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THE SAWYER LAKE IRON-ORE DEPOSIT, WESTERN LABRADOR: POTENTIAL FOR FUTURE HIGH-GRADE IRON-ORE DEPOSITS IN THE LABRADOR TROUGH

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ABSTRACT

The Sawyer Lake deposit, ca. *65 km southwest of Schefferville, is a new type of high-grade iron that differs markedly from other deposits in the northern Labrador Trough. The deposit was initially discovered in the 1930s and sporadic exploration since then has defined a significant iron-ore resource with up to 12 million tones of high-grade iron ore (>60% Fe). The main ore zone at the Sawyer Lake deposit is located in the lower Sokoman Formation, below a thick sequence of volcanic rocks of the Nimish Formation. The deposit forms a stratiform orebody, has a saddle-reef morphology and consists of hard, massive to weakly banded high-grade hematite, containing >90% fine-grained, microplaty hematite and minor microgranular quartz. The hard hematite ore is commonly brecciated, and has angular fragments of hematite in a quartz–hematite matrix. Brecciation is associated with the collapse of hematite into open spaces created by the leaching of silica. The high-grade hematite body is surrounded by oxidized iron formation consisting of alternating hematite and cherty bands, and abundant evidence for the remobilization of hematite and quartz, and secondary hematite enrichment.*

In contrast to high-grade direct-shipping ore deposits in the Schefferville area, no evidence of supergene enrichment has been recorded at the Sawyer Lake deposit, and syndiagenetic iron enrichment is also considered unlikely. Macroscopic and petrographic studies and comparisons with other high-grade hematite deposits worldwide, indicate that enrichment is related to hypogene processes, in which hydrothermal fluids leached silica and precipitated secondary hematite. Although the source of hydrothermal fluids is unknown, they may be related to dewatering of underlying shales during the Hudsonian orogeny or circulation of basinal brines during regional-scale thrusting.

INTRODUCTION

OVERVIEW

The Sawyer Lake iron-ore deposit is located in northwestern Labrador, approximately 65 km southwest of Schefferville (NTS map area 23I/05; Figure 1). Access to the area is *via* helicopter only, as there is no road access. The Sawyer Lake deposit consists of an irregularly shaped body of high-grade (>60% Fe) hard blue hematite, which defines the top of a small hill ~1.5 km west of Sawyer Lake (Plate 1). It was discovered in 1937, and exploration over the past 70 years has recognized that it is a distinct deposit type, markedly different from the soft high-grade direct-shipping ore (DSO) deposits of the Schefferville area.

This contribution presents the results of initial field and petrographic studies of the Sawyer Lake deposit and surrounding altered iron formation. Fieldwork in 2012 and 2013 included a number of site visits and detailed logging of drillcore stored in Schefferville; these data have been combined with industry reports to develop a genetic model for iron-ore enrichment. During the past 15 years, many studies have investigated the origin of high-grade hematite-rich, iron-ore deposits (*e.g.*, Barley *et al.*, 1999; Taylor *et al.*, 2001; Gutzmer *et al.*, 2006, 2008; Lascelles, 2007; Rosière *et al.*, 2008; Angerer and Hagemann, 2010; Ramanaidou and Morris, 2010; Lascelles, 2012); the results from these studies will be compared with the characteristics of the Sawyer Lake deposit. The implications of these comparisons for regional exploration in the Labrador Trough will be discussed, and other aspects of ongoing research will be briefly outlined.

REGIONAL GEOLOGY

The Sawyer Lake deposit lies within the geological belt known as the Labrador Trough. 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,

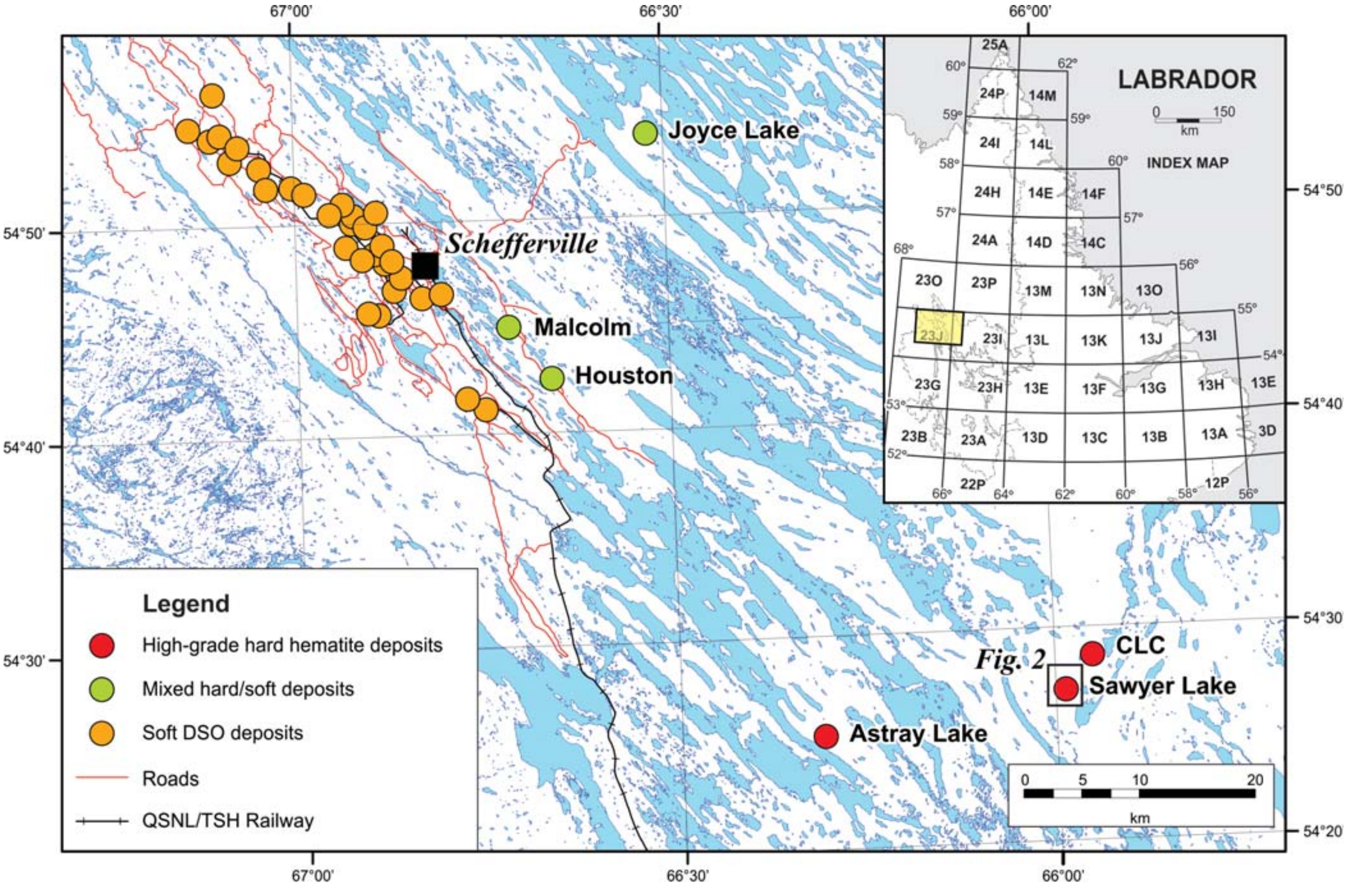

Figure 1. *Regional map showing location of the Sawyer Lake deposit and other high-grade hematite deposits discussed in text.*

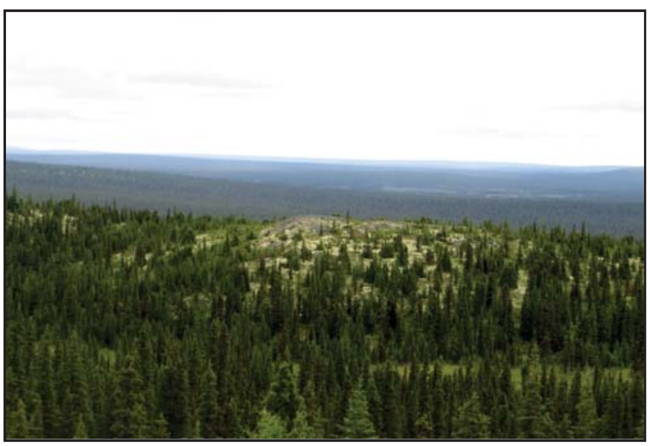

Plate 1. *Overview of Sawyer Lake deposit (view from southwest).*

1981; Le Gallais and Lavoie, 1982). The trough extends for more than 1100 km from the northwest corner of Ungava Bay south to Lake Pletpi (Clark and Wares, 2005), and it forms the western part of the larger New Québec orogenic belt. This 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).

The Kaniapiskau Supergroup is subdivided into three sedimentary and volcanic cycles deposited during the development of a foreland basin (Zajac, 1974; Wardle and Bailey, 1981; Le Gallais and Lavoie, 1982; Clark and Wares, 2005). Cycle 1 (the lower cycle) consists of a continental-rift basin overlain by passive margin sedimentary rocks that developed during rifting on the eastern margin of the Superior Craton at least 2.17 Ga ago (Rohon *et al.*, 1993). The immature sandstones and siltstones of the Seaward Formation were deposited in a fluvial to intertidal system, and grade upward into the passive margin sediments of the Attikamagen Group. The Attikamagen Group includes Attikamagen 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 (Wishart Formation sandstone and siltstones, and 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). In addition, the Wishart and Sokoman formations are intruded by a number of pre-tectonic gabbro sills, which may relate to the Nimish volcanism or later volcanic events (Evans, 1978; Watanabe, 1996). 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 Cycle 3 arkoses, which are interpreted as a synorogenic molasse. During the collision of the Superior Craton with the core zone in the Hudsonian Orogen (1.82 to 1.77 Ga), the Kaniapiskau Supergroup was folded and thrust westward over the Archean basement rocks (Wardle *et al.*, 1990, 2002).

The iron-ore deposits in the Labrador Trough are hosted in the Sokoman Formation, a 30- to 170-m-thick sequence of cherty iron-rich sedimentary rocks. The general stratigraphy of the Sokoman Formation is based on mapping around Schefferville (Zajac, 1974), and can be correlated throughout the Labrador Trough. The base of the Sokoman Formation is marked by a dark-green to black ferruginous shale and minor tuffs, sometimes called the Ruth formation (Zajac, 1974). Above this, the Sokoman Formation consists of three units. The lower unit (Lower Iron Formation) consists mostly of a carbonate–silicate facies with some magnetite. This grades upward into the Middle Iron Formation, an oxide facies with abundant coarse-grained hematite and/or magnetite and sugary-textured quartz. These oxide-rich beds are the most important, economically, and where the iron-rich layers and lenses commonly contain more than 50% hematite and magnetite. The upper part of the Sokoman Formation (Upper Iron Formation) is a carbonate–silicate facies with minor oxides.

PREVIOUS WORK AND HISTORY OF EXPLORATION

The occurrence of high-grade iron-ore deposits in the vicinity of Sawyer Lake was first reported in 1937 by Mathiau Andre, a Montagnais Innu guide, who brought a sample of high-grade hematite ore to the attention of Dr. Joseph Retty, chief geologist of Labrador Mining and Exploration Company (LME). Exploration activity by LME through the 1930s and 1940s included detailed field mapping, test pitting, trenching and sampling (Retty, 1938, 1939; Retty and Moss, 1945; Dufresne, 1950). In 1944, five drillholes (total 238 m) were completed on the property, with the deepest hole ending in high-grade ore at 61 m (Retty and Moss, 1945). Additional diamond drilling was carried out in 1949, with five drillholes on the main deposit (total 162 m) and an extensive program of test drilling in the surrounding area (60 short drillholes, total 650 m; Retty, 1950). Although this work identified a significant iron-ore resource at Sawyer Lake, no other nearby deposits were discovered, and LME focused their activities after 1949 on developing the large iron-ore deposits farther north in the Knob Lake area.

Exploration activity at Sawyer Lake from 1949 to the 1980s was restricted to regional government mapping and a number of short visits by company geologists (Price, 1979; Wardle, 1979). Bulk sampling and metallurgical test work in the late 1980s showed that lump ore (6–25 mm) from Sawyer Lake could successfully produce direct reduced iron (Bowie and Lepinski, 1989), and airborne VLF and magnetometer surveys were completed over the deposit in 1995 (Scott, 1996). In the 2000s, renewed exploration activity at the Sawyer Lake deposit included prospecting, mapping and trenching (Chavez *et al.*, 2005). Based on these results, Labrador Iron Mines commenced a diamond-drilling program in 2008, drilling nine drillholes having a cumulative length of 539.5 m (Vatcher *et al.*, 2009). All the drillholes encountered high-grade (>60% Fe) ore having a maximum thickness of 41.4 m (@ 67.9% Fe), and two holes terminating in ore.

The Sawyer Lake deposit does not have a NI-43-101 compliant mineral-resource calculation and estimates by LME and IOC geologists vary greatly, from 3 to 16 million tonnes, depending on assumptions regarding the size and density of the deposit. In 1998, Fenton Scott compiled all historical data from the Sawyer Lake deposit in an attempt to create an ore-reserve calculation (Scott, 1998). This resulted in a non-NI-43-101 compliant probable mineable reserve of 5.87 million tonnes (66% Fe), in addition to indicated and inferred resources of 2.32 and 3.8 million tonnes, respectively. However, care must be taken with these estimates, as they may overestimate the depth of mineralization and include areas of mineralization that are too narrow to be mined economically (Chavez *et al.*, 2005). Based on results of the 2008 drilling program, the Sawyer Lake deposit also has potential for expansion at depth and along strike.

SAWYER LAKE IRON-ORE DEPOSIT

LOCAL GEOLOGY

The stratigraphy in the vicinity of the Sawyer Lake deposit consists of sedimentary and volcanic rocks of the Kaniapiskau Supergroup (Figure 2; Dufresne, 1950; Evans, 1978; Wardle, 1979). The oldest exposed rocks are grey shales and siltstones of the Dolly Formation, which are overlain by orthoquartzites and siltstones of the Wishart Formation. The Wishart Formation is intruded by gabbro sills, which may be related to the overlying Nimish Formation (Evans, 1978). The lowest iron-bearing rocks are black

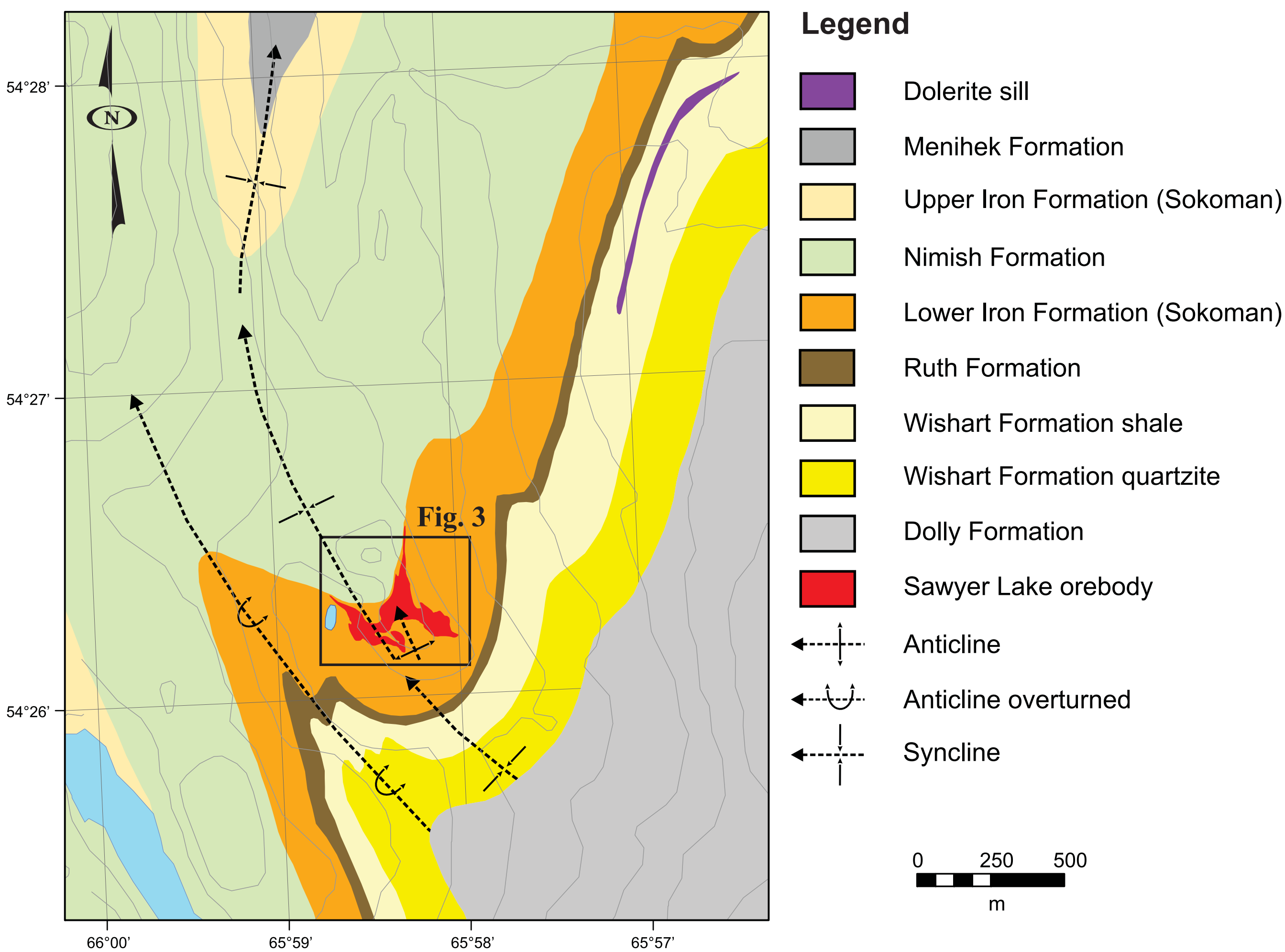

Figure 2. *Simplified geological map of the region around the Sawyer Lake deposit (adapted from Dufresne, 1950; Gross, 1968).*

ferruginous shales and minor tuffs that correlate to the Ruth formation in the Schefferville area (Dufresne, 1950; Wardle, 1979). These are not exposed in the study area, but have been recorded beneath altered iron formation in recent exploration drilling ~4 km northwest of the Sawyer Lake deposit.

The stratigraphy of the Sokoman Formation proper differs from the typical sequence described in the Schefferville area. The Middle Iron Formation is not recorded, and the Lower and Upper Iron formations are separated by a thick sequence of Nimish Formation volcanic rocks (Wardle, 1979). The Sawyer Lake deposit is hosted in the Lower Iron Formation, which consists of green- to grey-laminated silicate chert with disseminated and thin bands of magnetite. Close to the deposit this chert has been extensively altered and oxidized. The Nimish Formation volcanic rocks consist predominantly of green to grey, vesicular and plagioclase phyric basalts, interbedded with lesser conglomerates containing rounded clasts of lava and jasper (Wardle, 1979). The lavas are overlain by ferruginous tuffs and chert, which Wardle (1979) interpreted as a transition zone between waning Nimish volcanism and deposition of the thinly bedded Upper Iron Formation.

PETROGRAPHY

The Sawyer Lake deposit is subdivided into two main rock types, which are readily differentiated based on their mineralogical and physical characteristics. The core of the ore body consists of a lens of hard, high-grade hematite (>60% Fe), surrounded by pink oxidized iron formation. These units are interpreted as oxidized equivalents of the Lower Iron Formation, although the contact between the oxidized iron formation and unaltered iron formation was not observed.

High-Grade Hematite Ore

High-grade hematite is the dominant ore horizon in the Sawyer Lake deposit. It is a characteristic dark-grey/blue, and has a metallic lustre; it has been described by previous authors as a 'steel-rail hematite' due to its appearance in glacially polished outcrops (I.S. Zajac, personal communication, 2013). It is subdivided into two broad classes, based on macroscopic characteristics.

Most of the ore consists of massive hematite ore (Plate 2A, B). In places, this unit displays traces of banding, defined by more quartz-rich layers, or variations in porosity from 0 to 20%. These bandings/laminations reflect replacement of original textures in the unaltered iron formation, with the more quartz-rich and porous layers representing chert-rich bands. The massive hematite ore consists of almost pure hematite (>60% Fe), minor quartz and remnant magnetite. Hematite is very fine grained (<10 μm) and can be defined as microplaty hematite (Plate 3A). This microplaty hematite is thought to have originated through the oxidation of magnetite (martization) and secondary precipitation in pore spaces. No evidence of magnetite was found during petrographic examination but relatively high magnetic susceptibilities (up to 6 x10^{-3} SI) indicate that some remnant magnetite remains. Microcrystalline quartz is a minor constituent of massive hematite ore, typically making up <10% of the total mineralogy. This quartz is inconspicuous in hand sample and forms small irregularly distributed patches surrounded by hematite. Close to the contact with the oxidized iron formation the proportion of quartz increases (up to 30%; Plate 3B), which represent primary quartz that was not replaced during the mineralizing event. Goethite is rare in high-grade hematite ore, and where observed, fills pore spaces, veins and vugs.

Brecciated high-grade hematite ore is found locally throughout the ore zone, and has been recorded in both outcrop and drillcore. These breccias consist of angular fragments of massive microplaty hematite cemented by hematite and quartz (Plate 2C, D). The degree of displacement and brecciation is highly variable, ranging from massive hematite broken up and crosscut by veins of hematite and quartz (crackle breccia; Plate 3C), to angular fragments of massive hematite in a quartz matrix (rubble breccia; Plate 3D). Breccias are also associated with open vugs lined by euhedral quartz. The presence of these breccias indicates that open space was created during or after the main mineralizing event, due to the dissolution of cherty layers. Some of the open pore spaces and vugs are filled by late-stage goethite (Plate 2C), most likely related to influxes of groundwater in geologically recent times.

Oxidized Iron Formation

Fine-grained, oxidized iron surrounds the lenses of high-grade hematite ore in the Sawyer Lake deposit. The contact between the oxidized iron and the ore lenses is generally gradational with an increase in iron content from ~30% Fe to >45% Fe. Occasionally, sharp contacts with the high-grade hematite ore have been observed, which crosscut bedding in the oxidized iron.

The oxidized iron formation consists of alternating hematite and cherty bands ranging in thickness from 1 to 20 mm (Plate 2E). Cherty beds are pink to off-white and consist predominantly of two main quartz generations, *i.e.*, early microgranular quartz (<5 μm) with irregular boundaries and later recrystallized coarser grained quartz (>20 μm). Multiple generations of hematite have also been recorded. Fine-grained, dusty hematite is locally associated with microgranular quartz, giving the cherty layers a distinctive pink colour (jasper). This has been recrystallized to euhedral to subhedral blades of hematite (<10 μm) that are disseminated throughout the chert (Plate 4A). Locally, these form bands and subrounded aggregates of microplaty hematite (Plate 2F), which reflect the secondary enrichment of hematite in the cherty layers. Close to the contact with the high-grade hematite ore, secondary hematite makes up >50% of the chert bands. Numerous veinlets of quartz and hematite crosscut the cherty bands (Plate 4A, B) and are commonly associated with aggregates of microplaty hematite. Rare pseudomorphs have also been recorded in cherty bands, with hematite and quartz replacing an unknown mineral (carbonate or magnetite?).

The hematite-rich bands consist of >80% microplaty hematite with lesser intergranular quartz (Plate 4C). These bands commonly have diffuse and irregular boundaries and are associated with local hematite enrichment in the adjacent chert bands. Although no magnetite or kenomagnetite (partially oxidized magnetite) have been recorded in thin section, some areas are weakly magnetic indicating some remnant magnetite has survived alteration and oxidization.

Porosity in the oxidized iron formation is generally low, with rare vugs and pores filled by quartz and hematite. Late-stage goethite is also recorded in pore spaces and fractures (forming comb structures) and occasionally forms fine disseminations in cherty bands (giving the core a yellow colour). Rare collapse breccias have also been recorded, with bands of hematite and chert broken up and cemented by late-stage quartz and hematite.

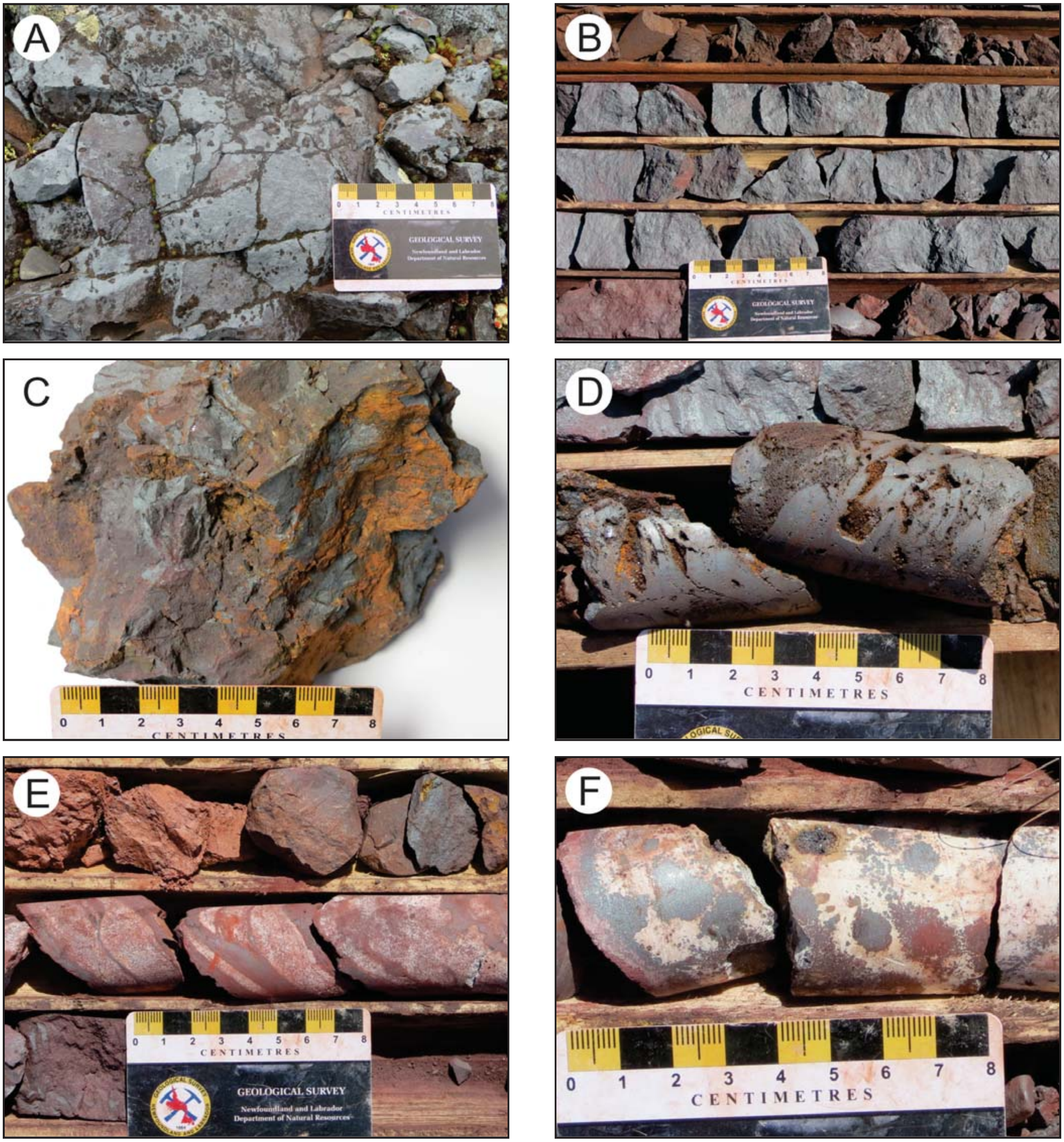

Plate 2. *Photographs of representative rock types of the Sawyer Lake deposit. A) Outcrop of massive high-grade hematite ore; B) Massive high-grade hematite ore (DDH-SL-004A @ 34 m); C) Brecciated high-grade hematite ore and angular fragments of hematite in a matrix of hematite, quartz and late-stage goethite; D) Partially brecciated high-grade hematite ore (DDH-SL-007 @ 19.3 m); E) Banded oxidized iron formation (DDH-SL-007 @ 37.5 m); F) Subrounded aggregates of secondary hematite and quartz-lined vugs in oxidized iron formation (DDH-SL-007 @ 50.4 m).*

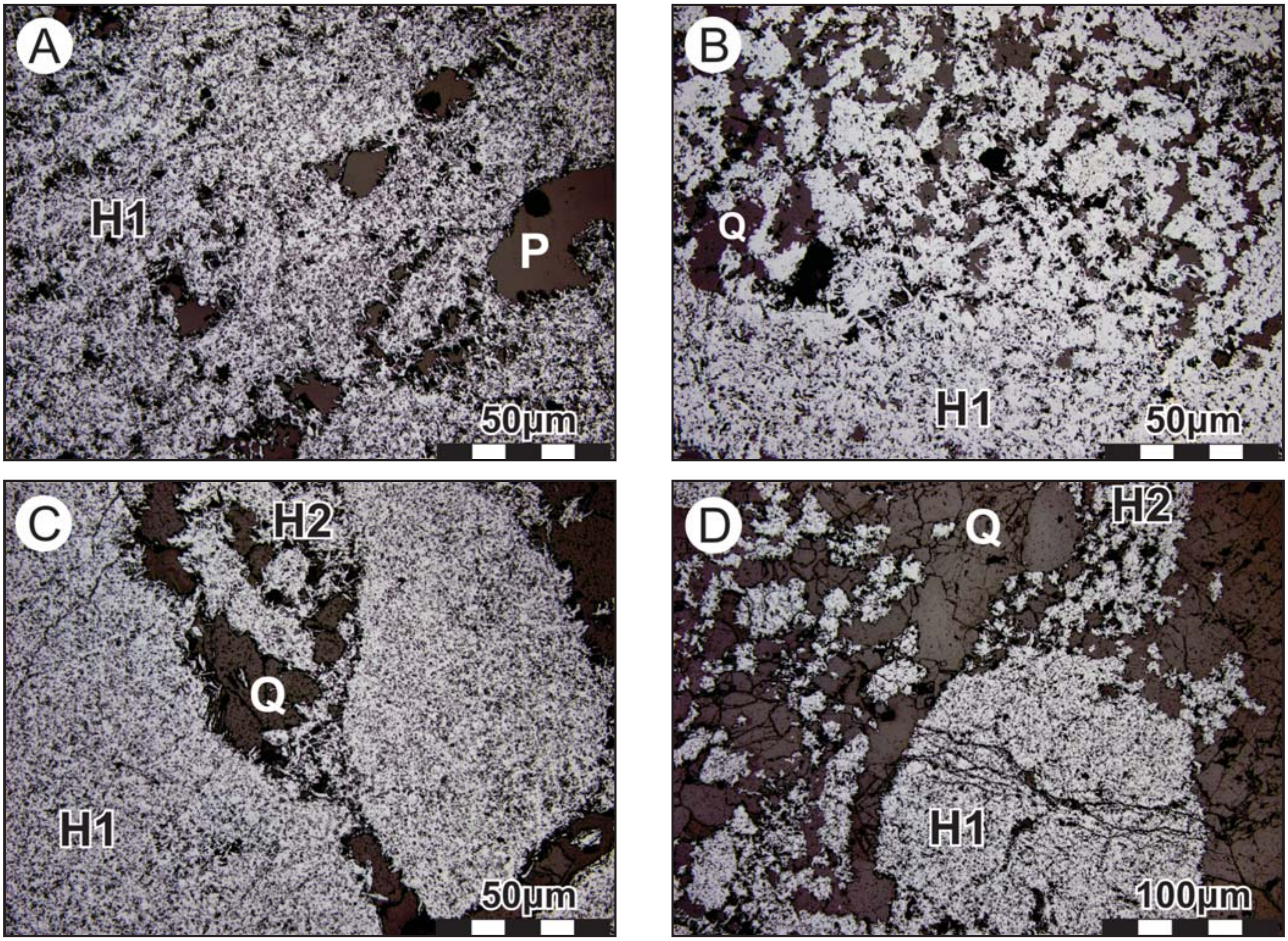

Plate 3. *Photomicrographs of high-grade hematite ore in reflected light. A) Massive microplaty hematite with well-developed porosity; B) Massive high-grade hematite ore close to contact with oxidized iron formation, with abundant microcrystalline quartz; C) Angular fragments of massive hematite crosscut by hematite and quartz veinlets (crackle breccia); D) Fragment of massive hematite engulfed by late-stage quartz and hematite (rubble breccia). H1 - early massive microplaty hematite, H2 - late hematite, Q - quartz, P - pore space.*

STRUCTURAL GEOLOGY

The Sawyer Lake deposit is located in the southeastern sector of the Petitsikapau synclinorium (Wardle, 1979), a major regional structure that formed during the Hudsonian Orogen. In contrast to the generally north-northwest–south-southeast-trending, southeast-plunging folds elsewhere in the orogen, the southeastern sector of the Petitsikapau synclinorium has been rotated clockwise due to late-stage sinistral-slip movement on the Mina Lake Fault (Wardle, 1979). This has formed a series tight upright folds plunging to the northwest, with the Sawyer Lake deposit located in the trough of a major north-trending syncline (Figure 2).

Bedding in the Sawyer Lake deposit is defined by bands of chert and hard, blue hematite in the oxidized iron formation as well as by variations in porosity in the high-grade hematite ore. The porosity variations reflect primary bedding features that existed prior to enrichment. The strike of these beds varies across the deposit (Figure 3) and outlines a small north-plunging anticline on the eastern limb of the larger syncline (Figure 2). Although the contact between the high-grade hematite ore and oxidized iron formation locally crosscuts bedding, cross-sections through the orebody show that the high-grade hematite ore forms a stratiform body with a saddle reef-like structure that thins toward the centre of the deposit and follows bedding across the crest of the anticline (Figure 4). Petrographic examination of moderately enriched iron formation, close to the contact with the high-grade hematite ore, reveals preservation of small-scale folding of the iron formation, defined by hematite-rich and hematite-poor layers (Plate 4D). This indicates that the original textures of the iron formation were preserved during mineralization, or that enrichment predates at least one

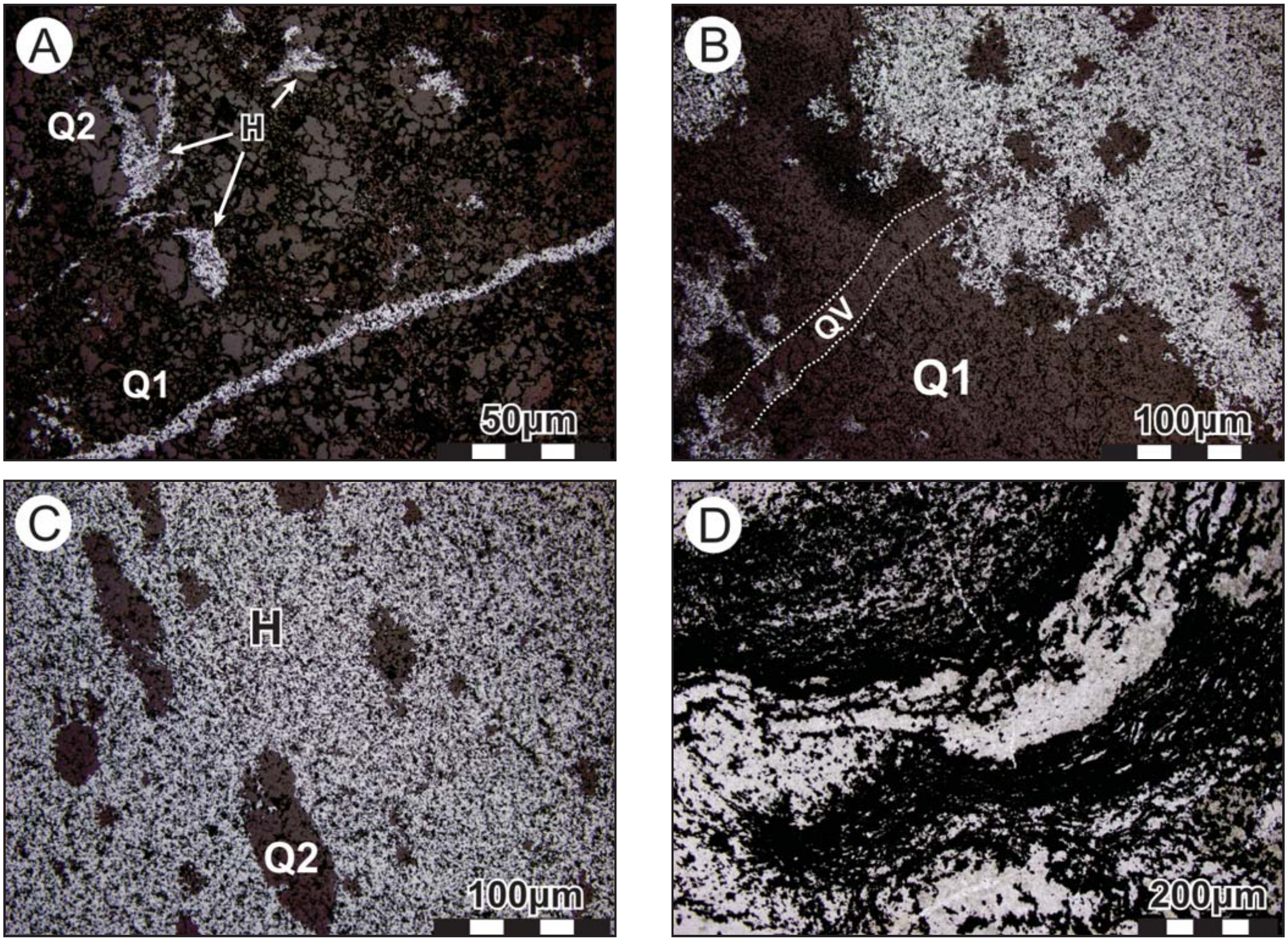

Plate 4. *Photomicrographs of oxidized iron formation. A) Early microcrystalline quartz and later coarser grained quartz, with aggregates of secondary hematite and hematite veinlet (reflected light); B) Bands of hematite and quartz-rich oxidized iron formation, with late quartz veinlet cutting chert band (reflected light); C) Hematite-rich band with microplaty hematite and pores filled by late quartz (reflected light); D) Folded bands in enriched oxidized iron formation close to contact with high-grade hematite ore (transmitted light). H - microplaty hematite; Q1 - early microcrystalline quartz; Q2 - late quartz; QV - quartz veinlet.*

phase of folding. No evidence of faulting was recorded during trenching at Sawyer Lake, but intervals of clay-like fault gouge were observed in drillcore. These small-scale faults could be important conduits for fluid flow through the deposit.

DISCUSSION

GENESIS OF THE SAWYER LAKE DEPOSIT

The hard, high-grade hematite ore at Sawyer Lake is very different from the ‘soft’ DSO deposits in the Schefferville area, which consist of friable high-grade (>55% Fe) material containing abundant secondary goethite. Previous work in the Schefferville area has attributed iron enrichment to deep supergene weathering during the Cretaceous, and leaching of primary silica and carbonates and precipitation of secondary iron oxides (Stubbins *et al.*, 1961; Gross, 1968). In contrast, the Sawyer Lake deposit consists of hard hematite ore with little or no goethite. Where present, goethite is volumetrically minor, restricted to late-stage pores, veins and vuggy chert (partially leached), and is most likely related to recent groundwater circulation. In addition, high-grade hematite ore at Sawyer Lake retains evidence of primary textures and has a well-developed alteration halo (oxidized iron formation), which is not compatible with a model of supergene enrichment. Therefore, the genesis of the Sawyer Lake deposit is not related to supergene or supergene-modified hypogene enrichment.

Syndiagenetic models suggest that chert-free iron formations formed during diagenetic processes, and have been suggested for a number high-grade hematite ores where no

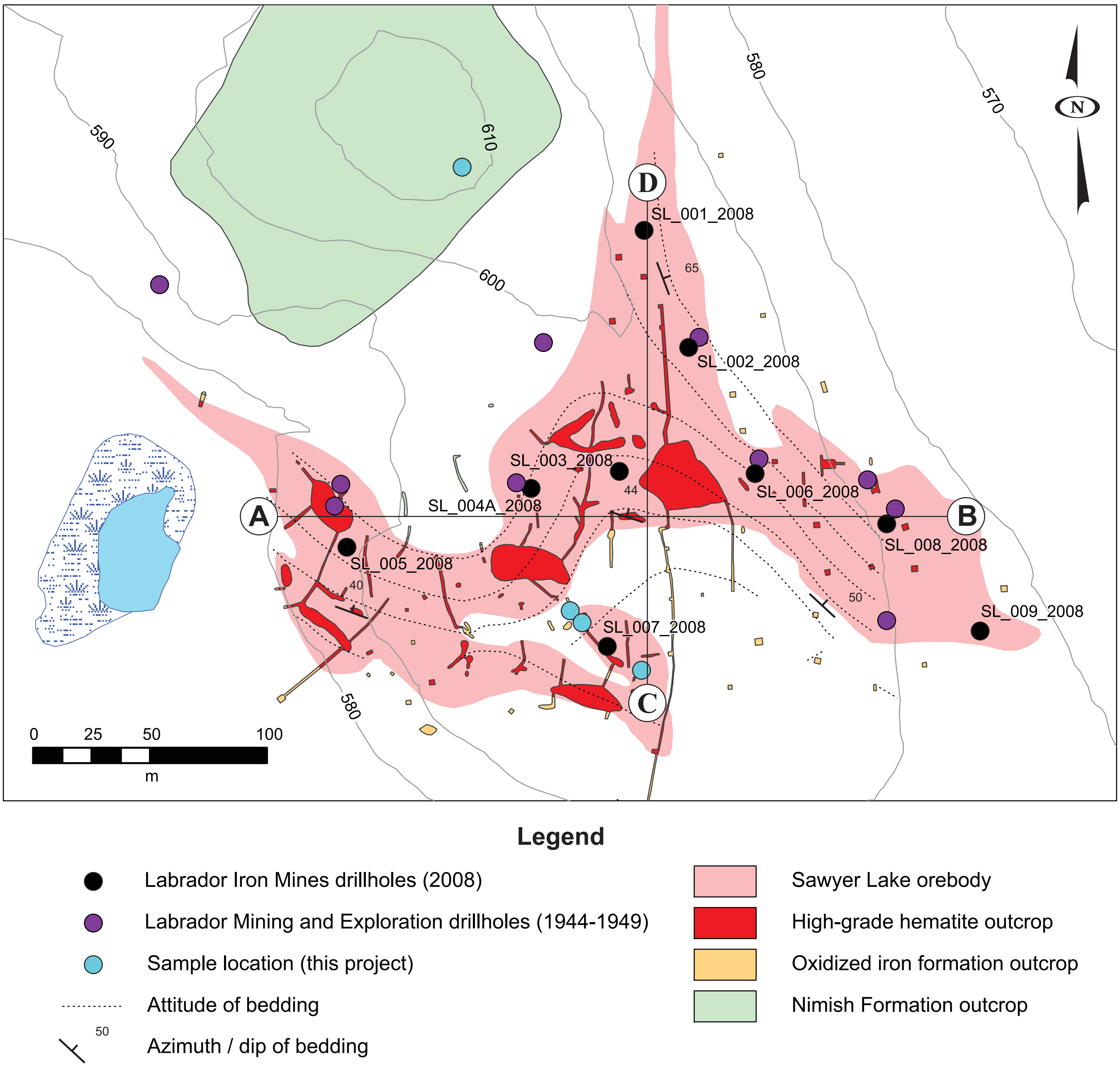

Figure 3. *Geological map of the Sawyer Lake deposit showing the distribution of outcrops, trenches and location of drillholes. Adapted from Retty and Moss (1945), Chavez* et al. *(2005) and Vatcher* et al. *(2009).*

evidence of chert bands have been recorded (Lascelles, 2007, 2012). However, the presence of highly porous bands and dissolution breccias at Sawyer Lake clearly show the leaching of chert beds and a wholly syndiagenetic model is also considered unlikely.

Based on this study, it is likely that iron enrichment at Sawyer Lake is related to hypogene processes, as was first suggested for the deposit by Gross (1968). In recent years, hypogene processes have been increasingly recognized as important in the formation of high-grade hematite deposits, particularly in Australia, Brazil, and South Africa (*e.g.*, Barley *et al.*, 1999; Taylor *et al.*, 2001; Netshiozwi, 2002; Harding, 2004; Rosière *et al.*, 2008; Angerer and Hagemann, 2010). The Sawyer Lake deposit shares several key characteristics with some of these deposits, notably the massive to brecciated high-grade hematite ores at the Thabazimbi and Zeekoebaart deposits in South Africa (Netshiozwi, 2002; Harding, 2004). Models of hypogene-related iron enrichment involve the circulation of hydrothermal fluids after diagenesis, in which fluids are concentrated in areas of structural deformation that facilitate increased fluid flow

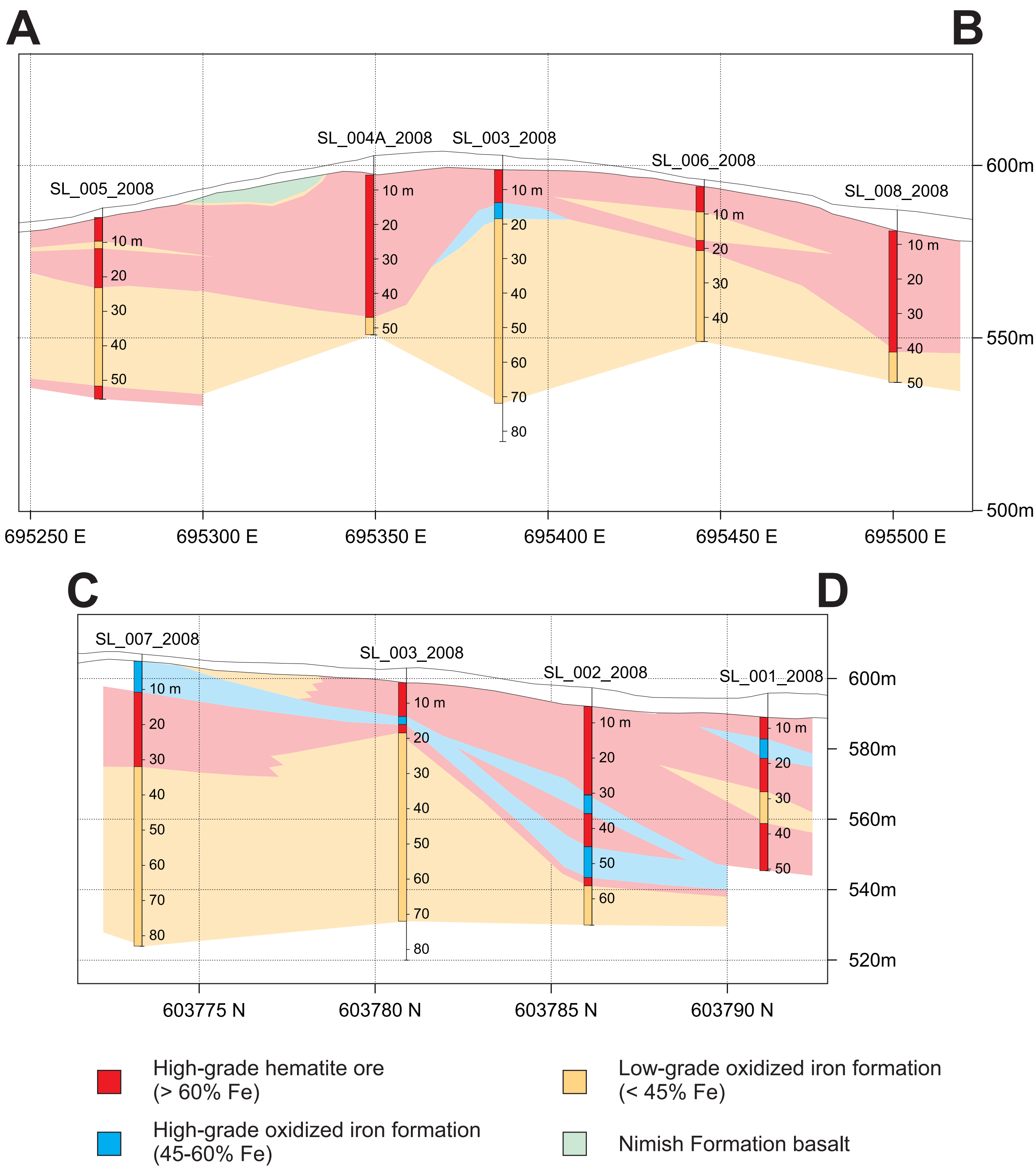

Figure 4. *Schematic east–west (A-B) and north–south (C-D) cross-sections through the Sawyer Lake deposit showing the saddle-reef morphology of the deposit. For location of the sections refer to Figure 3.*

(Dalstra and Rosière, 2008). The Sawyer Lake deposit is located across a minor anticline in the nose of a major syncline, and was capped by the relatively impermeable lavas of the Nimish Formation. Under these conditions, hydraulic conductivity and hinge-parallel fluid flow can be high (Sibson, 2005), and would have permitted the circulation of significant volumes of hydrothermal fluids.

As these oxidizing fluids circulate through the iron formation, they transform magnetite to hematite (liberating Fe^{2+}; Ohmoto, 2003) and form distinctive alteration zones around orebodies (Lobato *et al.*, 2008). At the Thabazimbi and Zeekoebaart deposits, a distal alteration zone consists of bands of partially leached chert and secondary hematite (Netshiozwi, 2002; Harding, 2004; Lobato *et al.*, 2008), which is very similar to the oxidized iron formation surrounding the orebody at Sawyer Lake. This alteration zone formed where oxidizing fluids transformed magnetite, Fe silicates and carbonates in the unaltered iron formation into hematite and chert. Iron and silica were remobilized by these fluids, as shown by the abundant hematite and quartz veinlets. Precipitation of secondary hematite is suggested by the association of hematite with secondary quartz and aggregates of secondary, microplaty hematite in the chert-rich bands. Minor leaching of chert and/or volume loss also increased porosity in the oxidized iron formation, which would have facilitated further fluid circulation.

The high-grade hematite ore at Sawyer Lake represents the zone of most intense hydrothermal alteration. Quartz in the chert-rich bands has been completely leached and replaced by microplaty hematite. Variations in porosity in the massive ores reflect the original bedding, with the higher porosity bands replacing former cherty layers. Dissolution of silica also generated open space in the high-grade hematite ore, which was reduced by collapse (forming breccia zones) and precipitation of secondary quartz and hematite in open pore spaces.

The source of the hydrothermal fluids at Sawyer Lake remains enigmatic. The only possible source of magmatic fluids is a series of gabbro sills that intrude the Sokoman and Wishart formations, which are either related to the overlying Nimish Formation volcanic rocks or the Montagnais Intrusive Suite (Evans, 1978). However, these gabbroic magmas were essentially dry and are not likely to have been the source of significant fluids. Although the heat anomalies associated with the intrusion of these sills may have resulted in the formation of hydrothermal convection cells in the Sokoman Formation, their emplacement predate folding and deformation of the Kaniapiskau Supergroup, which is necessary to create the hydraulic conductivity necessary for significant fluid flow. In addition, these sills are extensively altered, with olivine pseudomorphed by serpentine, chlorite and talc and clinopyroxene variably altered to tremolite and actinolite (Watanabe, 1996). Similar alteration of dykes spatially associated with hypogene hematite deposits have been noted in Brazil, Australia and South Africa (Lobato *et al.*, 2008) and indicates that these sills intruded the Kaniapiskau Supergroup prior to hydrothermal alteration.

An alternative source of the hydrothermal fluids is connate waters sourced in the underlying shales of the Ruth and Wishart formations, which was first suggested by Gross (1968). During the Hudsonian Orogeny, compaction of the shales would have resulted in dewatering and tectonic pumping of fluids through the relatively permeable Sokoman Formation, with the impermeable Nimish Formation acting as a barrier to upward fluid flow. Fluids may also be related to the circulation of basinal brines during regional-scale folding or thrusting, which has been suggested for a number of other hypogene hematite deposits, *e.g.* Mount Tom Price, Australia (Thorne *et al.*, 2004). In some respects, these models are analogous to those proposed for Mississippi Valley-Type (MVT) Pb–Zn deposits.

REGIONAL IMPLICATIONS

Exploration activities around the Sawyer Lake deposit have recognized the potential for discovery of similar high-grade hematite deposits. Localized iron enrichment in the Stewart Lake area (~5 km north-northeast of Sawyer Lake) was reported by Griffis *et al.* (1944). Recent drilling by Mamba Minerals Limited at the nearby CLC deposit (Figure 1) has shown that iron enrichment continues along strike from the Sawyer Lake deposit to the Stewart Lake area, with intersections of 101 m averaging 52% Fe and high-grade intervals of 63 and 65% Fe (Mamba Minerals Limited, press release, May 3rd 2013). Similar iron enrichment has been described from the Astray Lake deposit (Figure 1), with blue hematite replacing leached jasper, and abundant brecciated high-grade ore located below the Nimish Formation (Gross, 1968). In addition, several other high-grade hematite deposits display characteristics intermediate between those of the classic supergene deposits described by Stubbins *et al.* (1961) from the Schefferville area and those of the hard, high-grade hematite deposit at Sawyer Lake. The Houston and Malcolm deposits, located southeast of Schefferville (Figure 1), consist of areas of massive hard blue hematite similar to the Sawyer Lake deposit that grade into more friable ore with secondary goethite and pyrolusite. Oxidized iron formation is recorded close to these deposits and displays abundant evidence of secondary hematite enrichment. Similar alteration has also been recorded close to other high-grade hematite deposits previously considered to be purely supergene in origin (*e.g.*, Joyce Lake deposit; Figure 1). These deposits may have formed during supergene overprint of an early hypogene enrichment event, similar to the Thabazimbi deposit in South Africa (Netshiozwi, 2002). However, further geochemical and isotopic analyses are needed to determine an appropriate genetic model for these deposits.

A hypogene model for high-grade hematite enrichment in these deposits has important implications for future exploration activities in the Labrador Trough, particularly when combined with airborne magnetic and gravity studies. 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. In contrast, deposits similar to Sawyer Lake may be blind orebodies that are not related to the current land surface. Structures such as isoclinal folds and fault zones are important in concentrating fluid flow, particularly below relatively impermeable units such as the Nimish Formation volcanic rocks. Zones of hydrothermal alteration, including oxidation and partial leaching of the iron formation and alteration of pretectonic gabbro sills may be used as vectors toward iron mineralization. Secondary goethite enrichment may reflect recent groundwater flow and is common even in areas with no evidence of economic iron enrichment (Dufresne, 1950; Wardle, 1979). Therefore, the presence of goethite is not considered a good indicator of the presence of high-grade deposits.

FUTURE WORK

This research is focused on the determining the origin of high-grade hematite ore deposits in the Labrador Trough, including hard hematite ores similar to the Sawyer Lake deposit, soft DSO deposits of the Schefferville area and intermediate ore deposits (*e.g.*, Houston and Malcolm deposits). These studies include detailed field-based and petrographic studies of these deposits, as well as rare-earth element geochemistry and oxygen isotope studies. Such techniques have been shown to be able to differentiate between supergene and hypogene iron-ore enrichment (Gutzmer *et al.*, 2006, 2008) and will be important in developing new exploration models in the Labrador Trough.

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REFERENCES

Angerer, T. and Hagemann, S.G.
2010: The BIF-hosted high-grade iron ore deposits in the Archean Koolyanobbing Greenstone Belt, Western Australia: Structural control on synorogenic- and weathering-related magnetite-, hematite-, and goethite-rich iron ore. Economic Geology, Volume 105, pages 917-945.

Barley, M.E., Pickard, A.L., Hagemann, S.G. and Folkert, S.L.
1999: Hydrothermal origin for the 2 billion year old Mount Tom Price giant iron ore deposit, Hamersley province, Western Australia. Mineralium Deposita, Volume 34, pages 784-789.

Bowie, G. and Lepinski, J.A.
1989: First year assessment report on geochemical exploration for licence 331m on claims in the Sawyer Lake area, Labrador. Newfoundland and Labrador Geological Survey, Assessment File: 023I/05/0070.

Chavez, E., McKillen, T.N., Valliant, W. and Gauthier, G.
2005: First and second year assessment report on geological and geochemical exploration for licences 9690M and 10481M-10482M on claims in the Sawyer Lake area, western Labrador. Newfoundland and Labrador Geological Survey, Assessment File: 023I/05/0086.

Clark, T. and Wares, M.
2005: Lithotectonic and metallogenic synthesis of the New Québec Orogen (Labrador Trough). Ministère des Ressources naturelles, Québec, MM 2005-01, 175 pages.

Dalstra, H.J. and Rosière, C.A.
2008: Structural controls on high-grade iron ores hosted by banded iron formation: A global perspective. Reviews in Economic Geology, Volume 15, pages 73-106.

Dufresne, C.
1950: Geological report on the Sawyer–Snelgrove map-area, Labrador. Labrador Mining and Exploration Company Limited. Newfoundland and Labrador Geological Survey, Geofile Number: 023I/0003.

Evans, J.L.
1978: The geology and geochemistry of the Dyke Lake area [parts of 23J/8, 9], Labrador. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 78-04, 43 pages.

Findlay, J.M., Parrish, R.R., Birkett, T.C. and Watanabe, D.H.
1995: U–Pb ages from the Nimish Formation and Montagnais glomeroporphyritic gabbro of the central New Québec Orogen, Canada. Canadian Journal of Earth Sciences, Volume 32, pages 1208-1220.

Gutzmer, J., Chisonga, B.C., Beukes, N.J. and Mukhopadhyay, J.
2008: The geochemistry of banded iron formation-hosted high-grade hematite-martite iron ores. Reviews in Economic Geology, Volume 15, pages 157-183.

Gutzmer, J., Mukhopadhyay, J., Beukes, N.J., Pack, A., Hayashi, K. and Sharp, Z.D.
2006: Oxygen isotope composition of hematite and genesis of high-grade BIF-hosted iron ores. Geological Society of America, Memoir 198, pages 257-268.

Griffis, A.T., Moss, A.E. and Retty, J.A.
1944: Assessment report on geological exploration for the Labrador Mining and Exploration Company Limited Concession in the Attikamagen Lake, Fleming Lake, Ruth Lake and Wishart Lake areas, Labrador. Labrador Mining and Exploration Company Limited. Newfoundland and Labrador Geological Survey, Geofile Number: LAB/0491.

Gross, G.A.
1968: Geology of Iron Deposits of Canada, Volume III. Iron Ranges of the Labrador Geosyncline. Geological Survey of Canada, Economic Geology, Report 22, 179 pages.

Harding, C.J.
2004: Origin of the Zeekoebaart and Nauga East high grade iron ore deposits, northern Cape Province, South Africa. Unpublished M.Sc. thesis, Rand Afrikaans University, 123 pages.

Lascelles, D.F.
2007: Black smokers and density currents: A uniformitarian model for the genesis of banded iron-formations. Ore Geology Reviews, Volume 32, pages 381-411.

2012: Banded iron formation to high-grade iron ore: a critical review of supergene enrichment models. Australian Journal of Earth Sciences: An International Geoscience Journal of the Geological Society of Australia, Volume 59:8, pages 1105-1125.

Le Gallais, C.J. and Lavoie, S.
1982: Basin evolution of the Lower Proterozoic Kaniapiskau Supergroup, central Labrador Miogeocline (Trough), Quebec. Bulletin of Canadian Petroleum Geology, Volume 30, pages 150-160.

Lobato, L.M., Figueiredo e Silva, R.C., Hagemann, S.G., Thorne, W.S. and Zuchetti, M.
2008: Hypogene alteration associated with high-grade banded iron formation-related iron ore. Reviews in Economic Geology, Volume 15, pages 107-128.

Machado, N., Clark, T., David, J. and Goulet, N.
1997: U-Pb ages for magmatism and deformation in the New Quebec Orogen. Canadian Journal of Earth Sciences, Volume 34, pages 716-723.

Netshiozwi, S.T.
2002: Origin of high-grade hematite ores at Thabazimbi mine, Limpopo Province, South Africa. Unpublished M.Sc. thesis, Rand Afrikaans University, 135 pages.

Ohmoto, H.,
2003: Nonredox transformations of magnetite-hematite in hydrothermal systems. Economic Geology, Volume 98, pages 157-161.

Price, J.B.
1979: Report on sampling and geology for block 8, Labrador. Newfoundland and Labrador Geological Survey, Assessment File 23J/14/0209.

Ramanaidou, E.R. and Morris, R.C.
2010: Comparison of supergene mimetic and supergene lateritic iron ore deposits. Applied Earth Science, Volume 119, pages 35-39.

Retty, J.A.
1938: Geological report for 1937 on the geology and mineral deposits of the Dyke Lake map area and northern part of Ossokmanuan Lake map area, Labrador. Labrador Mining and Exploration Company Limited. Newfoundland and Labrador Geological Survey, Geofile Number: LAB/0487.

1939: Geological report for 1938 for Labrador. Labrador Mining and Exploration Company Limited. Newfoundland and Labrador Geological Survey, Geofile Number: 023J/0206.

1950: Geological report for 1949 for Labrador. Labrador Mining and Exploration Company Limited. Newfoundland and Labrador Geological Survey, Geofile Number: LAB/0504.

Retty, J.A. and Moss, A.E.
1945: Geological report for 1944 for Labrador. Labrador Mining and Exploration Company Limited. Newfoundland and Labrador Geological Survey, Geofile Number: LAB/0492.

Rohon, M.-L., Vialette, Y., Clark, T., Roger, G., Ohnenstetter, D. and Vidal, P.
1993: Aphebian mafic–ultramafic magmatism in the Labrador Trough (New Quebec): its age and the nature of its mantle source. Canadian Journal of Earth Sciences, Volume 30, pages 1582-1593.

Rosière, C.A., Spier, C.A., Rios, F.J. and Suckau, V.
2008: The itabirites of the Quadrilátero Ferrífero and related high-grade iron ore deposits: An overview. Reviews in Economic Geology, Volume 15, pages 223-254.

Scott, F.
1996: First year assessment report on geophysical exploration for licence 3986m on claims in the Sawyer Lake area, Labrador. Newfoundland and Labrador Geological Survey, Assessment File 023I/05/0082

1998: Third year assessment report on compilation and reserve estimation for licence 3986m on claims in the Sawyer Lake area, Labrador. Newfoundland and Labrador Geological Survey, Assessment File: 023I/05/0080.

Sibson, R.H.
2005: Hinge-parallel fluid flow in fold-thrust belts: how widespread? Proceedings of the Geologists Association, Volume 116, pages 301-309.

Stubbins, J.B., Blais, R.A. and Zajac, I.S.
1961: Origin of the soft iron ores of the Knob Lake Range. Canadian Mining and Metallurgical Bulletin, Volume 585, pages 43-58.

Taylor, D., Dalstra, H.J., Harding, A.E., Broadbent, G.C. and Barley, M.E.
2001: Genesis of high-grade hematite orebodies of the Hamersley Province, Western Australia. Economic Geology, Volume 96, pages 837-873.

Thorne, W.S., Hagemann, S.G. and Barley, M.
2004: Petrographic and geochemical evidence for hydrothermal evolution of the North deposit, Mt. Tom Price, Western Australia. Mineralium Deposita, Volume 39, pages 766-783.

Vatcher, H., Schrama, T. and Chavez, E.
2009: First, second, third, fourth and sixth year assessment report on remote sensing and geochemical and drilling exploration for licences 9690M, 10039M-10043M, 10481M-10483M, 10832M-10835M, 10874M-10875M, 10879M, 10883M-10884M, 11074M, 11121M, 11171M, 11201M, 11231M, 11305M-11307M, 11541M-11544M, 11928M-11930M, 12890M, 12894M, 14495M-14497M, 14510M-14512M and 14746M-14750M on claims in the Schefferville area, northern Labrador. Newfoundland and Labrador Geological Survey, Assessment File: LAB/1496.

Wardle, R.J.
1979: Geology of the eastern margin of the Labrador Trough. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 78-9, 21 pages.

Wardle, R.J. and Bailey, D.G.
1981: Early Proterozoic sequences in Labrador. *In* Proterozoic Basins of Canada. *Edited by* F.H.A. Campbell. Geological Survey of Canada, Paper 81-10, pages 331-359.

Wardle, R.J., Ryan, B., Nunn, G.A.G. and Mengel, F.C.
1990: Labrador segment of the Trans-Hudson Orogen: crustal development through oblique convergence and collision. *In* The Early Proterozoic Trans-Hudson Orogen of North America. *Edited by* J.F. Lewry and M.R. Stauffer. Geological Association of Canada, Special Paper 37, pages 353-369.

Wardle, R.J., James, D.T., Scott, D.J. and Hall, J.
2002: The Southeastern Churchill Province: synthesis of a Paleoproterozoic transpressional orogen: Proterozoic evolution of the northeastern Canadian Shield: Lithoprobe eastern Canadian Shield onshore–offshore transect. Canadian Journal of Earth Sciences, Volume 39, pages 639-663.

Watanabe, D.
1996: Petrology and geochemistry of the Nimish Formation, western Labrador, Newfoundland. Unpublished M.Sc. thesis, University of Ottawa, 122 pages.

Zajac, I.S.
1974: The stratigraphy and mineralogy of the Sokoman Iron Formation in the Knob Lake area, Quebec and Newfoundland. Geological Survey of Canada, Bulletin 220, 159 pages.