NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Processing and Interpretation of Geophysical Data

TOWNSHIP OF MANITOUWADGE, ONTARIO

APM-REP-06144-0077

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PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT

PROCESSING AND INTERPRETATION OF GEOPHYSICAL DATA

Township of Manitouwadge, Ontario

Prepared for

AECOM Canada Ltd.

and

Nuclear Waste Management Organization (NWMO)

by

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EXECUTIVE SUMMARY

On March 27, 2013, the Township of Manitouwadge, Ontario expressed interest in continuing to learn more about the Nuclear Waste Management Organization nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the Manitouwadge area for safely hosting a deep geological repository (Step 3). This request followed the successful completion of an initial screening conducted during Step 2 of the site selection process.

The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. The findings of the overall preliminary assessment are reported in an integrated report (NWMO, 2014). The objective of the desktop geoscientific preliminary assessment is to determine whether the Township of Manitouwadge, referred to as the "Manitouwadge area" contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

This report presents the findings of a geophysical data interpretation completed as part of the desktop geoscientific preliminary assessment of the Manitouwadge area (AECOM, 2014a). The purpose of this assessment was to perform a detailed interpretation of all available geophysical data for the Manitouwadge area (e.g., magnetic, electromagnetic, gravity and radiometric) to identify additional information that could be extracted from the data, in particular regarding the coincidence of geophysical units with mapped lithology and structural features in the Manitouwadge area.

The geophysical data covering the Manitouwadge area show variability in dataset resolution. Low-resolution geophysical data, particularly the magnetic, gravity and radiometric data obtained from the Geological Survey of Canada (GSC), cover the entire Manitouwadge area. Two additional magnetic/electromagnetic surveys obtained from the Ontario Geological Survey (OGS) and one GSC magnetic survey provided higher resolution coverage over approximately 80% (magnetic)/75% (electromagnetic) of the Manitouwadge area. A GSC radiometric survey improves the resolution in the southwest corner of the area.

The coincidence between the geophysical data and the mapped lithology (this report) and structural features (SRK, 2014) were interpreted using all available geophysical data sets (e.g., magnetic, electromagnetic, gravity and radiometric). In general the coincidence between the geophysical interpretations and the published geological maps is in good agreement, but in some locations the geophysical data provided new interpretations.

The magnetic data provide considerable information regarding the deformation and metamorphism across the collisional tectonic zone for several kilometers on either side of the Quetico-Wawa Subprovince boundary. Individual horizons show ductile deformation, and tight folding supported by the geological mapping. In the Wawa Subprovince, the geophysical data delineate different phases of the Black-Pic batholith, which is weakly magnetic and relatively homogeneous south of the collisional tectonic zone. The magnetic data, reinforced by the radioelement distribution in some cases, delineate several discrete intrusions. The magnetic data

are also useful for characterizing several lithologic units in the Manitouwadge greenstone belt. In the Quetico Subprovince, the geophysical data differentiate areas where the metasediments are more or less disturbed by subsequent tectonic events. The sparsely sampled gravity data show a gravity high within the Quetico Subprovince, and a gravity low over the Black-Pic batholith. Certain intrusions and a few of the other geological units have recognizable radiometric signatures, even though the data are generally coarse. The high-resolution electromagnetic data provide few bedrock conductors. Those that are interpreted are generally associated with magnetic stratigraphy in the Manitouwadge greenstone belt. Most of the conductive electromagnetic responses reflect surficial material (e.g. clay) associated with drainage, some of which are structurally controlled.

The Matachewan, Biscotasing and Marathon dyke swarms are clearly evident in both the high-resolution and low-resolution magnetic data. Their contributions to the structural framework and lineament analysis are discussed in SRK (2014).

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1 INTRODUCTION

On March 27, 2013, the Township of Manitouwadge expressed interest in continuing to learn more about the Nuclear Waste Management Organization nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the Manitouwadge area for safely hosting a deep geological repository (Step 3). The preliminary assessment is a multidisciplinary study integrating technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations (NWMO, 2014).

This report presents the findings of a geophysical data processing and interpretation assessment completed by Paterson, Grant & Watson Limited (PGW) as part of the desktop geoscientific preliminary assessment of the Manitouwadge area (AECOM, 2014a). The objective of the desktop geoscientific preliminary assessment is to determine whether the Manitouwadge area contains general areas that are potentially suitable for hosting a deep geological repository based on available geoscientific information and the geoscientific evaluation factors outlined in the NWMO site selection process. The assessment focused on the Township of Manitouwadge and its periphery, referred to as the “the Manitouwadge area”.

1.1 Objective of the Assessment

Geophysical data forms an important component of assessing a region for its potential suitability to host a deep geological repository, and to assist in the identification of general potentially suitable areas.

The purpose of this assessment was to perform a review of available geophysical data for the Manitouwadge area, followed by a detailed interpretation of all available geophysical data (e.g., magnetic, electromagnetic, gravity and radiometric) to identify additional information that could be extracted from the data, in particular regarding the coincidence of geophysical units with mapped lithology and structural features in the Manitouwadge area.

The role of the geophysical interpretation is to extrapolate our current understanding of the mapped lithology and extent of overburden cover to assess how the distributions of rock units may change at depth. Drillholes, wells and other underground information may be available at individual points to supplement geological data acquired on surface. However, where these individual data points are limited (or non-existent), such as for much of the Manitouwadge area, the critical advantage of airborne geophysical data is that it provides a basis for interpreting the subsurface physical properties across the area. This is particularly important in areas where bedrock exposure is limited by surface water bodies and/or overburden cover (i.e., glacial sediments) such as in parts of the Manitouwadge area. A secondary role of geophysics is that it often elucidates certain characteristics of geological formations and structures that may not be easily discerned from surface mapping and analysis. Thirdly, it highlights tectonic and regional-scale features that may not be easily extracted from studies of a particular area on a more detailed scale.

1.2 Township of Manitouwadge and Surrounding Area

The Manitouwadge area is located northeast of Lake Superior approximately 265 km northeast of Thunder Bay, and 310 km north-northwest of Sault Ste. Marie (straight-line distance). The area covered by this report contains approximately 4,016 square kilometres (km^2) (Figure 1). Within the Manitouwadge area the Township of Manitouwadge occupies 373 km^2 in the southwest quadrant and contains a population centre of the same name, while the hamlet of Hillsport is located in the northeast corner. Other nearby towns located outside the area are Marathon, 60 km to the southwest, and White River, 70 km to the southeast. Primary access to the area is via Ontario Highway 614, which ends at Manitouwadge after trending northward approximately 50 km from Highway 17 (Trans-Canada Highway).

1.3 Qualifications of the Geophysical Interpretation Team

The team responsible for the geophysical review, processing and interpretation investigation component of the Phase 1 geoscientific desktop preliminary assessment for the Manitouwadge area consisted of qualified experts from Paterson, Grant & Watson Limited (PGW). The personnel assigned to this assessment were as follows:

Stephen Reford, B.A.Sc., P.Eng. – project management, geophysical interpretation, report preparation

Mr. Reford is a senior consulting geophysicist and Vice-President of PGW. Mr. Reford has 32 years of experience in project management, acquisition and interpretation of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data for clients throughout Canada and around the world. Projects include management of the geophysical component of Operation Treasure Hunt for the Ontario Ministry of Northern Development and Mines as well as a similar role for the Far North Geoscience Mapping Initiative (2006-2009). Mr. Reford has served as a consultant to the International Atomic Energy Agency (IAEA) in gamma-ray spectrometry and is co-author of two books on radioelement mapping.

Winnie Pun, M.Sc. – data processing and map preparation

Ms. Pun will soon complete her second year as a consulting geophysicist for PGW after completing her M.Sc. in geophysics at the University of Toronto. She has prepared hundreds of geophysical maps for publication by government agencies in Nigeria and Botswana, and most recently has carried out several 2D/3D magnetic and gravity modelling studies on several iron ore projects.

Edna Mueller-Markham, M.Sc. – data processing and map preparation

Ms. Mueller-Markham is a senior consulting geophysicist for PGW. She has 19 years of experience in project management, acquisition, processing and modelling of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data for clients throughout Canada and around the world. In recent years, she has provided management and quality control for a number of OGS magnetic, gravity and electromagnetic surveys, and has reprocessed numerous industry surveys published by OGS.

Nikolay Paskalev, M.Sc. – GIS preparation

Mr. Paskalev has been the Manager of Geomatics and Cartography for Watts, Griffis and McOuat Limited (geological consultants) since 2006 and has been with the company since 2001. His work there has included a nationwide GIS of geology, ores and industrial minerals for Egypt, a GIS compilation of geological maps for a large part of Saudi Arabia and a Radarsat and DEM study for gold exploration in Sumatra. He has also worked part-time for PGW for the last 12 years, and most recently prepared a nationwide GIS for the geophysical interpretation of Nigeria. In 2011, he incorporated World GeoMaps Inc. for consulting in geomatics, cartography and GIS.

Dr. D. James Misener, Ph.D., P.Eng. – geophysical reviewer

Dr. Misener is President of PGW and a senior geophysicist with 38 years of experience in all aspects of geophysics and geophysics software applications. Dr. Misener founded Geosoft Inc. and led its development of world-leading geosciences software applications until he succeeded Dr. Paterson as President of PGW. He has directed implementation of geophysical data processing systems; initiated and managed major continental scale compilations of aeromagnetic/marine magnetic data in North America and worldwide including interpretation of aeromagnetic, radiometric, gravity and electromagnetic surveys in; Algeria, Brazil, Cameroon, Niger, Ivory Coast, Zimbabwe, Malawi, Kenya, China, Suriname, and Ireland.

2 SUMMARY OF PHYSICAL GEOGRAPHY AND GEOLOGY

The following sections on Physical Geography, Bedrock Geology, Structural History, Quaternary Geology and Land Use present summaries of the information presented in AECOM (2014a), SRK (2014) and AECOM (2014b) where applicable, in order to provide the necessary context for discussion of the results of this geophysical study (Section 5).

2.1 Physical Geography

Physical geography in the Manitouwadge area is described in detail in AECOM (2014b). A summary of the main features is provided here for reference.

The Manitouwadge area is within the Abitibi upland physiographic region of Thurston (1991) who subdivided the extensive James Region physiographic region of Bostock (1970). The region is characterized by bedrock outcrop with shallow drift cover and a rolling to moderately rugged surface, scattered with lakes.

The elevation difference within the Manitouwadge area is moderate with a maximum range of approximately 287 m above sea level (masl). The highest point of land within the area, 482 masl, occurs approximately 5 km west of the settlement area of Manitouwadge, and the lowest point

(195 masl) is in the Nama Creek valley where it intersects the western project area boundary, approximately 21 km southwest of the settlement area of Manitouwadge.

Within the Manitouwadge area, the upland regions, consisting of knobby bedrock hills, are characterized by moderate relief (approximately 60 m) over distances of hundreds of metres to a few kilometres. These uplands are scattered throughout the area and are the dominant terrain type. Glaciolacustrine and, to a lesser degree, glaciofluvial deposits and areas of ground moraine, represent areas of limited relief, although many of these deposits are characterized by protrusions of bedrock knobs. The glaciolacustrine deposits in the northeastern corner of the area and those within and around the Township of Manitouwadge display relief in the range of 20 to 40 m over the majority of their surface area. However, relief within the glaciolacustrine deposits of the Pic-White river and the Nama and Fourbay creek systems ranges from 20 to 60 m. This is due, in part, to erosion.

The Manitouwadge area straddles the Atlantic-Arctic watershed boundary, with the vast majority of the land draining southward to Lake Superior. The area's drainage network is contained within four tertiary level watersheds, two of which flow into Lake Superior with the others draining northward to James/Hudson Bay. Groundwater flow within drift deposits and in shallow bedrock aquifers in the Manitouwadge area is expected to mimic the pattern of surface flow, with groundwater divides coinciding with drainage divides and discharge occurring into creeks, rivers, lakes, and wetlands.

The Manitouwadge area has an abundance of lakes, streams, and rivers that provide good drainage of all parts of the area. Typically, segments of the waterways in the Manitouwadge area are on the order of 3 to 10 km, as they flow into and out of lakes occurring along the drainage paths. Gradients of the watercourses vary; those of smaller streams are generally moderate, while longer waterways, such as the Pic and White Otter rivers and Macutagon Creek, have lower gradients. Rapids and small waterfalls are common in the area. The majority of recharge to the waterways is through direct runoff or a shallow, fracture-controlled groundwater system in bedrock. Information on shallow aquifers in the region is cursory and completely lacking for deep bedrock flow systems.

The orientation of the drainage network within the study area is largely controlled by bedrock structural features (faults and lineaments) and the irregular topography of the terrain. Due to this control, the majority of waterways, including lakes, have, in order of dominance, a northeast, north, or northwest orientation. While the overall drainage in the Atlantic and Arctic watersheds are southwest and northeast, respectively, the catchment areas of individual lakes within the watersheds have stream segments with multiple flow directions (Figure 1).

The numerous lakes within the study area occupy approximately 4.5 percent (181.8 km^2) of the land surface and occur with an even distribution (Figure 1). In general, the lakes are of a modest size with the majority having a surface area of less than 1 km^2. As a generalization, it may be stated that lakes present in bedrock dominated areas (i.e., thin drift cover) are linear in outline, while those floored by glaciolacustrine deposits are more ovoid in shape. Many of the lakes within the glaciofluvial complexes are smaller and are elongate, parallel to the orientation of the hosting feature.

2.2 Bedrock Geology

A detailed discussion of the geological setting of the Manitouwadge area, including bedrock geology and structural history, is provided in a separate report (AECOM, 2014a), and a summary is presented below. The bedrock geology of the Manitouwadge area is shown on Figure 2.

The Manitouwadge area occurs within the Archean Wawa and Quetico subprovinces of the Superior Province (Figure 2), which developed 3.0 to 2.6 billion years ago (Ga). The Wawa Subprovince is composed of well-defined greenstone belts that comprise metamorphosed komatiite, basalt, dacite and rhyolite, and associated metasedimentary rocks, separated by granitoid plutons and batholiths. The metasedimentary rocks include turbiditic wacke, minor conglomerate, and iron formation. Stratigraphic and structural relationships between these units of volcanic and sedimentary rocks are usually unclear and commonly masked by later shearing (Williams et al., 1991). The granitoids that separate the greenstone belts comprise 20 to 30 percent of the landmass and consist of massive, foliated, and gneissic tonalite-granodiorite, cut by massive to foliated granodiorite and granite. The majority of the granitoids were intruded during or after the deposition of the greenstone belts with which they are associated (Williams et al., 1991).

The Quetico Subprovince, occurring in the northern portion of the area, consists of migmatitic metagreywacke and biotite schist that are compositionally layered (Zaleski et al., 1995b). Granitic intrusions are widely present while mafic to ultramafic intrusions occur sporadically (Williams, 1989; Sutcliffe, 1991). Proterozoic bedrock of the Southern Province, age 1.9 to 1.1 Ga, occurs to the south of the Manitouwadge area (Figure 2). These metasedimentary and metavolcanic rocks unconformably overlie and/or intrude the Archean rocks of the Superior Province.

Within the Wawa Subprovince, there are two semi-linear zones of greenstone belts, the northern of which includes the Shebandowan, Schreiber-Hemlo, Manitouwadge-Hornepayne, Dayohessarah, and Kabinakigami greenstone belts. The southern zone contains the Michipicoten, Mishibishu, and Gamitagama greenstone belts, which are located well southeast of the Manitouwadge area. The Manitouwadge-Hornepayne greenstone belt (herein referred to as the Manitouwadge greenstone belt) is an east-trending, variably dipping, strongly deformed and metamorphosed belt of supracrustal rocks. In the Manitouwadge area, the belt forms a 1 to 2 km thick, east- to northeast-trending synform containing mafic metavolcanic, subordinate felsic metavolcanic, and metasedimentary rocks, in addition to layered gabbro-anorthosite intrusions (Milne, 1968; Williams and Breaks, 1989; Williams et al., 1991; Zaleski et al., 1995b; Williams and Breaks, 1996). The greenstone belt is bounded on the south side by the Black-Pic batholith and on the north by the metasedimentary rocks of the Quetico Subprovince (Figure 2).

In the Wawa Subprovince, large granitoid bodies, commonly composed of tonalite to granodiorite, surround the greenstone belts and occur as intrusions within them. Such bodies in the Manitouwadge area include the Black-Pic batholith and several smaller plutons, including the Fourbay Lake, Loken Lake, and Nama Creek plutons. Granitic intrusions also occur in the Quetico Subprovince (Figure 2). Several generations of Paleoproterozoic diabase dyke swarms, ranging in age from 2.473 to 2.101 Ga, cut all bedrock units in the Manitouwadge area. These include: the northwest-trending Matachewan swarm, ca. 2.473 Ga; the northeast-trending Biscotasing dyke swarm, ca. 2.167 Ga; and the north-trending Marathon dyke swarm ca. 2.121 Ga.

Published bedrock geological maps (e.g., Zaleski and Peterson, 2001; Johns and McIlraith, 2003) of the region surrounding Manitouwadge display a number of faults that range in length from a few kilometres to several tens of kilometres (Figure 2). Faulting in the Manitouwadge area occurred over a protracted period of time. Faulting began during the formation of the greenstone belts and continued to be active until after the accretion of the Wawa and the Quetico subprovinces (i.e., ~2.7 to 2.68 Ga, Williams *et al.*, 1991; Corfu and Stott, 1996).

The main geological units occurring in the Manitouwadge area are further described below, including the Quetico Subprovince, the Faries-Moshkinabi intrusion, the Manitouwadge greenstone belt, the Black-Pic batholith and other felsic intrusions. Mafic dykes, faulting and metamorphism affecting the study area are also presented.

2.2.1 Metasedimentary Rocks of the Quetico Subprovince

Metasedimentary rocks of the Quetico Subprovince occupy the northern third of the Manitouwadge area and have a southern boundary approximately 6 km north of the Township (Figure 2). These 2.700 to 2.688 Ga clastic metasedimentary rocks have undergone various degrees of metamorphism (Percival, 1989; Zaleski et al., 1999). The Quetico Subprovince is understood to be an accretionary prism of an Archean volcanic island-arc system, which developed where the Wawa and Wabigoon belts form converging arcs (Percival and Williams, 1989). The timing of the Quetico-Wawa belt accretion has been constrained to between 2.689 Ga and 2.684 Ga (Percival, 1989).

Metasedimentary wacke-pelite-arenite rocks of the Quetico belt (Williams and Breaks, 1996; Zaleski et al., 1999) were interpreted by Stott et al. (2010) as having been formed in a basin setting. Small amounts of ironstone, conglomerate, ultramafic wacke and siltstone are present locally (Williams et al., 1991). The arenite, pelite and wacke are layered; however, no occurrences of bedding, unequivocal grain size grading or syn-sedimentary features, such as cross-stratification or dewatering structures, have been documented in the area (Williams and Breaks, 1996).

The metasedimentary rocks of the Quetico belt display evidence of variable deformation and metamorphism, and transformation into gneisses and migmatites. The rocks show a strong compositional layering, numerous small-scale folds, shearing, and sporadically distributed, narrow (<1 m) concordant, boudinaged and folded amphibolite layers (Williams and Breaks, 1996). The metasedimentary rocks display various states of migmatization; Williams and Breaks (1996) classified the metasedimentary rocks in the Manitouwadge area primarily as metatexite with a banded or stromatic structure. Metagreywacke in the Quetico Subprovince contains abundant migmatitic segregations comprising pegmatitic and tonalitic leucosomes, locally with garnet and cordierite (Zaleski et al., 1999).

Migmatitic veins and sheets of granitic material are ubiquitous in the Quetico Subprovince. The compositional layering differentiates two types: one type reflects a transposed or original layering upon which is superimposed a second type of layering resulting from the formation of leucocratic veins and elongate masses. The second type is a product of partial melting and segregation during high-grade metamorphism and includes lenses rich in hornblende-, diopside- and epidote that are commonly elongate along the layering in the enclosing migmatite (Williams and Breaks, 1996). In addition, metasedimentary rocks of the Quetico Subprovince are commonly intruded by tonalite and diorite along the Quetico-Wawa Subprovince boundary. The tonalite and diorite intrusions pre-date migmatization and exhibit low volumes of deformed leucosome. The leucosome is characteristic of the diatexite class of migmatite formation (Williams and Breaks, 1996).

2.2.2 Granite – Granodiorite of the Quetico Subprovince

A number of largely east-west-trending granite-granodiorite intrusions have been mapped in the Quetico Subprovince in the Manitouwadge area (Figure 2). The largest of these, located approximately 15 km north of the Township of Manitouwadge, is described by Coates (1970b) as migmatitic, and consisting of biotite-quartz-feldspar gneisses and hornblende-biotite-quartz-feldspar gneisses; Percival (1989) in turn described it as pink biotite leucogranite. In general, granitic rocks in the Quetico Subprovince are typically medium- to coarse-grained and massive to rarely foliated (Percival, 1989). Information on the depth or age of the intrusions in the Manitouwadge area is not available.

2.2.3 Black-Pic Batholith

The Black-Pic batholith is a large, regionally-extensive intrusion that encompasses an area of approximately 3,000 km^2 and forms the bedrock for the majority of the southern half of the Manitouwadge area (Figure 2). The Black-Pic batholith comprises a multi-phase suite that includes hornblende-biotite monzodiorite, foliated tonalite and pegmatitic granite, with subordinate foliated diorite, granodiorite, granite and cross-cutting aplitic to pegmatitic dykes (Williams and Breaks, 1989; Zaleski and Peterson, 1993). The thickness of the batholith in the Manitouwadge area is not known but regional geologic models of the area (e.g., Lin and Beakhouse, 2013) suggest it may extend to a considerable depth.

The age of emplacement of the Black-Pic batholith has been constrained by U-Pb (zircon) dating of the oldest phase recognized, a tonalite at 2.720 Ga (Jackson et al., 1998). A younger monzodiorite phase has been dated at 2.689 Ga (Zaleski et al., 1999). No readily available information regarding the thickness of the batholith was found.

The Black-Pic batholith is interpreted to be a domal structure with slightly dipping foliations radiating outward from its centre (Williams et al., 1991). Within the batholith, Williams and Breaks (1989) found that structurally deeper levels of the tonalite suite are strongly foliated with a subhorizontal planar fabric and a weak, north-trending mineral elongation lineation. Upper levels of the tonalite are frequently cut by granitic sheets of pegmatite and aplite and are generally more massive (Williams and Breaks, 1989). Within the Black-Pic batholith, zones of migmatized sedimentary rocks and zones of massive granodiorite to granite are also present. The contact between these rocks and the tonalitic rocks of the batholith is gradational and associated with extensive sheeting of the tonalitic unit (Williams and Breaks, 1989; Williams et al., 1991). Published compilation maps of the Manitouwadge area (Johns and McIlraith, 2003; Johns et al., 2003) include an east-trending belt of migmatized rocks occurring north and northwest of the Manitouwadge synform along the Quetico subprovince boundary (Figure 2). Milne et al. (1972) described these rocks as migmatized felsic igneous and metamorphic rocks; however, other information on this rock complex, including thickness and age, does not appear to be available within the public domain. While the Black-Pic batholith is generally considered to be monzodioritic, tonalitic and granitic, sporadic borehole data southeast of the Manitouwadge area toward the Township of White River indicate the presence of basalt and gabbro at depth within the Black-Pic batholith. As such, there may be local lithological variations in the Black-Pic batholith resulting in some uncertainty regarding the predominant composition of the batholith.

Within the Black-Pic batholith, magmatic features are destroyed or equivocal and metamorphic textures and mineralogies prevail. Inclusions of relatively melanocratic members of the suite occur as foliated inclusions within later, leucocratic members (Williams and Breaks, 1989; 1996). These intrusions include a pluton termed the Everest Lake pluton by Zaleski and Peterson (2001; not outlined on Figure 2), and another mapped, but unsubstantiated pluton toward the east of the Manitouwadge area (Figure 2). The Everest Lake pluton lies along the western side of the Wawa-Quetico boundary north of the Manitouwadge greenstone belt and comprises weakly to moderately foliated, hornblende-clinopyroxene-biotite monzodiorite to diorite. The S_2 tectonic fabric is concordant to the east-west trends and steep dips typical of the Quetico subprovince boundary (Zaleski et al., 1999).

In the Quetico Subprovince conformable sheets of composition equivalent to the Everest Lake pluton are interleaved with migmatitic paragneiss. While coarse igneous textures are preserved in enclaves, the Everest Lake pluton is pervaded by diffuse leucocratic patches that suggest local anatexis. Zaleski et al. (1999) estimated the age of the Everest Lake pluton to be ca. 2.679 Ga.

The existence of an unnamed, northeast-trending granite-granodiorite pluton located along the eastern side of the Manitouwadge area, south of the Manitouwadge greenstone belt could not be confirmed (outlined, but not labeled on Figure 2). Although depicted on a compilation map of the area (Johns and McIlraith, 2003), field geologic mapping of the area by Giguere (1972) could not confirm its existence.

2.2.4 Loken Lake Pluton

The Loken Lake pluton extends eastward from the northeastern portion of the Township of Manitouwadge and occupies the innermost area of the Manitouwadge synform (Figure 2). The surficial expression of the pluton, dated at 2.687 Ga (Jackson et al., 1998), forms an ellipse approximately 16.5 km across and 4 km wide. The Loken Lake pluton is described as foliated to massive granite to granodiorite, characterized by K-feldspar megacrysts, 5 to 15 cm in length, which vary in abundance from near zero to 25 percent, and by a relatively low abundance of mafic minerals (Zaleski et al., 1999). Locally, the Loken Lake pluton is cut by minor intrusions of foliated biotite granite. Information on the depth of the Loken Lake pluton is limited to a seismic survey which indicates the intrusion extends to at least 0.7 km (Roberts et al., 1997).

2.2.5 Foliated Tonalite Suite

A foliated tonalite intrusion that surrounds the Loken Lake pluton, between the arms of the Manitouwadge greenstone belt (Figure 2), is interpreted to be synvolcanic with the Manitouwadge greenstone belt, and has been dated at 2.72 Ga (Zaleski et al., 1999). The surficial expression of the intrusion spans approximately 50 km east-west and 6 km north-south. The tonalite is foliated with minor amounts of biotite and magnetite, and becomes more granite-like as it approaches the metavolcanic rocks (Zaleski and Peterson, 1995a). Data collected as part of a seismic survey indicates the intrusion extends to a depth of at least 1.5 km (Roberts et al., 1997).

2.2.6 Nama Creek Pluton

The Nama Creek pluton is located within the northwest quadrant of the Township of Manitouwadge (Figure 2). It is considered a distinct phase of the Black-Pic batholith and forms an approximately 33 km long and typically less than 1 km wide sinuous body along the contact with the Manitouwadge greenstone belt (Zaleski et al., 1999). It consists of foliated biotite-hornblende monzonite to monzodiorite, characterized by 1 to 5 cm K-feldspar phenocrysts. Compositionally, the Nama Creek pluton is similar to the Loken Lake pluton, albeit with a greater abundance of mafic minerals and less quartz. The pluton has been dated by Zaleski et al. (1999) at 2.680 Ga. There is no readily available information on its depth. The foliated Nama Creek pluton is antiformally folded (Zaleski et al., 1999) likely during the D_2 to D_4 deformation events.

2.2.7 Fourbay Lake Pluton

The Fourbay Lake pluton is located in the southwest corner of the Manitouwadge area (Figure 3). The pluton is described by Milne (1968) as consisting of pyroxene-hornblende-biotite granodiorite and by Beakhouse (2001) as a massive, uniform hornblende–biotite (± clinopyroxene) quartz monzodiorite with a medium-grained granular texture. The elliptically shaped pluton, covers approximately 64 km^2 (in the Manitouwadge area), is located entirely within the Black-Pic batholith and is distinguished from the Black-Pic batholith by a prominent aeromagnetic anomaly with clearly defined boundaries. Relatively abundant Fe and Fe-Ti oxides (~1-2 percent) likely account for the aeromagnetic signature of the pluton (Williams and Breaks, 1996). Dioritic enclaves are a minor component in several outcrops but their abundance is less than 1 percent overall (Beakhouse, 2001). The thickness of the pluton is not known but it is expected to be well beyond the planned repository depth (~500 m) based on the interpretation of regional gravity data (PGW, 2014) and the regional geological model for the area (Santaguida, 2002; Muir, 2003).

The Fourbay Lake pluton has a U-Pb (zircon) age of 2.678 Ga (Beakhouse, 2001), and Williams and Breaks (1996) considered it to be one of a series of late stage, likely post-tectonic plutons situated along the central axis of the Black-Pic batholith. No information is available on the depth of the Fourbay Lake intrusion.

2.2.8 Dotted Lake Batholith

The Dotted Lake batholith lies within the southeast corner of the Manitouwadge area (Figure 2). The surficial expression of the batholith is approximately 20 km long and 15 km wide, however only a small portion (approximately 8 km^2) lies within the Manitouwadge area. The pluton is a massive to weakly foliated, compositionally homogeneous leucogranodiorite to leucotonalite with an age of 2.697 Ga (Beakhouse, 2001). Enclaves or inclusions of any sort are not known to occur and leucogranitic pegmatite dykes are rare (Beakhouse, 2001).

The texture and mineralogy of the Dotted Lake batholith is extremely uniform across the batholith and straddles the granodiorite-tonalite field boundary (Beakhouse, 2001). Accessory and trace primary minerals include sphene, opaque oxides, epidote, apatite and zircon. Except where overprinted by intense deformational fabric, development of the batholith displays a coarse grained equigranular texture (Beakhouse, 2001).

The margin of the Dotted Lake batholith is highly strained with a well-developed penetrative fabric parallel to both the contact and penetrative fabrics in the adjacent mafic metavolcanic rocks. Localized narrow zones of high strain also occur in the interior of the pluton associated with narrow, brittle-ductile shear zones (Beakhouse, 2001). The batholith was emplaced prior to the development of the regional (S_2) deformational fabric (Jackson et al., 1998). The depth of the pluton is unknown.

2.2.9 The Manitouwadge Greenstone Belt

The Manitouwadge-Hornepayne greenstone belt (herein referred to as the Manitouwadge greenstone belt), together with the Faries-Moshkinabi intrusion (Williams and Breaks, 1990; 1996), is part of a semi-continuous supracrustal and mafic intrusive suite (Manitouwadge–Hornepayne assemblage, Williams et al., 1991) situated along the northern margin of the volcano-plutonic Wawa Subprovince (Figure 2).

The Manitouwadge greenstone belt comprises metasedimentary and metavolcanic rocks, the majority of which can be found interweaving along both strike and dip in a synform (Milne, 1969). The metasedimentary rocks within the synform comprise predominantly grey to buff psammite and pelite (Williams and Breaks, 1996). Bedding is rarely recognizable as strain and metamorphic recrystallization have produced a transposed layering (Zaleski *et al*., 1999). Most major minerals—mostly quartz, andesine, biotite, garnet, and microcline—are aligned parallel with the mineral foliation; garnet is also locally elongated along this planar anisotropy (Pye, 1960).

Mafic to felsic volcanic successions in the Manitouwadge greenstone belt includes iron formation and associated volcanogenic massive sulphide deposits. Along the southern limb of the Manitouwadge synform, metavolcanic rocks transition from mafic to felsic rocks toward a central belt of metagreywacke. A trondhjemite unit is present within the centre of the Manitouwadge synform, such that orthoamphibole-cordierite-garnet gneiss closely follows the mafic-felsic contact and the margin of this trondhjemite (Zaleski and Peterson, 1995). Similar orthoamphibole-bearing rocks are present in mafic rocks near the northern contact of the volcanic belt with felsic rocks and metagreywacke. Additionally, within the volcanic belt, sillimanite-muscovite-quartz schist and quartzose schist are present close to massive sulphide deposits and, in some cases, envelop ore bodies (Zaleski *et al*., 1999).

2.2.10 Gabbroic Intrusions

Three separate gabbroic intrusions are present within the southeast quadrant of the Manitouwadge area. All intrusions are limited in size and are largely surrounded by the Black Pic batholith.

Faries-Moshkinabi Intrusion

The Faries-Moshkinabi intrusion lies approximately 11 km to the east of the Township of Manitouwadge (Figure 2). The intrusion is a series of semi-continuous units of homogenous to interlayered mafic rocks, comprising websterite, hornblendite, metagabbro, gabbro, anorthositic gabbro, gabbroic anorthosite and anorthosite that have been delineated to the northwest, east and southeast of the Manitouwadge synform. The two largest bodies are the Faries Lake and Moshkinabi Lake plutons. Williams and Breaks (1996) suggested that the Faries Lake and Moshkinabi Lake plutons may have originally been part of one larger pluton and as such, they are here described together, including aspects of their composition and deformation. Together, these intrusions form an approximately 30 km long and typically less than 2 km thick elongate intrusion. No data are available on the age of this intrusion.

The Faries-Moshkinabi intrusion is a layered pluton with a maximum thickness of 700 m (Williams and Breaks, 1996). Preservation of primary textures can be observed; however, variable strain and alteration have commonly destroyed primary textures through recrystallization, grain size reduction and neoblastesis in much of the intrusion (Williams and Breaks, 1996). Compositional layering, defined by regular alternation of plagioclase-rich and plagioclase-poor layers in relatively undeformed peridotite, gabbro and leucogabbro to anorthosite, occurs over thicknesses of several tens of metres as part of cyclic successions. In the Faries and Moshkinabi lakes portions of the intrusion, hornblendic and anorthositic veins and sheets occur as layers and discordant plutons within both ultramafic and gabbroic rock types (Williams and Breaks, 1996).

Anorthositic rocks associated with the Faries-Moshkinabi intrusion overlie and underlie mafic to felsic metavolcanic rocks of the Manitouwadge greenstone belt (Williams and Breaks, 1996). The contact between the Faries-Moshkinabi intrusion and the Black-Pic batholith is a thrust-modified, tectonic breccia, composed of centimetre- to metre-scale blocks of anorthosite, metawacke and granitic rocks (Williams and Breaks, 1996). Near the lower, western contact of the intrusion, rocks are typically gneissic and show L > S fabrics. Contacts with the dioritic rocks west of Moshkinabi Lake are highly strained and sporadically mylonitic. In general, plagioclase-rich members of the suite are highly deformed, forming gneisses and mylonitic rocks that have subsequently been intruded by tonalites to form enclaves and breccias (Williams and Breaks, 1996).

Rawluk Lake Intrusion

The Rawluk Lake pluton is a small, 3 km by >6 km north-south trending elliptical intrusion located east of the Township of Manitouwadge boundary and west of the Faries-Moshkinabi intrusion (Figure 2). The pluton varies from a biotite-hornblende quartz diorite to tonalite, is slightly foliated, moderately to strongly lineated and is interpreted as a late tectonic magmatic intrusion (Williams and Breaks, 1996).

Bulldozer Lake Intrusion (informal name)

The informally named Bulldozer Lake intrusion is an approximately 15 km by 10 km ellipsoid gabbroic intrusion in the southeast corner of the Manitouwadge area (Figure 2). The extent of the intrusion is defined by the boundary of a magnetic anomaly observed in an OGS shaded relief total magnetic survey (as seen in OGS Map 2666; Santaguida, 2001). No additional information on this pluton, including its depth, was documented in the reviewed literature.

2.2.11 Mafic Dykes

Several diabase dyke swarms crosscut the Manitouwadge area (Figure 2), including:

- Northwest-trending Matachewan dykes (ca. 2.473 Ga; Buchan and Ernst, 2004). This dyke swarm is one of the largest in the Canadian Shield. Individual dykes are generally up to 10 m wide, and have vertical to subvertical dips. The Matachewan dykes comprise mainly quartz diabase dominated by plagioclase, augite and quartz (Osmani, 1991);
- North-trending Marathon dykes (ca. 2.121 Ga; Buchan *et al*., 1996; Hamilton *et al*., 2002). These form a fan-shaped distribution pattern around the northern, eastern, and western flanks of Lake Superior. A greater density of Marathon dykes is observed north of a nondescript east-west boundary within the Quetico Subprovince (Figure 2). This is a result of the combination of various datasets within the OGS database and does not reflect a geological boundary. The dykes vary in orientation from northwest to northeast, and occur as steep to subvertical sheets, typically a few metres to tens of metres thick, but occasionally up to 75 m thick (Hamilton et al., 2002). The Marathon dykes comprise quartz diabase (Osmani, 1991) dominated by equigranular to subophitic clinopyroxene and plagioclase;
- Northeast-trending Biscotasing dykes (ca. 2.167 Ga; Hamilton et al., 2002). Locally, Marathon dykes also trend northeast and cannot be separated with confidence from the Biscotasing Suite dykes. On occasion, Biscotasing dykes appear to deflect at intersections with Matachewan-aged dykes; this is thought to be due to a rheological contrast between the Matachewan-aged dykes and the surrounding country rock.

2.2.12 Mapped Regional Structure

The east-west-trending Wawa-Quetico Subprovince boundary transects the Manitouwadge area (Figure 2). Zaleski et al. (1995b) and Zaleski and Peterson (2001) deemed the Wawa-Quetico boundary in the Manitouwadge area to be transitional based on structural, lithological and metamorphic criteria. They state that the similarity in the depositional age constraints and in the composition between the metagreywacke in the Manitouwadge greenstone belt and the Quetico Subprovince, and the folding of the latter together with the metavolcanic rocks argue for correlation of the sedimentary sequence across the subprovince boundary (Zaleski and Peterson, 2001). Williams et al. (1991) reported that the contact zone along Wawa-Quetico Subprovince boundary in the Manitouwadge area contains foliated to gneissose intrusive sheets of tonalite-granodiorite that are highly strained.

In the Manitouwadge area, several faults are indicated on public domain geological maps. These faults display four dominant orientations: north, northeast, northwest, and east. Despite the interpretation of multiple faults, few of these structures are named. Named structures include the north-trending Cadawaja, Slim Lake and Fox Creek faults that offset folded stratigraphy in the hinge of the Manitouwadge synform (Figure 2). The northwest-trending Mose Lake fault also offsets stratigraphy near the hinge of the Manitouwadge synform. East-trending structures, including the Agam Lake and Rabbitskin faults, mimic the outline of the Manitouwadge synform and are typically offset by the north-trending faults. However, Chown (1957) indicated that the north-trending Slim Lake fault is truncated by an east-west-trending fault. Mapping, and interpretation of aeromagnetic data (e.g., Miles, 1998), indicates that these faults offset the regional fabric throughout the Manitouwadge area.

The Agam Lake fault strikes east and occurs within the metasedimentary rocks on the southern limb of the Manitouwadge synform. It forms a pronounced topographic lineament, and is primarily a brittle strike-slip fault (Chown 1957), that in part follows the volcanic-sedimentary contact and locally may have experienced ductile shear (Peterson and Zaleski, 1999).

Miles (1998) interpreted the Cadajwa, Slim Lake, and Fox Creek faults to be sinistral strike-slip faults with the Fox Creek fault displaying a sinistral strike-separation of the Geco VMS deposit by 60 m with a minor east side up vertical displacement. The Cadawaja fault cuts the outer hinge zone of the Manitouwadge synform and offsets the southern limb of the fold by 500 m (Miles, 1998). Miles (1998) noted that the southern limb to the east of the fault has significantly higher magnetic intensity and a more continuous anomaly pattern, and suggested that there may also be some vertical displacement along this fault. The northwest-trending faults are subparallel and adjacent to the similarly oriented Matachewan dykes. A complex history of brittle deformation is evidenced, in part, by offset of the Matachewan dykes by younger episodes of faulting (e.g., Miles, 1998).

Within the Quetico metasedimentary rocks a number of northeast-trending faults are indicated on the geological maps of the Manitouwadge area (Zaleski and Peterson, 2001; Johns and McIlraith, 2003; OGS, 2011). These faults are of modest length, ranging from approximately 5 to 20 km (Figure 2).

2.2.13 Metamorphism

Studies on metamorphism in Precambrian rocks across the Canadian Shield have been summarized in a few publications since the 1970s (e.g., Fraser and Heywood 1978; Kraus and Menard, 1997; Menard and Gordon, 1997; Berman et al., 2000; Easton, 2000a, 2000b; and Berman et al., 2005) and the thermochronological record for large parts of the Canadian Shield is documented in a number of studies (Berman et al., 2005; Bleeker and Hall, 2007; Corrigan et al., 2007; and Pease et al., 2008).

The Superior Province of the Canadian Shield largely preserves low pressure – high temperature Neoarchean (ca. 2.710-2.640 Ga) metamorphic rocks. The relative timing and grade of regional metamorphism in the Superior Province corresponds to the lithological composition of the subprovinces (Easton, 2000a; Percival et al., 2006). Subprovinces comprising volcano-sedimentary assemblages and synvolcanic to syntectonic plutons (i.e., granite-greenstone terranes) are affected by relatively early lower greenschist to amphibolite facies metamorphism. Subprovinces comprising both metasedimentary- and migmatite-dominated lithologies, such as the English River and Quetico, and dominantly plutonic and orthogneissic domains, such as the Winnipeg River, are affected by relatively late middle amphibolite to granulite facies metamorphism (Breaks and Bond, 1993; Corfu et al., 1995). Subgreenschist facies metamorphism in the Superior Province is restricted to limited areas, notably within the central Abitibi greenstone belt (e.g., Jolly, 1978; Powell et al., 1993).

A widespread Paleoproterozoic tectonothermal event, the Trans-Hudson Orogeny, involved volcanism, sedimentation, plutonism and deformation that affected the Churchill Province through northernmost Ontario, western Manitoba, northern Saskatchewan and Nunavut (e.g., Skulski et al., 2002; Berman et al., 2005). This event was associated with ca. 1.84 to 1.8 Ga collisional convergence of the Archean Hearne domain and Superior Province (Kraus and Menard, 1997; Menard and Gordon, 1997; Corrigan et al., 2007). Associated metamorphism at moderate to high temperatures and low to moderate pressures resulted in amphibolite facies metamorphism that overprinted Archean metamorphic signatures in Archean rocks of the Churchill Province, and a complex brittle overprint in Archean rocks of the Superior Province (e.g., Kamineni et al., 1990)

Along the eastern flank of the Canadian Shield, the Grenville Province records a complex history of episodic deformation and subgreenschist to amphibolite and granulite facies metamorphism, from ca. 1.300 Ga to 950 Ma (Easton, 2000b; Tollo et al., 2004 and references therein). Lower greenschist metamorphism was documented along faults in the vicinity of Lake Nipigon and Lake Superior and is inferred to be the result of ca. 1 Ga far-field reactivation during the Grenville Orogeny (Manson and Halls, 1994).

In northwestern Ontario, the concurrent post-Archean effects, including the Trans-Hudson Orogen, are limited to poorly documented reactivation along faulted Archean terrane boundaries (e.g., Kamineni et al., 1990 and references therein). Most late orogenic shear zones in the Superior Province and Trans-Hudson Orogen experienced lower to middle greenschist retrograde metamorphism (e.g., Kamineni et al., 1990 and references therein).

Overall, most of the Canadian Shield preserves a complex episodic history of Neoarchean metamorphism overprinted by Paleoproterozoic tectonothermal events culminating at the end of the Grenville orogeny ca. 950 Ma. The distribution of contrasting metamorphic domains in the Canadian Shield is a consequence of relative uplift, block rotation and erosion resulting from Neoarchean orogenesis, subsequent local Proterozoic orogenic events and broader epeirogeny during later Proterozoic and Phanerozoic eons.

In the Manitouwadge area, the metamorphic grade of the exposed rocks of the Manitouwadge greenstone belt ranges from greenschist to upper amphibolite facies (James et al., 1978; Petersen, 1984; Pan and Fleet, 1992). To the north, metasedimentary rocks of the Quetico Subprovince exhibit granulite facies metamorphic conditions close to the boundary between the Wawa and Quetico subprovinces (Williams and Breaks, 1989, 1990; Zaleski and Peterson, 1995a; Pan et al., 1994). The area overprinted by granulite facies metamorphism is defined by an ortho-pyroxene isograd located in a fringe approximately 10 km wide that extends approximately from the western portion of the Manitouwadge area westward for more than 100km, but fades before Hornepayne (Pan et al., 1998); outside the ortho-pyroxene isograd, the granulitic facies grades into the prevalent regional upper amphibolite facies metamorphic grade of the Quetico Subprovince (Pan et al., 1998). Within this granulitic zone, magnetite is abundant (Pan et al., 1994).

Geothermobarometric and geochronological calculations by Pan et al. (1994) and Pan et al. (1998) in the Manitouwadge area and surroundings, indicate that low pressure-high temperature, amphibolite facies metamorphism in metasedimentary rocks of the Quetico Subprovince had been in place before 2.666 Ga, in agreement with the period 2.671-2.665 Ga estimated by Percival and Sullivan (1988). In the Manitouwadge area, this prograde amphibolite facies regional metamorphism would have been initiated ca. 2.675 Ga, increased after ca. 2.666 Ga, and reached granulite facies under a thermal peak of 680-700°C and 4-6Kbar ca perhaps ca. 2.658 Ga. Granulite facies metamorphism would have lasted until ca. 2.650 Ga, after which a retrograde event would have occurred at 550-660°C, 3-4 Kbar. After the retrogression, hydrothermal alteration occurred at 200-400°C, 1-2 Kbar.

To the south of the greenstone belt, the Black-Pic batholith and other smaller plutons typically display greenschist facies metamorphism (Stott, pers. comm., 2013). Locally, higher metamorphic grades up to upper amphibolite facies are recorded in rocks along the margins of plutons. No records exist that suggest that rocks in the Manitouwadge area may have been affected by thermotectonic overprints related to post-Archean events.

2.3 Geologic and Structural History

Information on the structural history of the Manitouwadge area is based predominantly on structural investigations of the Manitouwadge and Dayohessarah greenstone belts (Polat, 1998; Peterson and Zaleski, 1999) and the Hemlo gold deposit and surrounding region (Muir, 2003). Additional studies by Lin (2001), Percival et al. (2006), and Williams and Breaks (1996) have also contributed to the structural understanding of the area. The aforementioned studies were performed at various scales and from various perspectives. Consequently, the following summary of the structural history of the Manitouwadge area should be considered as a “best-fit” model that incorporates relevant findings from all studies.

The Manitouwadge area straddles the structurally complex boundary between the metasedimentary-migmatitic Quetico Subprovince and the volcano-plutonic Wawa Subprovince within the Archean Superior Province. The structural history of the Manitouwadge and nearby Schreiber-Hemlo greenstone belts is generally well characterized and includes up to six phases of deformation (Polat, 1998; Peterson and Zaleski, 1999; Lin, 2001; and Muir, 2003). Polat et al. (1998) interpreted that the Schreiber-Hemlo and surrounding greenstone belts represent collages of oceanic plateaus, oceanic arcs, and subduction-accretion complexes amalgamated through subsequent episodes of compressional and transpressional collision.

On the basis of overprinting relationships between different structures, Polat et al. (1998) suggested that the Schreiber-Hemlo greenstone belt underwent at least two main episodes of deformation. These can be correlated with observations from Peterson and Zaleski (1999) and Muir (2003), who reported at least five and six generations of structural elements, respectively. Two of these generations of structures account for most of the ductile strain, and although others can be distinguished on the basis of crosscutting relationships, they are likely the products of progressive strain events. Integration of the structural histories detailed in Williams and Breaks (1996), Polat (1998), Peterson and Zaleski (1999), Lin (2001) and Muir (2003) suggest that six deformation events occurred within the Manitouwadge area. The first four deformation events (D_1-D_4) were associated with brittle-ductile deformation and were typically associated with deformation of the greenstone belts. D_5 and D_6 were associated with a combination of brittle deformation, and fault propagation through all rock units in the Manitouwadge area. The main characteristics of each deformation event are summarized below.

The earliest recognizable deformation phase (D_1) is associated with rarely preserved small-scale isoclinal folds, ductile faults that truncate stratigraphy (e.g., the faults in the hinge region of the Manitouwadge synform), and a general lack of penetrative foliation development. Peterson and Zaleski (1999) reported that S_1 foliation is only preserved locally in outcrop and in thin section. D_1 deformation is poorly constrained to between ca. 2.719 and ca. 2.691 Ga (Muir, 2003).

D_2 structural elements include prevalent open to isoclinal F_2 folds, an axial planar S_2 foliation, and L_2 mineral elongation lineations (Peterson and Zaleski, 1999). Muir (2003) interpreted D_2 to have resulted from progressive north-northeast to northeast directed compression that was coincident with the intrusion of various plutons. The S_2 foliation is the dominant meso- to macro-scale regional fabric evident across the study area. Ductile flow of volcano-sedimentary rocks between more competent batholiths may also have occurred during D_2. D_2 deformation is constrained to between ca. 2.691 and ca. 2.683 Ga (Muir, 2003).

D_3 deformation was the result of northwest-southeast shortening during regional dextral transpression. D_3 structural elements include macroscale F_3 folds, including the Manitouwadge synform, and local shear fabrics that exhibit a dextral sense of motion and overprint D_2 structures (Peterson and Zaleski, 1999; Muir, 2003). D_3 deformation did not develop an extensive penetrative axial planar and (or) crenulation cleavage. D_3 deformation is constrained to between ca. 2.682 and ca. 2.679 Ga (Muir, 2003).

D_4 structural elements include isolated northeast-plunging F_4 kink folds with a Z-asymmetry, and associated small-scale fractures and faults overprinting D_3 structures. D_3-D_4 interference relationships are best developed in the Manitouwadge greenstone belt and in rocks of the Quetico Subprovince. D_4 deformation is roughly constrained to between ca. 2.679 and ca. 2.673 Ga (Muir, 2003).

Details of structural features associated with the D_5 and D_6 deformation events are limited in the literature to brittle and brittle-ductile faults of various scales and orientations (Lin, 2001; Muir, 2003). Within the Hemlo greenstone belt, Muir (2003) suggested that local D_5 and D_6 faults offset the Marathon and Biscotasing dyke swarms (all ca. 2.2 Ga), and as such, suggested that in the Hemlo region D_5 and D_6 faults propagated after 2.2 Ga. However, since there are no absolute age constraints on specific events, the entire D_5-D_6 interval of brittle deformation can only be constrained to a post-2.673 Ga timeframe that may include many periods of re-activation attributable to any of several post-Archean tectonic events, as described above and summarized in Table 1.

Table 1: Summary of the Geological and Structural History of the Manitouwadge Area (adapted from AECOM, 2014a)

Approximate Time period (years before present)	Geological Event
2.89 to 2.77 Ga	Progressive growth and early evolution of the Wawa-Abitibi terrane by collision, and ultimately accretion, of distinct geologic terranes
2.770 – 2.673 Ga	- ca. 2.720 Ga: Volcanism and subordinate sedimentation associated with the formation of the Manitouwadge greenstone belt - ca. <2.693: Deposition of sedimentary rocks in the Manitouwadge greenstone belt and the Quetico Subprovince - ca. 2.720-2.678 Ga: Inferred emplacement of granitoid intrusions in the Manitouwadge area. - Emplacement of the Pukaskwa and Black-Pic gneissic complexes at ca. 2.72 Ga - Emplacement of Loken Lake pluton (ca. 2.687 Ga), Nama Creek pluton (2.680 Ga), and Fourbay Lake pluton (ca. 2.678 Ga) - ca. 2.719 to 2.673 Ga: Four periods of ductile-brittle deformation (D_1-D_4) - D_1: ca. 2.719 – 2.691 Ga - D_2: ca. 2.691 – 2.683 Ga - D_3: ca. 2.682 – 2.679 Ga - D_4: ca. 2.679 – 2.673 Ga
2.675 to 2.669 Ga	Peak metamorphism of the Manitouwadge greenstone belt
2.666 to 2.650 Ga	Peak metamorphism of the Quetico Subprovince
2.5 to 2.100 Ga	- ca. 2.5 Ga: Supercontinent fragmentation and rifting in Lake Superior area. Development of the Southern Province - ca. 2.473 Ga: Emplacement of the Matachewan dyke swarm - ca. 2.167 Ga: Emplacement of Biscotasing dyke swarm - ca. 2.121 Ga: Emplacement of the Marathon dyke swarm
1.9 to 1.7 Ga	Penokean Orogeny in Lake Superior and Lake Huron areas; possible deposition and subsequent erosion in the Manitouwadge area
1.150 to 1.090 Ga	Rifting and formation of the Midcontinent Rift structure. - ca. 1.1 Ga
540 to 355 Ma	Possible coverage of the area by marine seas and deposition of carbonate and clastic rocks subsequently removed by erosion.
145 to 66 Ma	Possible deposition of marine and terrestrial sediments of Cretaceous age, subsequently removed by erosion

Table 1: Summary of the Geological and Structural History of the Manitouwadge Area (adapted from AECOM, 2014a)

2.6 to 0.01 Ma	Periods of glaciation and deposition of glacial sediments

2.4 Quaternary Geology

Quaternary geology in the Manitouwadge area is described in detail in AECOM (2014b). A summary of the main features is provided here for reference.
The Quaternary sediments, commonly referred to as drift, soil or overburden, are glacial and post-glacial materials which overlie the bedrock in the Manitouwadge area. Their distribution, thickness and physical characteristics have an important influence on several aspects of the current assessment. Areas of thicker drift can hinder the interpretation of lineaments by masking their presence in satellite imagery or muting the response obtained from geophysical surveys. Coarser-grained surficial sediments typically have a moderate to high transmissivity and can serve as local aquifers as well as being a potential source of mineral aggregates for use in building and road construction.

All glacial landforms and related materials within the Manitouwadge area are associated with the Late Wisconsinan (30,000 to 10,000 years ago). The Quaternary (i.e., surficial) geology of the area has been mapped at a regional scale (>1:100,000) by several authors, including Boissonneau (1965), Zoltai (1965), Sado and Carswell (1987), and Barnett et al. (1991) and at a higher resolution (1:100,000) by Gartner (1979) and Gartner and McQuay (1980a, b, c). The area covered by the Manitouwadge, White Lake and Vein Lake NTS map sheets has been mapped at a scale of 1:50,000 by Kristjansson and Geddes (1986; 2009), Geddes and Bajc, (1985; 2009) and Kettles and Way Nee (1998), respectively. Quaternary deposits and landforms in the area are thought to have formed during the latter stages of ice cover.

Kristjansson and Geddes (1986) reported that glacial striae in the Manitouwadge area indicate the last direction of glacial movement was toward the south-southwest with little deviation from a general orientation of 210° to 220°. Geddes and Bajc (1986) noted that in the southern portion of the area a weakly developed, presumed older, striation direction is recognized that reflects a more southerly direction of ice flow. For the large parts of the Manitouwadge area, drift thickness over bedrock is limited and the ground surface reflects the bedrock topography (Kristjansson and Geddes, 1986). Over the majority of the area, bedrock outcrops are common and the terrain is classified, for surficial purposes, as a bedrock-drift complex, i.e., thin drift cover that only locally achieves thicknesses that mask or subdue the bedrock topography (Figure 3). Valleys and lowland areas typically have extensive and thicker surficial deposits that frequently have a linear outline.

The remote sensing and terrain evaluation completed as part of the Phase 1 preliminary assessment (AECOM, 2014b) provides a more detailed assessment of the type, distribution and thickness of surficial deposits in the Manitouwadge area (Figure 3).

The most common glacial deposit in the Manitouwadge area is ground moraine (till) which occurs as two main types (Geddes and Kristjansson, 1984; Geddes et al., 1985). Dominant in the rocky upland areas is a moderately loose, stony, sandy till of local derivation that forms a discontinuous veneer over the bedrock. The second till type has calcareous, silt matrix and contains abundant non-local pebble lithologies derived from the James Bay Lowland. Two facies of this calcareous till are noted by Kristjansson and Geddes (1986); a moderately compact to loose, silty-sand melt-out variety, and a very dense, blocky and silty variety. In general, the calcareous till is most prevalent in areas situated on the lee-side (down ice) of major bedrock highs.

Till thickness in the Manitouwadge area is variable; while depths of several metres are present locally; thicknesses are typically less than 3 m (Bajc, pers. comm., 2013). In relatively restricted areas immediately west, south and southeast of the settlement area of Manitouwadge the till forms a more continuous blanket over the bedrock that is, in places, gently fluted (Kristjansson and Geddes, 1986). In this area, zones of lesser relief indicate that the till thickness may be sufficient to subdue the bedrock topography, although bedrock outcrops occasionally protrude through the till cover.

Two types of glaciofluvial deposits are present in the Manitouwadge area, ice-contact stratified drift deposits (ICSD) and outwash deposits. The ICSDs deposits are associated with a number of esker and kame terraces complexes (Gartner and McQuay, 1980a). Kristjansson and Geddes (1986) noted that the orientation of the esker-kame complexes reflect the major bedrock lineaments present in the area, and as such the ICSD feature trend south and southwest (Figure 3). Most of the esker complexes have defined, if discontinuous, central ridge(s) that are flanked by kettled kame terraces or younger glaciolacustrine deposits. The ICSDs consist primarily of stratified, well to poorly sorted, sand and gravel, locally boulder-rich, that can achieve thicknesses of up to 30 m (Kettles and Way Nee, 1998).

Glaciofluvial outwash deposits in the Manitouwadge area have a restricted distribution with the largest deposits occurring to the east and southeast of the Township of Manitouwadge where they are associated with ICSD sequences (Figure 3). Locally, the outwash plains are heavily kettled and pitted indicating the deposition of sediment over buried ice blocks. The thickness of the outwash deposits is likely to be variable, but may be substantial where they are proximal to ICSD features. Deposits are generally well-sorted and consist predominantly of stratified sand, with a low clast content; however, locally they are coarser grained and gravel-rich (Kristjansson and Geddes, 1986).

Glaciolacustrine sediments in the area consist of stratified to laminated sand, silt and clay that were deposited during the incursion of glacial lakes post-Minong and Houghton into the Manitouwadge area (Prest, 1970; Gartner and McQuay, 1980a; Kettles and Way Nee, 1998). Northward expansion of the lakes allowed a connection with the waters of glacial Lake Barlow-Ojibway, via the Pic-White Otter river valley.

Glaciolacustrine sediments occur across the area, with extensive deposits occurring on the eastern and western sides of the Township of Manitouwadge and in the northeast quadrant of the area (Figure 3). The highest glacial lake level in the Manitouwadge area was approximately 340 m (Kettles and Way Nee, 1998). The thickness of glaciolacustrine deposits is variable, ranging from several tens of metres to a relative thin drape over bedrock. Deposit thickness in the Pic and White Otter river valleys may achieve 75 m (Kettles and Way Nee, 1998).

Organic-rich alluvial deposits, consisting of sand, silt and clay, are present along water courses across the area (Figure 3). Bog and swamp deposits, developed on rock and glaciolacustrine floored basins, are also common with larger deposits containing bedrock knobs and minor outwash. These deposits tend to have a limited thickness, as determined by regional studies, and generally have a limited aerial extent.

Eolian deposits, consisting of fine to medium sand, are present as parabolic dunes developed on some glaciofluvial and glaciolacustrine deposits (Gartner and McQuay, 1980a; Kristjansson and Geddes, 1986; Kettles and Way Nee, 1998). Dunes, formed in post-glacial time, have heights of only a few metres in the Manitouwadge area.

The impact that the variable distribution of Quaternary sediments has on the results of the geophysical interpretation will be discussed in Section 5.

2.5 Land Use

The vast majority of the Manitouwadge area is undeveloped Crown Land with privately held residential and business properties located almost exclusively within the settlement area of Manitouwadge and the hamlet of Hillsport. Mineral patents (private land) or leases (non-freehold public dispositions) occupy a significant portion of the northern half of the Township of Manitouwadge and some land immediately adjacent to its eastern boundary. All historic mine workings occur in the area of patented land. Narrow linear tracts of land reserved to the Crown are present along a length of the Pic River and a band extending west then northwest from the settlement area of Manitouwadge.

Mineral exploration is active in the area on the patented ground and numerous active mining claims held by prospectors and mining companies (MNDM, 2013). A large number of mining claims occur over the Manitouwadge greenstone belt, north and east of the patented/leased ground; smaller numbers of claims are located north and northeast of the boundary of the Township of Manitouwadge. A range of exploration work is conducted on the claims to assess the mineral potential including geologic mapping, drilling, and geochemical and geophysical surveys. Several base metal mines have operated in the area; however, all have ceased production. A number of aggregate operations are extracting sand and gravel in the area (MNR, 2013a). The majority of the pits are located adjacent to the routes of Highway 631 and the Caramat Industrial Road (Figure 1).

Forestry is a long-standing use of the land and has been an economic mainstay of the Manitouwadge area. The area falls within MNR’s Pic River and Big Pic forestry management units (MNR, 2013b). Timber harvesting has occurred over large expanses of the Manitouwadge area.

Forestry sector activities result in the development of an extended road and/or trail network, although some of this access is of a temporary (e.g., open only while logging is on-going) or seasonal nature (e.g., winter roads). Access to the many lakes and remote areas within the Manitouwadge area allows use of the land for hunting and fishing by the local population and visitors to the region.

3 GEOPHYSICAL DATA SOURCES AND QUALITY

For the Manitouwadge area, geophysical data were obtained from available public-domain sources, particularly the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC). To supplement these data, geophysical surveys performed in the Manitouwadge area by the mining industry were reviewed, as available from assessment files.

The quality of the available data was assessed to determine which data sets are suitable for inclusion in this assessment. The geophysical surveys covering the Manitouwadge area show variability in data set resolution, which is a function of the flight line spacing, the sensor height and equipment sensitivity. In particular, where more than one data set overlaps, the available data were assembled using the highest quality coverage. Various geophysical data processing techniques were applied to enhance components of the data most applicable to the current assessment. The integrity of the higher quality data was maintained throughout.

3.1 Data Sources

Low-resolution geophysical data, particularly the magnetic, gravity and radiometric data obtained from the Geological Survey of Canada (GSC), cover the entire Manitouwadge area. The higher resolution geophysical coverage consists of three magnetic and frequency-domain (FDEM) surveys. They cover all but the northern portion of the Manitouwadge area (Figure 4).

Due to the lack of high-resolution data over the northern part of the Manitouwadge area, data from the OGS Assessment File Research Imaging Database (AFRI) was reviewed. However, given the quality of the overall coverage, no assessment files were located that would improve the OGS and GSC geophysical data. The geophysical data sets are summarized in Table 2 and the characteristics of each of the data sources are discussed in detail below.

Table 2. Summary of the characteristics for the geophysical data sources in the Township of Manitouwadge and surrounding area

Product	Source	Type	Line Spacing/ Sensor Height	Line Direction	Location	Date	Additional Comments
Ontario #8	GSC, 2013	Fixed wing magnetic	805 m/305 m	0°	Entire Manitouwadge area	1959	Mostly superseded by high-resolution coverage.
GDS1205 Manitouwadge (blocks A to C, E to I)	OGS, 2002a	Helicopter magnetic, FDEM	150-200 m/ MAG 45 m FDEM 30 m	Varies (north to northwest)	All but northern part of Manitouwadge area	1989	4-frequency Dighem IV system, flown for Noranda Exploration Company, Ltd.
GDS1207 Hemlo	OGS, 2002b	Helicopter magnetic, FDEM, VLF-EM	100 m/ MAG 55 m FDEM 40 m VLF-EM 55 m	0°	Southern edge of Manitouwadge area	1983	3-frequency Aerodat system.
Dighem #1056 (Areas A & G)	GSC, 2013	Helicopter magnetic	150 m/ MAG 45m	173°/155°	West central part of Manitouwadge area	1988	FDEM data not available, fills the gap in OGS GDS1205, flown for Noranda Exploration Company, Ltd.
Coldwell, Hemlo, Schreiber	GSC, 2013	Fixed wing radiometric, magnetic, VLF-EM	1000 m/121 m	0°	Southwest part of Manitouwadge area	1990	Only higher resolution radiometric survey.
North Shore Lake Superior, section 1 (East)	GSC, 2013	Fixed wing magnetic, radiometric	5000 m/123 m	0°	Entire Manitouwadge area	1982	Provides majority of radiometric coverage.
GSC Gravity Coverage	GSC, 2013	Ground gravity measurements	5-15 km		Entire Manitouwadge area	1946-2001	

GSC – Geological Survey of Canada
OGS – Ontario Geological Survey
FDEM – Frequency-domain electromagnetic
VLF-EM – Very low frequency electromagnetic
MAG – magnetic

3.1.1 Magnetic Data

Magnetic data over the Manitouwadge area were collected by various surveys using different survey parameters outlined in Table 2. Magnetic surveys help in the understanding of geological and structural variations caused by different rock types associated with their content of magnetic minerals, such as magnetite and pyrrhotite. Magnetic maps show the distribution of magnetic and non-magnetic geologic bodies within the subsurface, and are particularly useful for delineating spatial geometry of bodies of rock, and the presence of faults and folds.

The resolution of the retrieved magnetic datasets varies within the Manitouwadge area. Surveys were flown over a period of 30 years, over which time the quality and precision of the equipment as well as the quality of the processing has improved. Variability in the quality of the survey coverage also influenced the ability of the magnetic data to identify geological structures of interest relevant to this assessment.

Low-resolution magnetic data from the GSC regional aeromagnetic survey (Ontario #8) provides complete coverage of the entire Manitouwadge area (GSC, 2013). Magnetic data from this survey forms part of the GSC Regional Magnetic Compilation data. The survey was flown at a terrain clearance of 305 m and flight line spacing of 805 m, providing it with a relatively low spatial resolution. One high-resolution survey is available from the GSC (Dighem 1056) in the west-central part of the Manitouwadge area, flown at a lower terrain clearance (45 m) compared to the older GSC surveys, and with tighter flight line spacing (150 m), providing this survey with a relatively high spatial resolution (GSC, 2013). Additional, high resolution surveys from the OGS (Manitouwadge Survey and Hemlo Survey) were flown at a lower terrain clearance (45 and 55 m) compared to the GSC surveys, and with tighter flight line spacing of 150 and 200 m and 100 m (OGS, 2002a, b) These surveys focused on areas of high mineral exploration potential, covering the greenstone belts and also the adjacent intrusive and metasedimentary rocks. The high resolution coverage amounts to approximately 80 percent of the Manitouwadge area, including the entire Wawa Subprovince and the southern half of the Quetico Subprovince.

3.1.2 Gravity Data

Gravity data provides complete coverage of the Manitouwadge area (GSC, 2013) consisting of an irregular distribution of 33 station measurements, comprising roughly a station every 5 to 15 km.

The gravity measurements were retrieved as Bouguer corrected data. The Bouguer correction is applied to compensate for the gravity effect of the material between the measurement station and the datum elevation. However, the contribution to the measurement of the gravity effects of the surrounding topographic features (i.e., terrain correction) was not applied by the GSC.

Despite the fact that data are of good quality, the sparseness of the measurement locations in the Manitouwadge area can only be used to provide information about large scale geologic features.

3.1.3 Radiometric Data

The GSC radiometric datasets provide complete coverage of the Manitouwadge area (GSC, 2013). The acquired data show the distribution of natural radioactive elements at surface: uranium (eU), thorium (eTh) and potassium (K), which can be interpreted to reflect the distribution of mineralogical and geochemical information in the area. The GSC radiometric data were flown at 5,000 m line spacing at a terrain clearance of 120 m above the surface over most of the Manitouwadge area. In the southwest part of the Manitouwadge area, the Coldwell, Hemlo, Schreiber survey flown by the GSC provides higher resolution with tighter line spacing (1,000 m) (Table 2).

Retrieved radiometric data consisted of measurements of the following four parameters:
- Potassium, K (%);
- Equivalent uranium, eU (ppm);
- Equivalent thorium, eTh (ppm);
- Total Air Absorbed Dose Rate (nGy/h);

3.1.4 Electromagnetic Data

One frequency-domain electromagnetic (FDEM) survey available from the OGS was retrieved from the Manitouwadge survey (OGS, 2002a) (Figure 4). The FDEM system used for the survey was a Dighem IV system to measure the inphase and quadrature components of four different frequencies (one coaxial and three coplanar coil pairs), towed below a helicopter with the sensor at a nominal terrain clearance of 30 m. The survey was flown at 150 m and 200 m flight line spacing (depending on survey block), providing relatively high spatial resolution.

A second frequency-domain electromagnetic (FDEM) survey available from the OGS was retrieved from the Hemlo survey (OGS, 2002b) (Figure 4). The FDEM system used for the survey was an Aerodat III system to measure the inphase and quadrature components of three different frequencies (two coaxial and one coplanar coil pairs), towed below a helicopter with the sensor at a nominal terrain clearance of 40 m. The survey was flown at 100 m flight line spacing, providing relatively high spatial resolution. The survey also acquired total field and quadrature VLF-EM data using the Cutler, Maine transmitter. The FDEM data were used in preference to the VLF-EM data in the interpretation due to their superior response to bedrock sources and less sensitivity to strike direction of the conductors.

The VLF-EM data from the Coldwell, Hemlo, Schreiber survey (GSC, 2013) were gridded and examined, but the line spacing of 1,000 m make them of little use in comparison to the Manitouwadge FDEM survey described above.

In addition, each FDEM survey included an EM anomaly database with the sources classified as bedrock, surficial or cultural.

3.2 Data Limitations

There is a fairly stark contrast between the high resolution of the magnetic surveys that cover the southern 80% of the Manitouwadge area and the older regional low resolution coverage in the north. Nevertheless, the magnetic data reflect quite coherent responses that reveal the mapped geology, particularly in areas of limited bedrock exposure. The smaller intrusions, dyke swarms and main structural regimes are clearly delineated by the magnetic data, regardless of resolution, but at different levels of detail.

All four data types considered (magnetic, gravity, radiometric and electromagnetic) contribute to the interpretation. The limitation in applying these data types to the Manitouwadge area is governed mainly by the following factors:

- Coverage and quality of data – types available, density of the coverage, vintage and specifications of the instrumentation;
- Overburden – areal extent, thickness and physical properties; and
- Bedrock lithologies – physical properties and homogeneity (e.g., batholith contacts can be easily mapped but batholiths themselves are sometimes quite homogeneous, making geophysical characterization of internal structure difficult).

The user of the geophysical information must bear in mind that each method relies on characterizing a certain physical property of the rocks. The degree to which these properties can be used to translate the geophysical responses to geological information depends mainly on the amount of contrast and variability in that property within a geological unit and between adjacent geological units. The usability of each data set also depends on its quality, especially resolution. The physical rock property data available for the Manitouwadge area consist of magnetic susceptibility measurements from Miles (1998). These are summarized in Table 3 (section 5.2.1).

4 GEOPHYSICAL DATA PROCESSING

All data were processed and imaged using the Oasis montaj software package (Geosoft, 2013). Three additional magnetic grids were prepared using the Encom PA software package (Pitney Bowes, 2013). The grids that resulted from the various processing steps were also loaded in ArcMAP 10 (ESRI, 2013) using a Geosoft plug-in.

4.1 Magnetic

All surveys in the Manitouwadge area where projected to the UTM16N/NAD83 coordinate system. Magnetic data from the surveys were gridded at a cell size of ¼ the line spacing. The resultant grids were examined for level noise along the survey lines and as a result, microlevelling was applied to the GSC survey Ontario #8. Geophysical data from the surveys were upward or downward continued (if necessary) to a common flying height of 45 m, and regridded to a common grid cell size of 40 m. Consequently, downward continuation of 260 m was only applied to the magnetic grid from the GSC regional survey (Ontario #8), which was followed by an 8th-order 800 m low pass Butterworth filter in order to reduce noise associated with the application of downward continuation and coarseness of the data. The Butterworth filter is a type of signal processing filter designed to have as flat a frequency response as possible in the pass band. The 800 m wavelength did not reduce the geological signal due to the line spacing of 805 m and the coarse sampling of the digitized data long the flightlines. The two OGS surveys were at a flying height of 45 m and 55 m so that they were not downward (or upward) continued.

The surveys were merged together using Oasis montaj (Geosoft, 2013) where the suture path between the grids was along the edge of the grid with the original higher resolution grid cell size so that the most detailed data was retained in the final product. The resultant grid was the residual magnetic intensity grid (i.e., total magnetic field after IGRF correction) and the basis for preparing the enhanced magnetic grids.

Reduction to the Pole (RTP)

The direction (inclination and declination) of the geomagnetic field varies over the Earth and influences the shape of the magnetic responses over geological sources. At the North Magnetic Pole the inducing magnetic field is vertical (i.e., inclination of 90° and declination of 0°), which results in the magnetic response being a symmetric positive magnetic peak over a source, in the absence of dip and magnetic remanence. Transforming the measured magnetic field to a pole reduced magnetic field simplifies the interpretation, particularly to determine the location and geometry of the sources (Baranov, 1957). For the Manitouwadge area, the residual magnetic intensity grid was reduced to the pole using a magnetic inclination of 77.8° N and magnetic declination of 4.7° W (Figure 5).

The RTP filter, computed from the residual magnetic field after it is transformed to the Fourier domain, is defined as follows:

$$L(\theta) = \frac{[\sin(I) - i \cdot \cos(I) \cdot \cos(D-\theta)]^2}{[sin^2(I_a) + cos^2(I_a) \cdot cos^2(D-\theta)] \cdot [sin^2(I) + cos^2(I) \cdot cos^2(D-\theta)]}$$

$$if\ (|I_a| < |I|), I_a = I \qquad \text{(eq. 4.1)}$$

Where:
L(θ) = pole-reduced magnetic field for wavenumber θ
I = geomagnetic inclination
I_a = inclination for amplitude correction (never less than I).
D = geomagnetic declination
i = imaginary number in the Fourier domain.

First Vertical Derivative of the Pole Reduced Field (RTP1VD)

The vertical derivative is commonly applied to the RTP magnetic field data in the Fourier domain to enhance shallower geologic sources in the data (Figure 7). This is particularly useful for locating contacts (e.g., the anomaly texture is revealed), and mapping structure (Telford et al., 1990). It is expressed as:

$$1VD = {dRTP}/{dZ} \qquad \text{(eq. 4.2)}$$

where Z is the vertical offset.

One limitation of this filter is that the higher order derivatives tend to also enhance the high frequency noise in the data set. To reduce noise that resulted from aliasing during the minimum curvature gridding process, an 8th-order 100 m low-pass Butterworth filter was also applied.

Directional Filters

The magnetic responses in the Manitouwadge area are significantly influenced by the Matachewan, Biscotasing and Marathon dyke swarms due to their widespread prevalence across the area and the amplitude of their magnetic anomalies compared to the relatively subdued responses over most of the bedrock. As a result, directional filters were applied along the approximate strike direction of each swarm to better image the bedrock responses (e.g., Fuller, 1967; Pilkington and Roest, 1997). Grids of the pole-reduced magnetic field, its first vertical derivative were prepared by removing the signal for a median strike direction of 142° (Matachewan swarm), 32° (Biscotasing swarm) and 11° (Marathon swarms) measured in the region near the Manitouwadge area. The strike direction is represented as a clockwise rotation from north. The result with all swarms removed is presented for the pole-reduced magnetic field (Figure 6) and its first vertical derivative (Figure 8).

The directional filter, applied in the Fourier domain, is defined as follows:

$$L(\theta) = |\cos\left(\alpha - \theta + \frac{\pi}{2}\right)| \qquad \text{(eq. 4.3)}$$

Where:
L(θ) = magnetic field for wavenumber θ
α = direction to be rejected

Upward continued grids of the pole-reduced magnetic field to levels 500 m, 1,000 m and 2,000 m above the observation surface were also prepared, as an alternate form of suppressing the dyke responses and viewing the bedrock geology responses on a regional scale.

Second Vertical Derivative of the Pole Reduced Field (RTP2VD)

The second vertical derivative is commonly applied to the RTP magnetic field data in the Fourier domain to further enhance shallower geologic sources in the data (Figure 9). This is particularly useful for locating contacts (e.g., the anomaly texture is revealed), and mapping structure close to surface (Telford et al., 1990). It is expressed as:

$$2VD = {d^2RTP}/{dZ^2} \qquad \text{(eq. 4.4)}$$

where Z is the vertical offset.

To reduce noise that resulted from aliasing during the minimum curvature gridding process, an 8th-order 300 m low pass Butterworth filter was also applied.

Tilt Angle of the Pole Reduced Field

The tilt angle (Miller and Singh, 1994) has been applied to the RTP magnetic field data to preferentially enhance the weaker magnetic signals (Figure 10). This is particularly useful for mapping texture, structure, and edge contacts of weakly magnetic sources. It is expressed as:

$$TILT = \tan^{-1}\left\{\frac{\frac{dRTP}{dZ}}{\sqrt{\left([\frac{dRTP}{dX}]^2+[\frac{dRTP}{dY}]^2\right)}}\right\} \qquad \text{(eq. 4.5)}$$

where X and Y are the horizontal offsets in the east and north directions.

The first vertical derivative is computed in the Fourier domain whereas the horizontal derivatives in X and Y are computed in the space domain. To reduce noise that resulted from aliasing during the minimum curvature gridding process, an 8th-order 200 m low pass Butterworth filter was also applied.

Analytic Signal Amplitude

The amplitude of the analytic signal (AS) (Figure 11) is the square root of the sum of the squares of the derivatives in the horizontal (X and Y) and vertical (Z) directions (i.e., the Fourier domain first vertical derivative and the space domain horizontal derivatives in X and Y), computed from the total magnetic field (Nabighian, 1972):

$$AS = \sqrt{\left([\frac{dT}{dX}]^2 + [\frac{dT}{dY}]^2 + [\frac{dT}{dZ}]^2\right)} \qquad \text{(eq. 4.6)}$$

To reduce noise that resulted from aliasing during the minimum curvature gridding process, an 8th-order 150 m low pass Butterworth filter was also applied.

The analytic signal is useful in locating the edges of magnetic source bodies, particularly where remanence complicates interpretation. It is particularly useful to interpret the contacts of intrusions.

Depth to Magnetic Sources Using Source Parameter Imaging (SPI™)

The SPI method locates the depths of edges in the gridded magnetic data (Thurston and Smith, 1997). It assumes a 2D sloping contact or 2D dipping thin sheet model. The SPI solutions extracted from the pole reduced magnetic field grid are stored in a database. The SPI values calculated are depths between the magnetic source and the instrument height. If the survey was flown at a constant terrain clearance, then the drape height could be subtracted from the SPI value to result in a depth below surface. For the GSC regional compilation, only the average flying height was known. For the remaining surveys (Manitouwadge, Dighem #1056 and

Hemlo), the radar altimeter data were included in the survey database and were consequently used to more accurately determine the distance between the magnetic sensor and the computed depth to the magnetic source. The radar altimeter channel was gridded at the original grid cell size and sampled back to the SPI database. If the value of the depth to source is <0, i.e., above ground, it is set to a value of zero. Thus, the SPI depth with respect to the ground surface is calculated as:

- SPI_depth = SPI_value – average flying height, if no radar data is available; or
- SPI_depth = SPI_value – radar value, if available.

The SPI depths were calculated for each individual data set in the Manitouwadge area, taking into account that the elevation of the magnetic sensor (Figure 12). Low resolution grids are biased with deeper basement depths due to the lack of high frequency content. Thus, where a high resolution survey overlaps with a low resolution regional survey, the SPI depths from the low resolution grid were excluded. The final SPI depth grid was calculated with a grid cell size of 200 m.

<u>Encom Magnetic Grids</u>

A series of grids were created to highlight the edges of both shallow and deep sources and to categorize anomalous zones into different areas (Shi and Butt, 2004). These grids are:

- rtpzsedge – gradient filters applied to the pole reduced magnetic field to emphasize edges;
- rtpzsedgezone – gradient filters and amplitude equalization filters applied to the pole reduced magnetic field to emphasize edges;
- rtpzsplateau – gradient filters and amplitude equalization filters applied to the pole reduced magnetic field to emphasize homogeneous blocks bounded by edges.

<u>Magnetic Peaks, Troughs and Edges</u>

The semi-automated extraction of magnetic anomaly peaks, troughs and edges is useful for delineating structure, foliation, texture and contacts. Anomaly peaks typically trace the center of a source or the more magnetic horizons within a larger source. Anomaly troughs often complement the peaks, indicating a less magnetic horizon. They also may map a remanent (i.e., reversely) magnetized source, or magnetite depletions (e.g., along a fault) which are a less magnetic source in a more magnetic host rock. Anomaly edges mark geological contacts or the boundaries of horizons within a geological unit. Offsets and orientation changes in the peaks, troughs and edges are useful for mapping faults and shears. Detection for peaks, troughs and edges was performed based on the CET (Centre for Exploration Targeting) Grid Analysis package in Oasis montaj (Geosoft, 2013).

The phase symmetry method, a frequency-domain approach based on axes of symmetry, is used to identify arbitrarily oriented line features. The 2D image is analyzed with 1D profiles in multiple orientations and varying scales. A line feature exhibits strong symmetry responses from profiles in all orientations not parallel to the line itself. Symmetry is closely related to periodicity: the symmetry point in the spatial domain corresponds to either a minimum or maximum of its local Fourier components. Thus the detection is carried out by frequency analysis.

The frequency analysis is performed by wavelet transform, which estimates local frequency using complex valued log-Gabor filters. The filters are comprised of an even symmetric (cosine) wavelet and an odd symmetric (sine) wavelet, each modulated by a Gaussian. These filters at different scales respond to particular bands of frequencies. The local frequency information is obtained from the convolution of the wavelet filters with the 2D data. An array of filter response vectors are generated for each point in the signal for each scale. Localized frequency representation is produced from these vectors. The frequency component is represented as a complex number; its real and imaginary parts are the outputs from the even and odd symmetry filter responses, respectively. At the point of symmetry, frequency components are at their amplitude extrema. This corresponds to where the absolute values of the outputs are high from even symmetry filter and low from odd symmetry filter, for all frequencies. This 1D analysis is performed in multiple orientations to extend to 2D analysis (Holden et al., 2008).

An amplitude threshold is then applied to the output symmetry grid, to distinguish cells that contain signal of interest from the background. A lower threshold value leads to the detection of more features, but may also introduce noise in the data. The resulting grid is binary: 1 for regions of interest and dummies for background. The grid is then skeletonized to trendlines. This process also sets the minimum valid line length.

The smallest filter wavelength used in this analysis for the Manitouwadge area was four cells (equivalent to 160 m), over three scales. The filter sizes were therefore 160 m, 320 m and 640 m. All orientations were considered in the search for symmetry. A threshold value of 0.1 was applied, and a minimum line length of 3 cells (120 m) was set.

Edges were enhanced by computing the balanced horizontal gradient magnitude (TDX) (Cooper and Cowan, 2006) from the RTP grid, as modified by Fairhead and Williams (2006):

$$TDX = \tan^{-1}\left\{\frac{\sqrt{\left([\frac{dRTP}{dX}]^2+[\frac{dRTP}{dY}]^2\right)}}{\frac{dRTP}{dZ}}\right\} \qquad \text{(eq. 4.7)}$$

The first vertical derivative is computed in the Fourier domain whereas the horizontal derivatives in X and Y are computed in the space domain.

The TDX of the pole-reduced magnetic field is a more accurate locator of source edges and less susceptible to noise in the data than other forms of edge detectors. Pilkington and Keating (2009) confirmed that TDX and its analog, “theta mapping”, produce identical results and are the most robust of the edge detection techniques applicable to potential field data.

The positive peak values are extracted by applying an amplitude threshold to the TDX grid to identify cells of interest. The resulting grid is binary and is skeletonized to locate the source edges. In this project, a threshold value of 0.9 was used.

The peaks, troughs and edges generated using the CET methods were not submitted directly for further lineament analysis. The ENCOM grids and TDX images are not presented in this report. However, all of these maps and images were used as guides during the manual interpretation process. The accuracy and reliability of these products were greatly influenced by the resolution of the original magnetic data.

4.2 Gravity

The following four gravity grids and their gravity station locations (33 gravity measurements) were downloaded for the Manitouwadge area, extracted from the GSC gravity compilation (GSC, 2013) at 2000 m grid cell size:

- Bouguer gravity field (Figure 13);
- First vertical derivative of the Bouguer gravity field (Figure 14);
- Total horizontal gradient of the Bouguer gravity field; and
- Isostatic residual gravity field.

All grids were reprojected to the Manitouwadge area's coordinate system, UTM16N/NAD83. The first vertical derivative was computed by the GSC using the same methodology applied to the pole reduced magnetic field, as described in Section 4.1. The total horizontal gradient of the Bouguer gravity provided similar results as the first vertical derivative, and therefore was not presented in this report. The isostatic residual compensates for mass deficiencies at depth predicted from topography, preserving the shorter wavelength components of the field due to nearer surface sources. In the Manitouwadge area, the isostatic residual field closely resembles the Bouguer gravity field due to the relatively gentle topography, and therefore was not presented in this report. The GSC applied standard gravity reduction methods to compute the free air and Bouguer gravity fields. A Bouguer correction density of 2.67 g/cm^3 was applied, the typical value for the Canadian Shield. As the regional data for the Manitouwadge area were collected in 1965 and earlier, station elevations were likely determined using barometric altimeters (much less accurate than GPS) and terrain corrections were not applied.

4.3 Radiometric

The following seven radiometric grids (radioelement concentrations and ratios) were downloaded for the Manitouwadge area, extracted from the GSC radiometric compilation (GSC, 2013) at 250 m grid cell size:

- Potassium (K %);
- Thorium (eTh ppm);
- Uranium (eU ppm);
- Total air absorbed dose rate (nGy/h);
- Thorium over potassium ratio (eTh/K);
- Uranium over potassium ratio (eU/K);
- Uranium over thorium ratio (eU/eTh).

The determination of the radioelement concentrations, dose rate and ratios followed the methods and standards published by the International Atomic Energy Agency, many of which were developed at the GSC. All grids were reprojected to the Manitouwadge area's coordinate system, UTM16N/NAD83. The dose rate is a calibrated version of the measured “total count”, and reflects the total radioactivity from natural and man-made sources. The radiometric data are presented in Figure 15 as a ternary RGB image of the three radioelements, with the intensity of potassium (%) displayed in red, equivalent thorium (ppm) in green and equivalent uranium (ppm) in blue. Areas of highest intensity of all three radioelements show light colours and trend towards white. Areas of lowest intensity of all three radioelements are dark colours and trend towards black.

4.4 Electromagnetic

The EM surveys flown by the Ontario Geological Survey were at 200 m line spacing, which provides good resolution for mapping. Some of the surveys acquired from industry and reprocessed were flown at a closer line spacing (e.g. OGS, 2002b).

These surveys typically focus on the greenstone belts, extending into the edges of neighbouring granites and sometimes encompassing smaller plutons where the greenstones wrap around them (Figure 16). Certain intrusions that have known mineral potential have also been flown (e.g., in the Abitibi Subprovince). Helicopter surveys generally have better signal/noise than fixed wing surveys due to closer proximity of the EM transmitter, EM receiver and magnetometer to the ground.

All surveys are delivered with an EM anomaly database, where individual anomalies have been picked along flightlines and then classified as bedrock source, surficial source (e.g., overburden) or cultural (e.g., hydro line). Bedrock anomalies usually incorporate a vertical plate or similar model to provide an estimate of depth-to-top and conductivity. The depth values give an indication of overburden thickness, assuming the conductor subcrops.

The analysis of the EM data herein consisted mainly of plotting the EM anomalies over the gridded images provided by OGS and joining bedrock anomalies into quasi-linear conductors, where the character of the EM response remained consistent along strike. Typically, these conductors follow the stratigraphy evident in the mapped geology and magnetic data.

For the electromagnetic surveys in the Manitouwadge area, the following data products were available:

- Manitouwadge (OGS, 2002a) - apparent resistivity grids from the 900 Hz, 7,200 Hz and 56,000 Hz coplanar coil pairs;
- Hemlo (OGS, 2002b) - apparent resistivity grid from the 4,500 Hz coaxial coil pair and VLF total field grid.

5 GEOPHYSICAL INTERPRETATION

5.1 Methodology

The coincidence of geophysical units with mapped lithology and structural features were identified and interpreted for the Manitouwadge area using all available geophysical data sets. In particular, the pole reduced magnetic field and its first vertical derivative were the most reliable for mapping variations in geological contacts, identifying heterogeneity, and delineation and classification of structural lineaments (faults, dykes). The results from the structural lineament interpretations are presented in the lineament report for the Manitouwadge area (SRK, 2014). The first and second vertical derivatives were used to trace quasilinear magnetic anomaly peaks to emphasize the ductile features. These ductile features are interpreted as being associated with the internal fabric to the rock units and may include in places sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation (shown on Figure 9). Enhanced grids of the magnetic field data were used to assist in the interpretation:

- Pole-reduced magnetic field – magnetic units (Figures 5 and 6);
- Pole-reduced first and second vertical derivatives – boundaries, texture, foliation (Figures 7, 8 and 9);
- Tilt angle – subtle magnetic responses (Figure 10); and
- Analytic signal – anomaly character, texture, boundaries (Figure 11).

Gravity data were of insufficient resolution to be used for interpretation of geological units and boundaries. However, some general characterizations of the regional scale units were possible (Figures 13 and 14). Similar comments apply to the radiometric data (Figure 15), except where the higher resolution data were available. The electromagnetic data (Figure 16) were not used for tracing geological contacts as the magnetic data proved greatly superior from a mapping perspective in the Manitouwadge area. However, certain geological features were evident in the electromagnetic data and are discussed below in the results.

The coincidence of the lithological units with the geophysical data was mainly recognized in the magnetic images from their anomaly amplitude, texture, width, and orientation characteristics. The automated peaks, troughs and edges generated from the magnetic data assisted in more accurate location of contacts. The magnetic anomaly characteristics and geophysical contacts were compared to the current bedrock geologic map in order to identify similarities and/or changes in the lithological contact locations. In some cases, difference in the boundaries determined from the magnetic data and the mapped boundaries may reflect a subsurface response which may not match the mapped surface contacts (e.g., dipping unit) and/or a contact extended through locations with limited outcrop exposure (e.g., under overburden and drainage cover). Results of the coincidence between the geophysical interpretation and the bedrock geologic map are presented in Figure 17. The geophysical data were evaluated against the following published geological maps:

- Ontario Geological Survey, 2011, 1:250,000 scale bedrock geology of Ontario, Miscellaneous Release Data 126-Revision 1 (OGS, 2011) (Figure 2);

- Ontario Geological Survey, 2001. Precambrian geology compilation series – White River sheet; Map 2666, scale 1:250,000 (Santaguida, 2001);
- Ontario Geological Survey, 2002. Precambrian geology compilation series – Schreiber sheet; Map 2665 - Revised, scale 1:250,000 (Santaguida, 2002);
- Ontario Geological Survey, 2003. Precambrian geology compilation series – Hornepayne sheet; Map 2668, scale 1:250,000 (Johns and McIlraith, 2003);
- Ontario Geological Survey, 2003. Precambrian geology compilation series – Longlac sheet; Map 2667, scale 1:250,000 (Johns et al., 2003); and
- Geological Survey of Canada, 1995. Manitouwadge greenstone belt overlain on shaded relief of total field magnetics, Open File 3034, scale 1:25,000 (Zaleski and Peterson, 1995b).

5.2 Results

The following section presents a regional-scale description and interpretation of each geophysical data set in the Manitouwadge area, followed by detailed interpretations of geophysical responses of the metasedimentary rocks within the Quetico Subprovince and the intrusive rocks within the Wawa Subprovince. Using the published regional bedrock geology maps as a starting point, the geophysical results discuss the relationship between the interpreted geophysical units and the mapped bedrock lithology for the Manitouwadge area. Outlines of geophysical units are presented in Figure 17. The geophysical units referred to in this section generally match those of the published regional bedrock geology (OGS, 2011).

5.2.1 Magnetic

The magnetic data over the Manitouwadge area exhibits distinct magnetic responses associated with a number of geological features, including the mapped distribution of bedrock units in the collisional tectonic zone on either side of the Quetico-Wawa Subprovince boundary, the Manitouwadge greenstone belts and discrete intrusions in the Wawa Subprovince. Although the majority of the Manitouwadge area is covered by high-resolution magnetic data, the boundaries of the geological units shown on the bedrock geology map are not always well-defined. This may result from a lack of magnetic contrast between the rock units mapped on the surface. This is particularly true in areas of low data resolution over the northern portion of the Quetico subprovince in the Manitouwadge area.

Table 3 provides a summary of the magnetic susceptibility data provided by Miles (1998) for several lithologies in the region of the Manitouwadge greenstone belt. The lithologies and unit numbers/names are simplified from Zaleski et al. (1995a). Although the statistical significance of these data is relatively low as a result of under sampling, they provide guidance when interpreting lithologies from the magnetic responses in the Manitouwadge area.

Table 3. Magnetic susceptibility statistics, after Miles (1998)

	Magnetic Susceptibility (x 10-3 SI)				
Lithology (unit)	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**	**Number of Samples**
orthoamphibole-garnet (2)	0.40	27.90	6.55	8.75	9
gabbro/mafic volcanic (3)	0.39	76.13	9.85	20.20	20
felsic volcanic (4)	2.33	29.30	11.93	15.07	3
mafic volcanic (5)	0.65	49.80	10.70	16.01	10
felsic/intermediate volcanic (6)	0.12	10.55	1.61	3.63	8
felsic volcanic (7)	0.10	8.11	1.84	3.51	5
felsic volcanic with quartz eyes (8)	0.11	2.84	1.07	1.54	3
iron formation (9)	42.22	287.89	155.08	105.42	5
tonalite (14c)	0.04	13.90	4.16	5.47	9
tonalite (BP-14)	0.00	21.80	3.82	5.15	20
trondhjemite/mafic volcanic (Dead Lake sulphides)	0.71	350.00	94.08	113.26	21
diorite/gabbro (Everest Lake pluton)	0.31	43.90	9.78	12.99	11
granite/trondhjemite (Geco)	0.05	91.20	19.19	21.31	29
tonalite (Loken Lake pluton)	0.03	1.61	0.89	0.66	8
Metagreywacke (Manitouwadge greenstone belt metasediments)	0.26	0.57	0.37	0.12	5
diabase (Marathon dyke)	14.50	33.72	22.81	8.17	4
diabase (Matachewan dyke)	8.04	26.50	14.45	10.45	3
granite/trondhjemite (Nama Creek pluton)	1.25	9.83	4.32	2.87	5
mica schist/pegmatite (Quetico migmatite)	0.02	180.00	24.60	62.89	8
mica schist (Quetico metasediment)	0.06	38.60	6.48	9.98	27

The central portion of the Manitouwadge area shows a strong east-trending magnetic response in the reduced to pole magnetic field (Figures 5 and 6), as well as the first (Figures 7 and 8) and second vertical (Figure 9) derivative grids. This response is characterized by several individual subparallel lineations that are each on the order of several hundred metres width. These alternating high and low magnetic lineations are thought to possibility reflect secondary development of magnetite within the bedrock, controlled by the availability of total iron in the bedrock and the overall metamorphic grade (Miles, 1998). Williams et al. (1991) and Zaleski et al. (1995b) interpret these alternating lineations as being inclusions of isolated units of mafic to intermediate metavolcanics rocks that are both highly metamorphosed, and contain variably developed magnetite content. Overall, the east-trending lineations form an anomalous zone that is roughly 30 km wide in the western side of the Manitouwadge area, and tends to narrow slightly towards the east to roughly 15 km wide. This anomalous zone is approximately bisected by the trace of the subprovince boundary shown on the bedrock geology map (Figure 2). The strong magnetic response along the boundary zone (both north and south of the subprovince boundary) may reflect the occurrence of mapped bedrock units affected by higher grade metamorphism (Williams et al., 1991; Pan et al., 1994). Miles (1998) suggests that the overall decrease in magnetic intensity moving away from the subprovince boundary reflects a shift of metamorphic grade from near granulite to amphibolite facies at greater distances.

North of the subprovince boundary the bedrock units are near uniformly mapped as undifferentiated metasedimentary rocks, with lesser amounts of granite to granodiorite and minor ultramafic intrusions in the Quetico Subprovince (Figure 2). Just north of the anomalous zone, these bedrock units show a weak magnetic background reflecting a rapid decrease in the magnetization and a lower magnetic mineral content. The granitic to granodiorite intrusive units shown on the bedrock geology maps tend to display similar magnetic responses as the adjacent host rocks. Although subtle differences in the magnetic response are visible, the lack of magnetic contrast between the two geological units hinders the ability to accurately trace the geological contacts. Locally, a few smaller east-trending magnetic high anomalies occur within the metasedimentary unit, particularly in the northeastern portion of the Quetico subprovince. These are interpreted to reflect isolated occurrences of higher grade metamorphic rocks, similar to those along the subprovince boundary zone.

South of the subprovince boundary zone the magnetic response of the Wawa subprovince bedrock units grade from low to high across the area. Over the majority of the area, magnetic results are highly varied and reflect mapped bedrock units that are dominated by large areas of gneissic tonalitic suite forming the Black-Pic batholith. Within the Black Pic batholith the identification of geological boundaries adjacent to the Manitouwadge greenstone belt and the larger granite to granodiorite and gabbroic plutons are evident in the magnetic data sets, and are largely emphasized by the presence of high resolution magnetic data. The Fourbay pluton and an unnamed gabbroic pluton (informally named the Bulldozer Lake intrusion in this report and AECOM (2014a)) in the southeastern portion of the Manitouwadge area show particularly high magnetic amplitudes, with sharp magnetic contacts adjacent to the Black Pic batholith. Mafic metavolcanic units around the edge of the Manitouwadge greenstone belt in contact with the Black Pic batholith show low, flat anomalies with few linear features along the outer part of the fold (Miles, 1998). In some instances, mapped intrusive units, such as the Faries-Moshkinabi intrusion are not evident in the high resolution magnetic data, indicating a lack of a magnetic susceptibility contrast with the surrounding Black Pic batholith.

Much of the observed magnetic response in the Manitouwadge area is cross-cut by the presence of northwest-trending and north to northeast-trending linear high anomalies, which are predominantly mapped as diabase dykes of the Matachewan, Biscotasing and Marathon swarms. The Matachewan dyke swarm shows clear linear magnetic highs across the entire area. Much of their signal is lost across the subprovince boundary, with some apparent offsets (both dextral and sinistral) observed along the east-west trending ductile structure. Miles (1998) interpreted that dyke responses become difficult to trace north of the Manitouwadge greenstone belt where dyke emplacement may not have propagated at the deeper crustal levels in those areas (Miles, 1998). Similar reasoning may also apply to tracing the dykes further north into the Quetico subprovince. Additionally, the contrast in magnetic susceptibility between the dykes and the more magnetic host rocks near the subprovince boundary is reduced, making the dyke responses more difficult to recognize. In places, the dykes are reflected locally by magnetic lows, where the adjacent host rocks possess a higher magnetic susceptibility.

The Biscotasing dyke swarm also shows clear linear magnetic highs across much of the Manitouwadge area, however tend to be less prevalent and variable in their spacing compared to the Matachewan dyke swarm, and are slightly more magnetic overall. The Marathon dykes strike north northeast and are mainly located in the south-central part of the Manitouwadge area. These dykes tend to be more poorly sampled due to their trend being near parallel to the flight line directions in the central part of the Manitouwadge area, and they generally have lower magnetic amplitude compared to the other two swarms. A more comprehensive interpretation of both dyke and fault lineaments in the Manitouwadge area is include in SRK (2014). In many cases, Matachewan dykes are interpreted to occupy faults and are observed to cross cut the subprovince boundary zone, some of which show offsets along strike.

Despite the widespread presence of dykes, foliation and ductile features are apparent in both the high and low-resolution data. In the Quetico Subprovince and northern part of the Wawa Subprovince, the lineaments have a roughly east-west orientation, subparallel to the subprovince boundary. In the southern part of the Wawa Subprovince, the foliation direction varies substantially within the intrusive rocks.

Most of the greenstones mapped in the Manitouwadge area form part of the Manitouwadge greenstone belt and a few splays to its northwest and southeast. Miles (1998) provides a more extensive interpretation of the mafic, intermediate and felsic volcanic rocks, iron formation and other lithologies that form the Manitouwadge greenstone belt. Most of the greenstones in the area do not possess a magnetic signature that distinguishes them from the neighbouring rocks. This is due in large part to their location within or near the tectonic collision zone in the northern part of the Wawa Subprovince. The metamorphism associated with this event has altered the magnetic character of the various rock types and overprinted their original signatures, which would have been more distinct prior to metamorphism in many cases. Miles (1998) considers the metasediments (metagreywacke and biotite schist) of the greenstone belt to be equivalent to the Quetico Subprovince metasediments other than the higher grade metamorphism and migmatization associated with the latter.

5.2.2 Gravity

The Bouguer gravity data and gravity station locations across the Manitouwadge area are presented in Figure 13, and its first vertical derivative in Figure 14. Although the gravity data were insufficient resolution to be used for interpretation of geological units and boundaries, some general characterizations of the regional-scale units were possible. The gravity data show two prominent regional-scale anomalies, with a difference of 30 mGal from high to low. The gravity high is centred within the metasedimentary rocks of the Quetico Subprovince roughly 6 km north of the subprovince boundary. It is oriented subparallel to the subprovince boundary and extends outside the Manitouwadge area to the east and southwest for a length exceeding 150 km. This anomaly is coincident with the east-trending strong magnetic responses associated with metasedimentary rocks to the north of the subprovince boundary. Similar to the interpreted cause of the magnetic anomaly in the Quetico, the gravity high may result from a higher metamorphic grade near the subprovince boundary (Pan et al., 1994). In addition, several other factors including the presence of mafic rocks at depth, thicker geological units in the Quetico Subprovince or the presence of small amounts of ironstone (Williams, 1991) or magnetite (Williams and Breaks, 1996) in the metasedimentary rocks of the Quetico Subprovince may also contribute to the elevated gravity response.

South of the subprovince boundary the gravity results gradually decrease towards the southern part of the Manitouwadge area. Based on the assumption that granitic to granodiorite units are typically have a lower volumetric density compared to supracrustal rocks, the decreasing values may reflect a progressive thickening of the Black-Pic batholith.

5.2.3 Radiometric

Radiometric data in the Manitouwadge area were of insufficient resolution to be used for interpretation of geological units and boundaries (Figure 15). In the case where the overburden material is locally derived from the underlying bedrock, it may serve as a proxy when interpreting the radiometric data. Nevertheless, some smearing of the signal is anticipated due to glacial or fluvial transport, particularly in higher resolution radiometric data.

The radiometric responses are to some extent governed by the topography in the area, with highlands offering better bedrock exposure and fewer wetlands. In the Quetico Subprovince, a broad east-trending zone displays elevated thorium concentrations, which are coincident with the east-trending magnetic anomalous zone adjacent to the Subprovince boundary (unit A). Further from the subprovince boundary, in the northern portion of the Manitouwadge area, the metasedimentary bedrock units show more uranium dominated responses. The bedrock in the northeastern part of the Quetico metasedimentary units reveals lower responses in all three radioelements. These responses are coincident with several isolated occurrences of east-trending horizons that appear in the lower resolution magnetic data (unit A′). This area tends to be coincident with a higher amount of glacial overburden units, as well as a lower amount of topographic relief (AECOM, 2014b).

In the Wawa Subprovince, the higher responses of the three radioelements occur mainly to the north adjacent to the Subprovince boundary. In general, the entire Wawa Subprovince tends to be elevated in potassium and locally elevated levels of uranium, reflecting the predominance of granite to granodiorite. The Bulldozer Lake intrusion in the southeast part of the Manitouwadge area and the Fourbay Lake pluton show high and sporadic radioelement responses in the higher resolution data, whereas the Loken Lake pluton is particularly low in all radioelement responses. The lower responses over Loken Lake pluton may reflect the presence of overburden deposits as well as a higher number of water bodies.

For the GSC radiometric compilation within the Manitouwadge area, the radioelement responses are summarized in Table 4.

Table 4. Radioelement response statistics

Radioelement	Minimum*	Maximum	Mean
Potassium (%)	0.02	1.97	0.86
Equivalent uranium (ppm)	-0.38	1.63	0.49
Equivalent thorium (ppm)	-0.10	7.61	2.53
Natural air absorbed dose rate (nGy/h)	-0.34	42,28	20.36

*Negative values are not unusual due to the statistical nature of gamma-ray spectrometer data and grid interpolation effects.

These levels are typical of those found in granitic to intermediate to mafic volcanic terrain (IAEA, 2003). The generally low uranium levels suggest low radon risk. However, radon risk is also quite dependent on soil permeability and should be verified by soil gas measurements

(IAEA, 2003). The highest uranium responses are located in the gneissic tonalite suite of the Black-Pic batholith.

5.2.4 Electromagnetic

The apparent conductivity grids derived from the FDEM data highlight the conductive responses (Figure 14). The EM anomaly databases includes a mixture of electrically conductive sources from cultural (e.g. power lines), surficial (e.g. clays and lake-bottom sediments) and bedrock units (e.g. conductive horizons, sulphide minerals). The interpretation focused on using the EM anomaly response to delineate bedrock sources into linear conductors which traverse a few to several flightlines (i.e. 200 m to 1000 m or more).

The electromagnetic (FDEM) responses can be generalized as electrically resistive over exposed bedrock and fairly extensive conductive cover (overburden and drainage-related sediments) (Figure 16). There is extremely good correlation between the low-lying areas (lakes, river valleys, creeks) and the conductive responses, particularly the areas mapped as glaciolacustrine terrain (Figure 3). Numerous faults are recognizable in the EM data where they control drainage, mainly striking north, northwest and north-northeast, correlate with some of the lineaments interpreted by SRK (2014).

The rocks of the Quetico Subprovince, particularly those east of the Cadawaja fault, are slightly less resistive than those in remainder of the area. Conductors with bedrock sources are quite limited. Two clusters of bedrock conductors have been interpreted from the Manitouwadge survey (OGS, 2002a), and none from the minimal coverage provided by the Hemlo survey (OGS, 2002b). One cluster is located in the metasedimentary rocks of the Quetico Subprovince towards the northern end of the EM coverage (Figure 16). The second cluster occurs in the Manitouwadge greenstone belt. Both clusters conform to the magnetic stratigraphy.

5.3 Geophysical Interpretation of the Prospective Geology in the Manitouwadge Area

The following section provides more detailed interpretations with a focus on the potentially suitable geology in the Quetico Subprovince (metasedimentary rocks and granitic to granodiorite intrusions) and Wawa Subprovince (Black-Pic batholith) within the Manitouwadge area. These interpretations include a description of the geophysical characteristics of each unit, as well as a refinement of geologic contacts, where possible, and the identification of internal heterogeneities within the structures where present. These interpreted features are presented alongside the current bedrock geology mapping on Figure 17, noting that the interpretations are preliminary and require future geologic validation.

5.3.1 Metasedimentary Rocks and Granitic-Granodioritic Intrusions of the Quetico Subprovince

The northern portion of the Manitouwadge area is mapped by the OGS as regionally-extensive metasedimentary units of the Quetico subprovince, with lesser amount of granitic intrusions (Figure 17), resulting in a number of different magnetic responses. The magnetic responses in the Quetico Subprovince are most intense within several kilometers of the subprovince boundary (units A and A′), where numerous curvilinear magnetic horizons reflect high grade metamorphism.

Unit A and nearby portions of unit A′ reflect a distinct set of units characterized by tight bands of curvilinear magnetic horizons, oriented subparallel to the subprovince boundary. These reflect high grade metamorphism (possibly migmatized rocks, Williams (1991)) within the metasedimentary unit of the Quetico Subprovince. Unit A covers a broad area immediately north of the subprovince boundary, 5 km wide at its east end (where the magnetic response is most intense) stretching to 14 km at its west end. The 5 km wide band shows continuity along its entire length whereas the remainder of unit A to the northwest shows a widening in the spacing of the magnetic horizons and some fold closures. Fold structures are interpreted where traces of ductile foliations tend to produce v-shaped or oval-shaped patterns, which are predominantly tight. These traces tend to be most prominent on the derivative maps (Figures 7 and 9), though in some cases are easily discerned on the reduced to pole magnetic field (Figure 5). These interpreted fold structures are consistent with the locations of those based on bedrock mapping (Figure 2). In the northwest, a band of granite-granodiorite is mapped extending eastwards into the area. However, the magnetic data indicate that if it is present in this part of unit A, it is restricted to a few relatively narrow, local magnetic lows. The interpretation of the southern contact of unit A and the adjacent rocks of the Quetico Subprovince results in a reasonable match of the mapped subprovince boundary on the west side of the Manitouwadge area and a northward shift on the east side, approaching two kilometres. This contact was determined by continuity of the units, especially unit A, along strike and in places, the truncation of magnetic horizons in the Wawa Subprovince rocks against the southern edge of unit A. Miles (1998) considers the subprovince boundary to be transitional both structurally and lithologically, so the placement of the contact along the southern edge of unit A may not be definitive.

Unit A′ delineates discrete groups of magnetic horizons north of the east end of unit A. They incorporate strongly magnetic horizons with curvilinear forms that show ductile deformation similar to unit A. Unit A′ also outlines several magnetic horizons in the northern part of the area. It occurs mainly within the low-resolution data coverage, and likely these horizons are narrower than represented by those data. The units are mostly oriented subparallel to the magnetic horizons of units A (to the south) and A′ (to the east), other than those more distant to the northeast, where the strike changes to east-northeast (as it does beyond the Manitouwadge area further to the north and east). Some of these horizons in the region show a loose correlation with mapped bands of granite-granodiorite.

Units B and C are the least magnetic units interpreted in the Quetico Subprovince, reflecting portions of the metasedimentary units. Unit B covers a large area or the northern Quetico subprovince where there are fewer magnetic horizons and a low amplitude background. The northwest part of the Manitouwadge area is particularly quiet magnetically. Unit C is located to the northeast of unit A. It is relatively quiet magnetically but contains a few magnetic horizons. Unit C is slightly more magnetic at its west end, where it narrows and the discrete magnetic horizons have more influence on the response of this unit. Within unit A, there are a few areas of weak to low magnetic response that may reflect a similar composition of less magnetic rocks within the migmatite horizons.

The gravity and radiometric responses of the northwest area are unremarkable whereas in the Hillsport area, there is a weak gravity low (associated with Unit A′ horizons) and a lack of radiometric response that reflects the numerous lakes there. Consequently, the portion of Unit B to the northwest appears to be the most homogeneous of the Quetico Subprovince rocks in the Manitouwadge area from a geophysical perspective.

5.3.2 Black-Pic Batholith

The southern portion of the Manitouwadge area is mapped by the OGS as regionally-extensive gneissic and foliated tonalite units of the Black-Pic batholith, with lesser amount of granite-granodiorite intrusions, gabbro and metavolcanic rock units (Figure 17), resulting in a complex distribution of magnetic responses. Magnetic units D to I and O all cover rocks mapped as gneissic tonalite suite within the Black-Pic batholith.

Units D, E, and F are located in the northern part of the Black-Pic batholith, where their stronger magnetic responses and curvilinear magnetic horizons are inferred to reflect the collisional tectonics (metamorphism and deformation) near the Wawa Subprovince boundary. Unit D delineates an area of highly magnetic horizons striking subparallel to the subprovince boundary, with a high amplitude background, covering the northwest part of the Wawa Subprovince rocks. The northern edge of this unit tends to coincide well with the mapped subprovince boundary. The similarity in magnetic responses north and south of the subprovince boundary may partially be due to the infolding of the Quetico metasediments south of the boundary (Zaleski et al., 1995). Within unit D, a band of mafic to intermediate metavolcanic rocks mapped at the west end is roughly coincident with highest magnetic intensity horizons and, based on extrapolating along the magnetic horizons, could potentially extend another 15 km to the east-northeast. To the south of unit D, units E and F outline areas of diminished magnetic intensity, although these units tend to show similar curvilinear magnetic horizons. The apparent decrease in magnetic intensity may reflect a lesser degree of metamorphism associated with the collisional tectonics further away from the subprovince boundary.

Unit H is consistent with the majority of the mapped distribution of gneissic tonalite suite within the Black-Pic batholith, south of the Manitouwadge greenstone belt. This unit covers a large area to the south which shows a relatively low magnetic activity with a moderate to low background amplitude. The central and northwest parts of unit H has the lowest magnetic background, and is also differentiated by variations in foliation orientation. Subtle variations in magnetic responses and foliation suggest further inhomogeneities within the less magnetic portion of the batholith. The south-central part of the batholith (unit H south and west of the Rawluk pluton) shows a large gap in the Matachewan and Biscotasing dyke swarms, whereas the younger Marathon swarm has no such break. Foliation orientations vary from north-northeast to east-northeast, conforming to the neighbouring metamorphic and intrusive rocks. The one exception is the southeast part of unit H, where the foliation has a northwesterly curvilinear orientation.

In the southwestern portion of the Black-Pic batholith, a moderately magnetic zone shows a different character than the surrounding weakly magnetic gneissic tonalite of unit H. This magnetic response extends in a northeastern direction from the Fourbay Lake pluton, outlined as Unit O. Unit O is interpreted to reflect, at least partially, a northeast extension of the Fourbay Lake pluton. The foliation within the unit is similar to the adjacent parts of unit H but the overall magnetic intensity is much stronger. At depth, the bedrock geology underlying Unit O may incorporate lithologies extending from the Fourbay Lake pluton underlying the gneissic tonalite.

The Black-Pic batholith is characterized by a regional gravity low, which indicates thickening in the eastern and southern parts of unit H. A local gravity high (defined by a few gravity stations) with north-northeast orientation in the northern part of unit H has no explanation from mapped geology, but perhaps reflects a southern root of the Manitouwadge greenstone belt. The metamorphosed part of the batholith to the north shows a relatively high radiometric response in all three radioelements whereas the southern part is low in uranium and thorium and moderate in potassium. The FDEM responses over the batholith are either uniformly resistive over exposed or thinly covered bedrock, or conductive at lower elevations, the latter associated with drainage-related overburden. The conductive material helps to illuminate the structural control of the drainage.

5.3.3 Other Intrusions

Several intrusions in the Wawa Subprovince have distinct geophysical signatures. They are:

Rawluk Lake pluton (unit L) – This gabbro intrusion is clearly delineated in the magnetic data, and is consistent with bedrock mapping, with a higher amplitude and contrasting strike to the surrounding Black-Pic batholith. It is cut by several Matachewan and Marathon dykes, and numerous faults. Smaller intrusions to the east, north and west, five of which are unmarked, are interpreted as gabbro plugs or sills.

Bulldozer Lake intrusion (unit M) – This 11 km by 6.5 km gabbro intrusion shows a strong magnetic contrast with the surrounding Black-Pic batholith and concentric outer and variable internal fabric. It also has relatively high responses in all three radioelements. It is cut by several Matachewan and Biscotasing dykes, and numerous faults. The interpreted trace of the Bulldozer Lake intrusion is consistent with the mapped distribution of the gabbroic intrusion, although the northeastern contact tends to extend a few kilometers (approximately 3 km) further northern than indicated by the geological mapping. It is however, possible that this discrepancy in the outlines may reflect the distribution of the pluton at depth.

Fourbay Lake pluton (units N and O) – The Fourbay Lake pluton (unit N) shows a strong magnetic contrast with the surrounding Black-Pic batholith. Its internal magnetic fabric is not particularly coherent, and is cut by a few Matachewan and Biscotasing dykes, and numerous faults. The interpreted trace of Unit N coincides well with the mapped distribution of the Fourbay Lake pluton, although minor discrepancies exist along the intrusive boundary. Unit O may reflect a buried northeast extension and/or phase of the Fourbay Lake pluton and shows a magnetic contrast with the Black-Pic batholith and intrusive character. The pluton is also associated with relatively high responses in all three radioelements.

Loken Lake pluton (unit P) – This weakly magnetic intrusion forms the core of the Manitouwadge greenstone belt along an east-striking synform. Internally, the northeastern portion of the pluton tends to be more magnetic than the remainder. This portion of the pluton has been mapped as foliated to massive granite to granodiorite, characterized by K-feldspar megacrysts (Zaleski *et al*., 1999). Magnetic modelling by Miles (1998) along the long axis of the pluton results in a 1.7 km thickness at its west end, thinning to the east. The pluton has a distinct low in all three radioelements which is not due entirely to the lakes present.

Nama Creek pluton (unit Q) – This intrusion corresponds to a narrow, curvilinear magnetic horizon that forms part of unit Q along the margin of the Manitouwadge greenstone belt. This unit is relatively magnetic, stronger to the east than west, which tends to be influenced by the presence of felsic metavolcanics. The pluton may be slightly wider along its northern boundary than is currently mapped. Numerous magnetic horizons exist within this unit are useful for tracing ductile horizons, including significant folding to the north and east that demarcate a series of synclines and anticlines.

6 SUMMARY OF RESULTS

The purpose of this study was to identify and obtain the available geophysical data for the Township of Manitouwadge and surrounding area, followed by a detailed interpretation of all available geophysical data (e.g., magnetic, electromagnetic, gravity and radiometric) to identify additional information that could be extracted from the data, in particular regarding the coincidence of geophysical features with mapped lithology and structural features in the Manitouwadge area.

The geophysical data covering the Manitouwadge area show variability in data set resolution. Low-resolution geophysical data, particularly the magnetic, gravity and radiometric data obtained from the Geological Survey of Canada (GSC), cover the entire Manitouwadge area. One additional GSC magnetic survey and two additional magnetic/electromagnetic surveys obtained from the Ontario Geological Survey (OGS) provided higher resolution coverage over approximately 80% in the southern and central part of the Manitouwadge area. One GSC radiometric survey provides medium-resolution coverage in the southwest corner of the area.

The coincidence between the geophysical data and the mapped lithology were interpreted using all available geophysical data sets (e.g., magnetic, electromagnetic, gravity and radiometric). The interpretation incorporated the dykes, faults and other structure prepared by SRK (2014). In particular, the pole reduced magnetic field (RTP) and its first vertical derivative (1VD) were the most reliable for mapping variations in geological contacts, identifying heterogeneity, and delineation and classification of structural lineaments (faults, dykes). At a regional scale, the coincidence between the geophysical interpretations and the published geological maps is in good agreement. The magnetic data provide considerable information regarding the deformation and metamorphism across the collisional tectonic zone for several kilometers on either side of the Quetico-Wawa Subprovince boundary. In the Wawa Subprovince, the geophysical data delineate different phases of the Black-Pic batholith, several discrete intrusions and several lithologic units in the Manitouwadge greenstone belt.

The metasedimentary rocks of the Quetico Subprovince are characterized by strongly magnetic responses with narrow curvilinear, magnetic horizons oriented subparallel to the subprovince boundary (unit A and southern portions of unit A′). Similar horizons that are more sparsely distributed through the metasedimentary units further away from the subprovince boundary may reflect similar lithologies (northern portions of unit A′). Elsewhere, the metasediments tend to be relatively non-magnetic (units B and C). Unit B in particular shows large, apparently homogeneous zones to the northwest, and to the north and east of Hillsport, which are coincidentally less disrupted by dykes than most of the Manitouwadge area.

The Black-Pic batholith can be divided into two main components according to their magnetic responses. Near the subprovince boundary the Black-Pic batholith shows stronger magnetic responses and curvilinear magnetic horizons are inferred to reflect the collisional tectonics (metamorphism and deformation). Unit D delineates an area of highly magnetic horizons striking subparallel to the subprovince boundary, with a high amplitude background. Within unit D, a band of mafic to intermediate metavolcanic rocks mapped at the west end is roughly coincident with highest magnetic intensity horizons and, based on extrapolating along the magnetic horizons, could potentially extend another 15 km to the east-northeast. To the south of unit D, units E and F outline areas of diminished magnetic intensity, although these units tend to show similar curvilinear magnetic horizons. The apparent decrease in magnetic intensity may reflect a lesser degree of metamorphism associated with the collisional tectonics further away from the subprovince boundary.

Further away from the subprovince boundary, the magnetic units are relatively quiet magnetically, with lesser effect from the collisional tectonics (Unit H). Some internal variation is apparent, especially in foliation orientation which may suggest further inhomogeneities within the less magnetic portion of the batholith. Foliation orientations vary from north-northeast to east-northeast, conforming to the neighbouring metamorphic and intrusive rocks. The one exception is the southeast part of unit H, where the foliation has a northwesterly curvilinear orientation. The central part of unit H is less affected by dykes due to the absence of the Matachewan and Biscotasing swarms in that area.

In the Wawa Subprovince, several gabbroic and granitic intrusions tend to have a distinct magnetic character. The Rawluk Lake Pluton (unit L), the Bulldozer Lake intrusion (unit M) and the Fourbay Lake pluton (unit N) are all more magnetic than the surrounding Black-Pic batholith. The Fourbay Lake pluton may extend to the northeast as a different and/or buried phase (unit O). The Loken Lake pluton (unit P) forms a distinct magnetic low at the center of the Manitouwadge greenstone belt whereas the Nama Creek pluton (unit Q) is characterized by a strongly magnetic horizon along the northwest margin of the belt.

Most of the greenstones mapped in the Manitouwadge area form part of the Manitouwadge greenstone belt and a few splays to its northwest and southeast. The mafic metavolcanics on the outer margin of the greenstone belt form a magnetic horizon. However, most of the greenstones in the area do not possess a magnetic signature that distinguishes them from the neighbouring rocks. The metamorphism associated with this event has altered the magnetic character of the various rock types and overprinted their original signatures, which would have been more distinct in many cases.

Resolution of the gravity data was insufficient to be used for interpretation of geological units and boundaries. However, some general characterizations of the regional scale geological units were possible. The gravity high is centred within the metasedimentary units of the Quetico Subprovince roughly 6 km north of the Subprovince boundary, and is oriented subparallel to the subprovince boundary and extends outside the Manitouwadge area to the east and southwest for a total length exceeding 150 km. The regional gravity low reflects the Black-Pic batholith, perhaps thickest to the east and south. In general the gravity response associated with the greenstone belt is weakly positive, suggesting a limited depth extent.

Radiometric responses due to the presence of potassium, uranium and thorium related minerals are typically elevated in granitic rocks compared to volcanic rocks, and this relationship is seen in the Manitouwadge area. The radiometric responses are to some extent governed by the topography in the area, with highlands offering better bedrock exposure and fewer wetlands. In the Quetico Subprovince, the higher responses are associated with the metasedimentary units near the Subprovince boundary (unit A). The lowest responses occur in the eastern part of unit B, where several horizons of unit A′ are prevalent. In the Wawa Subprovince, the higher responses occur mainly to the north where the metamorphosed tonalites are located near the Subprovince boundary. The Bulldozer Lake intrusion (unit M) and the Fourbay Lake pluton (unit N) show discrete high radioelement responses whereas the Loken Lake pluton (unit P) is particularly low.

The electromagnetic (FDEM) data cover roughly 75% of the Manitouwadge area. The responses can be generalized as electrically resistive bedrock and fairly extensive conductive cover (overburden and drainage-related sediments). The rocks of the Quetico Subprovince, particularly those east of the Cadawaja fault, are slightly less resistive than those in remainder of the area. Conductors with bedrock sources are quite limited. Most occur in the Manitouwadge greenstone belt, and a few in the Quetico Subprovince (unit A). They conform to the magnetic stratigraphy. Numerous faults are recognizable where they control drainage in the EM data. However, they are better defined in SRK's (2014) lineaments interpreted from terrain and magnetic data.

Respectfully Submitted,

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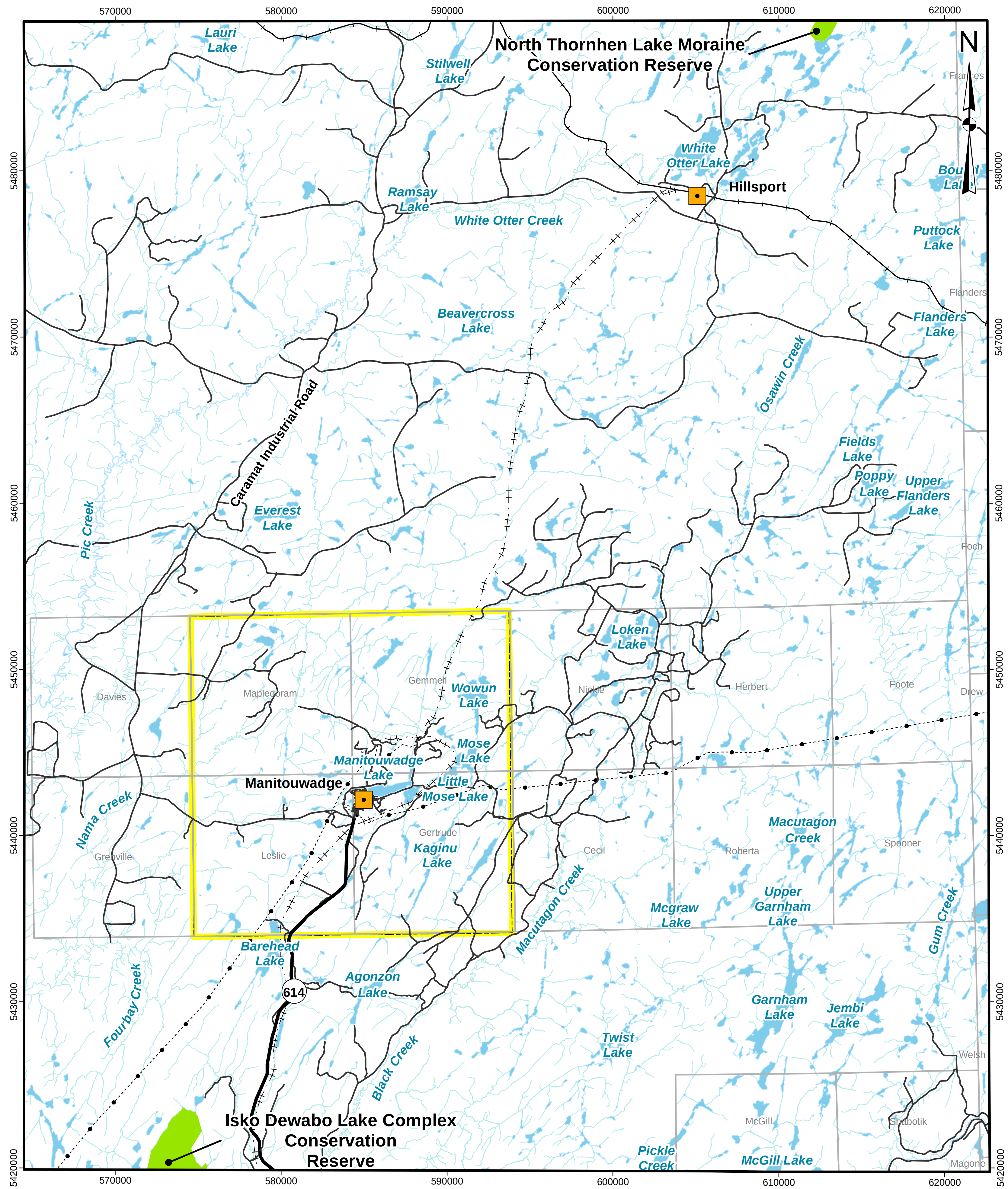
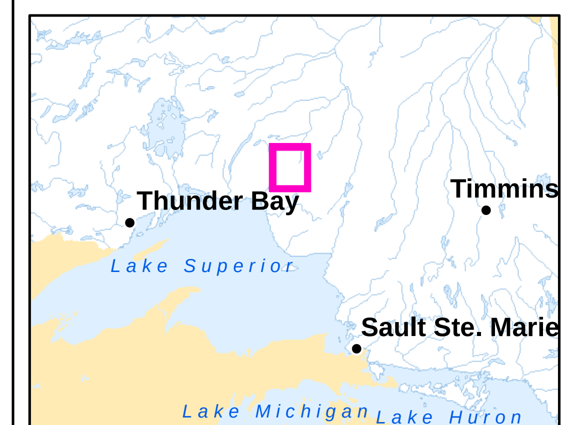


Legend

- Settlement
- Manitouwadge Municipal Boundary
- Township Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Hydro Line
- Waterbody
- Watercourse

Protected Areas

- Conservation Reserve



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
- Settlement: LIO Cities and Towns
- Road: LIO Road Segment
- Railway: LIO Railroad Segment
- Provincial Parks: LIO Provincial Parks
- Conservation Reserves: LIO Conservation Reserves
- Waterbody: LIO Waterbody
- Watercourse: LIO Watercourse
- Utility Lines: LIO Utility Lines
- Municipalities: LIO Upper, Single and Lower Tier

10 km

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Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Study, Manitouwadge

TITLE
Township of Manitouwadge and Surrounding Area

DESIGN	KR	14 JUN 2013	**Figure 1**	REVISION 1.1
GIS	KR	14 JUN 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

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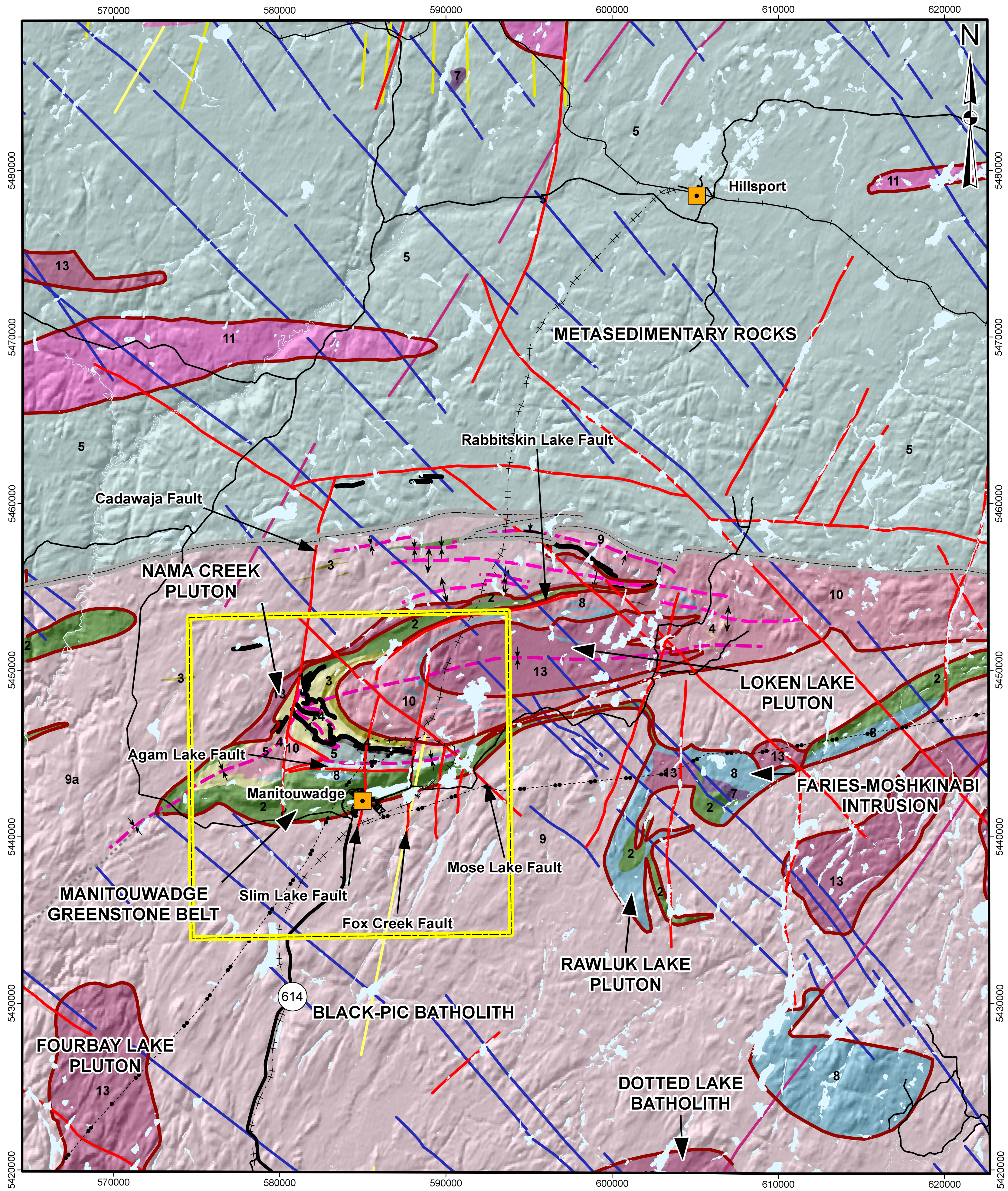

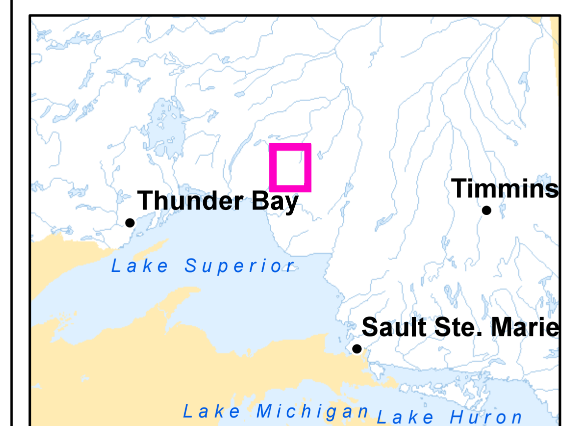

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)
Faults: OGS MRD 126-REV1, 2011; M2668, 2003; GSC 1917A, 2001
Dykes: OGS MRD 126-REV1, 2011
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003
Underlay: Hillshade DEM, MNR Elevation and Slope

10 km

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Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Study, Manitouwadge

TITLE
Bedrock Geology of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 2	REVISION 1.2
GIS	GF	29 AUG 2013		UTM ZONE 16
CHECK	SR	3 SEPT 2014		NAD 1983
REVIEW	MA	3 SEPT 2014		1:275,000

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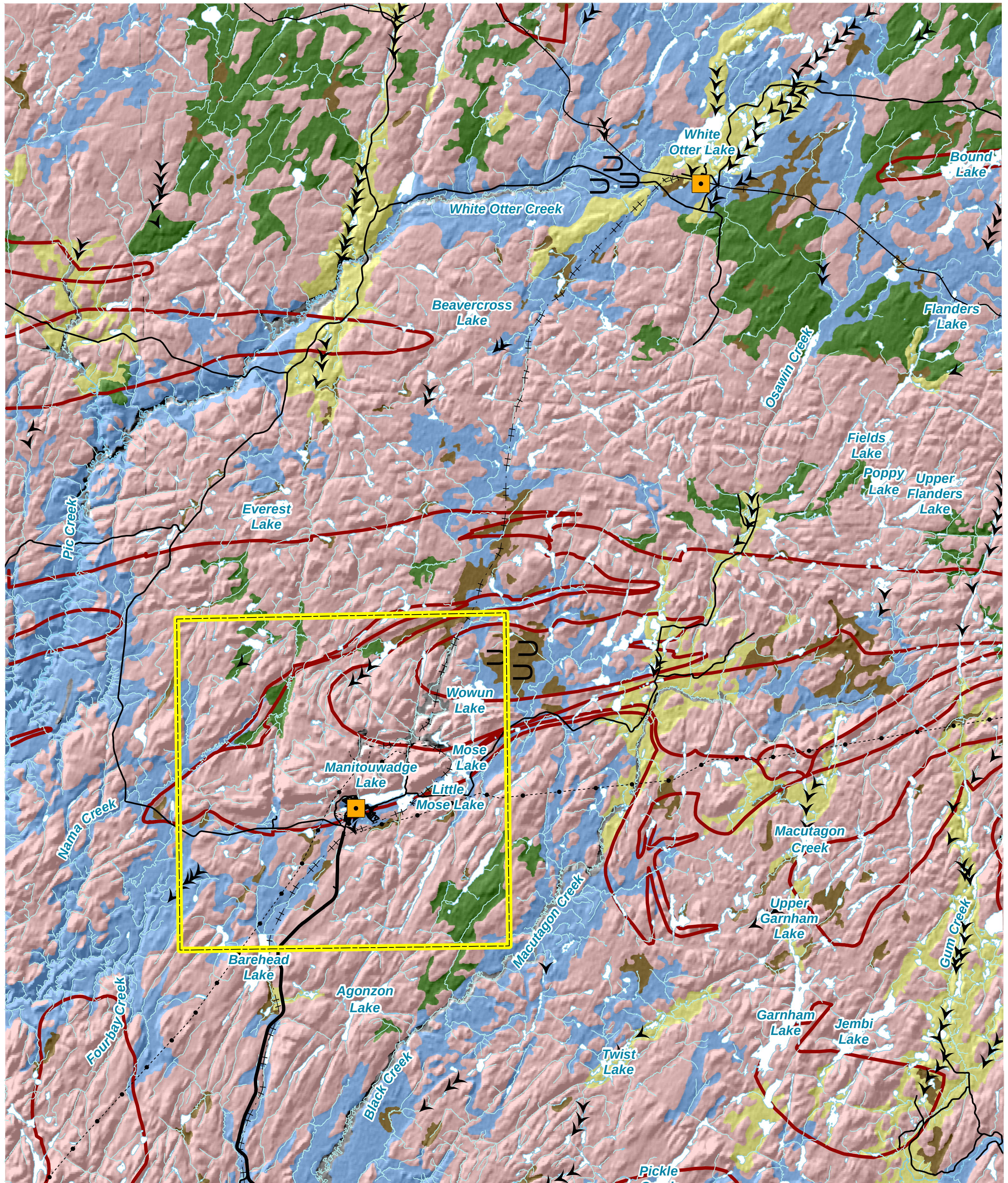

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PROJECT

TITLE

DESIGN	KR	14 JUN 2013	Figure 3	REVISION 1.1
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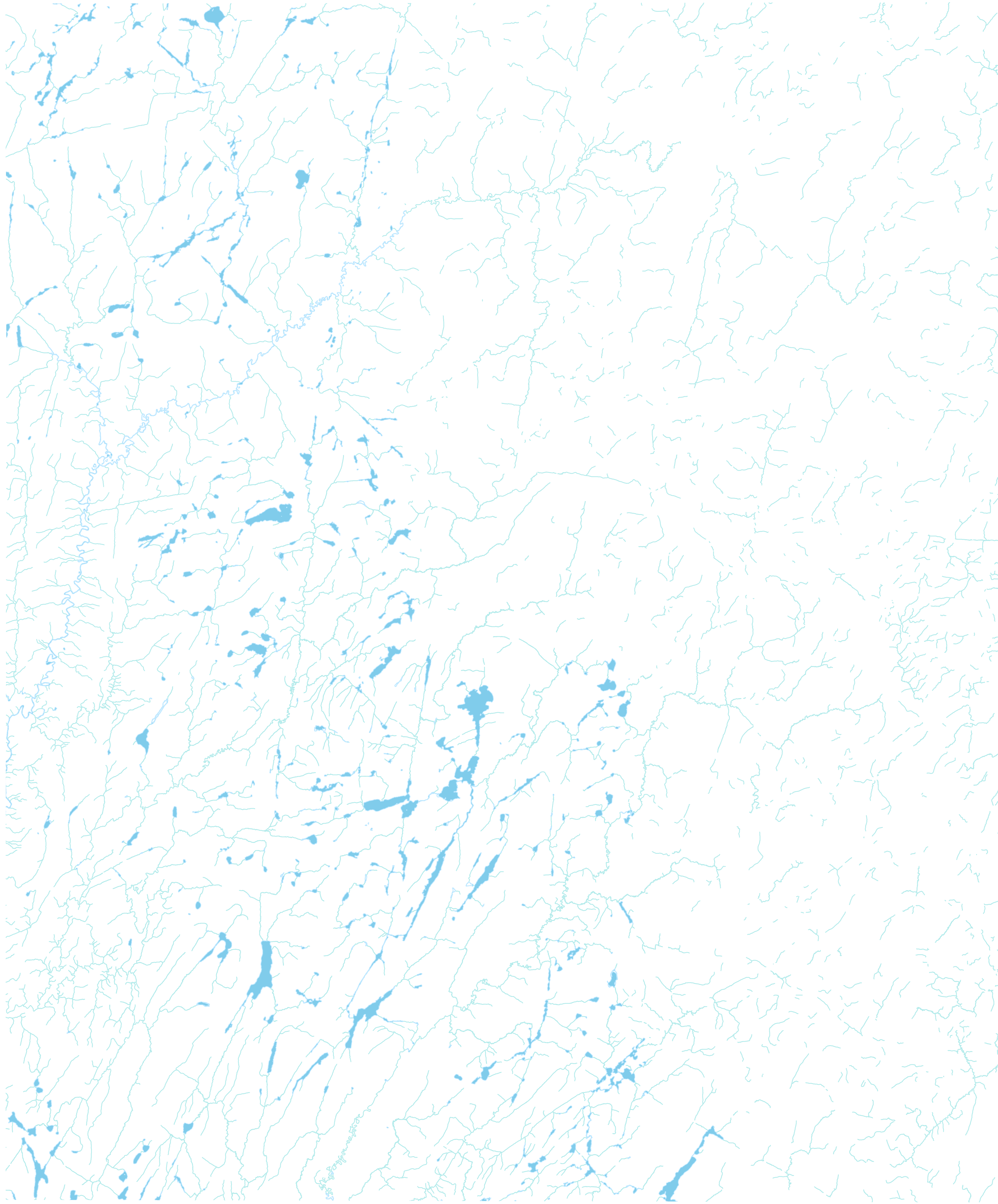
REVIEW	MA			



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PROJECT

TITLE

DESIGN	KR	14 JUN 2013	Figure 4	REVISION 1.1
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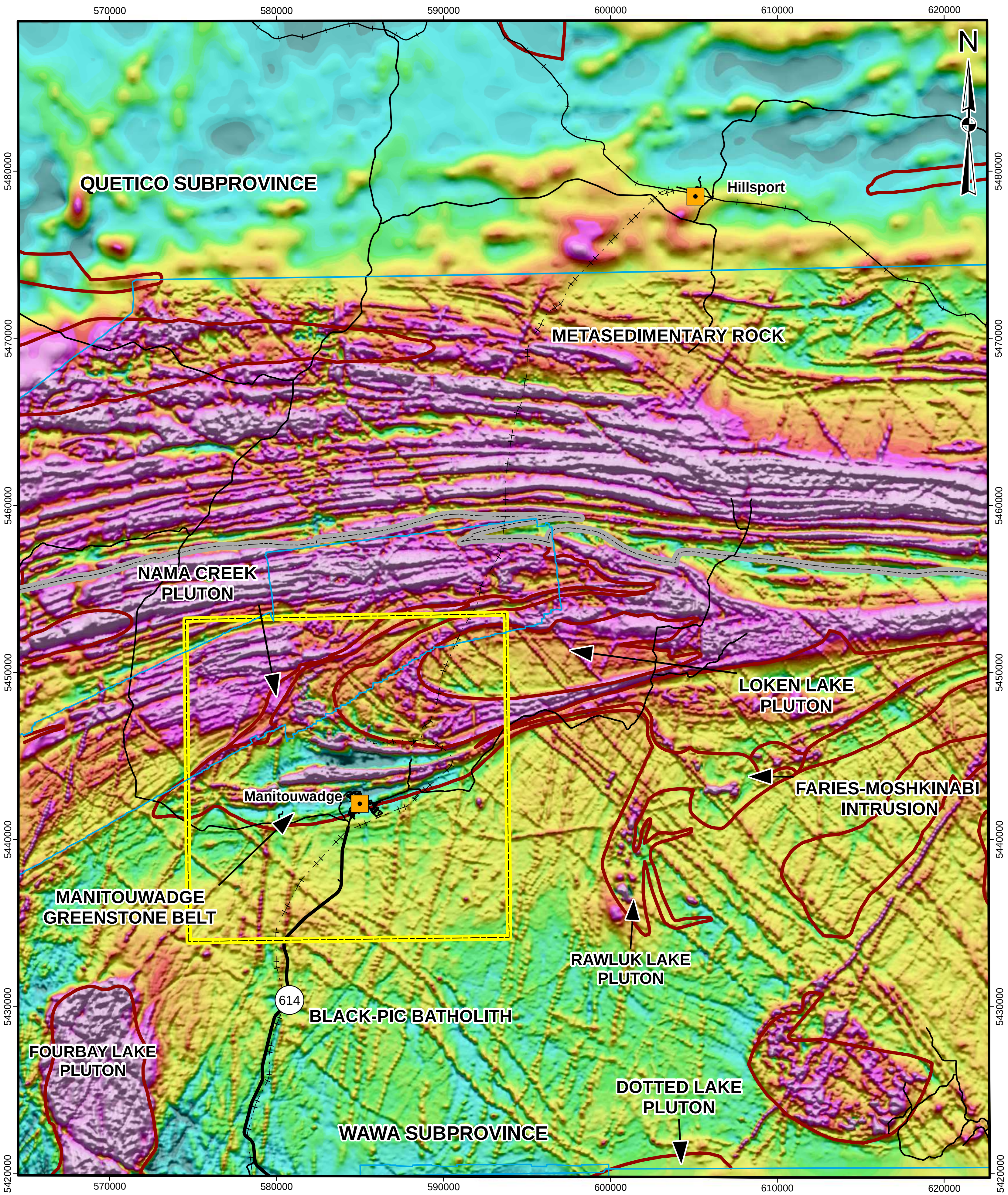

Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- High Resolution Geophysical Survey Outlines

Pole-reduced Magnetic Field (nT)

5044, 570, 410, 310, 250, 190, 150, 110, 80, 50, 30, 10, 0, -20, -30, -40, -60, -70, -90, -100, -120, -130, -150, -160, -180, -200, -220, -240, -260, -704

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Aeromagnetic Surveys - Ontario #8, Dighem 1056
Ontario Geological Survey - Geophysical Surveys - GDS1205, GDS1207
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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Geophysical Study, Manitouwadge

TITLE
Residual Magnetic Field Reduced to Pole

DESIGN	KR	14 JUN 2013	Figure 5	REVISION 1.1
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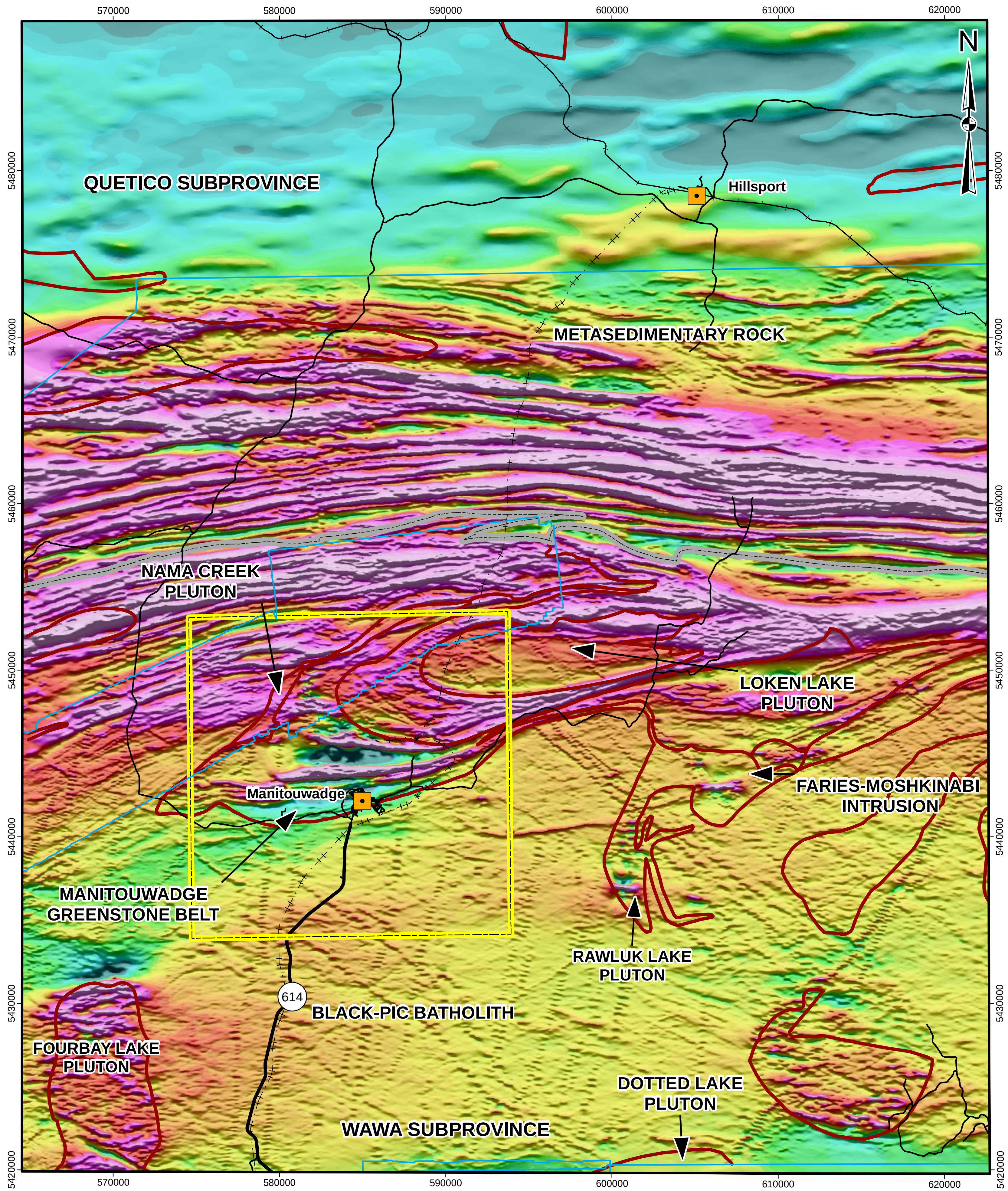
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

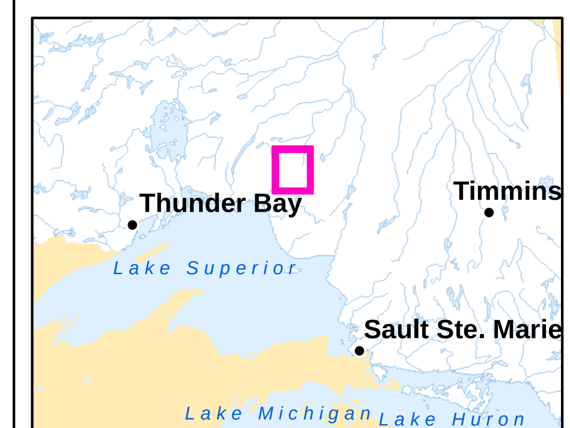


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- High Resolution Geophysical Survey Outlines

Pole-reduced Magnetic Field (nT)

2003
370
280
230
190
170
140
120
110
90
80
70
60
50
40
30
20
10
0
-20
-40
-70
-80
-90
-100
-110
-502



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Aeromagnetic Surveys - Ontario #8, Dighem 1056
Ontario Geological Survey - Geophysical Surveys - GDS1205, GDS1207
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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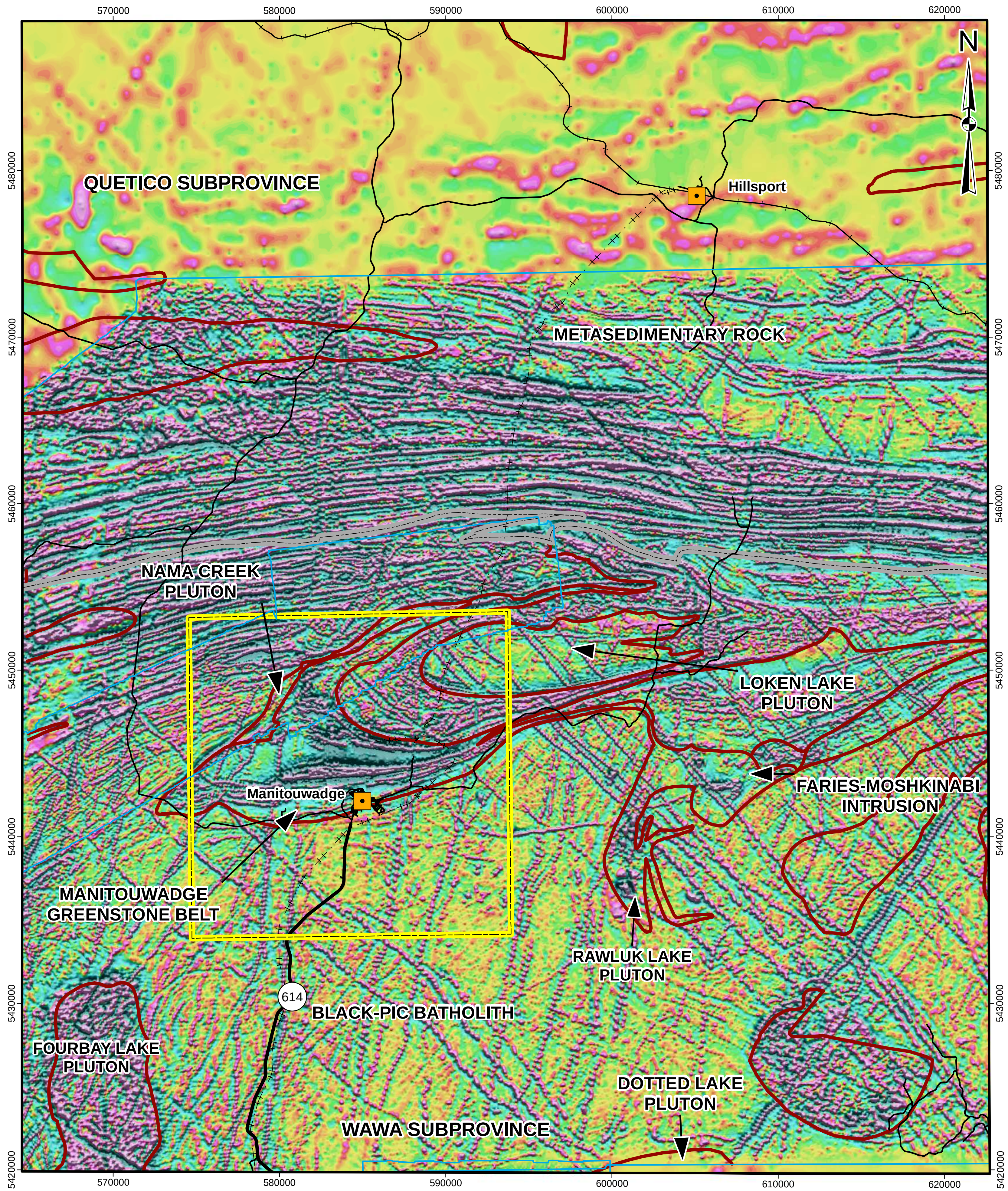
Geophysical Study, Manitouwadge

TITLE
Residual Magnetic Field Reduced to Pole with Dyke Responses Removed

DESIGN	KR	14 JUN 2013	Figure 6	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

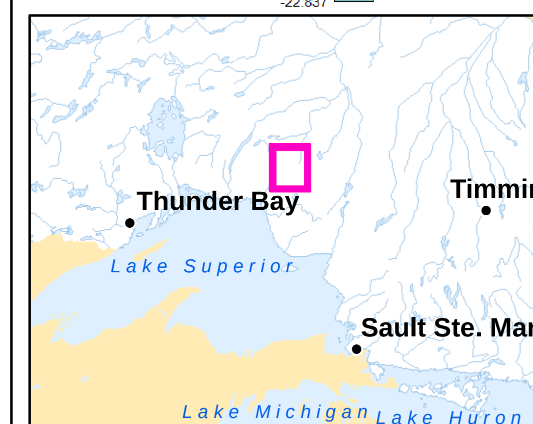


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- High Resolution Geophysical Survey Outlines

First Vertical Derivative of the Pole-reduced Magnetic Field (nT/m)

83.569
1.470
0.850
0.540
0.350
0.240
0.160
0.110
0.070
0.040
0.010
0.000
-0.010
-0.020
-0.030
-0.040
-0.060
-0.070
-0.090
-0.110
-0.140
-0.170
-0.220
-0.270
-0.350
-0.440
-0.590
-0.800
-1.220
-22.837



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Aeromagnetic Surveys - Ontario #8, Dighem 1056
Ontario Geological Survey - Geophysical Surveys - GDS1205, GDS1207
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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TITLE
First Vertical Derivative of the Pole-reduced Magnetic Field

DESIGN	KR	14 JUN 2013	Figure 7	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

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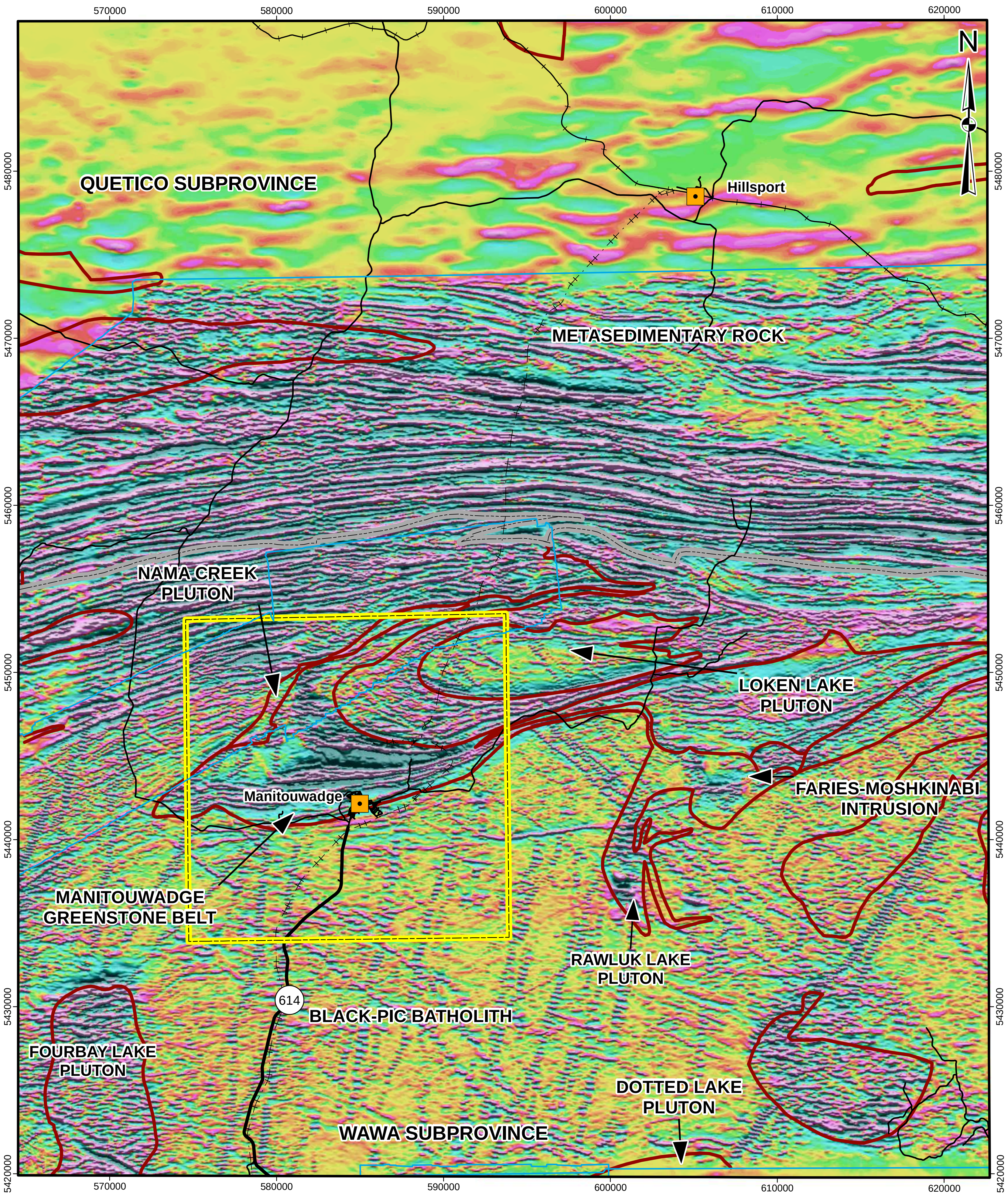
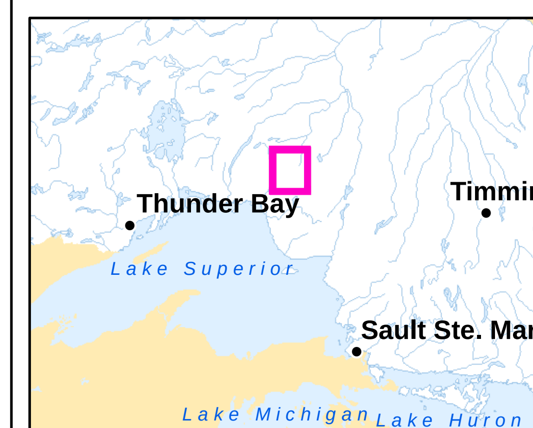


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- High Resolution Geophysical Survey Outlines

First Vertical Derivative of the Pole-reduced Magnetic Field (nT/m)

28.591
0.645
0.345
0.205
0.130
0.090
0.060
0.040
0.025
0.015
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.035
-0.045
-0.055
-0.070
-0.090
-0.120
-0.160
-0.230
-0.345
-0.580
-10.710



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Aeromagnetic Surveys - Ontario #8, Dighem 1056
Ontario Geological Survey - Geophysical Surveys - GDS1205, GDS1207
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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Geophysical Study, Manitouwadge

TITLE
First Vertical Derivative of the Pole-reduced Magnetic Field with Dyke Responses Removed

DESIGN	KR	14 JUN 2013	Figure 8	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

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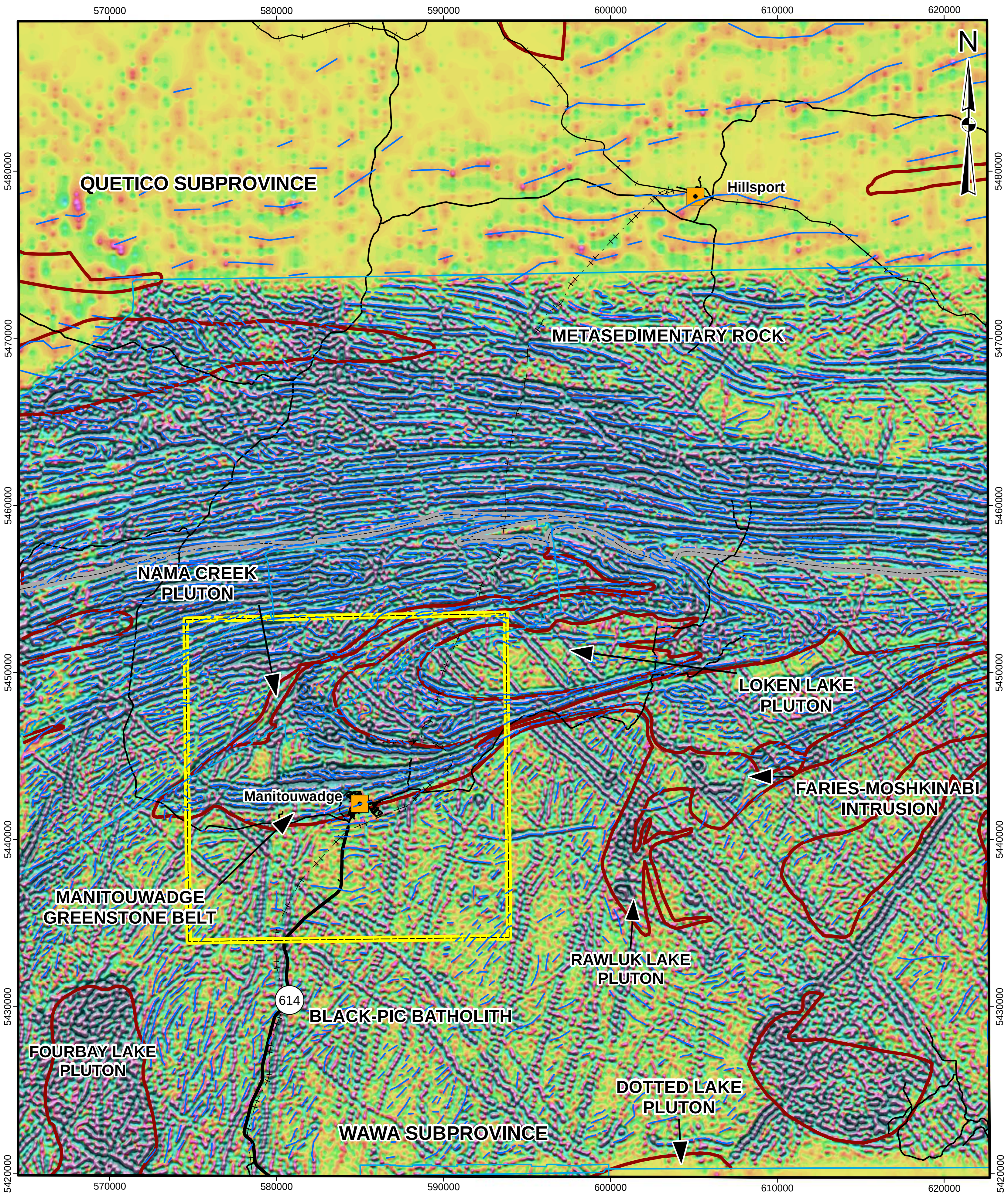
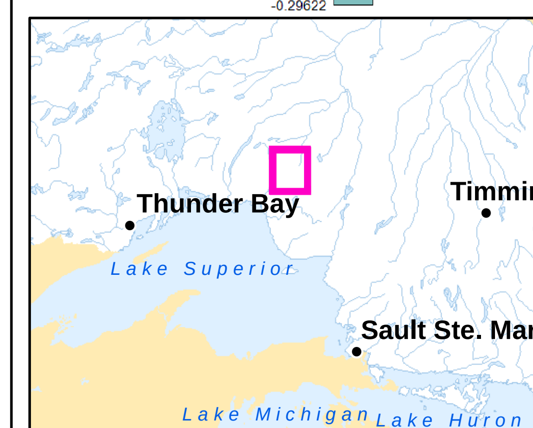


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- High Resolution Geophysical Survey Outlines
- Magnetic Foliation and Ductile Lineaments

Second Vertical Derivative of the Pole-reduced Magnetic Field (nT/m2)

0.47527
0.01360
0.00810
0.00528
0.00358
0.00246
0.00166
0.00108
0.00066
0.00038
0.00020
0.00010
0.00004
0.00000
-0.00002
-0.00006
-0.00010
-0.00016
-0.00028
-0.00046
-0.00074
-0.00114
-0.00164
-0.00226
-0.00306
-0.00414
-0.00566
-0.00806
-0.01272
-0.29622



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Aeromagnetic Surveys - Ontario #8, Dighem 1056
Ontario Geological Survey - Geophysical Surveys - GDS1205, GDS1207
Ductile lineaments and Foliation - SRK Consulting (Canada) Inc.
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Study, Manitouwadge

TITLE
Second Vertical Derivative of the Pole-reduced Magnetic Field

DESIGN	KR	14 JUN 2013	**Figure 9**	REVISION 1.2
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 JUL 2014		NAD 1983
REVIEW	CB	11 JUL 2014		1:275,000

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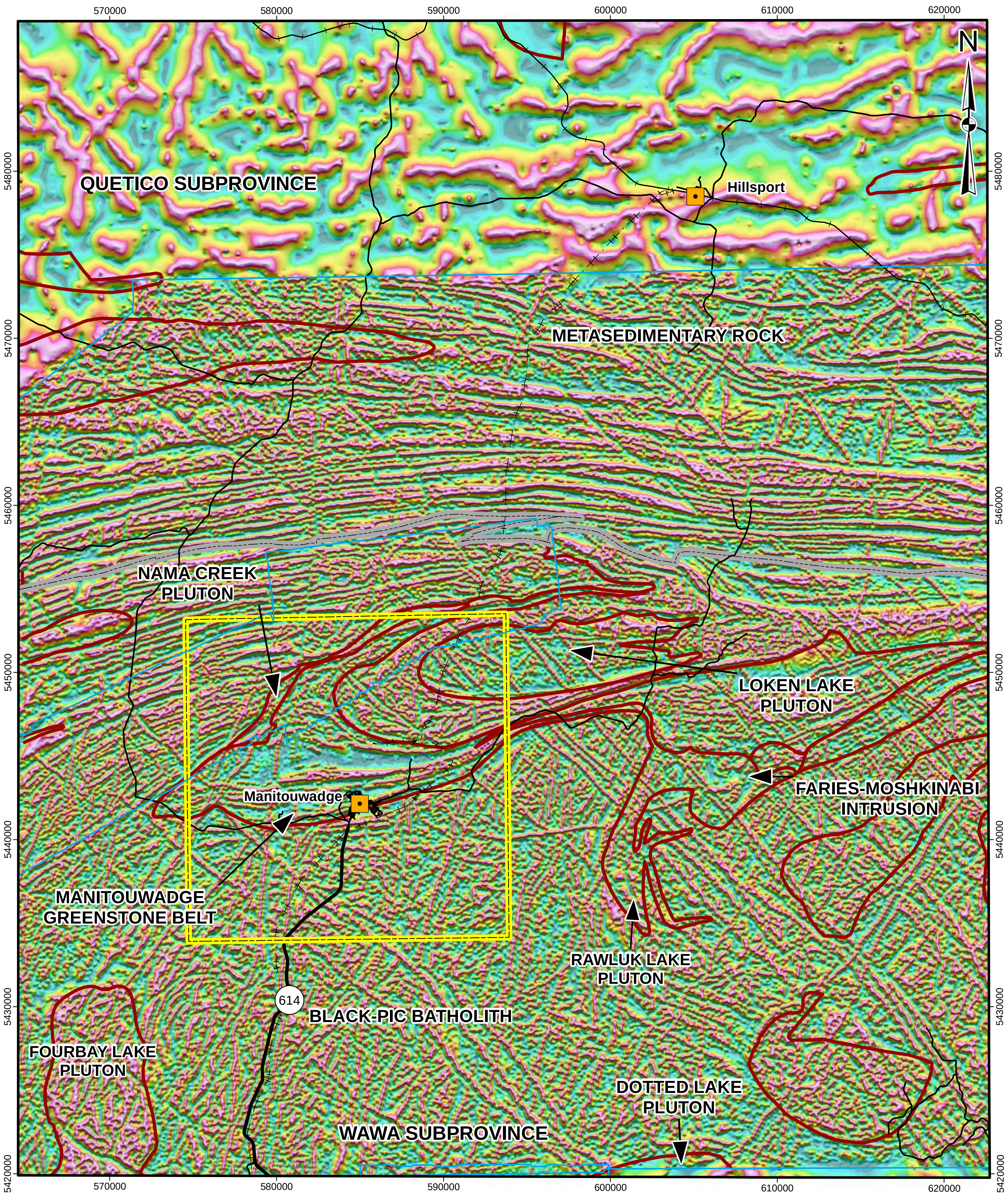
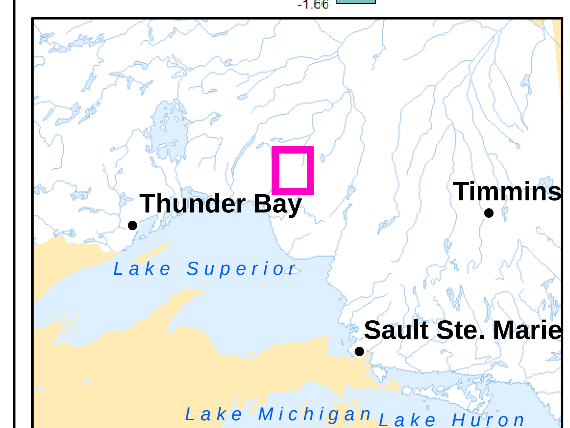


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- High Resolution Geophysical Survey Outlines

Tilt Angle of the Pole-reduced Magnetic Field (radians)

1.68, 1.20, 1.05, 0.90, 0.80, 0.70, 0.55, 0.45, 0.30, 0.20, 0.10, 0.00, -0.10, -0.20, -0.30, -0.40, -0.50, -0.55, -0.65, -0.75, -0.80, -0.90, -0.95, -1.00, -1.10, -1.15, -1.20, -1.30, -1.35, -1.66



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Aeromagnetic Surveys - Ontario #8, Dighem 1056
Ontario Geological Survey - Geophysical Surveys - GDS1205, GDS1207
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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Geophysical Study, Manitouwadge

TITLE
Tilt Angle of the Pole-reduced Magnetic Field

DESIGN	KR	14 JUN 2013	Figure 10	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

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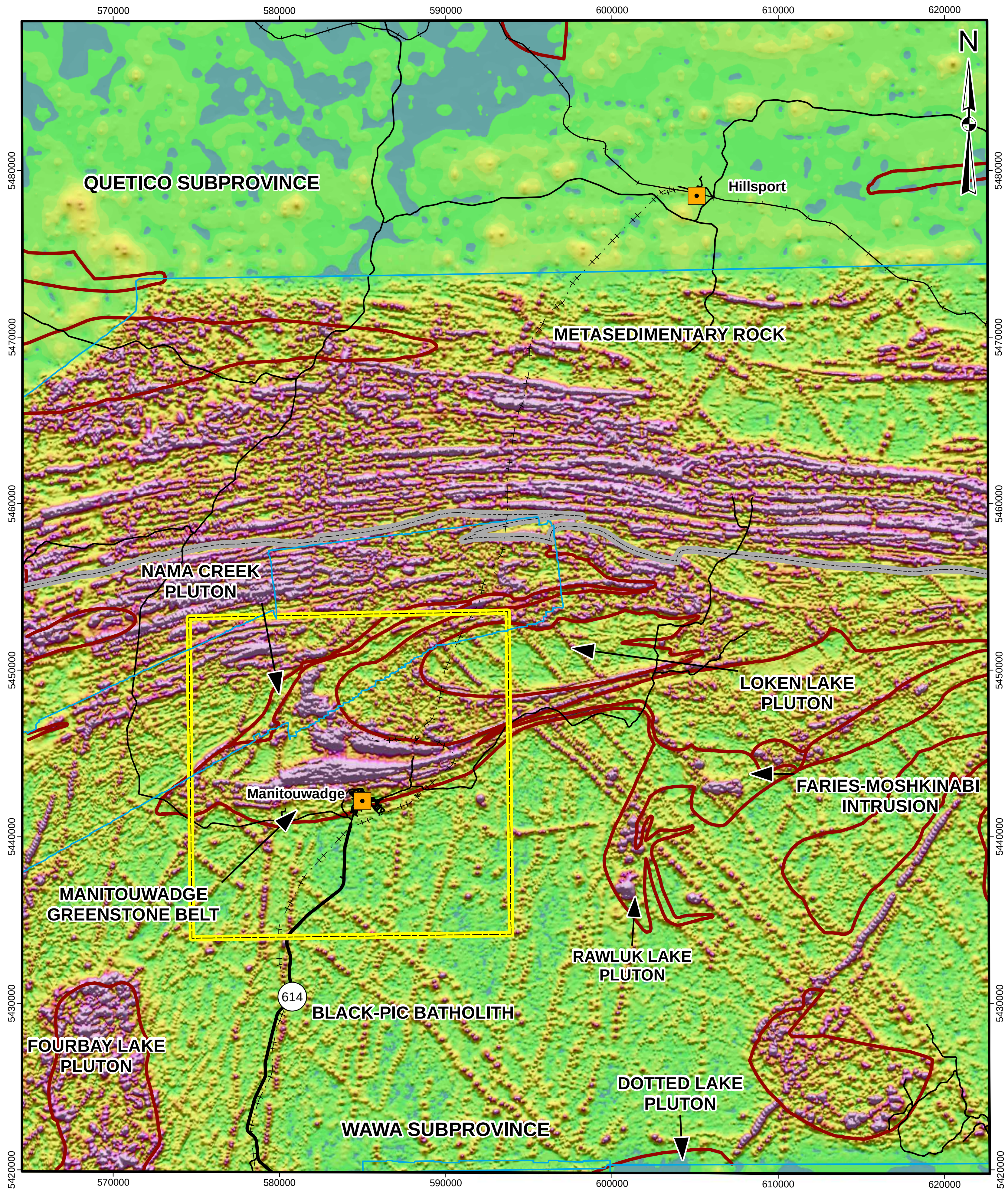
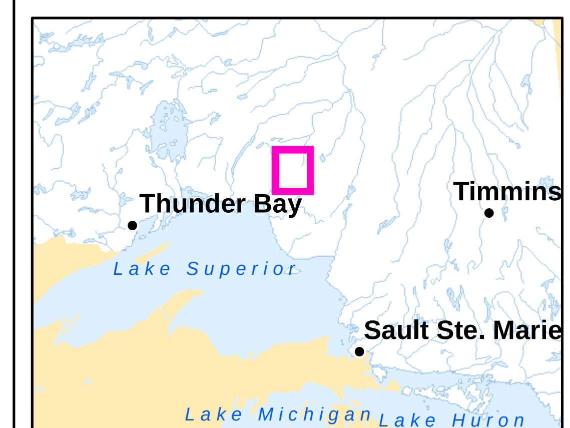


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- High Resolution Geophysical Survey Outlines

Analytic Signal Amplitude of the Residual Magnetic Field nT/m)

69.13
2.45
2.10
1.85
1.70
1.55
1.45
1.30
1.20
1.10
1.00
0.90
0.80
0.75
0.65
0.55
0.50
0.40
0.30
0.20
0.10
0.05
0.00



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Aeromagnetic Surveys - Ontario #8, Dighem 1056
Ontario Geological Survey - Geophysical Surveys - GDS1205, GDS1207
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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Geophysical Study, Manitouwadge

TITLE
Analytic Signal Amplitude of the Residual Magnetic Field

DESIGN	KR	14 JUN 2013	**Figure 11**	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

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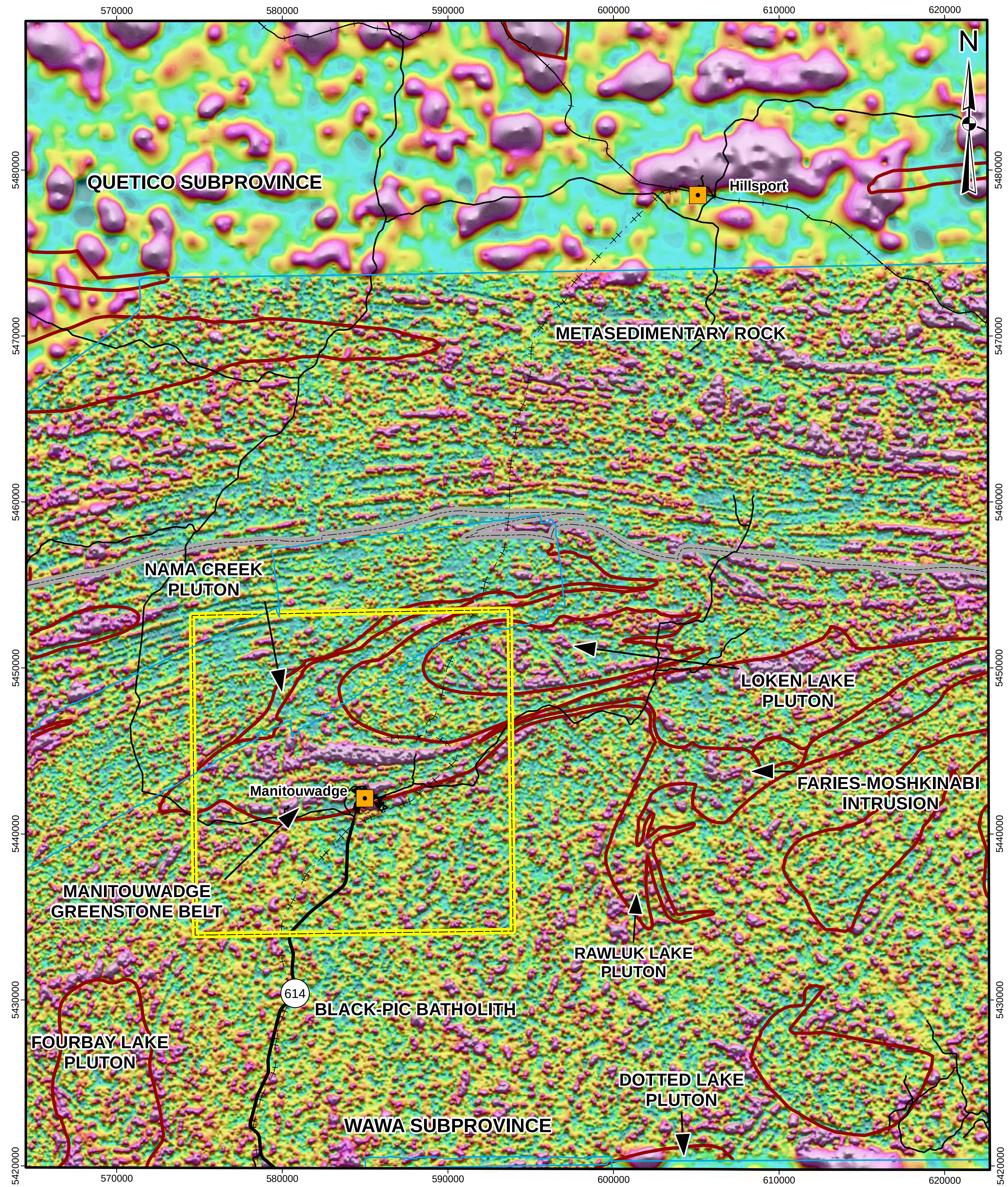
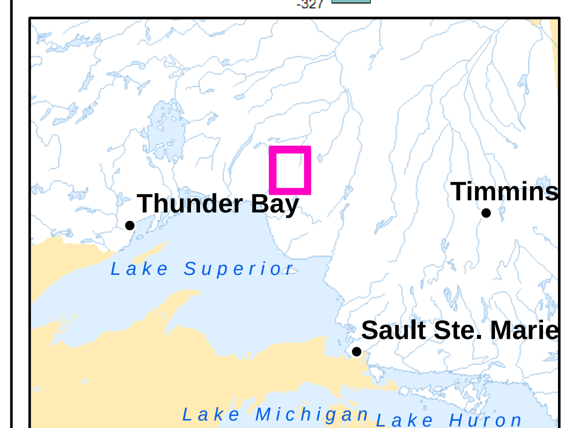


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- High Resolution Geophysical Survey Outlines

Depth to Magnetic Sources (m below surface)

7714, 805, 530, 395, 315, 260, 225, 190, 170, 150, 130, 115, 105, 90, 80, 70, 60, 55, 45, 35, 30, 20, 15, 5, 0, -5, -15, -35, -327



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Aeromagnetic Surveys - Ontario #8, Dighem 1056
Ontario Geological Survey - Geophysical Surveys - GDS1205, GDS1207
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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Geophysical Study, Manitouwadge

TITLE
Depth to Magnetic Sources from Source Parameter Imaging

DESIGN	KR	14 JUN 2013	Figure 12	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

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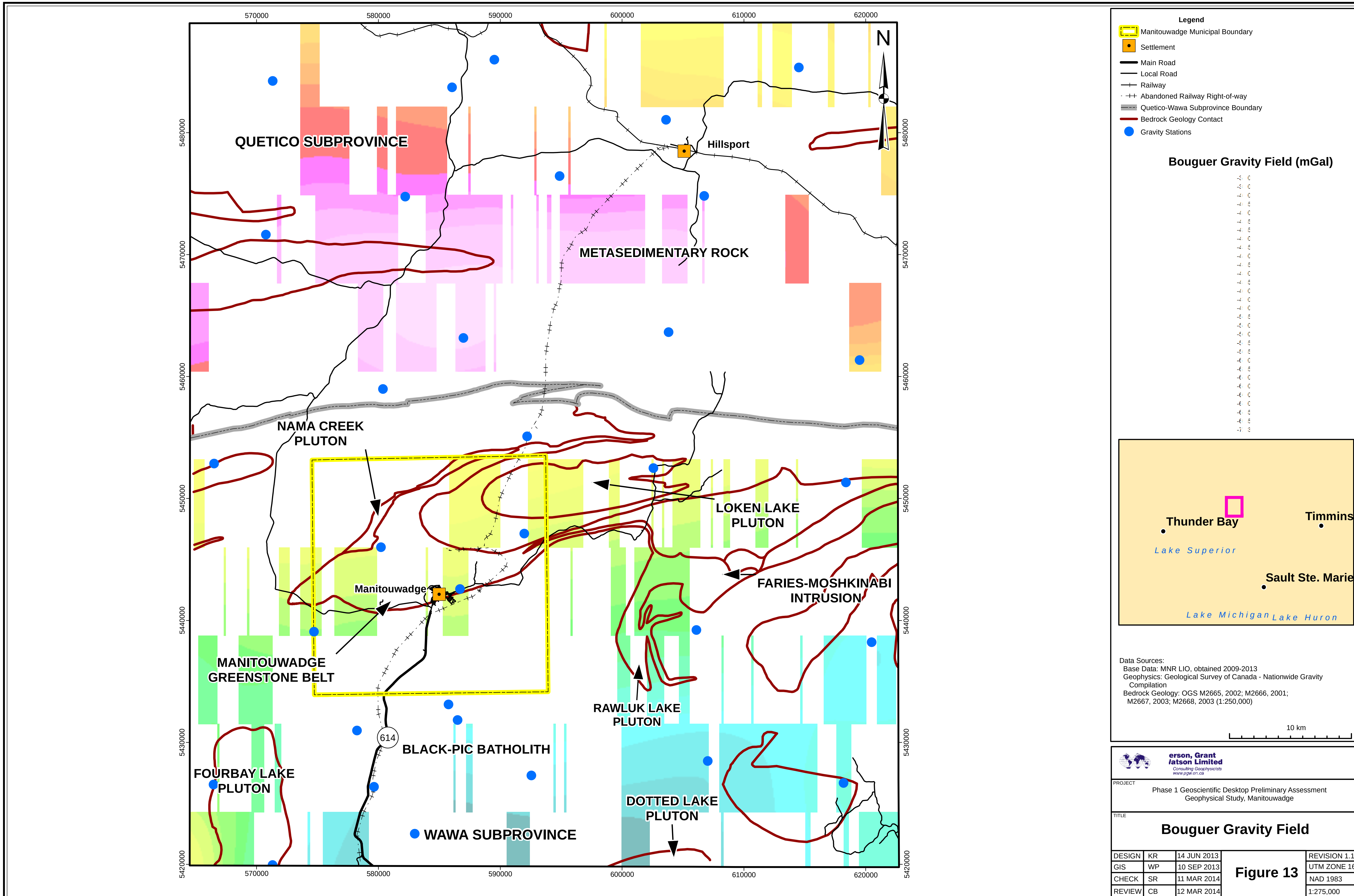

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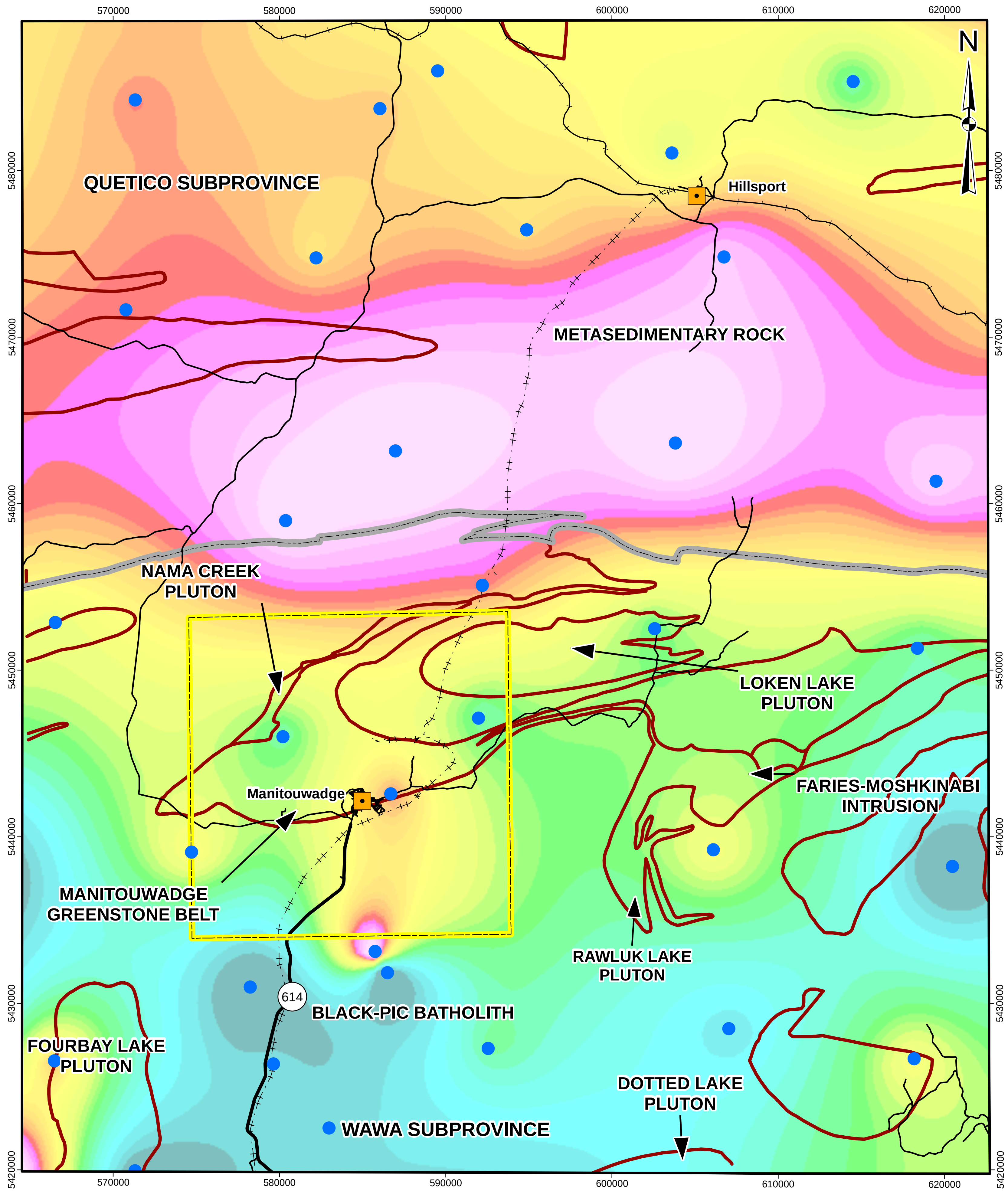
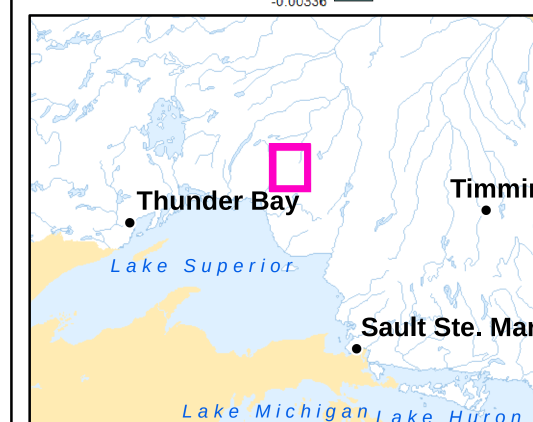


Legend

Manitouwadge Municipal Boundary
Settlement
Main Road
Local Road
Railway
Abandoned Railway Right-of-way
Quetico-Wawa Subprovince Boundary
Bedrock Geology Contact
Gravity Stations

First Vertical Derivative of the Bouguer Gravity Field (mGal/m)

0.00553
0.00100
0.00088
0.00078
0.00068
0.00062
0.00054
0.00050
0.00044
0.00038
0.00034
0.00028
0.00022
0.00016
0.00010
0.00004
-0.00004
-0.00016
-0.00024
-0.00032
-0.00038
-0.00046
-0.00058
-0.00068
-0.00078
-0.00090
-0.00104
-0.00120
-0.00134
-0.00336



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Nationwide Gravity Compilation
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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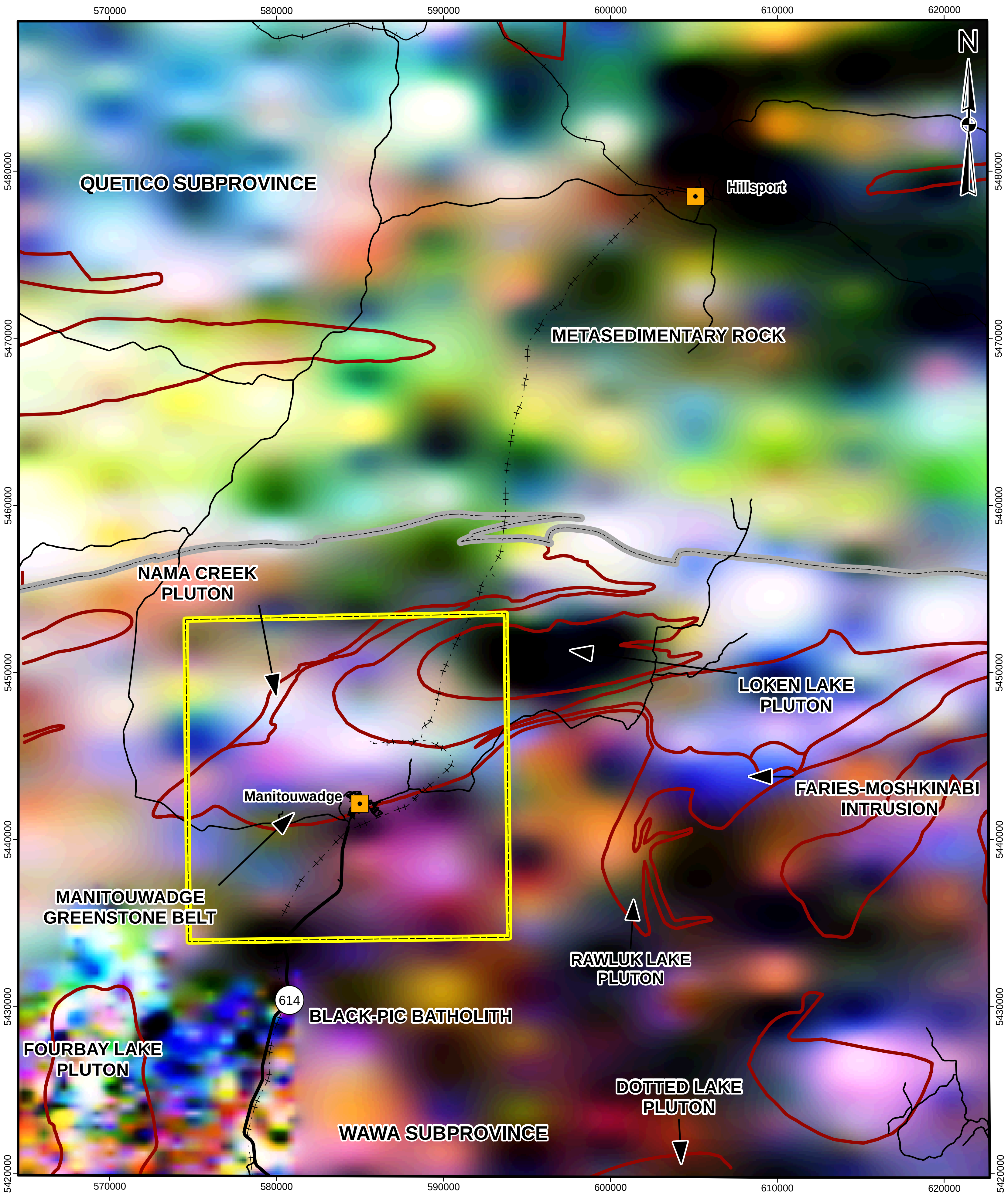
TITLE
First Vertical Derivative of the Bouguer Gravity Field

DESIGN	KR	14 JUN 2013	Figure 14	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

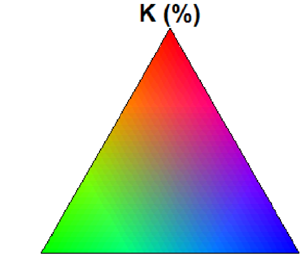
Path: C:\Users\Stephen\PGW\2013-18\Proc\maps\ArcGIS\Feb 2014\Manitouwadge\Fig14_PGW_Manitouwadge_Grav_Bouguer1VD_draft.mxd

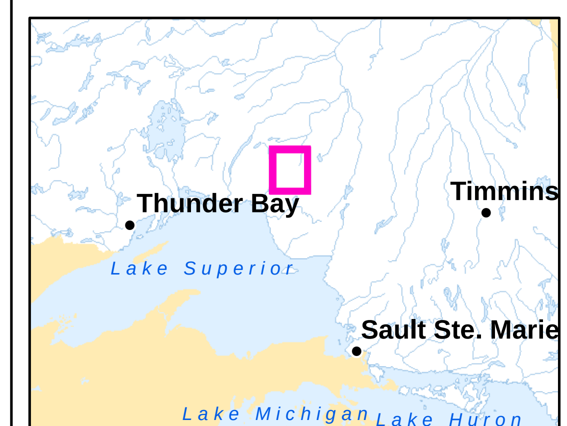


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact

Radiometric Ternary Image
RGB = K-eTh-eU





Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Geological Survey of Canada - Nationwide Radiometric Compilation
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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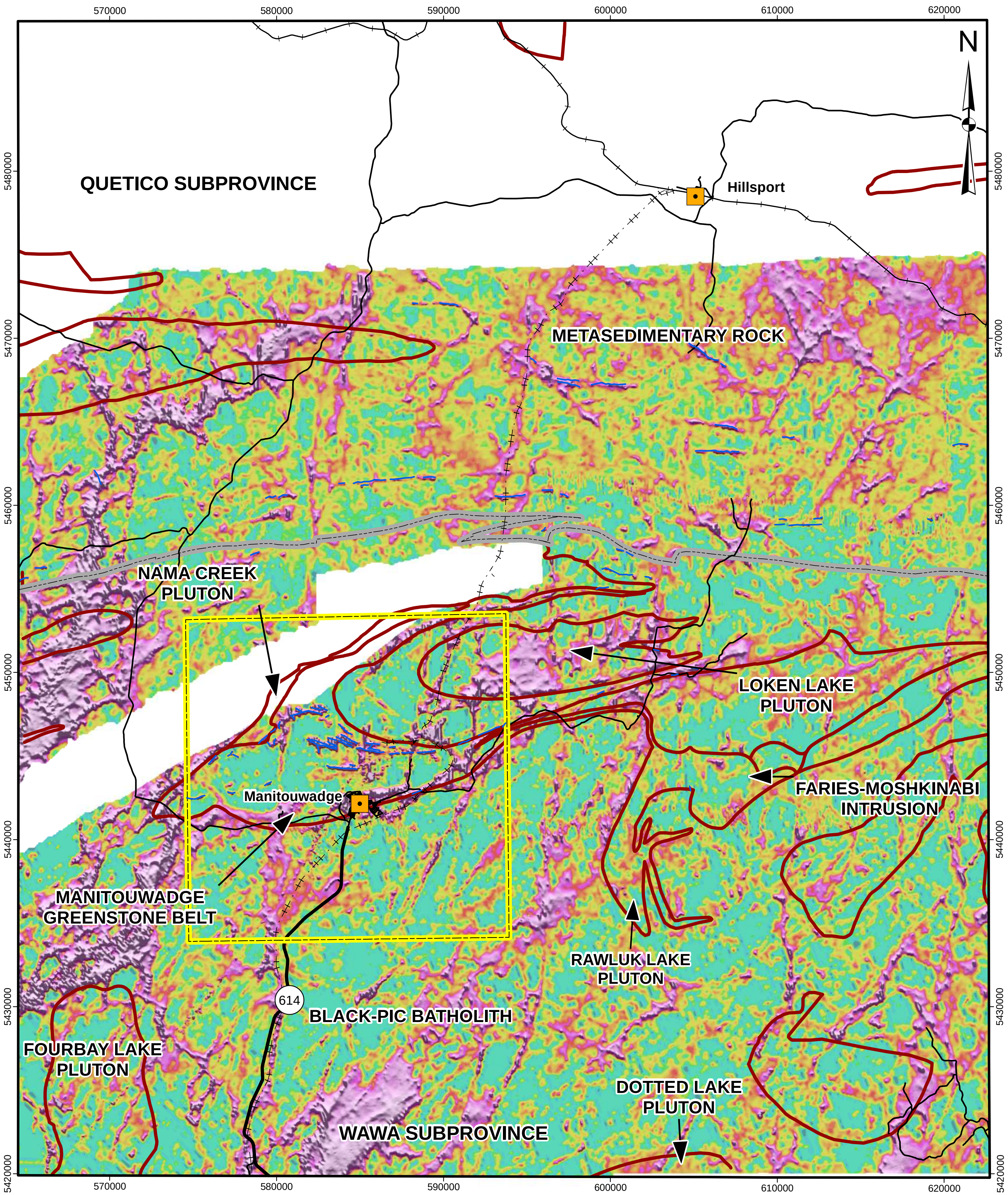
TITLE
Radiometric Ternary Image (RGB = K-eTh-eU)

DESIGN	KR	14 JUN 2013	Figure 15	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000

Path: C:\Users\Stephen\PGW\2013-18\Proc\maps\ArcGIS\Feb 2014\Manitouwadge\Fig15_PGW_Manitouwadge_Rad_Ternary_draft.mxd

Path: C:\Users\Stephen\PGW\2013-18\Proc\maps\ArcGIS\Feb 2014\Manitouwadge\Fig16_PGW_Manitouwadge_EM_Conductivity_draft.mxd

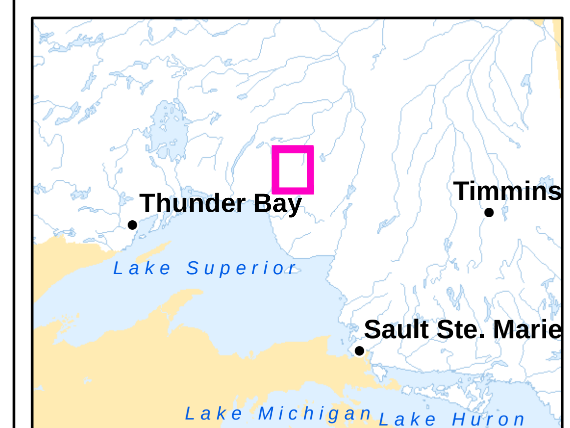


Legend

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Quetico-Wawa Subprovince Boundary
- Bedrock Geology Contact
- EM Conductors

Apparent Conductivity (S/m)

0.100000
0.007160
0.002785
0.001395
0.000855
0.000630
0.000515
0.000440
0.000385
0.000340
0.000305
0.000275
0.000250
0.000225
0.000205
0.000190
0.000175
0.000160
0.000150
0.000140
0.000135
0.000130
0.000125
0.000120
0.000115
0.000086



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Geophysics: Ontario Geological Survey - Geophysical Survey - GDS1205
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

10 km

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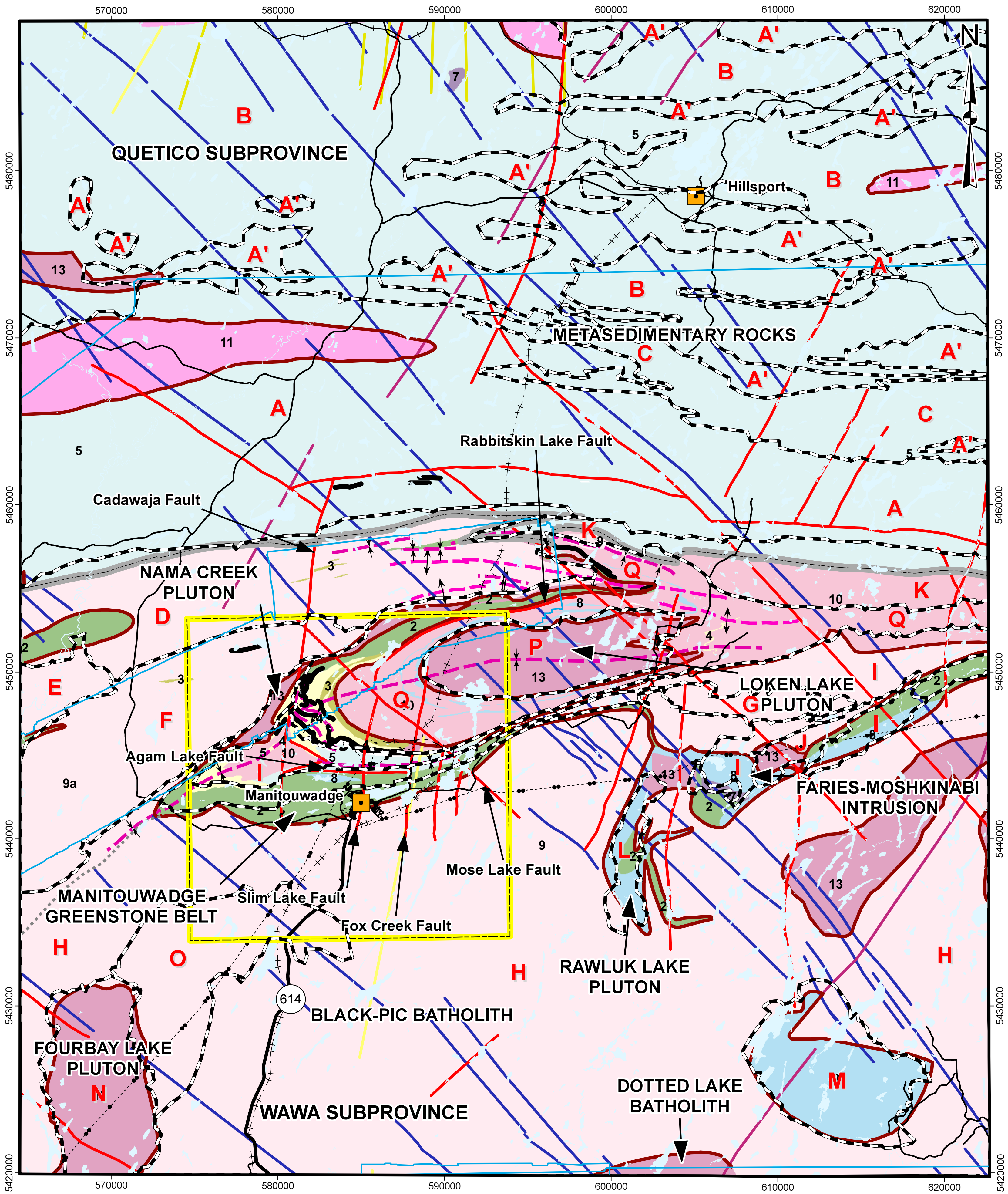
TITLE
EM Conductors over Apparent Conductivity

DESIGN	KR	14 JUN 2013	**Figure 16**	REVISION 1.1
GIS	WP	10 SEP 2013		UTM ZONE 16
CHECK	SR	11 MAR 2014		NAD 1983
REVIEW	MA	12 MAR 2014		1:275,000



Legend

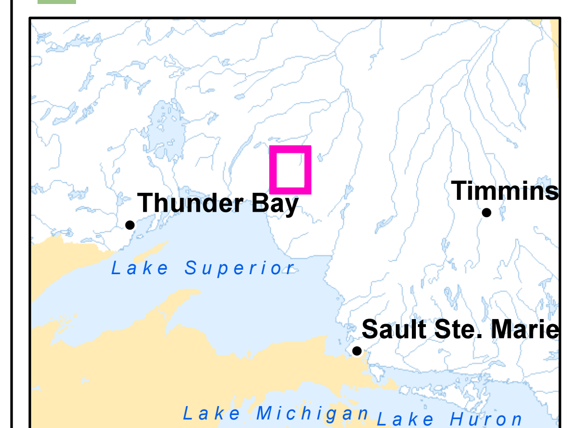
- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Hydro Line
- Waterbody
- Faults
- Syncline (Approximate)
- Anticline (Approximate)
- Iron Formation
- Bedrock Unit Subdivision
- Quetico-Wawa Subprovince Boundary

Mapped Dykes

- Biscotasing mafic dyke
- Marathon mafic dyke
- Marathon, Kapuskasing or Biscotasing mafic dyke
- Matachewan mafic dyke
- High resolution geophysical survey outlines
- A Geologic units interpreted from geophysics

Bedrock Geology

- 13: Granite-granodiorite
- 11: Granite-granodiorite
- 10: Foliated tonalite suite
- 9: Gneissic tonalite suite
- 9a: migmatized supracrustal rocks
- 8: Gabbro
- 7: Ultramafic plutonic rocks
- 5: Metasedimentary rocks
- 4: Felsic volcanic rocks
- 3: Felsic and intermediate metavolcanic rocks
- 2: Mafic metavolcanic rocks



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)
Faults: OGS MRD 126-REV1, 2011; M2668, 2003; GSC 1917A, 2001
Dykes: OGS MRD 126-REV1, 2011
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003

10 km

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TITLE
Geophysical Interpretation Showing Distribution of Bedrock Units for the Township of Manitouwadge and Surrounding Area

DESIGN	KR	14 JUN 2013	Figure 17	REVISION 1.3
GIS	GF	29 AUG 2013		UTM ZONE 16
CHECK	SR	4 SEPT 2014		NAD 1983
REVIEW	MA	4 SEPT 2014		1:275,000

Path: D:\2013-18\Proc\maps\ArcGIS\July 2014\Sept 2014\Fig17_PGW_Manitouwadge_Bedrock_Geology_Interpretation.mxd