Canadian Journal of Earth Sciences
Revue canadienne des sciences de la Terre

**Geologic Interpretation of Aeromagnetic and Chemical Data
from the Oaks Belt, Wabigoon Subprovince, Minnesota:
Implications for Au-rich VMS Deposit Exploration**

Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2015-0141.R1
Manuscript Type:	Article
Date Submitted by the Author:	02-Dec-2015
Complete List of Authors:	Hendrickson, Michael; 1341 Middle Gulf Dr. Suite 11D
Keyword:	Wabigoon, VMS, Aeromagnetic, Subvolcanic Intrusion

Geologic Interpretation of Aeromagnetic and Chemical Data from the Oaks Belt, Wabigoon Subprovince, Minnesota: Implications for Au-rich VMS Deposit Exploration

Michael D. Hendrickson^{1,*}

¹1341 Middle Gulf Drive, Suite 11D, Sanibel, FL, 33957, USA

*Corresponding Author
mike.hendrickson.6788@gmail.com

Draft

Abstract

The Oaks Belt (OB) is a Neoarchean volcanic complex located in northwestern Minnesota, USA. It is part of the Wabigoon granite-greenstone terrane that hosts the world-class Rainy River gold deposit in nearby Ontario, Canada. Rocks in the OB form a north-dipping homocline in the fault-bounded pressure shadow of a sigma-shaped volcano-plutonic wedge that spans E-W for 220 km across the Minnesota-Canada border. Exploration drilling in the area delineated pyrrhotite-pyrite massive sulfide deposits, iron formation, chert and semi-massive sphalerite mineralized zones. High-resolution aeromagnetic data indicate a large ($\sim 60 \text{ km}^2$) composite subvolcanic intrusion underlies these iron-rich strata in the OB. The position of this inferred intrusion elucidates the low base metal content of known massive sulfide deposits, as they were too far away (6-10 km) from a heat source to have been favorable sites for base metal deposition. The relative abundance of Au and Zn in the OB, alongside correlation coefficients between metals in massive sulfide deposits, iron formation, and chert, indicates the rocks were affected by a low-temperature hydrothermal system under relatively shallow water conditions (< 1000 meters). Negative correlation between Na_2O and CaO in basalt, and their mutual moderate positive correlation with immobile corundum (Al_2O_3), implies alteration in the upper part of the volcanic pile did not result in substantial element mobility in most samples. Geochemical data from mafic and felsic volcanic rocks plot mainly in the calc-alkaline field. Thus, the OB is most prospective for hosting Au-rich VMS deposits and future exploration should focus on paleo-thermal corridors and favorable stratigraphic horizons near the newly inferred composite subvolcanic intrusion.

Introduction

The Neoarchean Oaks Belt (OB) (Severson and Heine 2012) is a volcanic complex located in northwestern Minnesota (MN), USA, approximately 50 km south of the Canadian border (Fig. 1a). Situated in the westernmost extension of the Wabigoon Subprovince, volcano-plutonic rocks in the OB are on strike with the world-class Rainy River epithermal gold deposit (4 M Oz Au, 9 M Oz Ag; Hardie et al. 2014; Wartman 2011) in neighboring Ontario (ON), Canada (CN) (Fig. 1b, c). The area was explored from the 1960's to the 1990's for volcanogenic massive sulfide (VMS) and orogenic gold deposits. Due to a thick layer of glacial overburden (~30-50 meters), and absence of outcrop, exploration targets were chosen from airborne and ground-based electromagnetic data. Drilling of fifty-five diamond and reverse circulation holes on these targets resulted in delineation of uneconomic pyrrhotite-pyrite deposits, iron formation, and semi-massive sphalerite mineralized zones.

Post -dating most exploration in the OB, state and federal geologic surveys acquired high-resolution aeromagnetic data in northern MN (Chandler 1991; Chandler et al. 2004). Although these data have been used to supplement bedrock geologic mapping at the 1:250,000 scale (Day et al. 1994a; Day et al. 1994b; Jirsa et al. 2011), they have not been thoroughly analyzed in the OB to understand the regional and local geological setting.

The OB is interpreted to occur in the fault-bounded pressure shadow of a sigma-shaped wedge of volcanic and plutonic rocks that spans for 220 km across the MN-CN border. Drilling and aeromagnetic data from the area indicate several successions of base metal-poor massive sulfide deposits occur in an arcuate array overlying an inferred composite subvolcanic intrusion. This subvolcanic intrusion is 19 km long, 3 km thick and approximately 60 km² in area. Based on

heat and fluid modeling (Cathles 1983; Solomon et al. 1987; Schiffman and Smith 1988; Paradis et al. 1993; Hoy 1993; Cathles 1993; Yang et al. 1996; Cathles et al. 1997; Barrie et al. 1999b; Barrie et al. 1999a; Yang and Large 2001; Schardt et al. 2005) and empirical data (Galley 2003) the drilled massive sulfide deposits are too far away (6-10 km) from this inferred paleo-heat source to have been favorable sites for base metal deposition. Thus, an interpretation of volcanic stratigraphy and synvolcanic fault geometry has important implications for future mineral exploration in the area. This contribution combines historic drilling and geochemical data with analysis and modeling of aeromagnetic data to define the structural and stratigraphic architecture of the OB in Wabigoon terrane in MN. This interpretation is used to identify the most prospective areas for hosting VMS ($\pm$ epithermal) base and precious metal deposits.

Methods

Aeromagnetic Theory

Scalar aeromagnetic data comprise both induced and remanent magnetic fields. Induced magnetism is caused by the earth's magnetic field and is mainly the result of the magnetic susceptibility of the rock. Magnetic susceptibility is expressed as a unit-less proportionality constant (calculated as the induced magnetization divided by the applied field strength) denoted by an International System of Units (SI), which reflects the susceptibility of a rock to become magnetized in the presence of a magnetic field. This susceptibility is mainly a function of the rock's magnetite content. In general, higher susceptibility rocks produce greater variability in magnetic amplitudes than low-susceptibility counterparts (Ford et al. 2008; Anderson et al. 2013; Table 1). The remanent component is a function of the magnetic, structural, and thermal history

of a rock and is not affected by the inducing magnetic field in which it is measured. In most cases, the induced component of the magnetic field is predominant.

Aeromagnetic Data and Modeling

Aeromagnetic data used for this study were collected by the United States Geologic Survey (USGS) and the Minnesota Geologic Survey (MGS) (Chandler 1991; Chandler et al. 2004). These data were gathered at ~200-400 meter line spacing at an average elevation of 150 meters above terrain using a proton precession magnetometer. Data from the study area was base-station corrected and leveled (Chandler 1991; Chandler et al. 2004). The corrected total magnetic field was reduced-to-pole (RTP) using the IGRF values and magnetic field inclination and declination from the dates of the individual surveys (Baranov and Naudy 1964; Blakely 1995; Chandler 1991; Chandler et al. 2004). Following processing, the data set was filtered using derivative and upward continuation techniques to qualitatively understand the distribution and offsets in rock units. Original line and filtered data were gridded using the average of coincident points in a minimum curvature method. A cell size of 100 meters, an interior tension of 25, and exterior tension of 0 were applied.

2.5D forward and inverse modeling of aeromagnetic data was completed with Encom ModelVision Pro software and started with upward continuation of the corrected data to 300 meters to reduce noise from shallow, high frequency magnetic sources. The background magnetic field was determined graphically as 59,440 nT and the magnetic field inclination and declination used for modeling were 76° and 5°, respectively. The lithology of rocks in the OB was determined from private company and government data (Severson and Heine 2012; Frey and Venzke 1991). Previous drilling and geologic interpretation of the area constrained the geometry of rock units used for preliminary forward models. Inversion of the geologically controlled

forward models in 2.5D was completed by sequentially freeing parameters of the magnetic sources (e.g. thickness, depth, and magnetic susceptibility) until an acceptable root-mean-square error ($< 2.00\%$) between observed and calculated data was reached.

Geochemical Data

Whole rock and trace element geochemical data were obtained from the Minnesota Department of Natural Resources Division of Lands and Minerals (MN DNR). The MN DNR compiled these data from internal studies (Frey and Venzke 1991), the USGS (Klein 1988), and private companies. Whole rock geochemical data were used to classify volcanic and intrusive rocks as well as the magmatic affinity of mafic volcanic rocks (calc-alkaline or tholeiitic) (LeBas et al. 1986; Mullen 1983; Polat 2009). Trace element data were used to determine the ore potential of felsic volcanic rocks (Leshner et al. 1986).

Correlation coefficients (P values) were calculated using the Pearson product-moment method (Rodgers and Nicewater 1988) and tested for statistical significance at $\alpha \geq 0.05$ (95% confidence interval). This method defines the linear dependence of two variables, which is the covariance between two variables divided by the product of their standard deviations. P values range from +1 to -1, with positive values indicating positive correlation, near-zero values indicating no correlation, and negative values indicating negative correlation. The values presented in this study are statistically small, indicating they are not a random sampling artifact. Correlation coefficients between major elements and metals comprising iron formation, chert and massive sulfides were used to qualitatively determine contributing sources (e.g. detrital material, hydrothermal fluids, seawater) (Cox et al. 2013) and hydrothermal fluid characteristics (i.e. temperatures, oxidation state, and water depth).

Geologic Setting

Stratigraphy

The stratigraphy of the Wabigoon subprovince in MN has been described from sparse bedrock exposure, scattered drill holes and aeromagnetic data (Ojakangas et al. 1977; Ojakangas et al. 1979; Southwick and Ojakangas 1979; Day et al. 1994a; Day et al. 1994b; Jirsa et al. 2011). Rocks in the more exposed regions of the Wabigoon subprovince in ON, CN have been summarized by Czeck and Poulsen (2010), with a description of the main rock units taken from Davis et al. (1989) and Fralick and Davis (1999) (Table 2). Mafic to intermediate volcanic rocks are most common, with drilling data suggesting subordinate felsic volcanic and volcanoclastic rocks are locally prevalent. A schematic stratigraphic correlation of rock units and depositional environments in the Wabigoon, Quetico, and Wawa subprovinces is shown in Fig. 2. These data suggest the Wawa and Wabigoon subprovinces host similar lithologies that were deposited in Neoarchean island arc volcanic environments. Metasediments of the Quetico subprovince are unconformably bounded by the Wawa and Wabigoon terranes, and represent a greywacke dominant accretionary prism deposited during the collision of the Wawa terrane and Superior craton (Shebandowanian orogeny; Jirsa et al. 2011).

Structural Geology

Three major deformation events affected the area in the Neoarchean: the D₁ Shebandowanian orogeny (~2,695 Ma), the D₂ Minnesotan orogeny (~2,680 Ma), and a final D₃ event inferred from distortion of D₂ fabrics (Jirsa et al. 2011; Poulsen 1986; Davis et al. 1989; Tabor and Hudleston 1991; Poulsen 2000a; Druguet et al. 2008).

In the Wabigoon terrane, D_1 resulted in recumbent folding that overturned the stratigraphic sequence and the first regional schistosity (Poulsen et al. 1980). Although D_1 likely created significant thrust or oblique faulting, direct evidence for this is not possible due to lack of sedimentary marker horizons that allow recognition duplicated sequences of rock. However, early faulting is implied by the strain patterns, which are too low to account for the steeply dipping package of rock units (Schultz-Ela 1988; Hudleston and Schwerdtner 1997; Czeck and Poulsen 2010).

The second regional-scale deformation event (D_2) was associated with a northwest-directed, transpressional stress regime (Hudleston et al. 1988; Jirsa et al. 1992). Offsets in rock units and rotation fabrics suggest that the D_2 kinematic sense was dextral (Hudleston 1976; Schultz-Ela and Hudleston 1991; Czeck and Hudleston 2003; Czeck and Poulsen 2010). D_2 was responsible for folding and the penetrative foliation and lineation fabrics throughout the region. Metamorphic grades achieved during D_2 range from lower greenschist facies to middle amphibolite facies. The D_1 to D_2 transition was not necessarily contemporaneous across the Rainy Lake region (Czeck and Poulsen 2010).

Structural features that developed after the main metamorphic event (D_2) have been labeled as D_3 structures (Jirsa et al. 1992). However, studies in the Quetico subprovince (Bauer 1985) indicate that D_3 was actually part of the late stage of D_2 (Peterson 2001). Deformation during D_3 produced brittle northeast- and northwest-trending faults that offset metamorphic fabrics developed during D_2 .

Geology of the Oaks Belt

The OB is composed of mafic to felsic volcanic and volcanoclastic rocks, massive sulfide deposits, iron formation and several types of intrusive rocks (Frey and Venzke 1991; Severson and Heine 2012). Mafic volcanic rocks constitute the bulk of the stratigraphy in the OB and occur as pillowed basalts, massive flows and volcanoclastics. Intermediate volcanic rocks are almost exclusively feldspar-phyric tuffs and contain 20-30% mica and amphibole. Felsic volcanoclastic rocks vary from rhyolites to dacites and occur mainly near the stratigraphic top of the volcanic pile where they directly underlie massive sulfide and iron formation deposits. These highly siliceous rocks are mica- and amphibole-poor, and occur as both quartzphyric fragments and tuffs (Frey and Venzke 1991). Massive sulfide deposits are pyrrhotite-rich and thickest near the top of the volcanic pile where they are stratigraphic equivalents to iron formation and chert. Iron formation beds are typically intermixed with iron silicates and sulfides, and are up to one meter thick. These individual beds of iron formation occur as stacked lenses that span over 50 meters vertically through stratigraphy (Frey and Venzke 1991). Chert is typically sulfidic, with pyrite and pyrrhotite as the main sulfide minerals. Intrusive rocks in the OB vary from millimeter-scale dikes and veins to meter-scale sills and dikes. They vary compositionally through ultramafic, pyroxenite, mafic, granodiorite, and granitic. Granodiorite dikes intrude mafic rocks, and are in turn cut by granitic dikes (Frey and Venzke 1991).

An interpretation of the volcanic stratigraphy of the OB was created (Fig. 3b) by comparing aeromagnetic data to known lithologies defined by drilling data. An inferred subvolcanic intrusion underlies the volcanic pile in the OB and is here named the Lost Lake Intrusive Complex (LLIC). This intrusion was inferred from the geometry of magnetic halos (Fig. 5a, b) that represent high-temperature fluid interaction with surrounding rock (Galley et al. 2007). Other evidence for the presence of the LLIC is the distribution of the massive sulfide

deposits, iron-oxide layers, and felsic volcanic rocks. These rocks are more prolific over the eastern and western flanks of the inferred LLIC (Fig. 3b), which is a modeled result of heat flow over the edges of subvolcanic intrusions (e.g. Barrie et al. 1999b). Highly magnetic intrusive rock previously designated as the Oaks Intrusion (OI) occurs on the eastern flank of the OB. Ar-Ar dating of hornblende in the OI yielded an age 2671 ± 8 Ma (Keatts et al. 2003). The age of the OI and its relationship with regional faults suggests it was contemporaneous with D_2 . A magnetic sill, designated the Oaks Intrusion sill (OIS), was likely time correlative to the OI and intruded the volcanic pile in the OB.

Aeromagnetic Data

Structural Interpretation of Aeromagnetic Data

Pronounced linear lows in the aeromagnetic data indicate the OB is bound to the north by the Quetico fault and to the south by the Vermillion fault (Fig. 3, Fig. 4). The geometry of regional faults suggests the OB occurs in a pressure shadow of a regional-scale sigma-shaped wedge of volcano-plutonic rocks and the kinematic sense for D_2 - D_3 was dextral. This structural block, here named the Rainy River Block (RRB), strikes ~220 km E-W and tapers from ~30 km thick in the central portion to less than 5 km at its edges. Internally, the RRB is cut by several NE trending faults or shear zones that are reminiscent of S-C fabric (Fig. 4). Iterative upward continuation filters of the RTP aeromagnetic data to increasing heights retain the regional fault lineations, suggesting they continue to considerable depth

High-angle synvolcanic faults in the OB were inferred from breaks and/or offsets in magnetic anomalies (Fig. 5). Since the entire succession of rocks in the OB is interpreted to be overturned and steeply north-dipping, the current map represents an approximate inverted cross-

section of the volcanic complex. Inferred synvolcanic faults are N-S trending and occur in an arcuate array over the LLIC as upper and lower sets (Fig. 5). These upper and lower sets of synvolcanic faults likely represent two cycles of volcanism with associated extension. There is a close spatial association between inferred upper cycle synvolcanic faults and known base metal-poor massive sulfide deposits in the OB (labeled MS on Fig. 5a, b). Inferred lower cycle synvolcanic faults are also associated with magnetic anomalies overlying the center of the LLIC that are similar to those associated with massive sulfide deposits and iron formation layers in the upper cycle. Magnetic strata closely associated with these lower cycle synvolcanic faults are interpreted as focused paleo-fluid pathways and thus the most prospective for hosting VMS deposits in the OB (Fig. 5).

Filtered Data in Map View

The RTP transformed data effectively outline the LLIC, magnetic massive sulfide (MS) horizons, iron formation, the OI and OIS (Fig. 5a). The second-vertical derivative (SVD) of the RTP magnetic field in the OB further constrained the magnetic halos (MH) surrounding the LLIC (Fig. 5b). The SVD filter also highlights shallow magnetic anomalies overlying the LLIC. Especially strong SVD anomalies represent known massive sulfide and iron formation deposits. Several SVD highs similar to the geologically constrained anomalies occur down-section and closer to the LLIC.

Upward continuation filtering of magnetic data in the OB to 1, 2, 3, and 6 kilometers demonstrates the progressive geometry of magnetic bodies at depth. The upward continuation filter calculates the magnetic response of sources that are approximately one-half as deep as the upward continuation distance (i.e. an upward continuation to 6 km calculates the magnetic

response of sources deeper than 3 km) (Jacobsen 1987). Shallow SVD highs are removed by the 1 or 2 km upward continuation (Fig. 5c, d). The thicker massive sulfide deposits (and/or iron formation) are present in the data up to the 3 km upward continuation (Fig. 5e) but largely disappear in the 6 km continuation (Fig. 5f). The OI is the most magnetic body in the OB, and is easily seen in all upward continuation iterations. The magnetic response migrates north from the shallow parts of the magnetic sources during iterative upward continuation (Fig. 5c, d, e, f) which suggests the rocks are steeply north-dipping.

Filtered Data in Cross Section

Derivative and upward continuation filtering of individual line data was completed on three sections—A-A', B-B', and C-C' (shown on Fig. 3b, Fig. 5) — that are representative of the stratigraphy of the volcanic pile and the underlying subvolcanic intrusion (Fig. 6). The LLIC shows internal magnetic heterogeneity and is thicker in the west (A-A') than in the east (C-C'). Massive sulfide and iron formation in the upper part of the volcanic pile are highly magnetic, reaching amplitudes over 1500 nT. Derivative filtered data sharply enhance the known massive sulfide deposits and the upward continued data suggest they continue at depth. Importantly, these data in B-B' outline a magnetic high that likely represents massive sulfide or iron formation lenses closer to the upper contact of the LLIC (Fig. 6).

Forward and Inverse Modeling

Simple forward and inverse models of magnetic data on sections A-A', B-B', and C-C' were used to define the 2.5 dimensional geometry of the rocks in the OB (Fig. 7). Modeling of aeromagnetic data is inherently ambiguous, as multiple magnetic sources can produce the same magnetic signature. However, geologically constrained modeling (as used in this study)

improves the accuracy of models by limiting rock unit geometry and magnetic susceptibility to geologically reasonable and expected bounds. Detailed rock property analyses in the OB are recommended to better constrain the model presented in this study.

Forward models suggest magnetic sources have a maximum depth of ~5 km and the volcanic pile is overturned and steeply north-dipping. Inversion of these data also suggests the rocks are covered by 30-50m of nonmagnetic glacial debris. The iron formation and massive sulfide layers have magnetic susceptibilities that range from 0.0246 to 0.0631 SI and were modeled by individual sources up to 800 m thick. The LLIC and mafic intrusive rock (OIS) are modeled with multiple magnetic susceptibilities suggesting they are both compositionally layered. Stratigraphically underlying the massive sulfide or iron formation deposits in B-B' are sources with lower magnetic susceptibilities (0.0027 SI; Fig. 7) than intermediate to mafic volcanic rocks underlying base metal-poor massive sulfide and iron formation deposits in the upper part of the volcanic pile (A-A'; Fig. 7) indicating they may be different rock type (i.e. felsic volcanic and/or hydrothermally altered rocks).

Geochemical Data

Minor element geochemical analysis of mafic volcanic rocks indicates they are mainly calc-alkaline, with some samples plotting as tholeiitic (Fig. 8a). The metal content of mafic volcanic rocks is within normal background values for basalts. Major elements comprising mafic volcanic rocks in the OB show statistically significant negative correlation between Na_2O and CaO (Table 3) which are also both positively correlated with immobile Al_2O_3 (corundum) indicating the top of the volcanic pile did not experience high-temperature alteration.

Whole rock geochemical data from felsic volcanic rocks plot in the rhyolite and dacite fields (Fig. 8c). Data from both felsic and intermediate volcanic rocks in the area plot ubiquitously as calc-alkaline (Frey and Venzke 1991). Most sampled felsic volcanic rocks are enriched in Zn and Cu, with comparatively less Pb. Limited data (n=8) (Frey and Venzke 1991; Klein 1988) suggest felsic rocks in the OB are FII (calc-alkaline to transitional) and FI (alkaline to calc-alkaline) types (Leshner et al. 1986; Gaboury and Pearson 2008; Fig. 8b). The F-type classification system does not apply to epithermal systems, such as the world-class Rainy River gold deposit on strike with the OB, where FI base metal-poor dacitic rocks host gold mineralized zones (Wartman 2011).

Mafic intrusive rocks in the OB plot mainly as basalt (gabbro), but intrusive rocks logged as granodiorite (Frey and Venzke 1991) plot in the rhyolite (granite) field (Fig. 8d). Whole rock geochemical data from intrusive rocks display a strong bimodal distribution (Fig. 8d) that is correlative to data from volcanic rocks, indicating they represent the intrusive sources of the volcanic pile.

In massive sulfide deposits Zn is typically the most enriched, followed by lesser Cu and sporadic Pb. Au is locally elevated to ore-grade values (≥ 1 ppm). Statistically significant correlation coefficients between metals in massive sulfide deposits show that Cu, Pb, and Ag are strongly correlated and Ag and Zn are moderately correlated (Table 4).

Iron formation and chert in the OB occur on or near the same stratigraphic interval as massive sulfide deposits. Hypogene iron formation is magnetite rich. Iron formation may have originally been deposited as a hematite-rich chemical sediment that later converted to a magnetite-dominant assemblage during metamorphism. Locally significant supergene alteration

of the magnetite-rich iron formation resulted in near ore-grade hematite deposits. Major element correlation coefficients from iron formation and chert indicate a hydrothermal source of iron as it is negatively correlated with Al_2O_3 , Na_2O , and K_2O (Table 5) that are typically sourced from detrital material (Cox et al. 2013). Correlation coefficients of metals in iron formation and chert indicate Cu is positively correlated with Pb, Zn, and Ag, and negatively correlated with Au (Table 6). These statistically significant correlation coefficients are similar to data from massive sulfide deposits in the OB, corroborating drill data that suggests they were deposited contemporaneously.

Discussion

Drilling and aeromagnetic data indicate the OB occurs in the southwestern pressure shadow of a regional-scale sigma-shaped wedge of volcanoplutonic rocks. Critically, this structural setting implies the belt did not suffer high strain that would have destroyed VMS deposits during deformation. At the scale of the OB, aeromagnetic data suggest a composite subvolcanic intrusion (Lost Lake Intrusive Complex (LLIC); Fig. 3b, Fig. 5), roughly 60km^2 in area, provided the heat source for fluid circulation to generate the large, base metal-poor massive sulfide deposits and iron formation identified by drilling data. The massive sulfide deposits and iron formation layers are most common over the edges of the inferred LLIC, which is a modeled result of heat flow above the edges of subvolcanic intrusions (e.g. Barrie et al. 1999b). Inferred synvolcanic faults were zones of focused paleo-heat and fluid flow over the edges and the center of the LLIC that controlled the location of massive sulfide deposits. 2.5D forward modeling of aeromagnetic data confirm interpretations from drilling data that rocks in the OB form a north-dipping homocline.

Trace element plots (Zr vs. Y; Fig. 8b) of limited data (Frey and Venzke 1991; Klein 1988) from felsic volcanic rocks show they are FII and FI types which indicate favorable crustal melts were at least a part of the volcanic system (Leshner et al. 1986; Gaboury and Pearson 2008). These stratigraphically-high felsic volcanic rocks are confined to the flanks of the LLIC and likely represent the waning stages of volcanism, characterized by lower temperatures and lower VMS potential. Therefore, FII rhyolites may exist down-stratigraphy, where higher temperature and earlier volcanism were more conducive to economic VMS deposit formation.

Positive correlation between Al_2O_3 , Na_2O , and K_2O and their negative correlation with Fe_2O_3 in iron formation and chert indicate hydrothermal fluids were the main source of metals (Cox et al. 2013; Table 5). Base and precious metal correlation coefficients in massive sulfide deposits, iron formation, and chert show Cu, Pb, Zn and Ag are positively correlated, and that Au and Cu are negatively correlated (Table 6). VMS deposits formed in high temperature, reducing, and deep water environments typically show positive correlation between Au and Cu, and no correlation between Zn, Au, and Ag. Along with the relative abundance of Zn and Au in massive sulfides deposits, these metal relationships suggest the top of the volcanic pile experienced low temperature hydrothermal fluid conditions under shallow water depths (i.e. <1000 m; Monecke 2014) where boiling of the metalliferous fluid may have occurred. However, hydrothermal fluid characteristics and water depths may have differed during emplacement of the lower part of the volcanic stratigraphy in the OB.

Implications for Exploration

Galley (2003) demonstrated that most intrusion-related VMS camps are underlain by subvolcanic intrusions that range from 20-60 km². In this range, subvolcanic intrusions

approaching 60 km² are associated with higher tonnages of contained metals. These empirical relationships indicate the OB may contain ~60 Mt of base or precious metal-rich sulfide ore, with at least one large constituent deposit. The weathering of iron formation (and subsequent increased concentration of Fe) also suggests significant high-grade supergene VMS deposits may exist in the OB.

Although exploration targets have been identified in this study (Fig. 3b), they are 3-4 km above the upper contact of the LLIC making them marginally prospective for hosting economic Zn-Cu VMS deposits based on empirical data (Galley 2003) that suggests most base metal-rich deposits occur with 2 km of the upper contact of associated subvolcanic intrusions. However, modeled and real subvolcanic intrusions in VMS systems are generally 1-2 km thick, and result in high temperature fluid flow capable of sustaining copper and zinc in solution for roughly 2 km above the intrusion (e.g. Schardt et al. 2005). As the LLIC is ~3 km thick, it may have produced more heat, allowing Cu and Zn to remain in solution until reaching cool seawater, or a permeable sub-seafloor horizon, for longer distances (3-4 km).

Alternatively, the OB could be more prospective for hosting Neoproterozoic low-sulphidation epithermal deposits similar to the nearby Rainy River gold deposit (RRGD) (Wartman 2011). However, mafic rocks at the RRGD are tholeiitic and felsic rocks are exclusively FI type (Wartman 2011), suggesting rocks in the OB and rocks hosting the RRGD are not petrogenetic equivalents. In addition, the style of mineralization in the OB (i.e. ubiquitous pyrrhotite-rich massive sulfide and iron-oxide-rich deposits) suggests it was fundamentally different from mineralization that affected rocks at the RRGD (i.e. pyrite-rich and relatively diffuse gold mineralized zones).

Available data suggest the OB is most prospective for hosting Au-rich VMS deposits (Mercier-Langevin et al. 2007a; Mercier-Langevin et al. 2007b; Mercier-Langevin et al. 2011). The structural setting of the OB is similar to the Doyon-Bousquet-LaRonde (DBL) Au-rich VMS camp in Quebec, CN, where host rocks form a steep-dipping homocline in a laterally thinning volcanic wedge bounded by crustal-scale faults (Dubé et al. 2014; Beaudoin et al. 2014; Galley and Lafrance 2014). Although a genetic connection has been made between the relatively small Mooshla subvolcanic intrusion and adjacent VMS deposits in the DBL (i.e. Doyon, Mooshla A and B, Mic Mac, Mouska, Warrenmac/Westwood; Galley and Lafrance 2014), Dubé et al. (2014) suggested that a separate subvolcanic intrusion was associated with the world-class LaRonde and Bousquet Au-rich VMS deposits, but was not preserved during deformation.

Geochemically, Au-rich VMS deposits are often (but not always) hosted by FII ($\pm$ FI) felsic volcanic rocks that are calc-alkaline to transitional and therefore genetically correlative to rocks in the OB. Hydrothermal fluid characteristics inferred from metal assemblages and correlation coefficients between metals from massive sulfide deposits and iron formation in the OB more closely resemble those envisioned for Au-rich VMS systems than base metal-rich ones (Dubé et al. 2007). Although confirmation of these correlations requires more robust analyses of volcanic rocks in the OB, the available geochemical data combined with the geological and geophysical interpretations provided in this study suggest future exploration in the OB should focus on identifying Au-rich VMS deposits over the center and western edge of the LLIC, within 4 km of its upper contact (Fig. 3b).

Conclusions

The OB is composed of a bimodal mafic-dominated suite of volcanic rocks that are overturned and steeply north-dipping. The volcanic pile is ~6-8 km thick and underlain by a large (60 km²) inferred composite subvolcanic intrusion. Known base metal-poor massive sulfide deposits are underlain by felsic volcanic rocks and are more prolific at the top of the volcanic pile and over the flanks of the subvolcanic intrusion. The structural setting, petrogenesis of volcanic rocks, and hydrothermal fluid characteristics inferred from metal assemblages and correlation coefficients are analogous to volcanic systems that host Au-rich VMS deposits. Heat and fluid models indicate the known massive sulfide deposits in the OB are too far away from the inferred subvolcanic intrusion to have been favorable sites for metal deposition. Therefore, future exploration should focus on paleo-thermal corridors and favorable stratigraphic horizons identified in this study, which are near the inferred subvolcanic intrusion and more likely to host economic Au-rich VMS deposits.

Further study is required to constrain the paleotectonic setting and geochronology of volcanic and intrusive rocks, and massive sulfide and iron formation deposits in the OB. Geochemical data useful for developing a geodynamic interpretation (trace elements, REE patterns, Nd isotopes, etc.) can be generated from existing drill core. However, new drill holes and geochronology are necessary to constrain the genetic relationship between the inferred subvolcanic intrusion, volcanic rocks, and massive sulfide deposits. In addition, rock property studies and a gravity survey would significantly improve the model of aeromagnetic data presented in this study.

Acknowledgments

Barry Frey of the Minnesota Department of Natural Resources (MN DNR) Division of Lands and Minerals made available the geochemical data used for this study. Kevin Hanson of the MN DNR guided historic data acquisition. Quality reviews by associate editor Randy Enkin and an anonymous reviewer significantly improved the manuscript.

Draft

References Cited

- Anderson, E.D., Hitzman, M.W., Monecke, T., Bedrosian, P.A., Shah, A.K., and Kelley, K.D. 2013. Geological Analysis of Aeromagnetic Data from Southwestern Alaska: Implications for Exploration in the Area of the Pebble Porphyry Cu-Au-Mo Deposit. *Economic Geology*, 108: 421-436.
- Baranov, V., and Naudy, H. 1964. Numerical calculation of the formula of reduction to the magnetic pole. *Geophysics*, 22: 67–79.
- Barrie, C.T., Cathles, L.M., and Erendi, A. 1999a. Finite element heat and fluid-flow computer simulations of a deep ultramafic sill model for the Giant Kidd Creek volcanic-associated massive sulfide deposit, Abitibi subprovince, Canada. *Economic Geology Monograph*, 10: 529–540.
- Barrie, C.T., Cathles, L.M., Erendi, A., Schwaiger, H., and Murray, C. 1999b. Heat and fluid flow in volcanic-associated massive sulfide-forming hydrothermal systems. *Reviews in Economic Geology*, 8: 201–219.
- Bauer, R.L. 1985. Correlation of early recumbent and younger upright folding across the boundary between an Archean gneiss belt and greenstone terrane, northeastern Minnesota. *Geology* 13: 657-660.
- Beaudoin, G., Mercier-Langevin, P., Dubé, B., and Taylor, B. 2014. Low-Temperature Alteration at the World-Class LaRonde Penna Archean Au-Rich Volcanogenic Massive Sulfide Deposit, Abitibi Subprovince, Quebec, Canada: Evidence from Whole-Rock Oxygen Isotopes. *Economic Geology*, 109: 167-182

- Blakely, R.J. 1995. Potential theory in gravity and magnetic applications. Cambridge University Press, Cambridge, UK.
- Cathles, L.M. 1983. An analysis of the hydrothermal system responsible for massive sulfide deposition in the Hokuroku basin of Japan. *Economic Geology Monograph*, 5: 439–487.
- Cathles, L.M. 1993. Oxygen isotope alteration in the Noranda mining district, Abitibi greenstone belt, Quebec. *Economic Geology*, 88: 1483–1511.
- Cathles, L.M., Erendi, A.H.J., and Barrie, T. 1997. How long can a hydrothermal system be sustained by a single intrusive event?. *Economic Geology*, 92: 766–771.
- Chandler, V.W. 1991. Aeromagnetic anomaly map of Minnesota: Minnesota Geological Survey State Map Series S-17, scale 1:500,000, International Association of Geomagnetism and Aeronomy, Division I, Working Group 1, International Geomagnetic Reference Field revision 1987. *Geophysics*, 53: 576-578.
- Chandler, V.W., Lively, R.S., and Wahl, T.E. 2004. Gravity and Aeromagnetic Data Grids of Minnesota. Minnesota Geological Survey Open File Data.
- Corcoran, P.L., and Mueller, W.U. 2007. Time-transgressive Archean unconformities underlying molasse basin-fill successions of dissected oceanic arcs, Superior Province, Canada. *Journal of Geology*, 115: 655-674.
- Cox, G.M., Haverson, G.P., Minarik, W.G., Le Heron, D.P., Macdonald, F.A., Bellefroid, E.J., and Strauss, J.V. 2013. Neoproterozoic iron formation: An evaluation of its temporal, environmental and tectonic significance. *Chemical Geology*, 362: 232–249.

- Czeck, D.M., Fissler, D.A., Horsman, E., and Tikoff, B. 2009. Strain analysis and rheology contrasts in polymictic conglomerates: an example from the Seine metaconglomerates, Superior Province, Canada. *Journal of Structural Geology*, 31: 1365-1376.
- Czeck, D.M. 2001. Strain Analysis, Rheological Constraints, and Tectonic Model for an Archean Polymictic Conglomerate: Superior Province, Ontario, Canada. PhD Dissertation, University of Minnesota.
- Czeck, D.M., and Poulsen, H. 2010. Deformation in the Rainy Lake Region: A Fabulous display of Structures Controlled by Rheological Contrasts. *In* Institute on Lake Superior Geology Program with Abstracts, International Falls, MN, meeting 56, pp. 51-79.
- Czeck, D.M., and Fralick, P. 2002. Field trip 3: Structure and sedimentology of the Seine Conglomerate, Mine Centre area, Ontario. *In* Institute on Lake Superior Geology Proceedings and Abstracts, vol. 48, part 1, pp. 37-67.
- Czeck, D.M., and Hudleston, P.J. 2003. Testing models for obliquely plunging lineations in transpression: a natural example and theoretical discussion. *Journal of Structural Geology*, 25: 959–982.
- Czeck, D.M., Maes, S.M., Sturm, C.L., and Fein, E.M. 2006. Assessment of the relationship between emplacement of the Algoman plutons and regional deformation in the Rainy Lake region, Ontario. *Canadian Journal of Earth Sciences*, 43: 1653-1665.
- Davis, D.W., Poulsen, K.H., and Kamo, S.L. 1989. New insights into Archean crustal development from geochronology in the Rainy Lake area, Superior Province, Canada. *Journal of Geology*, 97: 379-398.
- Day, W.C., Klein, T.L., and Schulz, K.J. 1994a. Bedrock geologic map of the Roseau 1°x2° quadrangle, Minnesota, United States, and Ontario and Manitoba, Canada. United States Geological Survey, Miscellaneous Investigation Series. Map I-2358-A.

- Day, W.C., Southwick, D.L., Schulz, K.J., and Klein, T.L. 1994b. Bedrock geologic map of the International Falls 1°x2° quadrangle, Minnesota, United States, and Ontario, Canada. United States Geological Survey, Miscellaneous Investigation Series. Map I-1965-B.
- Druguet, E., Czeck, D.M., Carreras, J., and Castaño, L.M. 2008. Emplacement and deformation features of syntectonic leucocratic veins from Rainy Lake zone (Western Superior Province, Canada). *Precambrian Research*, 163: 384–400.
- Dubé, B., Gosselin, P., Mercier-Langevin, P., Hannington, M., and Galley, A. 2007. Gold-rich volcanogenic massive sulphide deposits. *In* Mineral deposits of Canada: a synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods. *Edited by* W.D. Goodfellow. Geological Association of Canada, Mineral Deposits Division, Special Publication no 5, pp. 75-94.
- Dubé, B., Mercier-Langevin, P., Kjarsgaard, I., Hannington, M., Bécu, V., Côté, J., Moorhead, J., Legault, M., and Bédard, N. 2014. The Bousquet 2-Dumagami World-Class Archean Au-Rich Volcanogenic Massive Sulfide Deposit, Abitibi, Quebec: Metamorphosed Submarine Advanced Argillic Alteration Footprint and Genesis. *Economic Geology*, 109: 121-166.
- Fissler, D.A., 2006. A quantitative analysis of strain in the Seine River metaconglomerates, Rainy Lake region, Northwestern Ontario, Canada. M.Sc. thesis, University of Wisconsin-Milwaukee, Milwaukee, WI.
- Ford, K., Keating, P., and Thomas, M.D. 2008. Overview of geophysical signatures associated with Canadian ore deposits. Special Publication no 5, Geological Association of Canada, Mineral Deposits Division.
- Fralick, P., and Davis, D. 1999. The Seine-Couchiching problem revisited: sedimentology, geochronology and geochemistry of sedimentary units in the Rainy Lake and Sioux Lookout

- Areas. *In* Western Superior Transect Fifth Annual Workshop, 70 Lithoprobe Secretariat. *Edited by* R.M. Harrap and H. Helmstaedt. University of British Columbia, Vancouver, B.C. pp. 66-75.
- Frantes, J.R. 1987. Petrology and sedimentation of the Archean Seine Group conglomerate and sandstone, Western Wabigoon Belt, Northern Minnesota and Western Ontario. M.Sc. thesis, University of Minnesota, Minneapolis, MN.
- Frey, B.A., and Venzke, E.A. 1991. Archean Drill Core Description and Assay in Lake of the Woods County, Minnesota. Minnesota Department of Natural Resources Division of Lands and Minerals Report 278, Hibbing, MN.
- Gaboury, F., and Pearson, V. 2008. Rhyolite Geochemical Signatures and Association with Volcanogenic Massive Sulfide Deposits: Examples from the Abitibi Belt, Canada. *Economic Geology*, 103: 1531-1562.
- Galley, A.G. 2003. Composite synvolcanic intrusions associated with Precambrian VMS-related hydrothermal systems. *Mineralium Deposita*, 28: 443-473.
- Galley, A.G., Hannington, M.D., and Jonasson, I.R. 2007. Volcanogenic massive sulphide deposits. *In* Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods. *Edited by* WD Goodfellow. Geological Association of Canada, Mineral Deposits Division, Special Publication No 5, pp 141-161.
- Galley, A.G., and LaFrance, B. 2014. Setting and Evolution of the Archean Synvolcanic Mooshla Intrusive Complex, Doyon-Bousquet-LaRonde Mining Camp, Abitibi Greenstone Belt: Emplacement History, Petrogenesis, and Implications for Au Metallogenesis. *Economic Geology*, 109: 205-229.

- Hardie, C., Runnels, D., Live, P., Daniel, S.E., Ritche, D.G., Coulson, A., Cole, G., El-Rassi, D., Keogh, C., Molavi, M. 2014. NI 43-101 Feasibility Study of the Rainy River Project, Ontario, Canada.
- Hoy, L.D. 1993. Regional evolution of hydrothermal fluids in the Noranda district, Quebec: Evidence from $\delta^{18}\text{O}$ values from volcanogenic massive sulfide deposits. *Economic Geology*, 88: 1526–1541.
- Hudleston, P.J. 1976. Early deformational history of Archean rocks in the Vermilion district, northeastern Minnesota. *Canadian Journal of Earth Sciences*, 13: 579-592.
- Hudleston, P.J., and Schwerdtner, W.M. 1997. Strain. *In Greenstone Belts. Edited by M.J. De Wit and L.D. Ashwal. Oxford Monographs on Geology and Geophysics*, 35, pp. 296-308.
- Hudleston, P.J., Schultz-Ela, D., and Southwick, D.L. 1988. Transpression in an Archean greenstone belt, northern Minnesota. *Canadian Journal of Earth Sciences*, 25: 1060-1068.
- Jacobsen, B.H. 1987. A case for upward continuation as a standard separation filter for potential-field maps. *Geophysics*, 52: 1138-1148.
- Jirsa, M.A., and Southwick, D.L. 2003. Geology and Mineral Deposits of the Archean in Minnesota [online]: Available from <http://www.mngsumnedu/mnpot/MnpotGlghtml> [cited 23 March 2015].
- Jirsa, M.A., Boerboom, T.J., Chandler, V.W., Mossler, J.H., Runkel, A.C., and Setterholm, D.R. 2011. Geologic Map of Minnesota, Bedrock Geology. Minnesota Geologic Survey State Map Series S-21, University of Minnesota, Minneapolis, MN.
- Jirsa, M.A., Southwick, D.L., and Boerboom, T.J. 1992. Structural evolution of Archean rocks in the western Wawa subprovince, Minnesota: Refolding of pre-cleavage nappes during D2 transpression. *Canadian Journal of earth Sciences*, 29: 2146-2155.

- Keatts, M.J., Jirsa, M., and Holm, D. 2003. Results of $^{40}\text{Ar}/^{39}\text{Ar}$ single-grain analyses of Precambrian mafic intrusions in northern and north-central Minnesota. *In* Institute on Lake Superior Geology Program with Abstracts 49, pp. 41-42.
- Klein, T.L. 1988. Tabulated geochemistry of bedrock samples from exploration drilling in the Roseau and the western-part International Falls 1°x2° quadrangles, northern Minnesota. U.S. Geological Survey Open-File Report 88-525, Denver, CO.
- LeBas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B. 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. *Journal of Petrology*, 27: 745-750.
- Leshner, C.M., Goodwin, A.M., Campbell, I.H., and Gorton, M.P. 1986. Trace-element geochemistry of ore-associated and barren felsic metavolcanic rocks in the Superior Province, Canada. *Canadian Journal of Earth Science*, 23: 222-237.
- Mercier-Langevin, P., Dubé, B., Hannington, M.D., Davis, D.W., Lafrance, B., and Gosselin, G. 2007a. The LaRonde Penna Au-Rich Volcanogenic Massive Sulfide Deposit, Abitibi Greenstone Belt, Quebec: Part I Geology and Geochronology. *Economic Geology*, 102: 585-609.
- Mercier-Langevin, P., Dubé, B., Hannington, M.D., Richer-Lafleche, M., and Gosselin, G. 2007b. The LaRonde Penna Au-Rich Volcanogenic Massive Sulfide Deposit, Abitibi Greenstone Belt, Quebec: Part II Lithogeochemistry and Paleotectonic Setting. *Economic Geology*, 102: 611-631.
- Mercier-Langevin, P., Hannington, M.D., Dubé, B., and Bécu, V. 2011. The gold content of volcanogenic massive sulfide deposits. *Mineralium Deposita*, 56: 509-539.
- Monecke, T., Petersen, S., and Hannington, M.D. 2014. Constraints on water depth of massive sulfide formation: Evidence from modern seafloor hydrothermal systems. *Economic Geology*, 109: 2079-2101.

- Mullen, E.D. 1983. MnO/TiO₂/P₂O₅: a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis. *Earth and Planetary Science Letters*, 62: 53-62.
- Ojakangas, R.W., Meineke, D.G., and Listerud, W.H. 1977. Geology, sulfide mineralization and geochemistry of the Birchdale-Indus area, Koochiching County, northwestern Minnesota. Minnesota Geological Survey Report of Investigations 17, Minneapolis, MN.
- Ojakangas, R.W., Mossler, J.H., and Morey, G.B. 1979. Geologic Map of Minnesota, Roseau Sheet, bedrock geology. Minnesota Geological Survey, Minneapolis, MN.
- Paradis, S., Taylor, B.E., Watkinson, D.H., and Jonasson, I.R. 1993. Oxygen isotope zonation and alteration in the northern Noranda district, Quebec: Evidence for hydrothermal fluid flow. *Economic Geology*, 88: 1512–1525.
- Peterson, D.M. 2001. Development of Archean lode-gold and massive sulfide deposit exploration models using geographic information system applications: targeting mineral exploration in northeastern Minnesota from analysis of analog Canadian mining camps. PhD thesis, University of Minnesota, Minneapolis, MN.
- Polat, A. 2009. The geochemistry of Neoarchean (ca 2700 Ma) tholeiitic basalts, transitional to alkaline basalts, and gabbros, Wawa Subprovince, Canada: Implications for petrogenetic and geodynamic processes. *Precambrian Research*, 168: 83-105.
- Poulsen, K.H. 1986 Rainy Lake Wrench Zone: An example of an Archean Subprovince boundary in Northwestern Ontario. In *Tectonic evolution of greenstone belts*. Edited by M.J. de Wit and L.D. Ashwal. Lunar and Planetary Institute, Houston, TX, pp. 177-179.
- Poulsen, K.H. 2000a. Archean metallogeny of the Mine Centre - Fort Frances area. Ontario Geological Survey Report 266, Sudbury, ON.

- Poulsen, K.H., Borradaile, G.J., and Kehlenbeck, M.M. 1980. An inverted Archean succession at Rainy Lake, Ontario. *Canadian Journal of Earth Science*, 17: 1358-1369.
- Rodgers, J.L., and Nicewander, W.A. 1988. Thirteen ways to look at the correlation coefficient. *American Statistics*, 42 (1): 59–66.
- Schardt, C., Yang, J., and Large, R. 2005. Numerical Heat and Fluid-Flow Modeling of the Panorama Volcanic-Hosted Massive Sulfide District, Western Australia. *Economic Geology*, 100: 547-566.
- Schiffman, P. and Smith, B.M. 1988. Petrology and oxygen isotope geochemistry of a fossil seawater hydrothermal system within the Solea graben, northern Troodos Ophiolite, Cyprus. *Journal of Geophysical Research*, 93: 4612–4624.
- Schultz-Ela, D. 1988. Strain patterns and deformation history of the Vermilion district, northeastern Minnesota. PhD thesis, University of Minnesota, Minneapolis, MN.
- Schultz-Ela, D.D., and Hudleston, P.J. 1991. Strain in an Archean greenstone belt of Minnesota. *Tectonophysics*, 190: 233-268.
- Severson, M.J., and Heine, J.J. 2012. Preliminary Evaluation of Drilling Activities in the Koochiching-Beltrami-Roseau-Lake of the Woods Counties in Northern Minnesota. Report of Investigation NRRI/RI-2012/02, Natural Resources Research Institute, University of Minnesota Duluth, Duluth, MN.
- Solomon, M., Walshe, J.L., and Eastoe, C.J. 1987. Experiments on convection and their relevance to the genesis of massive sulphide deposits. *Australian Journal of Earth Sciences*, 34: 311–323.
- Southwick, D.L., and Ojakangas, R.W. 1979. Geologic map of Minnesota, International Falls Sheet. Minnesota Geological Survey, Minneapolis, MN.

- Tabor, J.R., and Hudleston, P.J. 1991. Deformation at an Archean subprovince boundary, northern Minnesota. *Canadian Journal of Earth Science*, 28: 292-307.
- Wartman, J.M. 2011. Physical volcanology and hydrothermal alteration of the Rainy River Gold Project, northwest Ontario. M.Sc. thesis, University of Minnesota Duluth, Duluth, MN.
- Wood, J. 1980. Epiclastic sedimentation and stratigraphy in the North Spirit Lake and Rainy Lake areas; a comparison. *Precambrian Research*, 12: 227-255.
- Yang, J., and Large, R. 2001. Computational modelling of hydrothermal ore forming fluid migration in complex earth structures. *In Computer application in the mineral industries. Edited by H. Xie, Y. Wang, and Y. Jiang.* Rotterdam, AA Balkema, pp. 115–120.
- Yang, J., Edwards, R.N., Molson, J.W., and Sudicky, E.A. 1996. Three-dimensional numerical simulations of the hydrothermal system within the TAG-like sulfide mound. *Geophysical Research Letters*, 23: 3475.

Table 1

Magnetic susceptibility of common igneous rocks (data from Ford et al. 2008; Anderson et al. 2013).

Rock Type	Min.	Max.	Average
Basalt	0.2	175	70
Andesite	N.A.	N.A.	160
Rhyolite	0.2	35	N.A.
Peridotite	90	200	150
Pyroxenite	N.A.	N.A.	125
Gabbro	1	90	70
Diabase	1	160	55
Diorite	0.6	120	85
Quartz diorite, dacite	38	191	83
Granite	0	50	2.5
Acid igneous rocks	0	80	8
Basic igneous rocks	0.5	97	25

Magnetic Susceptibility (SI X 10⁻³)

N.A. = Not Available

Table 2

Major lithologic units of the Wabigoon subprovince in Canada that are on strike with the rocks in the study area (data from Davis et al. (1989), Fralick and Davis (1999), and Czeck and Poulsen (2010)).

Rock Type	Description
Keewatin Group calc-alkaline and tholeiitic metavolcanic rocks	Occur as interlayered sequences of ultramafic to felsic rocks, with basalts and andesites most common. Geochronology indicates crystallization ages range from 2728 ± 3 to 2725 ± 2 Ma.
Metagabbroic (with metadolerites and metaanorthosites)	Occur as sills and large intrusions that generally have compositional and textural layering. These include the Seine Bay-Bad Vermillion Complex (2728 ± 2 Ma for the trondhjemitic Mud Lake component) and the Grassy Portage Sill (2727 ± 2 Ma).
Gneisses	Most commonly occur as orthogneiss. They correspond to synvolcanic plutonic rocks aged at 2725 ± 2 Ma that range from granitic to tonalitic compositions. These rocks are from the central core at the Rice Bay dome as well as gneisses near Black Sturgeon Bay.
Couchiching Group metasedimentary rocks	Located south of the Quetico Fault and north of the Rainy Lake-Seine River Fault. The age of this package of metasediments is bracketed between 2692 ± 2 and 2704 ± 3 Ma by zircons in crosscutting intrusions. Metagreywackes and metapelites comprise the majority of this package and locally contain porphyroblasts of andalusite, staurolite, and garnet.
Quetico metasedimentary rocks	Interpreted as deformed turbidite sediments located south of the Rainy Lake-Seine River Fault. The youngest analyzed detrital zircon yielded an age of 2699 ± 1 Ma.

**Seine River Group
metasedimentary rocks**

Deposited contemporaneously with Couchiching metasedimentary rocks, with a bracketed depositional age of 2693±1-2692±1 Ma, (Fralick and Davis 1999). This group formed as a molasse basin-fill unit (Corcoran and Mueller 2007) that also includes the Seine River conglomerates (Wood 1980; Frantes 1987; Czeck 2001; Czeck and Fralick 2002; Czeck and Hudleston 2003; Fissler 2006; Czeck et al. 2009; Czeck and Poulsen 2010).

**Algoman calc-alkaline
granitoids**

Occur as poorly deformed granite, granodiorite, and quartz monzonite rocks in discrete plutons. Previously interpreted as post-kinematic, their age was used as a marker of the end of regional deformation (Davis et al. 1989; Poulsen 2000a). However, field relationships, anisotropy of magnetic susceptibility, microstructural analysis, and gravity inversion techniques suggest these plutons formed syntectonically (Czeck et al. 2006).

Table 3

Statistically significant Pearson product-moment correlation coefficients of major elements comprising mafic volcanic rocks in the OB (data used for calculations were from Frey and Venzke (1991) and Klein (1988)).

	SiO2	Al2O3	TiO2	Fe2O3	CaO	MgO	MnO	Na2O	K2O	P2O5
SiO2	1.00	0.30	-0.37	-0.77	-0.56	-0.48	-0.55	0.62	0.43	-0.16
Al2O3		1.00	0.39	-0.68	0.23		-0.22	0.50	0.25	0.10
TiO2			1.00		0.44	0.34	0.17		-0.19	
Fe2O3				1.00		0.08	0.52	-0.61	-0.37	
CaO					1.00		0.47	-0.39	-0.46	0.15
MgO						1.00	0.23	-0.49	-0.28	0.24
MnO							1.00	-0.37	-0.29	
Na2O								1.00	0.37	-0.13
K2O									1.00	
P2O5										1.00

n=116

Table 4

Statistically significant Pearson product-moment correlation coefficients of metals in massive sulfide deposits (data used for calculations were from Frey and Venzke (1991) and Klein (1988)).

	Cu	Pb	Zn	Au	Ag
Cu	1.00	0.96			0.74
Pb		1.00			0.58
Zn			1.00		0.46
Au				1.00	
Ag					1.00
n=40					

Table 5

Statistically significant Pearson product-moment correlation coefficients of major elements comprising iron formation and chert in the OB (data used for calculations were from Frey and Venzke (1991) and Klein (1988)).

	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	CaO	MgO	MnO	Na ₂ O	K ₂ O
SiO ₂	1.00	0.52		-0.85	-0.54		-0.68	0.43	0.71
Al ₂ O ₃		1.00	0.60	-0.88		0.42		0.68	0.72
TiO ₂			1.00		0.55	0.90			
Fe ₂ O ₃				1.00			0.44	-0.53	-0.77
CaO					1.00	0.80	0.78		
MgO						1.00			
MnO							1.00	-0.63	-0.46

Na2O	1.00	0.81
K2O		1.00

n=7

Table 6

Statistically significant Pearson product-moment correlation coefficients of metals in iron formation and chert (data used for calculations were from Frey and Venzke (1991) and Klein (1988)).

	Cu	Pb	Zn	Ni	Au	Ag
Cu	1.00	0.64	0.23	0.27	-0.22	0.71
Pb		1.00				0.52
Zn			1.00	0.31	-0.27	0.19
Ni				1.00		0.46
Au					1.00	
Ag						1.00

n=29

Fig. 1

(A) North America with the location of Fig. 1B outlined by the black box. (B) Simplified map of the tectonostratigraphic terranes comprising the Superior Province with locations of mineral deposits (modified from Jirsa and Southwick (2003)). (C) Tectonostratigraphic terranes of Minnesota (MN) (modified from Jirsa et al. (2011)). The location of Fig. 3a is denoted by the black box. Terrane boundaries are denoted by thick black lines.

Fig. 2

Lithostratigraphic correlation of major rock units and tectonic events in the Neoarchean terranes of MN (modified from Jirsa et al. (2011)).

Fig. 3

(A) Regional geologic map of the Wabigoon and Quetico subprovinces in northwestern MN based on aeromagnetic and drill data, with some lithologic interpretations modified from Jirsa et al. (2011). The OB is outlined by the thin black box. (B) Geologic map of the OB. An inferred composite subvolcanic intrusion (Lost Lake Intrusive Complex, LLIC) underlies a pile of bi-modal volcanic rocks in the OB.

Fig. 4

Traces of regional scale faults (nomenclature from Jirsa et al. (2011)) overlain on aeromagnetic data upward continued to various heights: (A) Reduced-to-pole (RTP); (B) Upward continued to 1000 meters; (C) Upward continued to 3000 meters; (D) Upward continued to 6000 meters. The location of the OB is outlined by a dashed black box.

Fig. 5

Traces of regional and synvolcanic faults (black lines), intrusives contacts (white lines), and volcanic stratigraphy (white lines) overlain on aeromagnetic data from the OB: (A) Reduced-to-pole (RTP); (B) Second vertical derivative; (C) Upward continued to 1000 meters; (D) Upward continued to 2000 meters; (E) Upward continued to 3000 meters; (F) Upward continued to 6000 meters. Drill holes are denoted by small black circles. Cross section lines used in Fig. 6 and Fig. 7 are denoted by thin vertical lines. Two sets of synvolcanic faults (upper and lower) are labeled with brackets.

Fig. 6

Profiles of magnetic data on cross sections A-A', B-B', and C-C'. The location of these cross section lines is shown on Fig. 3b and Fig. 5. The location of massive sulfides and iron formation (MS), the Lost Lake

Intrusive Complex (LLIC), magnetic halos (MH) surrounding the LLIC, the Oaks Intrusion sill (OIS), and faults (FLT) are labeled on residual magnetic field data plots.

Fig. 7

Forward and inverse models of the residual magnetic field upward continued to 300 meters. Data are from the same lines shown in Fig. 6. The location of these cross section lines are shown in Fig. 3b and Fig. 5.

Drilling data corroborate that rock units are steeply north dipping.

Fig. 8

(A) Magma series classification of mafic rocks in the OB (Mullen 1983). These data indicate mafic rocks in the OB are mainly calc-alkaline, with fewer samples plotting as tholeiitic. (B) Trace element classification of felsic rocks after Leshner et al. (1986). Limited data indicate felsic rocks in the OB are FII and FI types. (C) Classification of volcanic rocks (LeBas et al. 1986) from the OB. (D) Chemical classification of intrusive rocks into volcanic categories (Lebas et al. 1986) for comparison to data from volcanic rocks. Geochemical data were from Frey and Venzke (1991), Klein (1988), and private companies.

121x76mm (300 x 300 DPI)

180x117mm (300 x 300 DPI)

500x492mm (600 x 600 DPI)

154x88mm (300 x 300 DPI)

822x539mm (600 x 600 DPI)

dit

203x184mm (300 x 300 DPI)

178x115mm (300 x 300 DPI)

189x141mm (300 x 300 DPI)