ore, with goethite and Mn-oxides filling vugs; C) Altered iron formation exposed in bulk sample pit; and D) Altered iron formation, with red hematite and yellow limonite alteration along bedding planes.*

using ceramic and tungsten carbide mills, and due to possible contaminations from the tungsten carbide mill, W and Co values are not reported. Major-element compositions were analyzed by ICP-OES methods, following lithium tetraborate and metaborate fusion. Rare-earth elements and selected trace elements were determined by ICP-MS analysis following an identical sample digestion procedure, whereas the remaining trace elements (Be, Cu, Li, Mn, Ni, Pb, Rb, Sc, Ti, Zn) were analyzed by ICP-MS after total acid digestion. In order to determine accuracy, reference standards and analytical duplicates were inserted at a frequency of one in 20.

RESULTS

The major-element, trace-element and rare-earth element (REE) compositions of high-grade ore, altered iron formation and high-Mn ore samples are summarized in Table 1. SiO_2 and Fe_2O_3 are the dominant major elements in high-grade ore and altered iron formation samples, having >90 wt. % total SiO_2 + Fe_2O_3 contents. Other constituents have low concentrations, with MnO and Al_2O_3 contents of >1 wt. % and other elements generally >0.10 wt. %. Manganese-rich ores from the Houston and Malcolm deposits are characterized by MnO values of up to 35 wt. %. LOI ranges from 0.24 to 5.88 wt. %, the higher values reflecting the presence of significant amounts of goethite.

In Figure 8, the major-element composition of high-grade ore and altered iron formation from the three study areas have been normalized to the average composition of unaltered taconites in the Eastern Labrador Trough. Unaltered taconite compositions are calculated from data in Lachance (2015) and from this author's unpublished data. High-grade ores show enrichment of Fe_2O_3 with a corresponding depletion of SiO_2, whereas altered iron-formation samples have similar SiO_2 and Fe_2O_3 contents as the unaltered taconites. All samples are moderately to strongly

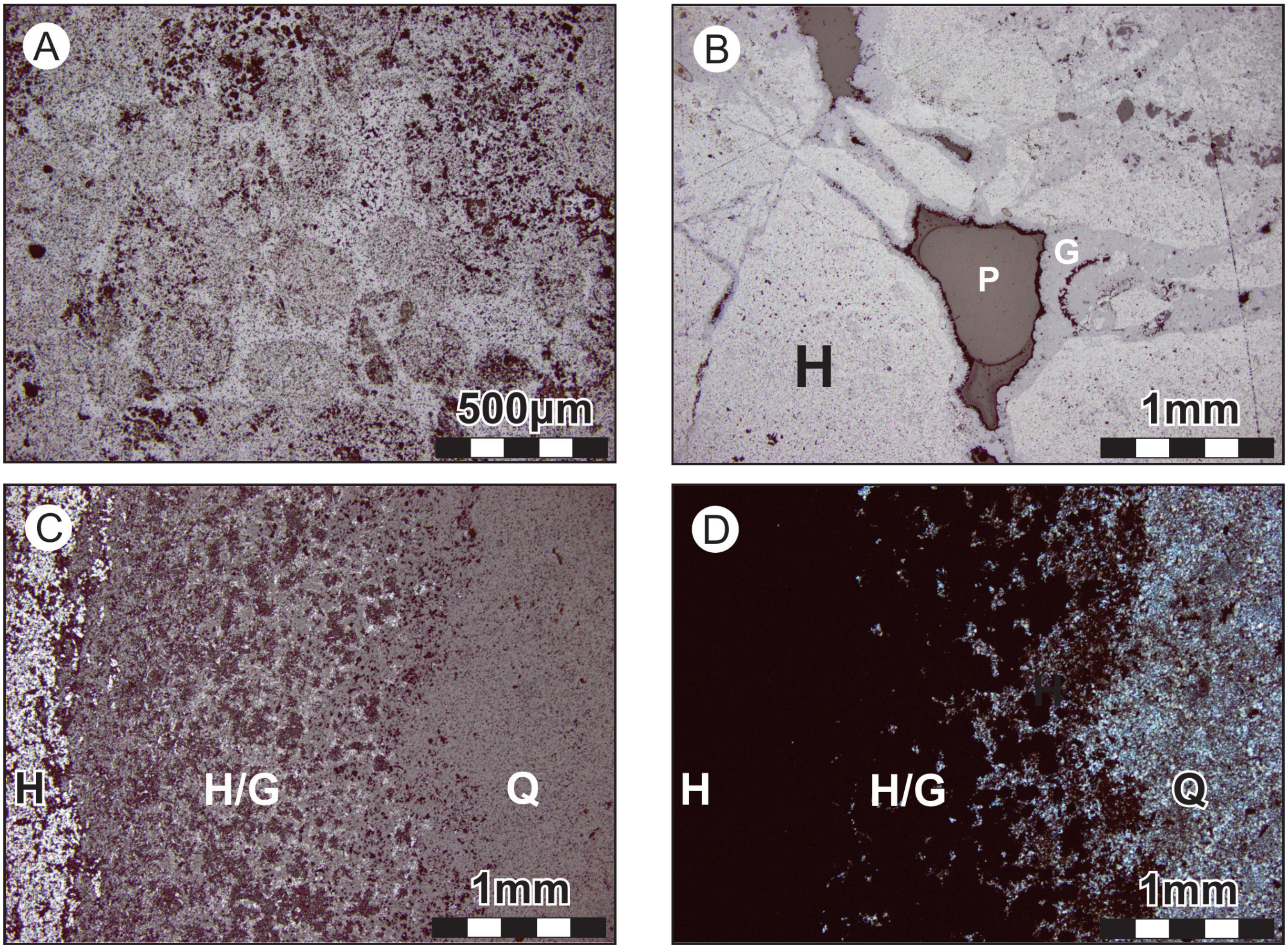

Plate 5. *Photomicrographs of high-grade and altered iron formation samples, Houston deposit. A) Massive high-grade hematite ore with peloidal texture (reflected light); B) Brecciated high-grade ore with hematite fragments and secondary goethite filling vugs (reflected light); C) Boundary between hematite and chert layers in altered iron formation, with late-stage goethite alteration between layers (reflected light); and D) Same view in cross-polarized light. H = hematite; P = pore space; G = goethite; Q = quartz.*

depleted in MgO, CaO and Na_2O (mobile elements) and weakly depleted to unchanged in Al_2O_3 and TiO_2 (immobile elements). With the exception of MnO contents of altered iron formation at the Houston and Malcolm deposits, samples from all areas are weakly to moderately enriched in MnO and P_2O_5.

The trace-element contents are usually low (<50 ppm, most values <10 ppm), but some samples are enriched (>100 ppm) in selected trace elements *e.g.*, Sr, Ba, V, Zn (Table 1). These anomalous values are attributed to residual enrichment and/or late-stage weathering and no systematic variation in trace-element compositions was recorded.

The total REE contents (Σ REE) of all samples ranges from 2.6 to 360 ppm, with most samples having Σ REE of <100 ppm (Figure 9A, B). When normalized to PAAS (Post-Archean Australian Shale; McLennan, 1989), high-grade ore samples usually are weakly to moderately enriched in HREE (La/Yb_{PAASN} <1) compared to the average unaltered taconites (Figure 9A and C). The only high-grade sample that is depleted in HREE is a brecciated ore sample from the margins of a zone of high Mn-ore in the Houston deposit. In contrast, the distribution of REE in altered iron formation is highly variable (Figure 9B and D), with some samples strongly depleted in HREE (La/Yb_{PAASN} >2) and others enriched in HREE (La/Yb_{PAASN} <0.2). Most samples have a positive Eu anomaly (Eu/Eu^*_{PAASN} >1), although this is generally less pronounced than in the average unaltered taconite (Figure 9C, D).

Table 1. Summary statistics for major-element, trace-element and REE content of high-grade hematite ore, altered iron formation and high-Mn ore. [1] La/Yb_{SN} and Eu/Eu^*_{SN} data from the Houston deposit calculated without single anomalous value

	High-Grade Hematite Ore						**Altered Iron Formation**						**High Mn Ore**	
Deposit	Sawyer Lake/CLC		Joyce Lake		Houston/ Malcolm		Sawyer Lake		Joyce Lake		Houston		Houston/ Malcolm	
n	3		8		6		13		9		7		3	
	Av	StDev	Av	StDev	Aver.	StDev	Av	StDev	Av	StDev	Av	StDev	Av	StDev
SiO_2 (wt %)	2.55	3.20	1.61	1.38	2.30	1.50	46.66	12.48	44.95	13.23	63.36	18.60	1.32	1.31
Al_2O_3	0.09	0.05	0.36	0.33	0.17	0.08	0.23	0.18	0.35	0.23	0.21	0.22	0.50	0.24
Fe_2O_3	96.09	2.74	95.43	2.93	94.00	3.06	48.06	12.54	52.31	11.63	34.90	19.26	64.00	13.19
Fe	67.21	1.92	66.68	1.90	65.74	2.14	33.61	8.77	36.59	8.14	24.41	13.47	44.77	9.22
MgO	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01
CaO	0.03	0.01	0.03	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.04	0.02
Na_2O	0.05	0.03	0.04	0.01	0.05	0.03	0.04	0.03	0.02	0.02	0.04	0.03	0.06	0.03
K_2O	0.08	0.07	0.05	0.02	0.07	0.04	0.06	0.03	0.05	0.02	0.07	0.04	1.01	0.27
TiO_2	0.01	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.00	0.01	0.00
MnO	0.16	0.13	0.50	0.53	0.22	0.16	0.30	0.49	0.52	0.72	0.03	0.01	25.68	11.37
P_2O_5	0.03	0.04	0.11	0.05	0.32	0.24	0.05	0.03	0.06	0.03	0.08	0.08	0.08	0.05
LOI	0.48	0.25	1.07	0.52	2.88	2.18	1.06	0.98	0.91	0.35	1.15	0.85	4.92	0.93
Rb (ppm)	12.7	21.1	6.1	2.2	4.8	2.2	2.7	2.1	4.6	1.2	2.9	2.2	13.2	3.3
Sr	3.6	2.3	68.0	116.9	20.9	31.1	9.0	5.6	13.3	6.3	11.6	20.6	28.2	8.5
Ba	10.1	7.9	43.9	52.8	27.8	20.9	83.3	190.3	135.3	297.8	12.7	9.6	1513.4	2629.7
V	55.0	19.8	53.7	19.9	60.5	33.2	55.3	41.7	68.8	41.0	29.6	12.5	45.8	19.4
Cu	12.5	13.0	7.2	5.0	12.6	15.6	5.4	1.3	5.5	1.1	4.5	0.6	5.7	2.0
Zn	48.2	34.8	31.1	8.0	51.9	15.3	20.0	6.9	24.7	8.1	16.2	6.3	75.9	33.5
Y	2.2	1.3	9.6	7.4	12.4	3.7	6.6	5.3	9.7	7.1	3.8	2.4	14.8	11.5
Zr	29.4	1.9	27.3	15.0	25.6	4.8	16.1	8.2	17.6	10.7	9.3	4.0	19.4	2.3
Th	0.2	0.1	0.4	0.4	0.1	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1
U	0.4	0.3	1.9	1.2	0.9	0.7	0.8	0.7	1.2	0.7	0.4	0.4	1.7	1.7
La	1.62	0.83	5.53	4.63	21.96	37.16	4.02	2.49	4.03	2.45	15.86	19.29	20.99	24.73
Ce	2.58	1.27	13.83	9.54	31.40	45.95	7.51	4.74	8.92	6.10	16.33	18.93	39.09	39.82
Pr	0.25	0.14	1.31	1.01	4.08	6.75	0.96	0.82	1.06	0.94	2.18	2.89	5.13	6.57
Nd	1.20	0.73	5.76	4.39	17.40	29.62	4.37	3.88	4.84	4.27	7.94	9.85	24.24	33.06
Sm	0.27	0.18	1.36	0.94	3.51	5.91	0.99	0.82	1.14	0.90	1.06	1.09	5.34	7.26
Eu	0.08	0.07	0.46	0.32	0.94	1.45	0.29	0.25	0.37	0.28	0.27	0.25	1.39	1.60
Tb	0.05	0.00	0.45	0.65	0.39	0.44	0.54	0.82	1.04	1.12	0.11	0.08	0.52	0.46
Gd	0.32	0.25	1.41	1.25	3.17	4.47	0.67	0.56	0.50	0.37	0.81	0.68	4.49	4.91
Dy	0.37	0.25	1.63	1.13	2.21	1.61	0.98	0.72	1.38	0.88	0.63	0.42	2.75	1.95
Ho	0.08	0.04	0.29	0.24	0.42	0.20	0.19	0.16	0.29	0.19	0.11	0.08	0.50	0.35
Er	0.21	0.15	0.93	0.65	1.11	0.34	0.63	0.51	0.94	0.67	0.34	0.23	1.37	0.99
Tm	0.04	0.02	0.11	0.09	0.14	0.06	0.08	0.08	0.13	0.10	0.04	0.03	0.17	0.13
Yb	0.24	0.18	0.75	0.46	0.79	0.17	0.54	0.48	0.82	0.63	0.26	0.15	0.98	0.74
Lu	0.03	0.02	0.11	0.07	0.09	0.07	0.07	0.06	0.11	0.09	0.03	0.03	0.13	0.11
Σ REE	7.3	3.9	33.9	23.8	87.6	133.6	21.7	14.0	25.6	16.8	46.0	51.0	107.1	120.7
La/Yb_{SN}	0.5	0.2	0.7	0.7	0.6 [1]	0.1 [1]	1.1	1.2	0.6	0.5	3.5	2.9	2.0	1.6
Eu/Eu^*_{SN}	1.4	0.2	1.4	0.1	1.3 [1]	0.2 [1]	1.4	0.2	1.3	0.2	1.2	0.3	1.4	0.4

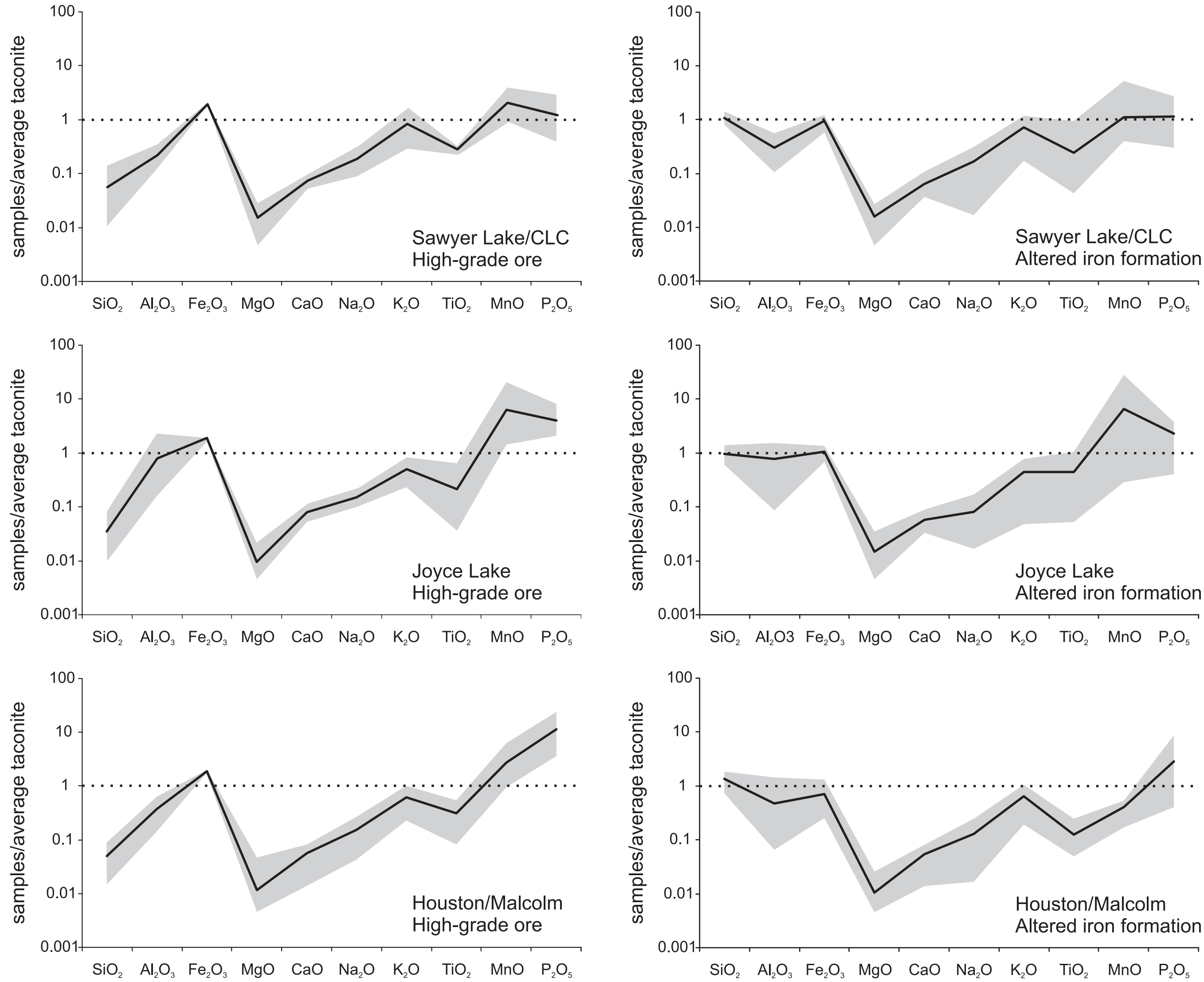

Figure 8. *Major-element concentrations of high-grade ore and altered iron formation from the three study areas, normalized against the composition of average unaltered taconite from the eastern Labrador Trough (Lachance, 2015; this author's unpublished data). Solid line shows average normalized values, grey-shaded area shows range of normalized values.*

OXYGEN-ISOTOPE CHEMISTRY

METHODS

Eight high-grade hematite samples were selected for oxygen-isotope analysis. Small chips were selected and hematite was separated by heavy liquid separation (bromoform, specific gravity 2.89g/cm^3) followed by fine crushing, hand magnet separation and reaction with dilute acetic acid to remove all possible impurities. All analyses were carried out at the Laboratory for Stable Isotope Science (LSIS) at the University of Western Ontario, London, Ontario, under the supervision of Dr. F. Longstaffe, who provided the following summary of the protocols applied to the XRD procedure and the methodology for determination of the oxygen isotope composition.

Prior to oxygen-isotope analyses, sample purity was checked by powder X-ray diffraction (pXRD). The samples were analyzed using a high-brilliance Rigaku X-ray diffractometer, equipped with a rotating anode (CoKα source operated at 160 mA and 45 kV) and a graphite monochromator. Scans were performed at 2° 2θ/min with a step size of 0.02° 2θ. The results confirmed that the samples consisted of >97% hematite. In addition, Davis Tube concentrates from three unaltered taconite samples from the Snelgrove Lake area were obtained from Altius Minerals Corporation. Davis Tube magnetic separation was undertaken by SGS Canada Inc. and the concentrates consist of nearly pure magnetite (>98% Fe_2O_3).

For oxygen-isotope analyses, approximately 8 mg of sample powder were weighed into spring-loaded sample

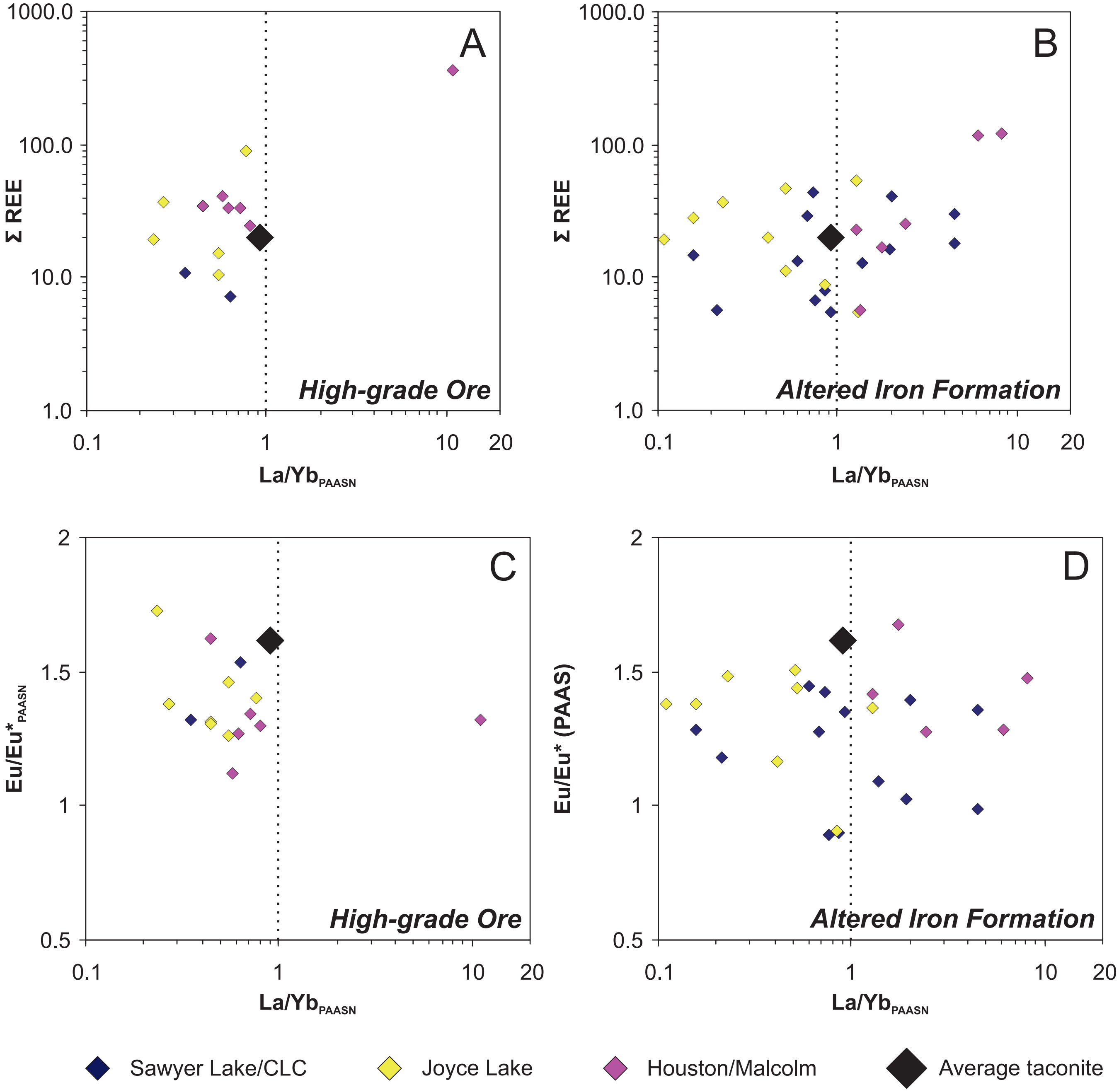

Figure 9. *Bivariate plots La/Yb$_{PAASN}$ vs ΣREE (A and B) and La/Yb$_{PAASN}$ vs Eu/Eu*$_{PAASN}$ (C and D). Eu/Eu* = Eu$_{PAASN}$/((Sm$_{PAASN}$+ Gd$_{PAASN}$)/2).*

holders, evacuated overnight at *ca.* 150ºC, and then placed into nickel reaction vessels and heated in vacuo at 300ºC for a further 3 hours to ensure removal of surface water. The samples were then reacted overnight at *ca.* 580ºC with ClF_3 to release silicate-bound oxygen (Borthwick and Harmon, 1982 following Clayton and Mayeda, 1963). The oxygen was converted to CO_2 over red-hot graphite for isotopic measurement using a Prism II dual-inlet, stable-isotope-ratio mass-spectrometer. The oxygen-isotopic analyses are reported using the normal δ-notation in parts per thousand (‰) relative to Vienna Standard Mean Ocean Water (VSMOW). The $\delta^{18}O$ values for standards analyzed at the same time (accepted values in parentheses) were: LSIS-Quartz, +11.4 ± 0.2‰, n = 7 (+11.5‰) and LSIS-Carbon Dioxide, +10.26 ± 0.06‰, n = 8, (+10.30‰).

Table 2. Oxygen-isotope data from magnetite from unaltered taconites and hematite from selected high-grade hematite ore bodies

Deposit	Sample ID	Mineralogy	$\delta^{18}O_{VSMOW}$ (‰)	$\delta^{18}O_{fluid}$ (‰) 150°C	250°C
Unaltered Taconite					
Snelgrove	NL-11-02-02	Magnetite	**1.57**		
	NL-11-02-13	Magnetite	**3.23**		
	NL-11-03-10	Magnetite	**2.96**		
High-grade iron-ore deposits					
Sawyer Lake	JC12-074	Hematite	**-2.59**	0.61	3.75
	13JC C99	Hematite	**-4.62**	-1.42	1.72
CLC	13JC C115	Hematite	**-4.66**	-1.46	1.68
	13JC C109	Hematite	**-6.10**	-2.90	0.24
Joyce Lake	JC12-082	Hematite	**-4.32**	-1.12	2.02
	492059	Hematite	**-5.58**	-2.38	0.76
	501053	Hematite	**-4.83**	-1.63	1.51
Houston	13JC055	Hematite	**-4.38**	-1.18	1.96

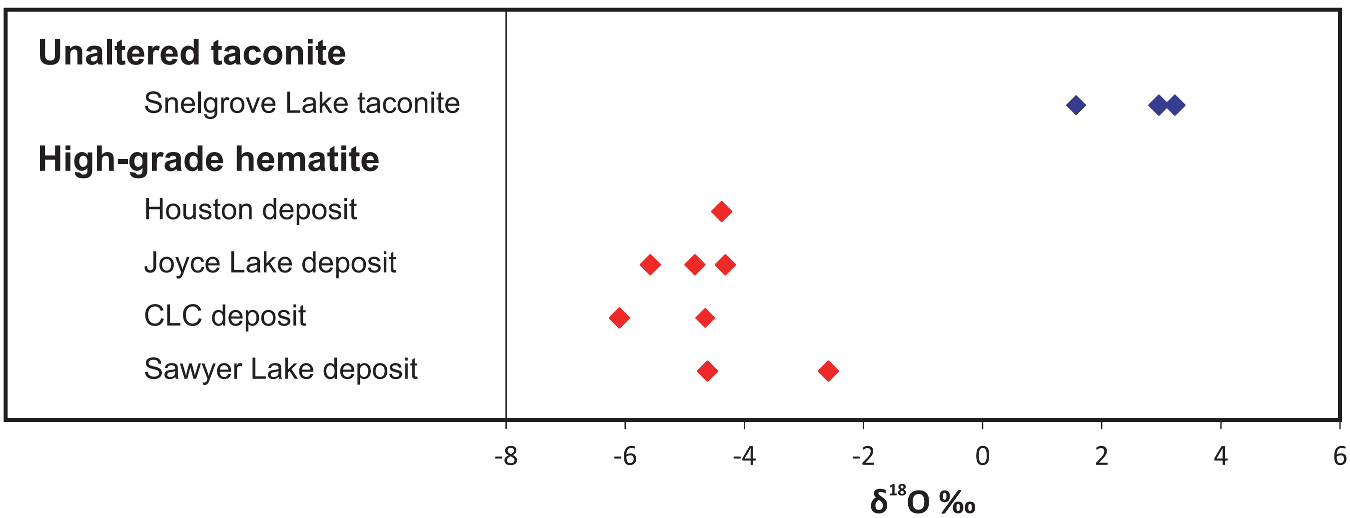

Figure 10. *The $\delta^{18}O_{VSMOW}$ isotope values for magnetite from unaltered taconites and hematite from selected high-grade hematite ore bodies.*

RESULTS

The results of oxygen-isotope analysis for magnetite from taconites in the Snelgrove Lake area and hematite from the Sawyer Lake, CLC, Joyce Lake and Houston deposits are provided in Table 2 and Figure 10. The $\delta^{18}O_{VSMOW}$ values of magnetite from the unaltered taconite range from 1.57 to 3.23‰. Hematite from high-grade DSO deposits has $\delta^{18}O_{VSMOW}$ values of -6.1 to -2.59‰ (average of -4.64‰, 1σ = 1.02‰) and are depleted in ^{18}O by up to 9.3 per mil compared to unaltered taconites (Table 2, Figure 10).

DISCUSSION

Field and petrographic data show that high-grade iron-ore deposits in the Eastern Zone of the Labrador Trough share a number of important characteristics. High-grade ore forms tabular stratabound bodies that are parallel or subparallel to the bedding in the parent iron formation. These ore bodies are located near the base of the Sokoman Iron Formation, close to the contact with the shales of the Lower Iron Formation and Ruth Shale. High-grade ore bodies also have a strong structural control, with the Sawyer Lake and

Joyce Lake deposits located in the hinges of folds and the Houston deposit cut by a number of high-angle reverse faults.

Hard, massive to laminated hematite-rich ores are the dominant ore type, with lesser soft friable ores recorded at the Joyce Lake and Houston deposits. These hard ores retain the original fabrics of the iron formation protolith (laminations, peloids), but the primary constituents (chert ± iron silicates and carbonates) have been completely leached and replaced by fine-grained hematite. Leaching of silica is also associated with the development of secondary porosity, vugs and collapse breccias. The ore bodies are surrounded by an envelope of leached and altered iron formation comprising alternating layers of iron oxides (dominantly fine-grained microplaty and patchy hematite and martite) and pink to white chert. This altered iron formation is fabric retentive (secondary hematite replacing original structures such as peloids) and microplaty hematite commonly occurs in the cherty layers giving a pink colour. The altered iron formation is crosscut by numerous hematite and quartz-filled microfractures, and secondary porosity and collapse breccias have been also recorded. This indicates that leaching of silica and iron remobilization occurred during alteration.

A later, low-temperature alteration has variably affected both the high-grade ore bodies and the surrounding altered iron formation. This alteration is characterized by the transformation of hematite to goethite (particularly in brecciated ore and along the boundary between oxide- and chert-rich layers) and by the precipitation of goethite, hematite and Mn-oxides in vugs and pore spaces.

A comparison of the major-element composition of high-grade ores and altered iron formation and the average composition of unaltered taconites shows the almost complete loss of mobile elements like Mg, Ca and Na from the high-grade ore and altered iron formation. Given the pervasive nature of this depletion, it likely occurred during the main phase of alteration and iron enrichment, and similar depletion has been recorded from other high-grade hematite deposits (Gutzmer *et al.,* 2008). Importantly, the enrichment of Fe and depletion of Si in the high-grade ore bodies is not matched by a corresponding enrichment in immobile elements like Al or Ti. This shows that the formation of these ore bodies was not simply due to the leaching of silica but involved the addition of significant iron, which is supported by the fabric retentive nature of the high-grade ore. Enrichment of MnO and P_2O_5 (± K_2O) is likely associated with the late-stage alteration, during which Mn-oxides (pyrolusite, manganite, manjiroite) were precipitated along joint fractures and in open pore spaces. The consistent enrichment of HREE in high-grade ore bodies is likely due HREE being mobilized in the fluid phase, which was also associated with the main iron enrichment phase. Altered iron formation has highly variably REE ratios, most likely due to remobilization of REE during the later, low-temperature alteration phase, with HREE concentrated in the mobilized phase and LREE enriched in the weathered residue.

The $\delta^{18}O_{VSMOW}$ values for hematite in the high-grade ore bodies are depleted by up to 9.3 per mil compared to magnetite in the unaltered taconites. Similar depletion of ^{18}O from host iron formation to high-grade hematite ores has been reported from other deposits (Gutzmer *et al.*, 2006; Beukes *et al.*, 2008; Thorne *et al.*, 2009; Hensler *et al.*, 2014), and these data can be used to calculate the $\delta^{18}O$ composition of fluids associated with iron enrichment. Temperate dependant oxygen-isotope fractionation curves for hematite and water generally deal with temperatures of less than 120°C (Clayton and Epstein, 1961; Yapp, 1990), and previous oxygen-isotope studies of high-grade iron-ore deposits have used the calibration of Yapp (1990) and extrapolated it to 300°C (*e.g.*, Gutzmer *et al.*, 2006; Beukes *et al.*, 2008; Thorne *et al.*, 2009; Hensler *et al.*, 2014). The equations of Yapp (1990) show that above 92°C hematite precipitating in isotopic equilibrium with the parent fluid should be depleted in ^{18}O. Although no temperature data are available for iron-ore deposits in the Labrador Trough, similar high-grade hematite deposits are believed to have formed at temperatures ranging from 100°C to >300°C (Gutzmer *et al.*, 2006; Beukes *et al.*, 2008; Thorne *et al.*, 2009; Hensler *et al.*, 2014). The leaching of quartz, iron carbonates and iron silicates associated with iron enrichment requires significant volumes of fluid (Evans *et al.*, 2013) and therefore it is likely that secondary hematite is close to, or in equilibrium with, the infiltrating fluid. Therefore the calculated $\delta^{18}O_{fluid}$ ranges from -2.9 to 0.6‰ at 150°C and 0.24 to 3.75‰ at 250°C (Table 2).

GENESIS OF HIGH-GRADE ORE DEPOSITS

The processes responsible for the upgrading of unaltered iron formation with ~30% Fe to high-grade ore bodies with >50% Fe are the subject of much ongoing debate (Beukes *et al.*, 2003; Clout and Simonsen, 2005). Recent studies on the genesis of high-grade hematite ore bodies in Australia, Brazil, South Africa and India have been used to develop several genetic models for the origin of these deposits, including early syngenetic enrichment (Lascelles, 2007), supergene and supergene-metamorphic enrichment (Morris, 1983; Morris and Kneeshaw, 2011), and hypogene and supergene-modified hypogene enrichment (Barley *et al.*, 1999; Taylor *et al.*, 2001; Netshiozwi, 2002; Angerer and Hagemann, 2010; Figueiredo e Silva *et al.,* 2013). Based on this research, Angerer *et al.* (2014) developed a crustal depth continuum for high-grade ore formation based on mineral assemblages, fluid-rock ratios and silica-solubility (Figure 11).

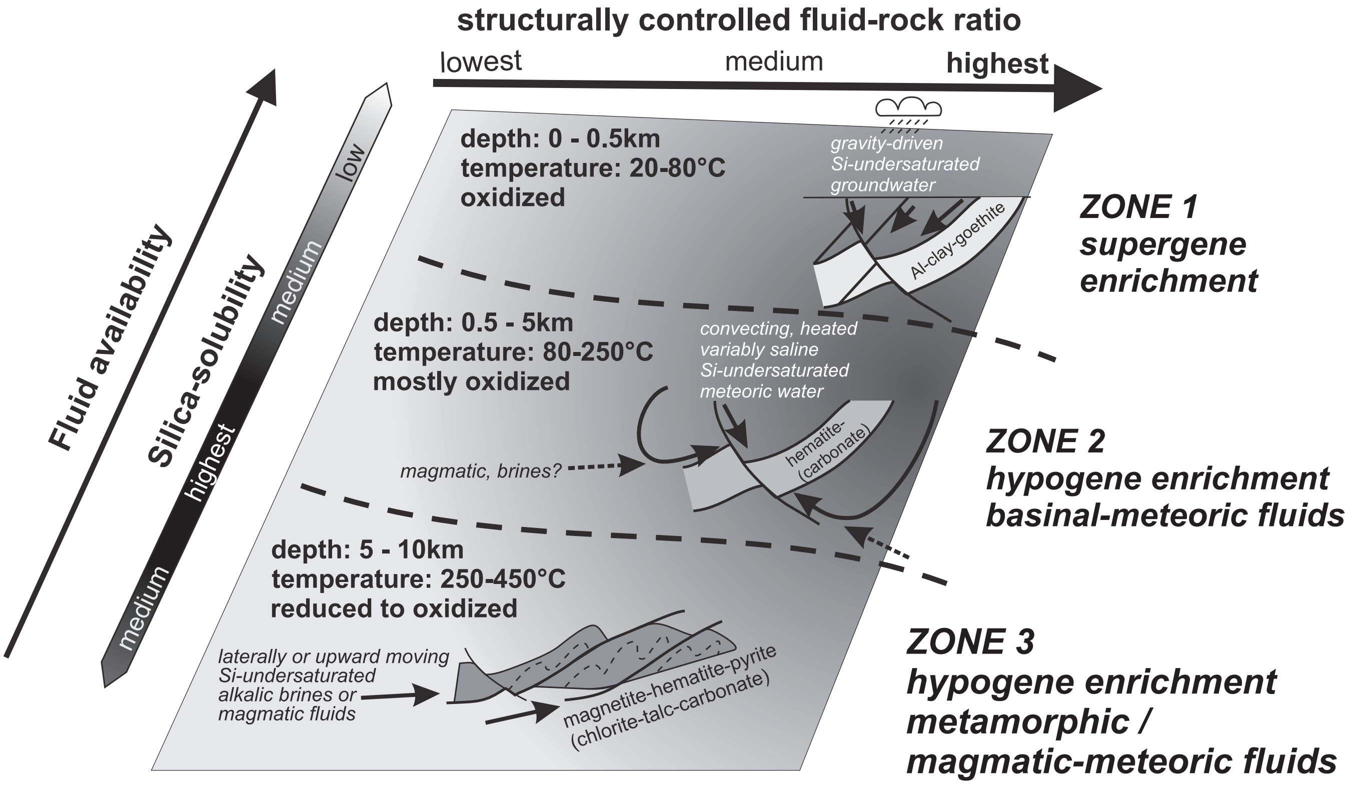

Figure 11. *Fluid flow associated with iron enrichment at a range of crustal depths, adapted from Angerer* et al. *(2014). Shaded grey areas indicate potential for iron enrichment, with darker zones indicating higher potential.*

Previous studies of high-grade iron-ore deposits in the Labrador Trough have attributed iron enrichment and the associated leaching of primary silica and carbonates and the precipitation of secondary iron oxides to supergene weathering during the Cretaceous (Stubbins *et al.*, 1961; Gross, 1968). Whereas this model is generally accepted as accounting for the origin of most of the worlds martite–goethite-rich ores (Clout and Simonsen, 2005) and is applicable to some of the deposits in the Schefferville area, it does not explain the features of the hematite-rich hard ore bodies in the Eastern Zone of the Labrador Trough. Morris and Kneeshaw (2011) proposed a supergene-metamorphic model to explain the formation of hematite-rich ores. This model hypothesizes that early supergene weathering soon after deposition formed goethite-rich ores, which were subsequently dehydrated and transformed to hematite-rich ores during low-grade metamorphism. However, there is no evidence for pre-metamorphic supergene weathering in the Labrador Trough, where the unaltered Sokoman Formation is conformably overlain by thick sequences of shales of the Menihek Formation. In addition, alteration to goethite is shown to be associated with late-stage alteration, and occurred after the formation of the main ore bodies.

On the basis of the results of the current study, a supergene-modified hypogene enrichment origin is proposed for the genesis of high-grade hematite-rich iron-ore deposits in the Labrador Trough. Models of hypogene-related iron enrichment involve the circulation of hydrothermal fluids after diagenesis (Angerer *et al.,* 2014; Figure 11), with fluid flow concentrated in areas of structural deformation (Dalstra and Rosière, 2008). The rocks of the Kaniapiskau Supergroup were deformed in a fold and thrust belt in the New Québec Orogen (1.82 to 1.77 Ga; Wardle *et al.*, 2002). In the Eastern Zone, this deformation is characterized by open to tight folds and widely spaced reverse faults (Harrison *et al.,* 1972) and was associated with low-grade "greenschist-facies" metamorphism (Wardle, 1979). Studies of other fold and thrust belts show that significant volumes of meteoric fluids and basinal brines can flow through fold hinges (Sibson, 2005) or along thrust faults (Lacroix *et al.,* 2014). The source of the fluids associated with iron enrichment is likely formation waters sourced in the underlying shales and/or meteoric fluids that penetrated from the surface *via* seismic pumping (Zone 2 in Figure 11). Oxygen-isotope data indicate that the $\delta^{18}O_{fluid}$ ranges from -2.9 to 0.6‰ at 150°C and 0.24 to 3.75‰ at 250°C. These values are within the expected range for meteoric fluids and basinal brines, but are lower than typical magmatic or metamorphic waters (Sheppard, 1986).

As these fluids circulated through the iron formation, they transformed magnetite into hematite (liberating Fe^{2+}; Ohmoto, 2003) and leached silica (Angerer *et al.*, 2014). This leaching would have created porosity in the iron formation, which would in turn have facilitated increased silica solubility, precipitating hematite in the leached silica layers, and leading to the development of collapse breccias. In the zones of the most intense fluid flow, this process resulted in zones of almost pure hematite, which retained the fabric of the original iron formation. These high-grade ore bodies are surrounded by a zone of altered iron formation with layers of partially leached chert and secondary hematite. Similar alteration zones have been reported from high-grade iron-ore deposits, notably the massive to brecciated high-grade hematite ores at the Thabazimbi and Zeekoebaart deposits in South Africa (Netshiozwi, 2002; Harding, 2004). Evidence for significant fluid flow in the Sokoman Formation during the New Québec Orogen is supported by paleomagnetic studies, which show that the magnetism was acquired continuously during deformation at 1.84–1.83 Ga (Williams and Schmidt, 2004). A similar model for iron enrichment during Paleoproterozoic folding and thrusting has also been proposed for high-grade iron-ore deposits in the Mesabi Range of Minnesota (Morey, 1999).

Late-stage alteration is associated with supergene weathering after the uplift and exposure of the altered iron formation. The flow of surface-derived, low-temperature groundwater caused the partial alteration of hematite to goethite and the precipitation of goethite and hematite in open pore spaces. These fluids also mobilized Mn, forming pockets of Mn-rich ores along major structures. The intensity of alteration is highly variable, both on a deposit scale and on a regional scale. At the Sawyer Lake and CLC deposits, low-temperature alteration is most pronounced in zones around north-northwest-trending faults (Lyons and Brown, 2013). In contrast, low-temperature alteration is more pervasive at the Houston deposit, with pockets of friable soft ore and strong limonite alteration. There is no evidence that this alteration is associated with significant iron enrichment, and the intensity of alteration is likely due to higher porosity and fracturing of the enriched iron formation, which would have facilitated the downward flow of groundwater. The timing of this alteration is unknown, but may represent the same pre-Cretaceous supergene alteration recorded in the DSO deposits of the main ore zone or more recent groundwater circulation.

CONCLUSIONS

High-grade iron-ore deposits in the Eastern Zone of the Labrador Trough, including the Sawyer Lake, CLC, Joyce Lake, Houston and Malcolm deposits, have a number of similar characteristics: 1) dominantly hard, massive to laminated hematite-rich ore with lesser pockets of soft friable ore; 2) distinct alteration zone with layers of partially leached chert and secondary hematite; 3) structural and stratigraphic control on mineralization; 4) strong depletion of Mg, Ca and Na during alteration, with enrichment of Fe not associated with corresponding enrichment of immobile elements such as Al and Ti; and 5) strong depletion of $\delta^{18}O_{VSMOW}$ of hematite from high-grade ore bodies compared to magnetite in unaltered taconites. On the basis of these characteristics, a supergene-modified hypogene enrichment model is proposed for the genesis of these deposits. Iron enrichment would have been associated with the flow of large volumes of meteoric and/or formational waters during the deformation of the Kaniapiskau Supergroup in the New Québec Orogen. These fluids were focussed in structural zones (faults and fold hinges) and silica was leached and replaced by secondary hematite. This early stage of enrichment was followed by later supergene alteration, which partially transformed hematite to goethite and remobilized Mn.

The results of this study support future exploration models in the Labrador Trough based on hypogene- and supergene-modified hypogene iron enrichment. Previous exploration models based on the soft DSO ore deposits in the Schefferville area have focused on areas of potential supergene enrichments, preferentially located in synclinal depressions and/or down-faulted blocks. However, these models may significantly underestimate the size of ore bodies at depth (*e.g.*, Joyce Lake), and are unlikely to discover “blind” orebodies that do not outcrop at the current exposure surface. Distinct alteration zones, with transformation of magnetite to hematite, leaching of silica and evidence of iron mobilization have been recorded around all deposits discussed in this report, and the recognition of similar alteration zones elsewhere may provide a vector toward other ore bodies. Geochemical and oxygen-isotope analysis may also define vectors to ore bodies. Detailed structural and stratigraphic mapping is required to pinpoint areas where enhanced syndeformational fluid flow may have occurred, such as fold hinges and/or faults, and thus increase the opportunity to locate high-grade ore bodies.

Ongoing research by the author is aimed at determining the origin of the soft DSO deposits in the Schefferville area. These studies include detailed field-based and petrographic studies of these deposits, as well as rare-earth element geochemistry and oxygen-isotope studies. They aim to determine whether iron enrichment is solely due to supergene fluid flow as proposed by previous authors (Stubbins *et al.*, 1961; Gross, 1968) or they may have a more complex history with multiple hypogene and supergene fluid-flow events.

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