NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment of Potential Suitability for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel

TOWNSHIP OF MANITOUWADGE, ONTARIO

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Township of Manitouwadge, Ontario

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Executive Summary

In March, 2013, the Township of Manitouwadge, Ontario, expressed interest in continuing to learn more about the Nuclear Waste Management Organization (NWMO) nine-step site selection process, 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 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 preliminary assessment report (NWMO, 2014).

This report presents the results of a desktop geoscientific preliminary assessment to determine whether the Manitouwadge area contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors. The assessment builds on the work previously conducted for the initial screening and focuses on the Township of Manitouwadge and its periphery, which are referred to as the "Manitouwadge area".

The geoscientific preliminary assessment was conducted using available geoscientific information and a subset of key geoscientific evaluation factors that can be realistically assessed at this early stage of the site evaluation process. These include: geology; structural geology and distribution of lineaments; distribution and thickness of overburden deposits; surface conditions; and the potential for economically exploitable natural resources. The desktop geoscientific preliminary assessment included the following review and interpretation activities:

- Detailed review of available geoscientific information such as geology, structural geology, natural resources, hydrogeology and overburden deposits;
- Interpretation of available geophysical surveys (magnetic, electromagnetic, gravity, radiometric);
- Lineament studies using available satellite imagery, topography and geophysical surveys to provide information on the characteristics (location, orientation, length, etc.) of interpreted structural bedrock features;
- Terrain analysis studies to help assess overburden type and distribution, bedrock exposures, accessibility constraints, watershed and subwatershed boundaries, groundwater discharge and recharge zones; and
- The identification of general potentially suitable areas based on key geoscientific characteristics and the application of NWMO's geoscientific site evaluation factors.

The desktop geoscientific preliminary assessment showed that the Manitouwadge area contains at least four general areas that have the potential to satisfy NWMO's geoscientific factors. Two of these areas are located within the Black-Pic batholith in the south central portion of the area, one in the Quetico metasedimentary rocks in the north and one in the Fourbay Lake pluton in the southwest of the Manitouwadge area. Given the geographic extent of the Manitouwadge area, there may be additional areas that are also potentially suitable for hosting a deep geological repository.

The four general areas in the Manitouwadge area have a number of geoscientific characteristics that are favourable for hosting a deep geological repository. The geological units appear to have sufficient depth and lateral extent. The four areas identified have a low potential for natural resources, good bedrock exposure and limited surface water

constraints making the areas amenable to geological site characterization activities. In addition, three of the areas are covered by high resolution geophysical surveys.

While the identified general potentially suitable areas appear to have favourable geoscientific characteristics, there are inherent uncertainties that would need to be addressed during subsequent stages of the site evaluation process. The main uncertainties relate to the influence of regional structural features, the presence of numerous dykes, and the variable degree of metamorphism that the metasedimentary rocks experienced in the past.

The identified potentially suitable areas are located away from regional structural features, such as the Gravel River fault and Wawa-Quetico subprovince boundary. However, the potential impact of these regional features on the suitability of the areas needs to be further assessed. The Manitouwadge area contains numerous dykes. While the spacing between mapped and interpreted dykes appears to be favourable, the potential presence of smaller dykes not identifiable on geophysical data, the potential damage of the host rock due to the intrusion of dykes, and the hydraulic properties of the dykes would need to be assessed. In addition, uncertainty remains in relation to the lithological homogeneity at a local scale, particularly the varying degree of metamorphism that the metasedimentary rocks may have experienced.

Should the Township of Manitouwadge be selected by the NWMO to advance to Phase 2 study and remain interested in continuing with the site selection process, several years of progressively more detailed studies would be required to confirm and demonstrate whether the Manitouwadge area contains sites that can safely contain and isolate used nuclear fuel. This would include the acquisition and interpretation of higher resolution airborne geophysical surveys, detailed geological mapping and the drilling of deep boreholes.

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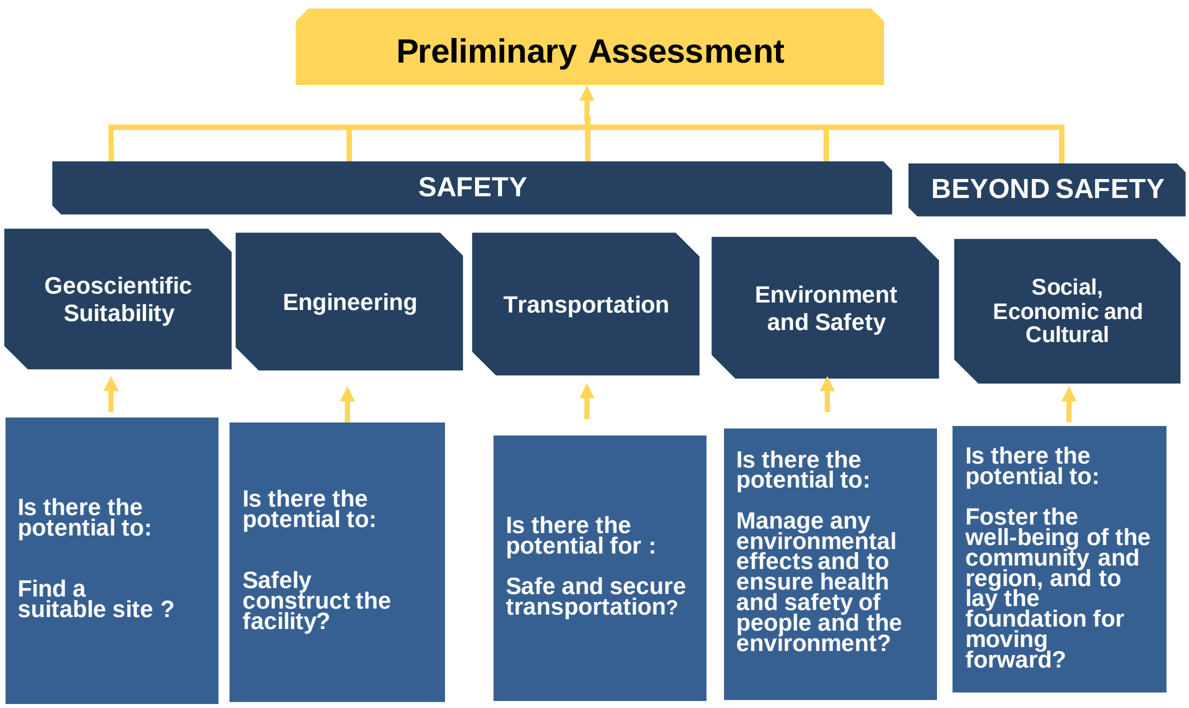
1. INTRODUCTION

1.1 Background

In March, 2013, the Township of Manitouwadge, Ontario, expressed interest in continuing to learn more about the Nuclear Waste Management Organization (NWMO) nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess the 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 (Geofirma Engineering Ltd., 2013a).

The overall preliminary assessment is a multi-component study integrating both technical and community well-being assessments as illustrated in the diagram below. The five components of the preliminary assessment address geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. A brief description of the project, the assessment approach, and findings of the preliminary assessment are documented in an integrated preliminary assessment report (NWMO, 2014).



The objective of the geoscientific preliminary assessment is to assess whether the Manitouwadge area contains general areas that have the potential to meet NWMO's site evaluation factors. The preliminary assessment is conducted in two phases:

- ***Phase 1 - Desktop Study.*** For all communities electing to be the focus of a preliminary assessment. This phase involves desktop studies using available geoscientific information and a set of key geoscientific characteristics and factors that can be realistically assessed at the desktop phase of the preliminary assessment.

- ***Phase 2 - Preliminary Field Investigations**.* For a subset of communities selected by the NWMO, to further assess potential suitability. This phase will involve a site investigation that includes high resolution geophysical surveys, geological mapping and the drilling of deep boreholes.

The subset of communities considered in Phase 2 of the preliminary assessment will be selected based on the findings of the overall desktop preliminary assessment considering both technical and community well-being factors presented in the above diagram.

1.2 Desktop Geoscientific Preliminary Assessment Approach

The objective of the Phase 1 geoscientific preliminary assessment is to assess whether the Manitouwadge area contains general areas that have the potential to satisfy the geoscientific evaluation factors outlined in the site selection document (NWMO, 2010). The location and extent of potentially suitable areas would be confirmed during subsequent site evaluation stages.

The desktop preliminary assessment built on the work previously conducted for the initial screening (Geofirma Engineering Ltd., 2013a) and focused on the Township of Manitouwadge and its periphery, which are referred to as the “Manitouwadge area” in this report (Figure 1.1). The boundaries of the Manitouwadge area were defined to encompass the main geological features within the Township of Manitouwadge and its surroundings. The Phase 1 Desktop Geoscientific Preliminary Assessment included the following review and interpretation activities:

- Detailed review of available geoscientific information related to geology, structural geology, natural resources, hydrogeology, overburden deposits;
- Interpretation of available geophysical surveys (magnetic, electromagnetic, gravity, radiometric);
- Lineament studies using available satellite imagery, topography and geophysical surveys to provide information on the characteristics such as location, orientation and length of interpreted structural bedrock features;
- Terrain analysis studies to help assess overburden type and distribution, bedrock exposures, accessibility constraints, watershed and subwatershed boundaries, groundwater discharge and recharge zones; and
- The identification of general potentially suitable areas based on the key geoscientific characteristics and the systematic application of NWMO’s geoscientific site evaluation factors.

The details of these various studies are documented in three supporting documents: Terrain Analysis (AECOM, 2014), Geophysical Interpretation (PGW, 2014), and Lineament Interpretation (SRK, 2014). Key findings from these studies are summarized and integrated in this report.

1.3 Key Geoscientific Site Evaluation Factors

As discussed in the NWMO site selection process, the suitability of potential sites will be evaluated in a staged manner through a series of progressively more detailed scientific and technical assessments using a number of geoscientific site evaluation factors, organized under five safety functions that a site would need to ultimately satisfy in order to be considered suitable (NWMO, 2010):

- ***Safe containment and isolation of used nuclear fuel**:* Are the characteristics of the rock at the site appropriate to ensuring the long-term containment and isolation of used nuclear fuel from humans, the environment and surface disturbances caused by human activities and natural events?

- ***Long-term resilience to future geological processes and climate change**:* Is the rock formation at the siting area geologically stable and likely to remain stable over the very long-term in a manner that will ensure the repository will not be substantially affected by geological and climate change process such as earthquakes and glacial cycles?

- ***Safe construction, operation and closure of the repository**:* Are conditions at the site suitable for the safe construction, operation and closure of the repository?

- ***Isolation of used fuel from future human activities:*** Is human intrusion at the site unlikely, for instance through future exploration or mining?

- ***Amenable to site characterization and data interpretation activities:*** Can the geologic conditions at the site be practically studied and described on dimensions that are important for demonstrating long-term safety?

The list of site evaluation factors under each safety function is provided in Appendix A.

The assessment was conducted in two steps. The first step assessed the potential to find general potentially suitable areas within the Manitouwadge area using key geoscientific characteristics that can realistically be assessed at this stage of the assessment based on available information (Section 7.2). The second step assessed whether identified potentially suitable areas have the potential to meet all the safety functions outlined above (Section 7.3).

1.4 Available Geoscientific Information

Geoscientific information for the Manitouwadge area was obtained from many data sources, including maps, reports, databases, and technical papers. In summary, the review of existing information identified that there was sufficient geoscientific information available to conduct the Phase 1 preliminary assessment studies and to identify general potentially suitable areas in the Manitouwadge area. Key geoscientific information sources are summarized in this section, with a complete listing provided in Appendix B.

1.4.1 Airborne Geophysics, Digital Elevation Model, Satellite Imagery and Aerial Photography

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) (Table 1.1, Table B.1). In addition, the OGS Assessment File Research Imaging (AFRI) database was interrogated but no files of interest (i.e., with useful high-resolution geophysical images) were located within the Manitouwadge area. Figure 1.2 shows the outline of the available airborne geophysical surveys for the Manitouwadge area. The higher resolution geophysical coverage consists of three magnetic and frequency-domain (FDEM) surveys that cover all but the northern portion of the Manitouwadge area.

The electromagnetic coverage consists of frequency-domain (FDEM) surveys that form part of the high-resolution surveys noted above. The electromagnetic data grids provided for the OGS surveys are as follows:

- GDS1205 (Manitouwadge): apparent resistivity grid from the 900 Hz, 7,200 Hz, and 56,000 Hz coplanar coil pairs;
- GDS1207 (Hemlo): apparent resistivity grid from the 4,500 Hz coaxial coil pair and VLF total field grid.

In addition, each FDEM survey included an EM anomaly database with the sources classified as bedrock, surficial, or cultural. The third survey (Dighem #1056 from GSC) originally acquired FDEM data but these are not available in the public domain.

The northern quarter of the Manitouwadge area is covered by a low resolution survey Ontario #8. This survey forms part of the single master gravity and aeromagnetic data for Ontario (SMGA - GDS1036).

The GSC radiometric and gravity coverage for the Manitouwadge area is the typical regional coverage available for most of the country. The exception is in the southwest part of the area where the GSC's Coldwell, Hemlo, Schreiber radiometric survey has improved resolution (i.e., 1,000 m line spacing) in the area surrounding the Coldwell alkalic intrusive complex. The radiometric data were microlevelled and gridded from the GSC's profile archive as this improved the resolution and reduced the noise relative to the GSC's nationwide grids of dose rate, potassium, equivalent uranium and equivalent thorium. Similarly, the gravity data were gridded from the GSC's profile archive to improve the resolution over the GSC's nationwide Bouguer gravity grid.

Data sets containing remote sensing data were available for use in the Manitouwadge Phase 1 Desktop Geoscientific Preliminary Assessment. The digital elevation model (DEM) data for the Manitouwadge area, referred to as the Canadian Digital Elevation Data (CDED), consists of a 1:50,000 scale, ~20 m resolution elevation model (Table 1.1; GeoBase, 2011a). SPOT multispectral/panchromatic orthoimagery (20 m / 10 m resolution) were also available for the Manitouwadge area as was Landsat 7 orthoimages (30 m resolution) (Table 1.1; GeoBase, 2011b).

Aerial photographic coverage of the northern portion of the Manitouwadge area was obtained from the archives of the Ontario Geological Survey. The 1:50,000 scale images, part of the OGS's Northern Ontario Engineering Geology Terrain Study (NOEGTS) collection, were captured during seasons with limited vegetation cover thus permitting the identification of topographic features.

The SPOT and Landsat data sets cover the entire Manitouwadge area and all have a good level of resolution allowing the interpretation of surficial geology. In addition, meaningful and accurate bedrock structural information could be gained from each of the data sets for the majority of the Manitouwadge area. The only areas where this was not the case was a zone along the northern edge of the Manitouwadge area and a linear 10 km wide zone in the south-central portion of the area. In these instances, a significant thickness of glacial cover limited the usefulness of CDED and Landsat/SPOT data for identifying surficial lineaments.

Table 1-1: Summary of Satellite, Airborne and Geophysical Source Data Information for the Manitouwadge Area

Data set	Product	Source	Resolution	Coverage	Acquired	Additional Comments
DEM	Canadian Digital Elevation Data (CDED); 1:50,000 scale	Geobase	8-23 m (0.75 arc seconds) depending on latitude	Entire Manitouwadge area	1995 (published in 2003)	Hillshade and slope rasters used for mapping
Aerial Photography	Images	OGS	1:54,000 scale	Northern half of Manitouwadge area	1978	
Satellite Imagery	Spot 4/5; Orthoimage, multispectral/ panchromatic	Geobase	10 m (panchromatic) 20 m (multispectral)	Entire Manitouwadge area	2005 -2010	

Table 1-1: Summary of Satellite, Airborne and Geophysical Source Data Information for the Manitouwadge Area

	Landsat 7 orthorectified imagery	Geobase	30 m (multispectral)	Entire Manitouwadge area	2001	
Geophysics	Ontario #8 Fixed wing magnetic	GSC	805 m line spacing; Sensor height 305 m	Entire Manitouwadge area	1959	Mostly superseded by high-resolution coverage.
	Manitouwadge (GDS1205) (blocks A to C, E to I)	OGS	150 and 200 m line spacing; Sensor height 45 m Mag 30 m FDEM	Covers large portion of Manitouwadge area (excludes northern most area)	1989 (published 2002)	4-frequency Dighem IV system flown for Noranda Exploration Company, Ltd.
	Dighem #1056 Helicopter magnetic (Areas A & G)	GSC	150m/MAG 45m	West central Manitouwadge	1988	Fills the gap in OGS GDS1205, flown for Noranda Exploration Company, Ltd.
	Coldwell, Hemlo, Schreiber Fixed wing radiometric, magnetic, VLF-EM	GSC	1000m/121m	Southwest Manitouwadge	1990	Only higher resolution radiometric survey
	Hemlo Helicopter magnetic, FDEM, VLF-EM (GDS1207)	GSC	100m line spacing; Sensor height 55m Mag 40 m FDEM 55 m VLF-EM	Southern edge of Manitouwadge area	1983	3-frequency Aerodat system
	North Shore Lake Superior, section 1 (East) Fixed wing magnetic, radiometric	GSC	5000 m/123 m	Entire Manitouwadge area	1982	Provides majority of radiometric coverage.
	Ground Gravity Measurements	GSC	5-15 km Station Spacing	Stations sparsely located over Manitouwadge area	1946- 2001	Good data quality but sparse density of points

1.4.2 Geology

There is an extensive history of Precambrian geological mapping in the Manitouwadge area and surrounding region with the majority of the studies completed by the Ontario Geological Survey (and its predecessor agencies). Notable early milestones are the regional mapping of Thompson (1932) and the mapping of the Manitouwadge area by Pye

(1957; 1960). During the period 1963 to 1972 a series of maps at a scale of 1:63,360 were produced that covered most of the northern half and the western edge of the area (Milne, 1963; Coates, 1967a; 1967b; 1970a; Giguere, 1972). Also in this time period the area south of the settlement of Manitouwadge was mapped by Milne (1967a, 1967b; 1967c; 1968a) at a scale of 1:31,680. This mapping led to the creation of regional-scale compilation maps (1:253,000) for the area produced by Innes and Ayres (1971) and Milne *et al.* (1972). Detailed mapping of the Manitouwadge mining camp, at a scale of 1:12,000, was completed by Milne (1974) and a regional scale review of the geology of the area at a scale of 1:50,000 was published by Williams and Breaks (1990). Figure 1.2 shows a summary of available recent bedrock geological map coverage for the Manitouwadge area.

Updated regional and provincial compilations of the bedrock geology of the area have been published at scales of 1:250,000 (Santaguida, 2001; 2002; Johns and McIlraith, 2003; Johns *et al.*, 2003; Ontario Geological Survey, 2011) and 1:1,000,000 (Ontario Geological Survey, 1991a; 1991b; 1997), respectively. A provincial-scale tectonic assemblage map was generated from an interpretation of this latest generation of mapping (Ontario Geological Survey, 1992a; 1992b).

More recent mapping of the area, largely completed by the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC), is of varying detail depending on scale but is considered to be of high quality (e.g., Williams, 1989; Card, 1990; Williams *et al.*, 1991; Williams and Breaks, 1996; Zaleski and Peterson, 1993a; 2001). The focus of most of the bedrock mapping in the area was on defining the lithologies, structural controls and the mineral potential of the Manitouwadge area.

Bedrock maps covering the Manitouwadge area identified the position and orientation of a number of large scale faults and lineaments. The density of the structural data is greatest within the greenstone belt, as a result of its known and potential mineral endowment and its complex tectonic history. Information on the structural history of the Manitouwadge area is based dominantly 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 Williams and Breaks (1996), Lin (2001), and Percival *et al.* (2006) have also contributed to the structural understanding of the Manitouwadge area. The aforementioned studies were performed at various scales and from various perspectives.

Several geochronological investigations have been completed that assist in determining the age of bedrock units within and surrounding the Manitouwadge area (e.g., Zaleski *et al.*, 1994; 1995; 1999). This research has principally focused on defining the age and structural relationship of bedrock units within and adjacent to the Manitouwadge greenstone belt with an aim of understanding ore genesis (e.g., Schandl *et al.*, 1991; Davis *et al.*, 1994). Dates of the granitoid rocks surrounding the greenstone belt are far fewer and show greater variability in ages. In general, the quality of geochronological data are high, especially dates generated within the past few decades. A database of geochronological dates is maintained by the GSC.

Information on the geochemical analysis of bedrock samples collected from the 1970s to the early 1990s is contained in the OGS lithogeochemistry (formerly Petroch) database (MNDM, 2013a). The majority of the results in this database are of supracrustal greenstone belt rocks with far fewer analyses of felsic intrusive rocks. In general, the quality of the analytical results is dependent on when the analyses were conducted, since modern analytical equipment tends to have better detection levels. Furthermore, the location information recorded for samples taken prior to modern GPS technology may be less reliable in some cases.

A provincial compilation of Quaternary geology at a scale of 1:1,000,000 includes the Manitouwadge area (Barnett *et al.*, 1991). This is complemented by mapping (1:100,000) of the surficial sediments from airphoto interpretation with limited ground checking, completed during the Northern Ontario Engineering Geology Terrain Study (NOEGTS; Gartner, 1979; Gartner and McQuay, 1980a; 1980b; 1980c; OGS *et al.*, 2005). The mapping is of sufficient quality to illustrate the distribution of glacial materials and to determine that they are generally thin over the majority of the Manitouwadge area. Exceptions include some bedrock-controlled valleys, notably those occupied by the Pic and White Otter creeks, and areas in the northeast corner of the Manitouwadge area where surficial deposits are more continuous. Data on overburden thickness are also available from well records in the Ontario Ministry of Environment Water Well Information Systems database (Ontario Ministry of Environment, 2013) and from the OGS drill hole database (MNDM, 2013a) discussed in Section 1.5.4.

The glacial history for the area is reasonably well understood having been constructed on the basis of detailed mapping in surrounding areas and regional studies assessing glaciation events (e.g., Geddes *et al.*, 1985; Kristjansson and Geddes, 1986; 2009; Geddes and Bajc, 1985; 2009; Barnett, 1992; Kettles and Way Nee, 1998). Research on glacial lake levels in the Superior Basin has allowed an understanding of isostatic recovery rates in the area (Farrard and Drexler, 1985; Barnett, 1992; Lee and Southam, 1994; Mainville and Craymer, 2005).

Several databases contain records of publications with information on the Manitouwadge area's bedrock geology, geological history, structural evolution and economic potential (Table B.3). The most relevant databases to the Desktop Preliminary Assessment are referenced and/or available through GEOSCAN and Geology Ontario (OGS publications).

National seismicity data sources were used to provide an indication of seismicity in the Manitouwadge area (Hajnal *et al*., 1983; Hayek *et al*., 2011; NRCan, 2013).

1.4.3 Hydrogeology and Hydrogeochemistry

The Land Information Ontario (LIO) data warehouse, held by the Ontario Ministry of Natural Resources, contains a database of tertiary and quaternary level watersheds (LIO, 2013) and lakes, including flow direction of all waterways. Shallow groundwater flow is expected to mimic the pattern of surface flow suggested by the configuration of these watersheds. Limited stream/river flow data are available for the region surrounding the Manitouwadge area (Environment Canada, 2013).

Data on the hydrogeology of the Manitouwadge area are largely lacking. The reliance on surface water sources and the very limited number of water wells recorded in the Ministry of Environment's Water Well Information Systems (Ontario Ministry of Environment, 2013) results in only a basic and localized understanding of surficial and shallow bedrock flow systems. The completeness of the information in the few water well records for the Manitouwadge area, most of which are located in and around the settlement area of Manitouwadge, is uneven.

Groundwater flow regimes and the positions of recharge and discharges areas are inferred from other bedrock dominated areas and the type and distribution of surficial materials. The absence of information in the area on deep aquifers or groundwater geochemistry necessitates inferring conditions from similar geologic settings elsewhere in the Canadian Shield. Specific reports/studies include Gascoyne (1994; 2000; 2004), Everitt *et al.* (1996), Gascoyne *et al*. (1996), Ophori *et al. (*1996), and Everitt (1999).

1.4.4 Natural Resources – Economic Geology

The Manitouwadge area has had an extensive history of mineral exploration and development, mainly focused on base metals. The mineral potential of the Manitouwadge-Hornepayne greenstone belt (herein referred to as the Manitouwadge greenstone belt) has resulted in bedrock geological mapping being concentrated on these rocks and the majority of geologic maps and reports noted in Section 1.5.1 containing information relevant to assessing the mineral potential of the Manitouwadge area. The various types of mineral deposits in the Manitouwadge area are described in Pye (1960), Friesen *et al.* (1982), Zaleski and Peterson (1993b; 1996), Zaleski *et al.* (1994), McKay

(1994) and Williams and Breaks (1996). The mineral resource potential for other commodities is described by Springer (1978), Gartner (1979), Gartner and McQuay (1980a; 1980b; 1980c), Sage (1982), Hinz *et al*. (1994), and MNDM (2013b).

Several databases resulting from mineral exploration and/or mining activities in the Manitouwadge area are held by the MNDM/OGS and contain information useful to understanding the area's resource potential. The largest of these is the Assessment File Research Imaging (AFRI) database, which consists of technical results of exploration programs on Crown Land (MNDM, 2013a). The AFRI database outlines the type of geoscience investigations completed and a summary of findings. The quality and usefulness of the files is highly variable; information varies from site-specific to regional and the level and/or amount of information from low to very high.

The OGS drillhole database is a collection of surface and underground drilling data compiled from some of the AFRI records (MNDM, 2013a). The database includes several fields including drillhole location, drillhole orientation and depth, overburden depth, and the presence of assay results, if available.

The Mineral Deposits Inventory (MDI) database contains a record of base, precious, and industrial mineral deposits, occurrences and showings in the Manitouwadge area and beyond (MNDM, 2013a). The level of information in each MDI record is highly variable, notably for small occurrences. In general, information is available on geological structure, lithology, minerals and mineral alteration, in addition to production and reserve data. Information quality is variable as the data are compiled from a range of sources, and may not always be verified.

The Abandoned Mines Information System (AMIS) contains the location of past-producing mines sites in the Manitouwadge area and augments mineral potential evaluations (MNDM, 2013a). The database has records on mining-related features including mining hazards and abandoned mines, and is generally considered to be accurate.

Regional-scale geochemical sampling of glacial materials, lake sediments and lake waters has been conducted by the GSC and reported on for the Manitouwadge area by Friske *et al.* (1991). The sampling, conducted in the late 1970s, is useful in defining mineral potential and can play a role in establishing environmental baseline conditions. The geochemical data from this survey, while of high quality, is reflective of the methods and analytical capabilities of the time.

1.4.5 Geomechanical Properties

Available geotechnical studies in the Manitouwadge area are restricted to near-surface investigations involving surficial materials and the upper few metres of bedrock. The geotechnical investigations in the area, especially the more recent ones, are of high quality, but add little to the understanding of conditions at depth as they were primarily completed for surface infrastructure projects (i.e., water systems, road construction).

While a large amount of mineral exploration drilling has been completed in the Manitouwadge area, some to considerable depths, the bulk of the boreholes are within the metavolcanic units associated with the Manitouwadge greenstone belt. Whereas numerous boreholes have high quality information on lithology variations, and some geophysical logs, geotechnical testing on core is largely absent.

As geomechanical information on the felsic intrusive bodies at repository depth is lacking, it must be inferred from studies completed on other locations. As such, inferences have been made from geomechanical information derived from other sites elsewhere in the Canadian Shield with similar types of rock; the majority of this information was obtained under the auspices of Atomic Energy of Canada Ltd. (AECL) in the 1980s and 1990s as part of the Canadian Nuclear Fuel Waste Management Program. Information on the geomechanical properties of granitic rocks with conditions ranging from intact rock to highly fractured fault zones is available from AECL's Underground

Research Laboratory (URL) near Pinawa, Manitoba, and the Atikokan research area in Ontario (Brown *et al*., 1989; Stone *et al.*, 1989).

2. PHYSICAL GEOGRAPHY

2.1 Location

The Township of Manitouwadge, located northeast of Lake Superior approximately 265 km northeast of Thunder Bay, and 310 km north-northwest of Sault Ste. Marie (straight-line distance), encompasses 373 km^2. The Township of Manitouwadge and its periphery, referred to as the “Manitouwadge area” in this report, is approximately 4,016 km^2 in size (Figure 1.1). Nearby towns include Marathon, 60 km to the southwest, White River, 70 km to the southeast, and Hornepayne, 78 km to the east. The eastern boundary of the Manitouwadge area is coincident with the western boundary of the Hornepayne area, for which a geoscientific desktop preliminary assessment was completed (Geofirma Engineering Ltd., 2013b).

A Landsat colour composite image of the Manitouwadge area is presented as Figure 2.1. The composite image was created by assigning a primary colour to three of the Landsat multispectral bands (i.e., band 1- blue; band 2 – green; band 3 – red). Different materials reflect and absorb solar radiation differently at different wavelengths and, therefore, have varying intensities within each of the Landsat bands. When combined into a single image, the chosen colour scheme approaches a “natural” representation, where, for example, vegetation appears in shades of green. Exposed soil or rock can appear in lighter tones that can, in some cases, have a pinkish to whitish hue. On Figure 2.1, the widespread whitish patches represent areas where the vegetation has been disturbed, most commonly by forestry operations, such that the “whiter” the area, the more recent the disturbance.

Access to the area is via Ontario Highway 614, which ends at Manitouwadge after trending northward approximately 55 km north from Highway 17 (Trans-Canada Highway). The Caramat Industrial Road exits the Township of Manitouwadge on its western side before heading north and then northwest, eventually connecting with Ontario Highway 11 (Figure 1.1). Access to the interior of the Manitouwadge area is provided by an extensive network of secondary roads and trails primarily developed during forestry operations. Both CN and CPR constructed branchlines from their transcontinental routes from Hillsport (CN) and Pringle (CPR) circa 1950s to service the Noranda Geco and Willroy Mines North of Manitouwadge. Both railways abandoned these lines in the late 1990s and removed the rail infrastructure. The current ownership status and availability for redevelopment is unknown at this time. An airport with a single, paved 1,050 m runway is located 5 km south of the settlement area of Manitouwadge.

2.2 Topography and Landforms

A detailed terrain analysis was completed as part of the preliminary assessment of potential suitability for the Manitouwadge area (AECOM, 2014). This section provides a summary of this analysis.

The Manitouwadge area is located within the Abitibi Upland physiographic region (Thurston, 1991), a subdivision of the extensive James physiographic region (Bostock, 1970). The region is generally characterized by abundant bedrock outcrop with shallow drift cover and a rugged topography. The topography of the Manitouwadge area is presented on Figure 2.2. Bedrock-controlled terrain dominates the majority of the area and results in a notable difference in elevation over short distances; the maximum relief within the Manitouwadge area is approximately 287 m. 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 approximately 21 km southwest of the settlement area of Manitouwadge. Notable variations in elevation caused by bedrock knobs and ridges are prevalent in parts of the Manitouwadge area.

Across large parts of the Manitouwadge area, the elevation of knobs and intervening valleys is commonly between 320 and 380 m (Figure 2.2). Localized areas of higher elevation are present in the central portion of the Township of Manitouwadge, as well as areas to the northeast and southeast. These areas are underlain by the Manitouwadge greenstone belt, metasedimentary rocks of the Quetico Subprovince, and the Black-Pic batholith, respectively. Elevations in these areas commonly range between 380 to 440 m.

Elevations of 280 to 320 m are found in the northeastern portion of the Manitouwadge area and immediately flanking the Pic and White Otter creeks, as well as a northeast-trending band flanking the Black Creek in the southern portion of the area and extending to the east of the Township of Manitouwadge (Figure 2.2). These areas generally correspond to the distribution of glaciolacustrine and glaciofluvial deposits, and, to a lesser degree, ground moraine.

The Pic and White Otter river valleys and some of their tributaries are at elevations less than 280 m over the majority of their length. Located in the west-central and northwest portion of the Manitouwadge area, the river valleys are narrow and are floored with glaciolacustrine sediments.

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 Manitouwadge 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 (Figure 2.3).

The glaciolacustrine deposits in the vicinity of Hillsport 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 Otter Creek and the Nama and Fourbay creek systems ranges between 20 to 60 m due, in part, to erosion (Figure 2.2).

In the region surrounding Manitouwadge, steep slopes (i.e., >6°) are generally associated with areas of bedrock terrain, with the only notable exception being the Pic-White Otter river system. Not surprisingly, the steep slopes associated with bedrock are concentrated in areas of higher relief, including the northern half of the Township of Manitouwadge, the southwestern corner of the Manitouwadge area, and a defuse zone in the east-central portion of the Manitouwadge area. A high density of steep slopes occurs over the nose of the Manitouwadge greenstone belt, in the southwest corner of the Manitouwadge area along the Nama Creek and segments of the Pic Creek.

Broad areas of higher slope density are present over the remainder of the Manitouwadge area, excepting the northeastern and northwestern corners, and restricted pockets in the south-central parts of the area. Areas of low slope density are potential areas of thicker overburden that may obscure the surface expression of lineaments, or introduce uncertainty to the mapping and geologic interpretation of the Manitouwadge area.

2.3 Watersheds and Surface Water Features

The Manitouwadge area straddles the Atlantic and Arctic watershed divide; the watersheds drain via the Lake Superior/Great Lakes/St. Lawrence River and James/Hudson Bay water systems, respectively (Figure 2.4) (LIO, 2013). The Arctic watershed is represented in the area by two tertiary level watersheds, the Nagagami and the Upper Kenogami, which drain pockets of land across the northern edge and a belt along the eastern edge of the area (Figure 2.4, inset map). Drainage to Lake Superior is through the Pic and White tertiary watersheds which cover approximately 85 percent of the land in the Manitouwadge area. Primary waterways within the Pic watershed

are, from west to east, the Pic Creek and its tributary the White Otter Creek, the Black Creek, and the Macutagon Creek. The Gum River is the major drainage feature of the White watershed.
The orientation of the drainage network within the Manitouwadge 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 the 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 2.4).

The larger rivers draining the area's watersheds are fed by numerous smaller creeks and streams that effectively drain all parts of the Manitouwadge area. A higher density of streams is locally present along reaches of the Pic Creek and where Nama Creek exits the area along its western boundary. Here a number of short streams draining adjacent uplands have eroded thick glaciolacustrine deposits occupying bedrock valleys. In contrast, the northern portion of the area has a lower stream density likely due to the fact that the surface relief is more subdued and drainage is not as well developed.

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 creeks and Macutagon Creek, have lower gradients. Rapids and small waterfalls are common in the Manitouwadge area.

The numerous lakes within the Manitouwadge area occupy approximately 4.5 percent (181.8 km^2) of the land surface and occur with an even distribution (Figure 1.1). 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.

In general, the lakes are of a modest size with the majority having a surface area of less than 1.0 km^2. The larger water bodies (≥1.5 km^2) in the Manitouwadge area are listed in Table 2.1.

Table 2-1: Size of lakes equal to or larger than 1.5 km^2 in the Manitouwadge area.

Lake	Area (km^2)	Perimeter (km)
Garnham Lake	4.8	27.9
White Otter Lake	4.7	22.6
Jembi Lake	3.4	21.4
Wowun Lake	2.5	12.9
Barehead Lake	2.2	11.6
Flanders Lake	2.1	21.5
Everest Lake	1.7	8.1
Macutagon Lake	1.7	15.1
Upper Flanders Lake	1.6	13.3
Agonzon Lake	1.5	12.5

Bathymetric surveys have been conducted by the MNR for 67 lakes in the Manitouwadge area; however, the accuracy of these surveys is deemed as questionable (C. Bolton, written comm., 2013). A lake sediment sampling survey conducted by the GSC recorded lake depths at approximately 478 locations in the Manitouwadge area (Friske *et al.*, 1991). While it was the intent of this survey to sample the deepest part of the lakes, this cannot be confirmed. Nevertheless, the lake sediment survey data do provide a general picture of minimum lake depths.

Table 2.2 indicates that approximately 56 percent of the sample sites measured by Friske *et al.* (1991) have a water depth of less than 5 m and nearly 88 percent are less than 10 m deep. Lakes deeper than 20 m account for only 1.0 percent of the sites sampled.

Lakes with a smaller surface area tend to be shallower, but there is only a weak correlation between lake depth and lake size, and no overall relationship between these parameters can be concluded. Lakes occur with near equal consistency over both granitic, greenstone and metasedimentary terrain. Although different rock types could be assumed to be susceptible to more or less erosion or fracturing, the bedrock geology does not appear to be a significant factor in controlling the depth or size of lakes in the Manitouwadge area. Depth data from lakes scattered over the northern half of the Quetico Subprovince does indicate that the percentage of shallower water bodies is higher in this region (AECOM, 2014). This could be a reflection of the fact that a number of these lakes are floored by glaciolacustrine deposits which filled-in bedrock depressions.

Table 2-2: Lake depth data in the Manitouwadge area (from Friske *et al.*, 1991).

Lake Depth (m)	Number of Lake Sites	Percentage
<5.0	267	55.9
5.1 – 10.0	152	31.8
10.1 – 15.0	42	8.8
15.1 – 20.0	12	2.5
>20.1	5	1.0

2.4 Land Use and Protected Areas

Figure 2.5 shows a summary of land disposition and ownership within the Manitouwadge area, including known protected areas (Golder Associates, 2014).

2.4.1 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 (Figure 2.5). 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 Creek and a band extending west then northwest from the settlement area of Manitouwadge.

Mineral exploration is active in the Manitouwadge area on the patented ground and numerous active mining claims held by prospectors and mining companies (MNDM, 2013b). 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 614 and the Caramat Industrial Road. Natural resources are discussed further in Section 5.

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). The southeastern corner of the Manitouwadge area is located within the White River Forest. A sliver of the Nagagami Forest is located along the eastern edge of the Manitouwadge area. 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.

2.4.2 Parks and Reserves

Two protected areas are partially located within the Manitouwadge area (Figure 2.5). The Isko Dewabo Lake Complex Conservation Reserve straddles the southern boundary of the Manitouwadge area west of Highway 614 and covers 29.67 km^2 of which 8.2 km^2 are within the Manitouwadge area. This conservation reserve was established as an outcome of the Ontario's Living Legacy initiative and is described as consisting of "weakly and moderately broken ground (i.e., degree of relief) moraine and weakly and moderately broken bedrock with bog" (Ontario Parks, 2010). No commercial timber harvesting is permitted.

The North Thornhen Lake Moraine Conservation Reserve encompasses an area of 4.54 km^2 northeast of Hillsport, of which approximately 1.5 km^2 is with the Manitouwadge area. The conservation reserve encompasses a portion of a glaciofluvial complex and a small amount of surrounding terrain.

2.4.3 Heritage Sites

Information on archaeological sites in Ontario is provided by the Ontario Ministry of Tourism and Culture, through their Archaeological Sites Database (Ontario Ministry of Tourism and Culture, 2013). Within the Manitouwadge area there are two known archaeological sites. One is located northeast of the settlement area of Manitouwadge in Nickle Township and is described as a pre-contact Aboriginal campsite consisting of lithic material (R. von Bitter, written comm., 2013). The second site, located 35 km north of town, is a pre-contact Aboriginal and historic Euro-Canadian campsite containing a lithic material workstation, possibly from the Shield Archaic and/or contact period (R. von Bitter, written comm., 2013).

Archaeological potential is established by determining the likelihood that archaeological resources may be present on a subject property. In archaeological potential modelling, a distance to water criterion of 300 m is generally employed for primary water courses, including lakeshores, rivers and large creeks, as well as secondary water sources, including swamps and small creeks (Government of Ontario, 2011). Additional First Nation and/or Métis-related archaeological and/or sacred sites may exist within the Manitouwadge area, notably along lake shores and water ways, given the length of time the region has been inhabited by First Nation and/or Metis peoples. The presence of locally protected areas and heritage sites would need to be further confirmed in discussion with the community and First Nation and Métis communities in the vicinity during subsequent evaluation stages, if the community is selected by the NWMO, and remains interested in continuing in the site selection process.

3. GEOLOGY

3.1 Regional Bedrock Geology

3.1.1 Geological Setting

The Canadian Shield forms the stable core of the North American continent and is dominated by the Superior Province comprising ca. 3.0 to 2.6 billion-year-old (Ga) bedrock. The Superior Province is a stable craton created from a collage of ancient plates and accreted juvenile arc terranes that were progressively amalgamated over a period of more than 2 billion years (Figure 3.1) (e.g., Percival *et al*., 2006). The Superior Province covers an area of approximately 1,500,000 km^2 stretching from the Ungava region of northern Québec through the northern part of Ontario and the eastern portion of Manitoba, and extending south to Minnesota and the northeastern part of South Dakota. It is divided into subprovinces: medium- to large-scale regions that are each characterized by their similar rock types, structural style, isotopic age, metamorphic grade, and mineral deposits (Figure 3.1).

A modest majority of the Manitouwadge area is within the Wawa Subprovince, a volcano-sedimentary-plutonic terrane bounded to the east by the Kapuskasing structural zone and to the north by the metasedimentary-dominated Quetico Subprovince (Figures 3.1 and 3.2). The Wawa Subprovince is composed of well-defined greenstone belts of metamorphosed volcanic rocks and associated metasedimentary rocks, separated by granitoid rock units (Figure 3.3 and 3.4). The granitoids that separate the greenstone belts comprise 20 to 30 percent of the landmass of the Wawa Subprovince, and consist of massive, foliated and gneissic tonalite-granodiorite, which is cut by massive to foliated granodiorite and granite. The majority of the granitoids were emplaced 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 (Figures 3.2 to 3.4), consists of migmatitic metasedimentary rocks (Zaleski *et al.,* 1995). Granitic intrusions are widely present throughout the Quetico Subprovince, while mafic to ultramafic intrusions occur sporadically (Williams, 1989; Sutcliffe, 1991).

In more recent years, a tectonic subdivision of the Superior Province into lithotectonic terranes and domains has been developed (Percival *et al*., 2006; Percival and Easton, 2007; Stott, 2010; Stott *et al*., 2010). Terranes are defined as regions with tectonic boundaries with distinct characteristics, while domains refer to lithologically distinct portions within a terrane (Stott, 2010; Stott *et al.,* 2010). The southern portion of the Manitouwadge area is located in the Wawa-Abitibi terrane, a region composed of a series of plutonic and gneissic rocks interspersed with greenstone belts (Figure 3.2), which corresponds to the Wawa and Abitibi Subprovinces (Figure 3.1). This terrane has a length of approximately 2,200 km, stretching westward from central Québec, across the width of Ontario and into northern Minnesota. Within Ontario, the terrane is juxtaposed to the north by the Quetico Basins terrane and to the south by overlying Paleoproterozoic basins (the rocks of the Southern Province (Figure 3.1) dominantly comprising the Animikie foreland basin and the Huronian Supergroup (Ojakangas *et al.,* 2001).

Within the Wawa Subprovince there are two semi-linear zones of greenstone belts, the northern of which includes the Shebandowan, Schreiber-Hemlo, Manitouwadge, Dayohessarah and Kabinakagami greenstone belts. The southern zone comprises the Michipicoten, Mishibishu and Gamitagama greenstone belts which are located west of the Kapuskasing structural zone, well southeast of the Manitouwadge area (Figure 3.2). The Manitouwadge greenstone belt is a northeast- to east-trending, variably dipping, highly deformed and metamorphosed belt of supracrustal rocks. In the Manitouwadge area the greenstone belt forms a 1 to 2 km thick, east- to northeast-trending synform of metavolcanic and subordinate metasedimentary rocks, in addition to layered gabbro-anorthosite

intrusions (Milne, 1968b; Williams and Breaks, 1989; Williams *et al.*, 1991; Zaleski *et al.*, 1995; 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.
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. Granitoid intrusions also occur in the Quetico Subprovince (Figure 3.2).
Several generations of Paleoproterozoic diabase dyke swarms, ranging in age from ca. 2.473 to 2.101 Ga. (Hamilton *et al*., 2002; Buchan and Ernst, 2004; Halls *et al*., 2006), cut all bedrock units in the Manitouwadge area.

Published bedrock geological maps of the region surrounding Manitouwadge (e.g., Zaleski and Peterson, 2001; Johns and McIlraith, 2003) indicate a number of faults that range in length from a few kilometres to several tens of kilometres (Figure 3.3). The largest of these is the Gravel River fault, located approximately 17 km to the northwest of the Manitouwadge area. There are also several mapped northwest- and northeast-trending faults which appear to coincide with the orientations of distinct Paleoproterozoic dykes that transect the Manitouwadge area. In addition, an east-trending fault is mapped in the Quetico Subprovince immediately north of the east-trending Wawa-Quetico subprovince boundary (Figure 3.4).

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., ca. 2.7 to 2.68 Ga, Williams *et al.*, 1991; Corfu and Stott, 1996). Tectonic forces active during the accretion process period produced a zone of highly sheared rocks that extends approximately 15 km at either side of the subprovince boundary (Williams, 1991). It is possible that fault reactivation may have occurred during Proterozoic events such as development of the ca. 1.9 Ga Kapuskasing structural zone (e.g., Percival and West, 1994) or the ca. 1.1 Ga Midcontinent Rift event (Van Schmus, 1992), as evidenced by offsets of dykes that occupy some faults (SRK, 2014). Additional fault movement may also have occurred as a result of Phanerozoic tectonism; however, no tectonic activity associated with this event is evident in the Manitouwadge area.

3.1.2 Geologic History

The initial development of the Wawa-Abitibi terrane took place during the period between ca. 2.89 and 2.77 Ga through progressive accretion of rock assemblages produced in several geological environments. A collage of intraoceanic fragments, including remnants of volcanic arcs, backarcs, and oceanic plateaus, assembled in a migrating subduction-accretion complex (Kerrich *et al.*, 1999; Kerrich *et al.*, 2008), ultimately formed an emerging land mass. Accretion was followed by calc-alkalic volcanism and emplacement of major batholithic complexes (Williams *et al.*, 1992; Corfu and Stott, 1998; Polat, 1998).

The development of the northern portion of the Wawa-Abitibi terrane that comprises the Manitouwadge greenstone belt began ca. 2.72 Ga and continued to as late as ca. 2.677 Ga (Zaleski *et al.*, 1999). Zaleski *et al.* (1999) considered the Manitouwadge belt to be a remnant of volcanic and sedimentary rocks, which were highly deformed and metamorphosed to upper amphibolite facies. It is suggested that the belt may possibly be correlative with the Black River assemblage of the Schreiber-Hemlo belt, as well as the Dayohessarah and Kabinakagami greenstone belts, and as such they would represent dismembered parts of a once continuous greenstone terrane (Stott, 1999). Early work by Tilton and Steiger (1969) and Corfu (reported in Williams and Breaks, 1996) suggested the possibility of older Neoarchean, lower crustal sources for granitoid rocks in the Manitouwadge area, but the large precision errors associated to estimated dates and the lack of field evidence of basement rocks do not favor the existence of older rocks in the Manitouwadge area. Current evidence documented by Zaleski *et al.* (1999) suggests that magmatic ages in the Manitouwadge area are ca. 2.722 Ga and younger.

Felsic metavolcanic rocks associated with the Manitouwadge belt are dated at ca. 2.722 ± 3 Ga (Zaleski *et al.*, 1994) and ca. 2.720 ± 2 Ga (Davis *et al.,* 1994). This volcanic activity coincides with the intense plutonic activity in the Manitouwadge area and beyond in the regional area extending to Wawa and Hornepayne, as attested by the emplacement of the Pukaskwa and Black-Pic gneissic complexes at around ca. 2.72 Ga (Corfu and Muir, 1989; Jackson *et al.*, 1998; Beakhouse *et al.*, 2011). Deposition of metawackes in the Manitouwadge belt, which are intercalated with metavolcanics, did not occur before ca. 2.693 Ga; these are correlative with rocks of the Quetico Subprovince to the north, but not necessarily genetically related (Zaleski *et al.*, 1995; 1999), and constrain the timing of regional, late Neoarchean orogenic uplift and erosion of the crust.

The later stages of development of the Manitouwadge greenstone belt coincided with the accretion of the Wawa and Quetico subprovinces during the period of ca. 2.690 to ca. 2.680 Ga (Corfu and Stott, 1996; Zaleski *et al.,* 1999). The intrusion of a late phase of the Black-Pic batholith recognized in the Manitouwadge area is interpreted to have occurred in this time as Zaleski *et al.* (1995) dated it to be ca. 2.689 Ga. The timing of the emplacement of late-stage granite-granodiorite intrusions, of which there are several in the Manitouwadge area, is not well constrained, although they are believed to be generally less than ca. 2.69 Ga in age. The Loken Lake pluton has been dated at ca. 2.687 Ga (Jackson *et al.*, 1998), the Nama Creek pluton at ca. 2.680 ±3 Ga (Zaleski *et al.*, 1995) and the Fourbay Lake pluton at ca. 2.678 Ga (Beakhouse, 2001); however, regional mapping suggests intrusions may have occurred as late as ca. 2.677 Ga (Zaleski *et al*., 1999).

Based on ages obtained from metamorphic monazites, Zaleski *et al.* (1995; 1999) suggested that near-peak metamorphism of the Manitouwadge greenstone belt occurred between ca. 2.675 and ca. 2.669 Ga; in the Quetico Subprovince, regional upper amphibolites facies metamorphism would have increased after ca. 2.666 Ga to likely peak ca. 2.658 Ga (Pan *et al*., 1994; 1998).

The geological history of the Manitouwadge area during the Proterozoic Eon (i.e., after 2.5 billion years ago) is enigmatic. At the beginning of the Proterozoic Eon, an Archean supercontinent (Williams *et al*., 1991) began fragmenting into several continental masses, including the Superior craton, caused by a widespread and voluminous magmatic event that took place in the Lake Superior region (Heaman, 1997). The rift setting ultimately evolved into a passive margin setting, allowing development of intracratonic basins in many areas across the Lake Superior region, including deposition of the Huronian Supergroup between ca. 2.497 Ga and ca. 2.22 to ca. 2.10 Ga (Corfu and Andrews, 1986; Rainbird *et al*., 2006) along the north shore of Lake Huron. While it is likely that Huronian strata once covered a much larger area than their present distribution, there is no direct evidence to indicate the former existence of Huronian rocks in the Manitouwadge area. However, the occurrence of tillites in the Huronian package elsewhere in Ontario points to the occurrence of several glaciations periods (Young *et al*., 2001), which may suggest that at least one period of glaciation could have affected the Manitouwadge area. If this were the case, any deposits related to this glacial event have been removed by subsequent erosion.

The most prominent indicators of Proterozoic tectonic activity in the Manitouwadge area are the well-defined swarms of diabase dykes that have intruded the Manitouwadge area (Figure 3.4) and a broader region beyond (Figure 3.3). These include: the northwest-trending Matachewan swarm, emplaced ca. 2.473 Ga (Buchan and Ernst, 2004); the Biscotasing swarm, dated at ca. 2.167 Ga (Hamilton *et al.*, 2002) which trends northeast through the Manitouwadge area; and the north-trending Marathon dykes, dated at ca. 2.121 Ga (Buchan *et al*., 1996; Hamilton *et al*., 2002).

During the middle Paleoproterozoic Era, two more major tectonic events occurred south of the Manitouwadge area, in the Lake Superior-Lake Huron area: the ca. 1.89 to ca. 1.84 Ga (Sims *et al.*, 1989) Penokean Orogeny and the younger ca. 1.75 Ga Yavapai Orogeny (Piercey, 2006); there is no evidence of these two orogenies on rocks of the Manitouwadge area.

Around ca. 1.1 billion years ago, a continental-scale rifting event in the Lake Superior area, to the southwest of the Manitouwadge area, produced the Midcontinent Rift structure (Van Schmus, 1992) that extends southward via an eastern branch down through Minnesota, and via a western branch from Sault Ste. Marie to central Michigan. The rifting event included deposition of large volumes of volcanic rocks and voluminous emplacement of mafic intrusions (Heaman *et al*., 2007). Early rift-related alkalic intrusions (e.g., Killala Lake, Prairie Lake and Coldwell Complexes) are located immediately to the west and southwest of the area and are described by Sage (1991). The emplacement of these intrusions is believed to have been influenced by the Trans Superior Tectonic Zone, which is located immediately west of the Manitouwadge area. In spite of the proximity of the Manitouwadge area to the Midcontinent Rift structure, no tectonic activity has yet been documented to have occurred in the Manitouwadge area.

At the start of the Paleozoic Era (ca. 540 Ma), a large portion of Ontario was covered by seas in which carbonate and clastic sedimentary units were deposited. Whilst it can be inferred that Cambrian to Devonian sedimentary rocks once covered large portions of the Canadian Shield between Hudson Bay and Lake Ontario (Johnson *et al.*, 1992), there is no direct evidence that they were present in the Manitouwadge area. It is also possible that the primary control on deposition of these rocks might be largely epeirogenic (e.g., infilling of the Michigan Basin to the south and that of the Moose River Basin to the northeast).

Erosion is believed to have been the dominant geological process affecting the Manitouwadge area from the late Paleozoic Era until at least the late Mesozoic Era (Johnson *et al.*, 1992). Sedimentary deposits resulting from this erosional event have not been documented in the Manitouwadge area. Marine and terrestrial deposits of Cretaceous age are found in the Moose River Basin, James Bay Lowland area, ~225 km to the northeast of Manitouwadge; rocks of similar age have not been documented in the Manitouwadge area.

Erosion is also thought to have been the dominant process affecting the Manitouwadge area during the Paleocene and Neogene Periods (ca. 66 to 2.6 Ma; Johnson *et al.*, 1992), but no sedimentary deposits of this age have been recorded in the Manitouwadge area. During the Quaternary Period (2.6 Ma to present), large parts of North America were covered by continental ice sheets. In the Manitouwadge area, glacial and interglacial deposits, associated with the most recent ice advance during the Late Wisconsinan glaciation (ca. 30 to 10 Ka), have been recorded.

Table 3.1 outlines the major events in the geological history of the Manitouwadge area.

Table 3-1: Summary of the Geological and Structural History of the Manitouwadge area

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 (ca. 2.680 Ga), and Fourbay Lake pluton (ca. 2.678 Ga)
	- ca. 2.719 to ca. 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	ca. 1.1 Ga: Rifting and formation of the Midcontinent Rift structure.
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.
2.6 to 0.01 Ma	Periods of glaciation and deposition of glacial sediments.

3.1.3 Regional 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 Williams and Breaks (1996), Lin (2001), and Percival *et al.* (2006) have also contributed to the structural understanding of the Manitouwadge 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 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 ca. 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- ca. 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 3.1.

3.1.4 Mapped Regional Structure

The east-west-trending Wawa-Quetico subprovince boundary transects the Manitouwadge area (Figure 3.3 and 3.4). Zaleski *et al*. (1995) 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 greentstone 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 3.4). 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 metasedimentary rocks of the Quetico Subprovince, 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 3.4).

3.1.5 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; 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; 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 ca. 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 ca. 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; Pan *et al*., 1994; Zaleski and Peterson 1995). 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 100 km, 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 ca. 2.666 Ga, in agreement with the period ca. 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 4-6 Kbar 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 (G. 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.

3.1.6 Erosion

There is no specific information on erosion rates for the Manitouwadge area. Past studies reported by Hallet (2011) provide general information on erosion rates for the Canadian Shield. The average erosion rate from wind and water on the Canadian Shield is reported to be a few metres per 100,000 years. Higher erosion rates are associated with glaciation. The depth of glacial erosion depends on several regionally specific factors, such as the ice-sheet geometry, topography, and history (occupation time and basal conditions: temperature, stress, and amount of motion), as well as local geological conditions, such as overburden thickness, rock type and pre-existing weathering.

Flint (1947) made one of the first efforts to map and determine the volume of terrestrial glacial sediment in North America, on the basis of which he inferred that the Plio-Pleistocene advances of the Laurentide ice-sheet had accomplished only a few tens of feet of erosion of the Canadian Shield. White (1972) pointed out that Flint's (1947) study ignored the much larger quantity of sediment deposited in the oceans, and revised the estimate upward by an order of magnitude. Subsequently, Laine (1980; 1982) and Bell and Laine (1985) used North Atlantic deposits and all marine sediment repositories of the Laurentide ice-sheet (excluding the Cordilleran Ice Sheet), respectively, to calculate a minimum value for erosion of 120 m averaged over the ice-sheet over 3 million years. Hay *et al.* (1989) contended that the depth of sediment of Laurentide provenance in the Gulf of Mexico was greatly overestimated by Bell and Laine (1985) and reduced the estimate of regional erosion to 80 m over the same period.

3.2 Local Bedrock and Quaternary Geology

3.2.1 Bedrock Geology

The bedrock geology of the Manitouwadge area is shown on Figures 3.3, 3.4 and 3.5. The reduced to pole residual magnetic field and its first vertical derivative over the Manitouwadge area are shown in Figures 3.6 and 3.7, respectively, and regional Bouguer gravity data are shown on Figure 3.8. A detailed interpretation of geophysical data was carried out as part of this preliminary assessment (PGW, 2014) and summarized in this section.

The main geological units in the Manitouwadge area include: the Quetico metasedimentary rocks; the Black-Pic batholith; several granitoid plutons (Fourbay Lake, Loken Lake, Nama Creek, Dotted Lake); a tonalite intrusion; the supracrustal rocks of the Manitouwadge greenstone belt; and several suites or swarms of mafic diabase dykes. Each of these sets of rock units is discussed in more detail below.

A cross-section of the bedrock in the Manitouwadge area, modified from Zaleski and Peterson (2001) and Johns and McIlraith (2003), is presented in Figure 3.5. The figure illustrates the spatial relationship of the metasedimentary rocks of the Quetico Subprovince, the Manitouwadge greenstone belt, the Black-Pic batholith and several smaller felsic intrusions. The Black-Pic batholith is interpreted to underlie the supracrustal rocks south of the Quetico-Wawa subprovince boundary to an undetermined depth, and may be cut by deep faults.

3.2.1.1 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 3.4). These ca. 2.700 to ca. 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 ca. 2.689 Ga and ca. 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).

The geophysical interpretation of the metasedimentary rocks completed as part of the preliminary assessment (PGW, 2014) subdivides the metasedimentary rocks of the Quetico Subprovince based on the results of aeromagnetic surveys (Figures 3.6 and 3.7). The magnetic responses in the Quetico Subprovince are most intense in proximity to the subprovince boundary where individual subparallel lineations are on the order of several hundred metres width. These alternating high and low magnetic lineations are thought to possibly 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) interpreted these alternating lineations as being inclusions of isolated units of mafic to intermediate metavolcanics rocks that are both highly metamorphosed and containing variably developed magnetite content. Miles (1998) suggested 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.

In the Quetico Subprovince a large portion of the metasedimentary rocks are dominanted by low magnetic response; in particular, the northwest part of the Manitouwadge area is weakly magnetized. Locally, higher magnitude magnetic horizons in the northern portion of the Quetico Subprovince, within the area of low-resolution magnetic coverage, may reflect isolated occurrences of higher grade metamorphic rocks, similar to those along the subprovince boundary zone.

Although, the resolution of the gravity and radiometric data for the area underlain by the metasedimentary rocks of the Quetico Subprovince is insufficient to be used for interpretation of geological units and boundaries, this data does provide regional scale information (PGW, 2014). A gravity high is centred within the Quetico Subprovince roughly 6 km north of, and sub-parallel to, the subprovince boundary (Figure 3.8). The high extends outside the Manitouwadge area to the east and southwest for a length exceeding 150 km, and tends to be coincident with a strong east-trending magnetic response associated with deformed metasedimentary rocks to the north of the subprovince boundary. Similar to the interpreted cause of the magnetic anomaly in the Quetico Subprovince, 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.

In the Quetico Subprovince the radiometric response for the majority of the area is unremarkable; however, in the Hillsport area there is a weak gravity low. This low may reflect thicker drift cover in an area of lower elevation and the presence of numerous lakes (PGW, 2014).

3.2.1.2 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 3.4). 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.

The geophysical interpretation of the Manitouwadge area (PGW, 2014) suggests that the geological boundaries of the granite-granodiorite units mapped as occurring in the Quetico Subprovince are not well delineated in the geophysical data sets. The largest of these granitic intrusions, which extends approximately 25 km into the Manitouwadge area from the western boundary (Figure 3.4), is not readily apparent in the magnetic data. The magnetic data suggests that this body may not exist as a continuous belt, but may be restricted to a series of small intrusions as indicated by the presence of a few, relatively narrow, local magnetic lows (PGW, 2014). The other mapped areas of granite-granodiorite rocks in the Manitouwadge area also cannot be discerned from the magnetic data, nor are they evident in the low resolution radiometric and gravity data sets (Figure 3.8).

3.2.1.3 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 3.4). 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, 1993b). 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 ca. 2.720 Ga (Jackson *et al*., 1998). A younger monzodiorite phase has been dated at ca. 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 3.4). 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 3.4), and another mapped, but unsubstantiated pluton toward the east of the Manitouwadge area (Figure 3.4). 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 3.4). Although depicted on a compilation map of the area (Johns and McIlraith, 2003), neither field geologic mapping of the area by Giguere (1972) or interpretation of a recent high resolution geophysical survey yielded evidence to support its existence.

The magnetic data over the Black-Pic batholith shows highly varied response associated with the distribution of mapped gneissic tonalitic suite showing apparent magnetic foliations throughout, and lesser amounts of granite-granodiorite intrusions, gabbro, and metavolcanic rock units (Figure 3.4). The northern part of the Black-Pic batholith contains highly magnetic horizons that strike sub-parallel to the subprovince boundary and which are inferred to reflect deformation along the subprovince boundary (Figures 3.6 and 3.7). Further south, an apparent decrease in magnetic intensity likely reflects a lesser degree of metamorphism further away from the subprovince boundary (Miles, 1998). Several geological boundaries are identified within the Black-Pic batholith, including boundary adjacent to the Manitouwadge greenstone belt and a number of larger granite to granodiorite and gabbroic plutons. These geological boundaries are evident in the magnetic data sets, and are largely emphasized by the presence of high resolution magnetic data.

There is a regional gravity low present across the southern portion of the Black-Pic batholith (Figure 3.8), suggesting that the intrusion may be somewhat thicker in this region. A belt of higher gravity values trending east-northeast across the northern half of the batholith has no explanation from mapped geology, but perhaps reflects deeper levels of the Manitouwadge greenstone belt (PGW, 2014). The radiometric data for the Black-Pic batholith yields higher values in the northern portion of the intrusion (PGW, 2014).

3.2.1.4 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 3.4). The surficial expression of the pluton, dated at ca. 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).

The Loken Lake pluton is a weakly magnetic intrusion whose concentric magnetic horizons are evident in the core of the Manitouwadge greenstone belt (PGW, 2014). Internally, the northeastern portion of the pluton tends to be more magnetic than the remainder. This portion of the pluton has been mapped as potassium-feldspar megacrystic granite and quartz monzonite (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.

3.2.1.5 Foliated Tonalite Suite

A foliated tonalite intrusion that surrounds the Loken Lake pluton, between the arms of the Manitouwadge greenstone belt (Figure 3.4), is interpreted to be synvolcanic with the Manitouwadge greenstone belt, and has been dated at ca. 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, 1995). 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).

The foliated tonalite suite is characterized by several moderate to strongly magnetic horizons which are useful for tracing ductile deformation, notably at its western end (PGW, 2014).

3.2.1.6 Nama Creek Pluton

The Nama Creek pluton is located within the northwest quadrant of the Township of Manitouwadge (Figure 3.4). 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 long 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 ca. 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.

The Nama Creek pluton incorporates a strong magnetic horizon corresponding to a narrow, curvilinear magnetic horizon. In the interpretation of the magnetic data (PGW, 2014), the pluton is included in a package of rocks with similar geophysical signature that surround the Loken Lake pluton. The pluton may be slightly wider along its northern boundary than is currently mapped. Numerous magnetic horizons that 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. The narrow width of the Nama Creek pluton does not allow it to project a gravity or radiometric signature.

3.2.1.7 Fourbay Lake Pluton

The Fourbay Lake pluton is located in the southwest corner of the Manitouwadge area (Figure 3.4). The pluton is described by Milne (1968b) 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 ca. 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.

The Fourbay Lake pluton shows a strong magnetic contrast with the surrounding gneissic tonalite of the Black-Pic batholith, although its internal fabric is not particularly coherent (PGW, 2014). The geological contacts apparent in the magnetic data coincide well with the mapped distribution of the Fourbay Lake pluton, although minor discrepancies exist along the boundary. The pluton is also associated with a gravity high and relatively high response in three radioelements.

To the northeast of the pluton, there is a moderately magnetic zone that has a different character than the surrounding weakly magnetic gneissic tonalite of the Black-Pic batholith and may represent a buried extension and/or phase of the Fourbay Lake pluton (PGW, 2014). This zone may indicate an area where the granite-granodiorite of the Fourbay Lake pluton underlies gneissic tonalite, with variations in its depth-to-top reflected in the magnetic response.

3.2.1.8 Dotted Lake Batholith

The Dotted Lake batholith lies within the southeast corner of the Manitouwadge area (Figure 3.4). 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 ca. 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.

3.2.1.9 Manitouwadge Greenstone Belt

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 3.4). 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).

Strong east-trending magnetic horizons are present with the Manitouwadge greenstone belt in the areas on either side of the settlement area of Manitouwadge and along the northern limb of the synform. Discrete northeast-oriented magnetic horizons are also present in the part of the greenstone belt located adjacent to the eastern boundary of the Manitouwadge area (PGW, 2014). Mapping the extent of the greenstone belt on the basis of its magnetic signature is difficult due to its narrow width and/or to the intense tectono-metamorphic overprint that it has experienced related to its proximity to the Quetico-Wawa subprovince boundary.

3.2.1.10 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 3.4). 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). The Faries-Moshkinabi intrusion is marked by a moderate magnetic intensity that strikes northeastward (PGW, 2014).

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 3.4). 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). A northward oriented magnetic signature of moderate intensity is present over the Rawluk Lake intrusion (PGW, 2014).

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 3.4). 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.

The Bulldozer Lake intrusion stands out as a strongly magnetic area in contrast to the more subdued surrounding magnetic signal of the Black-Pic batholith's gneissic tonalite (Figure 3.6). The intrusion has some concentric foliation along its margins and variable internal fabric (PGW, 2014). The intrusion has a high radioelement response and, although it is within an area of a gravity low, this may be largely due to the influence of the surrounding Black-Pic batholith.

3.2.1.11 Mafic Dykes

Several diabase dyke swarms crosscut the Manitouwadge area (Figure 3.4), 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 3.4). This is a result of the combination of various data sets 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.

The three dyke swarms in the Manitouwadge area are generally distinguishable by their unique strike directions, cross-cutting relationships and, to a lesser extent, by magnetic amplitude. Where the dykes cut the more magnetic rocks on either side of the Wawa-Quetico subprovince boundary, many appear as locally magnetic lows rather than the typical highs further to the north and south. This is due to their lower magnetic susceptibility relative to the host rocks of the subprovince boundary zone (PGW, 2014). SRK (2014) notes that several of the dykes occupy faults, some of which show offsets along strike.

One aspect of uncertainty is the likelihood that thin dykes, while known to be present in the host rock, could be too small to be identified with any confidence from the available geophysical data. For example, Halls (1991) characterized the Matachewan dykes as having a median width of ca. 20 m, but also described minor dykelets as narrow as several cm in width that were recognized during detailed field mapping. West and Ernst (1991) suggested further that narrow dykes may produce anomalies of insufficient magnetic intensity to be traced with any confidence. Halls (1982) discussed the bifurcating and branching geometry of the Matachewan dykes which was also determined based on detailed field mapping. In addition, it is well understood, but not easily quantifiable from geophysical data alone, that dyke propagation could induce damage to the host rock within an envelope around the dyke that varies with the size of the intrusion (e.g., Meriaux *et al*., 1999). The presence of smaller dykes and the potential for damage to the host rock between dykes would need to be evaluated at later stages of the assessment, through the collection of site-specific information.

3.2.2 Quaternary Geology

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 glaciation (30,000 to 10,000 years ago). The Quaternary (i.e., surficial) geology of the Manitouwadge 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; 1980b; 1980c). 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, 1985). Over the majority of the Manitouwadge 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 2.3). 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, 2014) provides a more detailed assessment of the type, distribution and thickness of surficial deposits in the Manitouwadge area (Figure 2.3).

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 (A. 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 Manitouwadge area, and as such the ICSD feature trend south and southwest (Figure 2.3). 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 2.3). 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 Manitouwadge 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 2.3). 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 Manitouwadge area (Figure 2.3). 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.

3.2.3 Lineament Investigation

A detailed lineament investigation was conducted for the Manitouwadge area (SRK, 2014) using publicly available remote sensing data sets, including airborne geophysical data, digital elevation model data and satellite imagery data. Lineaments are linear features that can be observed on remote sensing and geophysical data and which may represent geological structures (e.g., fractures). However, at this stage of the assessment, it is uncertain if interpreted lineaments are a reflection of real geological structures, and whether such structures extend to depth. The assessment of these uncertainties would require detailed geological mapping and borehole drilling.

The lineament investigation identified interpreted brittle structures, dykes, and ductile lineaments in the Manitouwadge area, and evaluated their relative timing relationships within the context of the local and regional geological setting. A detailed analysis of interpreted lineaments is provided by SRK (2014), and key aspects of the lineament investigation are summarized in this section.

At this desktop stage of the investigation, the remotely-sensed character of interpreted features allows only for their preliminary categorization, based on expert judgement, into three general lineament classes, including ductile, brittle, and dyke lineaments. Each of these three lineament categories is described in more detail below in the context of its usage in this preliminary desktop assessment.

- **Ductile lineaments** represent all interpreted features that conform to the penetrative ductile rock fabric in the Manitouwadge area, including foliation traces and lithostructural contacts.
- **Brittle lineaments** Features interpreted as fractures (joints or joint sets, faults or fault zones, and veins or vein sets), including those that offset the continuity of the ductile fabric described above, were classified as brittle lineaments. This category also includes brittle-ductile shear zones, and brittle partings interpreted to represent discontinuous re-activation parallel to the ductile fabric. At the desktop stage of the investigation, this category also includes features of unknown affinity. This category does not include interpreted dykes, which are classified separately (described below).
- **Dyke lineaments** represent all interpreted non-conforming features that have been distinguished from the brittle lineaments based on their distinct character (e.g., scale, continuity, orientation, and geophysical signature), and often also based on pre-existing knowledge of the bedrock geology of the Manitouwadge area.

For each data set, brittle lineaments were interpreted by two independent experts using a number of attributes, including certainty and reproducibility (SRK, 2014). The certainty attribute describes the clarity of the lineament within each data set based on the expert judgement and experience of the interpreter (i.e., with what certainty is a feature interpreted as a lineament). Reproducibility was assessed in two stages (RA_1 and RA_2). Reproducibility assessment RA_1 reflects the coincidence between lineaments interpreted by the two experts within a data set. Reproducibility assessment RA_2 reflects the coincidence of interpreted lineaments between the three data sets used (geophysical, satellite imagery, topographic data). Combined surficial and geophysical lineaments are presented in Figure 3.9 and 3.10, respectively. In addition, ductile features (i.e., magnetic form lines) were identified from the geophysical data set (Figure 3.11). These features are included to provide context to the understanding of the tectonic history of the Manitouwadge area, but were not included in the merged lineament sets or statistical analyses. A detailed description of the lineament investigation workflow, and discussion of the results of the analysis, is provided by SRK (2014). The key aspects of the lineament investigation are summarized in this section.

The resolution of each available data set has a strong impact on the resolution and number of interpreted lineaments. The GDS1205 data set has a high resolution (150 – 200 m line spacing; 30 m grid cells) and covers approximately 77 percent of the Manitouwadge area (Figure 1.2; Table 1.1). The remainder of the Manitouwadge area is covered by the lower resolution Single Master Gravity and Aeromagnetic (SMGA) data for Ontario (GDS1036) data set (805 m line spacing; 200 m grid cells). In the area covered by the high-resolution data set, it was considered that other available data sets with lower resolution were not favorable for the use in the lineament investigation (Figure 1.2).

The Spot 4/5 satellite and Landsat 7 satellite images cover the entire Manitouwadge area and have resolutions of 20 m and 30 m, respectively (Figure 2.1). The CDED topography data covers the entire Manitouwadge area with a resolution of 8 to 23 m (Figure 2.2). The satellite and topography data cover the entire Manitouwadge area with a good resolution. However, the bedrock structural information available from these three data sets is limited in various sectors of the Manitouwadge area due to Quaternary cover (Figure 2.3). The sectors of the Manitouwadge area where bedrock structures are concealed by Quaternary cover include the northernmost quarter of the Manitouwadge area and an approximately 10 km wide linear zone trending northeast in the central south sector of the area (Figure 2.3). The total area of Quaternary cover where the satellite and topography data were of limited use is approximately 200 km^2 of the Manitouwadge area (Figure 2.3). In addition, the majority of the area affected by Quaternary cover (i.e., the northern extent of the Manitouwadge area) is not covered by high resolution geophysics. Consequently, in this area, few lineaments associated with bedrock features were identified with certainty, resulting in a low lineament density. The remaining areas affected by Quaternary cover in the Manitouwadge area are covered by the high resolution GDS1205 survey, which allowed for the interpretation of reliable bedrock structures.

Combined interpretation of CDED and satellite data sets yielded 2,716 lineaments that were reported as surficial lineaments, 2,553 interpreted brittle lineaments, and 163 as dyke lineaments (Figure 3.9; SRK, 2014). Of this total, 933 lineaments (34%) were coincident in both CDED topography and satellite imagery data. The coincidence between these data sets is in part explained by the fact that lineaments interpreted from the satellite imagery and the digital elevation data represent surficial expressions of the same bedrock feature. Conversely, the lack of coincidence between the two surficial data sets can be attributed to a significant quantity of structures observed in the topography data that are obscured by vegetation and other surficial elements in the satellite data.

The surficial lineaments range in length from 230 m to 83.5 km, with a geometric mean length of 3.6 km and a median length of 2.2 km (SRK, 2014). Surficial brittle lineament orientations exhibit dominant northwest, northeast, and north trends, and a minor east-west trend. Of these orientations, the northwest- and north-trending brittle lineaments are sharply defined, and the northeast- and east-west-trending brittle lineaments exhibit a diffuse pattern. Surficial dyke lineament orientations exhibit dominant well-defined northwest, northeast, and north trends (Figure 3.9 inset).

The 163 dyke lineaments in the Manitouwadge area were divided into three groups (SRK, 2014) on the basis of their orientation:

- 53 dyke lineaments are interpreted to belong to the northwest-trending Matachewan dyke swarm;
- 40 dyke lineaments are interpreted to belong to the northeast-trending Biscotasing dyke swarm; and
- 70 dyke lineaments are interpreted to belong to the north-trending Marathon dyke swarm.

Interpretation of the geophysical magnetic data resulted in a data set containing 1,679 geophysical lineaments (SRK, 2014). Of the 1,679 lineaments, 1,286 are interpreted as brittle lineaments, while 393 are interpreted as dyke lineaments (Figure 3.10). The length of the magnetic lineaments ranges from 200 m to 83.5 km, with a geometric mean length of 4.6 km and a median length of 2.7 km. Azimuth data, weighted by length, for the magnetic lineaments interpreted as brittle lineaments exhibit a dominant orientation to the northwest, northeast, north and east-west. Lineaments interpreted as dykes exhibit a dominant northwest orientation, and less dominant north-northeast to northeast orientations. Each orientation of dyke lineament likely corresponds to a separate suite of dykes (SRK, 2014).

A total of 393 of the 1,679 lineaments interpreted from geophysical data in the Manitouwadge area are interpreted as dyke lineaments. On the basis of their orientation the 393 dyke lineaments were divided into three groups:

- 129 dyke lineaments are interpreted to belong to the northwest-trending Matachewan dyke swarm;
- 83 dyke lineaments are interpreted to belong to the northeast-trending Biscotasing dyke swarm; and
- 181 dyke lineaments are interpreted to belong to the north-trending Marathon dyke swarm.

The final merged data set (Figure 3.12) containing both surficial and geophysical lineaments yielded 3,743 lineaments, 3,336 of these were interpreted as brittle lineaments, while 407 were interpreted as dyke lineaments. The merged data set total contains all lineaments, regardless of how their reproducibility was attributed. Orientation data for the merged lineament data set exhibit the same dominant trends as described in the previous section, namely dominant northeast-, northwest-, and north-trending lineaments, in addition to significant but less dominant east-west trending lineaments. It should be noted that the rose diagrams for the brittle and dyke lineaments (Figure 3.12 inset, Figure 3.13) are weighted by lineament length; thus, these orientations are influenced by longer lineaments. Lineaments longer than 10 km (N = 218) and lineaments from 5 to 10 km in length (N = 406) represent 6% and 11% of the merged lineaments, respectively, while lineaments from 1 to 5 km long (N = 2,647) and less than 1 km long (N = 472) represent 71% and 12% of the merged lineaments, respectively. SRK (2014) noted the following with regard to the final merged lineament data set:

- The resolution of each available data set has a strong impact on the reproducibility and number of interpreted lineaments. The higher resolution of the surficial data sets over the entire Manitouwadge area may explain why a larger number of lineaments are identified from the combination of these data sets compared to the geophysical data sets;
- Longer lineaments generally have a higher certainty and reproducibility;
- There is a higher confidence that the longer features that were identified are related to bedrock structures;
- The observed overlap in dominant lineament orientation between all data sets (Figures 3.9, 3.10 and 3.13) suggests that all data sets are identifying the same regional sets of structures;
- Resolution and distribution of the data sets used form a suitable basis to conduct a robust lineament interpretation in the Manitouwadge area.

The drawing of ductile features (i.e., stratigraphic and structural form lines) was completed using first vertical-derivative magnetic data. These lineaments are shown in Figure 3.11 and were not used in lineament statistics (e.g., rose diagrams, density plots). The form lines trace the geometry of magnetic high lineaments and represent the geometry of stratigraphy within metavolcanic and metasedimentary rocks, or the internal fabric (foliation) within batholiths and gneissic rocks. This process highlighted discontinuities between form lines, particularly in stratigraphic form lines (e.g., intersecting form lines) that represent structural lineaments (e.g., faults, folds, unconformities, or intrusive contacts).

Of the 1,679 lineaments observed in aeromagnetic data, 652 lineaments (39%) were reproduced in at least one surficial data set. The coincidence between these data sets is in part explained by the fact that lineaments are related to significant bedrock structure and are, therefore, observed in multiple data sets. The lack of coincidence between the magnetic data and the surficial data may be the result of various factors, such as: deeper structures identified in geophysics may not have a surface expression, surficial features may not extend to great depth, and structural features may not possess a magnetic susceptibility contrast with the host rock.

In particular, geophysical data was very effective in identifying dykes, whereas surficial data sets were rarely able to identify dyke lineaments. However, during the reproducibility / coincidence process, it was observed that certain surficial lineaments initially interpreted as brittle lineaments were coincident with dyke lineaments identified from the geophysical data sets. In this case, these surficial lineaments were characterized as dyke lineaments.

The total density of lineaments in the Manitouwadge area (surficial and geophysical) is presented as Figure 3.14. This figure was constructed using all lineaments regardless of how their reproducibility was attributed. In general, lineament density is higher in and around the Manitouwadge greenstone belt, over the Rawluk Lake pluton and in the Twist Lake area north of the Dotted Lake batholith.

As a means of evaluating the influence of lineament length on lineament density across the Manitouwadge area, the results of progressive “filtering” by lineament length are shown in Figures 3.15 to 3.17. These figures illustrate only lineaments >1 km, >5 km, and >10 km, respectively. This process allows longer lineaments to be viewed more easily. Limited change in the density pattern exists with the exclusion of the <1 km lineaments (Figure 3.15). However, a marked decrease in lineament density occurs when only those lineaments of >5 in length are considered (Figure 3.16) as a large percentage of the surficial lineaments no longer form part of the database. Another notable, but somewhat less significant, decrease in density occurs when all lineaments <10 km are excluded (Figure 3.17). When considering lineaments >10 km, geophysical lineaments are dominant with the surficial lineaments largely restricted to the Quetico Subprovince.

Although the brittle lineaments density in the Manitouwadge area is high, areas with a relatively low density of brittle lineaments can be identified. In addition, as the progressive filtering by lineament length is applied, the position of these low density areas remains the same.

Figure 3.18 shows the combined data sets (i.e., mapped regional faults, brittle lineaments, dykes and ductile features) which helps provide a structural understanding of the Manitouwadge area. All mapped faults shown on Figure 3.4 were reproduced to some degree during the lineament analysis. Some mapped faults were reproduced in their entirety, while others were partially reproduced and/or were interpreted as multiple lineament segments. Certain mapped faults were also interpreted as dykes and dykes coincident with faults. For most mapped faults at least a segment of the fault was observed in all three data sets (CDED, satellite and geophysical).

The orientation of the dense network of lineaments in the Manitouwadge area provides a framework to interpret the geological history of the area by linking the lineaments with the structural history of the Manitouwadge area. This was accomplished by defining the age relationships of the interpreted lineaments on the basis of crosscutting relationships between different generations of brittle lineaments.

3.2.3.1 Relative Age Relationships of Lineaments

The structural history of the Manitouwadge area, outlined in Section 3.1.3, provides a framework that may aid in constraining the relative age relationships of the interpreted bedrock lineaments. In brief summary, previous work in and around the Manitouwadge area has identified six regionally distinguishable deformation episodes (D_1 – D_6) that are inferred to have overprinted the bedrock geological units of the Manitouwadge area. The lineament interpretation is fairly consistent with regional observations; however, the D_5 and D_6 events interpreted from the current lineament analysis differ from the D_5 and D_6 events described in the literature.

D_1 developed a compositional layering and isoclinal folds between ca. 2.719 and ca. 2.691 Ga. D_2-D_4 produced the dominant brittle-ductile structures observed within the greenstone belts, including steeply dipping foliations, isoclinal folds, and thrust faults prior to ca. 2.680 Ga. D_5 was a brittle deformation event that involved the activation and possible re-activation of major regional faults sub-parallel to S_2 between ca. 2.680 and ca.1.100 Ga. D_6 represents another regional brittle deformation event that occurred between ca. 2.680 and ca. 1.100 Ga.

The 3,743 brittle lineaments identified in the Manitouwadge area are interpreted to represent successive stages of brittle-ductile and brittle deformation. Therefore, these lineaments can be classified into three main stages based on relative age and in consideration of the structural history described above: 527 D_2-D_4 lineaments; 1,190 D_5 lineaments; and 2,026 D_6 lineaments. D_2-D_4 brittle lineaments are interpreted as Archean brittle-ductile faults characterized as zones of pervasive foliation and phyllonite development, potentially with hydrothermal veining. D_5

and D_6 brittle lineaments are interpreted as brittle faults characterized as zones of pseudotachylite, gouge, and/or breccia. Limited information exists on the character of each interpreted fault set. At the desktop stage of preliminary assessment, it is still uncertain whether or not each interpreted lineament is, in fact, an actual brittle-ductile or brittle geological feature with a significant expression at depth.

Three populations of dykes have been identified in the lineament interpretation that appear to correspond to: the ca. 2.473 Ga, northwest-trending Matachewan dyke swarm (Buchan and Ernst, 2004); the ca. 2.167 Ga northeast-trending Biscotasing dyke swarm (Hamilton *et al.*, 2002); and the ca. 2.121 Ga north-trending Marathon dyke swarm (Buchan *et al*., 1996; Hamilton *et al*., 2002), respectively. The timing between D_6 faults and the Marathon dyke swarm (ca. 2.1 Ga) appears ambiguous. D_6 faults can be coincident with Marathon dykes and, as such, earlier structures can appear offset along the trend of an individual dyke. Elsewhere, Marathon dykes are observed to crosscut D_6 faults with no observable offset. Biscotasing or Marathon dykes were not observed to be offset by D_6 faults. It is therefore likely that D_6 faults formed prior to emplacement of the Marathon dyke swarm and that the dykes exploited pre-existing weaknesses along the D_6 faults. It is also possible that some fault reactivation may have occurred coeval with, or after dyke emplacement, and this could account for the apparent offset of structures observed along dykes. Apart from these timing constraints, there are no additional absolute age constraints for these phases of deformation.

No information is available on the depth of fault penetration in the Manitouwadge area; however, brittle lineament strike length may be a proxy for the depth extent. In general, D_6 faults have the longest strike length (3.9 km average length, 2.4 km median length), followed by D_2-D_4 faults (3.8 km average length, 2.1 km median length), and D_5 faults (2.8 km average length, 2.1 km median length).

3.2.3.2 Lineament distribution in selected lithologic units

As described in Section 3.2.1, the bedrock geology of the Manitouwadge area is dominated by the metasedimentary rocks in the Quetico Subprovince; in the Wawa Subprovince, the bedrock is dominated by the granitic Black-Pic batholith and smaller intrusive bodies that intrude older metavolcanic and metasedimentary rocks associated with greenstone belts. The following subsections describe the characteristics of the interpreted lineaments for select lithological units, consisting of the Quetico Subprovince, the Black-Pic batholith, and the Fourbay Lake pluton. Lineament orientation trends for these units are presented in Figure 3.13 and discussed below.

Quetico Subprovince

The Quetico Subprovince covers approximately 1,740 km^2 in the northern half of the Manitouwadge area. A total of 1,423 lineaments (1,332 brittle, 91 dyke) were interpreted in the Quetico Subprovince, including those that cross the boundary of the Quetico Subprovince (Figures 3.13 and 3.18; SRK, 2014). Of the 1,332 brittle lineaments, 288 are interpreted as D_2- D_4 faults, 362 as D_5 faults, and 682 as D_6 faults. The interpreted lineaments within the Quetico Subprovince range in strike length from 230 m to 82.5 km.

The different types of lineaments (brittle and dyke) have different dominant orientations (Figure 3.13). Brittle lineaments trend predominantly northwest, northeast, and east-west. Lineaments interpreted as dykes trend predominantly toward the northwest, and are interpreted as members of the Matachewan dyke swarm. Minor dyke lineaments trend north and northeast, and are interpreted as members of the Marathon and Biscotasing dyke swarms, respectively.

Areas of low lineament density are observed within the Quetico Subprovince, particularly along the northern boundary of the Manitouwadge area (Figure 3.18). These low density areas are likely the result of low resolution geophysical data and considerable amounts of Quaternary cover, limiting the ability to interpret lineaments from both geophysical and surficial data sets.

Black-Pic Batholith

A total of 1,903 lineaments (1,629 brittle and 274 dyke) were interpreted in the Black-Pic batholith, an area that covers approximately 1,607 km^2 in the southern half of the Manitouwadge area (Figures 3.13 and 3.18; SRK, 2014). These lineaments include all lineaments that are contained within and crosscutting the boundary of the batholith. Of the 1629 brittle lineaments, 112 are interpreted as D_2- D_4 faults, 686 as D_5 faults and 831 as D_6 faults. The interpreted lineaments within the Black-Pic batholith range in strike length from 270 m to 83.5 kilometres.

The different types (brittle and dyke) lineaments show different dominant orientations (Figure 3.18). Brittle lineaments trend predominantly northwest and northeast, with a lesser number trending north. Lineaments interpreted as dykes trend predominantly north-northeast and are interpreted as members of the Marathon dyke swarm. A lesser number of dyke lineaments trend northwest and northeast, and are interpreted as members of the Matachewan and Biscotasing dyke swarms, respectively. Local areas of relatively low lineament density are observed throughout the central portion of the Black-Pic batholith (Figure 3.18).

Fourbay Lake Pluton

The Fourbay Lake pluton covers approximately 64 km^2 in the southwest corner of the Manitouwadge area. A total of 84 lineaments (78 brittle, 6 dykes) were interpreted in the Fourbay Lake pluton (Figures 3.13 and 3.18; SRK, 2014), including all lineaments that are contained within and crosscutting the boundary of the pluton. The interpreted lineaments within the Fourbay Lake pluton range in strike length from 460 m to 38.6 km. Of the 78 brittle lineaments, 18 are interpreted as D_5 faults and 60 as D_6 faults.

Brittle and dyke lineaments show dominant northeast and northwest orientations (Figure 3.13). Northwest-trending dykes are interpreted as members of the Matachewan dyke swarm, and northeast-trending dykes as members of the Biscotasing dyke swarm. The centre of the pluton exhibits a low lineament density (Figure 3.18).

3.3 Seismicity and Neotectonics

3.3.1 Seismicity

The Manitouwadge area lies within the Superior Province of the Canadian Shield where large parts have remained tectonically stable for the last 2.5 billion years (Percival and Easton, 2007). Figure 3.19 illustrates the location of earthquakes with a magnitude 3 or greater that are known to have occurred in Canada from 1627 to 2012 (Earthquakes Canada, 2013). The Canadian Shield is considered the least seismically active portion of the North American continent (Maloney *et al.*, 2006). Hayek *et al.* (2011) indicated that the general western Superior Province has experienced a number of low magnitude, shallow seismic events, with all recorded earthquakes since 1982 being of a magnitude less than 3 (Earthquakes Canada, 2013).

Within the Manitouwadge area, for the period 1985 to 2013, two earthquakes with magnitudes of 2.1 and 2.2 have been recorded in the Quetico Subprovince immediately northwest of Hillsport (Figure 3.20). Other seismic events in close proximity to the area have epicentres 7 km to the east, near Granitehill Lake (magnitude 2.6) and 15 km to the south (magnitude 2.1). A number of low magnitude earthquakes, with magnitudes between 1 and 3, have occurred in scattered locations in the region surrounding Manitouwadge (Figure 3.20).

In summary, available literature and recorded seismic events indicate that the Manitouwadge area is located within a region of low seismicity, the tectonically stable portion of the Superior Province of the Canadian Shield.

3.3.2 Neotectonic Activity

Neotectonics refers to deformations, stresses, and displacements in the Earth's crust of recent age or which are still occurring. These processes are related to tectonic forces acting in the North American plate as well as those associated with the numerous glacial cycles that have affected the northern portion of the plate during the last million years, including all of the Canadian Shield (Shackleton *et al*., 1990; Peltier, 2002).

The movement and interaction of tectonic plates creates horizontal stresses that result in the compression of crustal rocks. The mean of the current major horizontal principal stress orientation in central North America, based on the World Stress Map (Zoback, 1992) is northeast (63° ±28°). This orientation coincides roughly with both the absolute and relative plate motions of North America (Zoback, 1992; Baird and McKinnon, 2007), and is controlled by the present tectonic configuration of the North Atlantic spreading ridge (Sbar and Sykes, 1973), which has likely persisted since the most recent Paleocene-Eocene plate reorganization (Rona and Richardson, 1978; Gordon and Jurdy, 1986).

The geology of the Manitouwadge area is typical of many areas of the Canadian Shield, which have been subjected to numerous glacial cycles during the last million years, resulting in post-glacial isostatic rebound in the northern portion of the North America plate. During the maximum extent of the Wisconsinan glaciation, approximately 21,000 years ago (Barnett, 1992), the Earth's crust was depressed by more than 340 m in the Minnesota/North Dakota area (Brevic and Reid, 1999), due to the weight of glacial ice. The amount of crustal depression in the Manitouwadge area would be of a somewhat greater magnitude, due to its closer proximity to the main centre of glaciation located over Hudson Bay.

Post-glacial isostatic rebound began with the waning of the continental ice sheets and is still occurring across most of Ontario. Vertical velocities show present-day uplift of about 10 mm/a near Hudson Bay, the site of thickest ice at the last glacial maximum (Sella *et al*., 2007). The uplift rates generally decrease with distance from Hudson Bay and change to subsidence (1-2 mm/a) south of the Great Lakes. The ‘‘hinge line’’ separating uplift from subsidence is consistent with data from water level gauges along the Great Lakes, showing uplift along the northern shores and subsidence along the southern ones (Mainville and Craymer, 2005). Current rates of isostatic uplift in the Manitouwadge area are not precisely known; although Lee and Southam (1994) estimated that the land is rising at a rate of 2.9 mm/a at Michipicoten, Ontario, some 150 km to the southeast.

As a result of the glacial unloading, acting along with tectonic stresses, principal stress magnitudes and orientations are changed. Seismic events could be associated with these post-glacial stress changes as a result of reactivation of existing fracture zones. In addition, natural stress release features can include elongated compressional ridges or pop-ups such as those described by McFall and Allam (1990), McFall (1993) and Karrow and White (2002).

No neotectonic structural features are known to occur within the Manitouwadge area. It is therefore useful to review the findings of previous field studies involving fracture characterization and evolution as it pertains to glacial unloading. McMurry *et al*. (2003) summarized several studies conducted in a number of plutons in the Canadian Shield and in the crystalline basement rocks in western Ontario. These various studies found that fractures below a depth of several hundred metres in the plutonic rock were ancient features. Early-formed fractures have tended to act as stress domain boundaries. Subsequent stresses, such as those caused by plate movement or by continental glaciation, generally have been relieved by reactivation along the existing zones of weakness rather than by the formation of large new fracture zones.

Under the appropriate conditions, glacial deposits may preserve neotectonic features indicative of paleo-seismic activity. Existence of such features can be used to extend the seismic record for a region well into the past. In the Manitouwadge area should any pop-up features be present, they may be recognized by their narrow, linear shape which could extend for hundreds of metres (White *et al.,* 1973). Such features would likely only be found in areas of bedrock outcrop or thin overburden cover (<1 to 2 m). It is possible that tree cover, typical of that found in the boreal forest, would assist in making their identification difficult when interpreting air photo or other remotely sensed imagery. Faults resulting from neotectonic activity may be equally challenging to discern from ancient features. Recent faults (i.e., post-glacial faults) may show evidence of displacement, fresh brecciation or an unhealed character suggestive of recent formation.

4. HYDROGEOLOGY

4.1 Groundwater Use

The Township of Manitouwadge obtains its municipal water supply from five drilled wells located within the settlement area (Tourout and Richard, 2012).

There is limited information on groundwater resources in the Manitouwadge area as the Ontario Ministry of Environment Water Well Database (MOE, 2013) contains records of only 50 water wells and two monitoring nest installations. The majority of the wells are within the township boundary (Figure 4.1). A summary of available data from the well records, regarding aquifer type, yield and other parameters, is listed in Table 4.1.

Table 4-1: Water Well Record Summary for the Manitouwadge Area

Water Well Type (water source)	Number of Wells	Total Well Depth (m)	Average Well Depth (m)	Depth to Top of Bedrock (m)	Static Water Level (mbgs)	Tested Well Yield (L/min)
Overburden	20	4.6 to 30.2	16.8	N/A	0.9 to 11.0	68 to 2,795
Bedrock	30	1.8 to 119.2	28.7	0 to 29.6	0.6 to 10.7	4.5 to 27
Monitoring Nest	2					

Blank fields - no data available

4.2 Overburden Aquifers

There are 20 water wells in the Manitouwadge area that extract groundwater from an overburden aquifer. Water wells confirmed to be developed in overburden are largely within glaciolacustrine deposits that transect the central portion of the Township of Manitouwadge, around the town site, and have depths of between 4.6 and 30.2 mbgs indicating that bedrock is at a greater depth (MOE, 2013). Wells terminating in sand and gravel have reported test pumping rates of 68 to 2,795 L/min; however, these yields may not be reflective of aquifer capacity, as the wells primarily supply residences with limited demand. Static water levels in the wells are shallow, ranging from 0.9 to 11.0 mbgs. The limited number of well records limits the interpretation of available information regarding the extent and characteristics of overburden aquifers in the Manitouwadge area.

4.3 Bedrock Aquifers

No information was found on deep bedrock groundwater conditions in the Manitouwadge area at a typical repository depth of approximately 500 m. Within the Manitouwadge area, 30 water wells are recorded as being developed in bedrock (MOE, 2013). These wells encountered bedrock at depths ranging from 0 to 29.6 mbgs, and have maximum depths of between 1.8 and 119.2 mbgs. Reported test yields range from 4.5 to 27 L/min with static water levels ranging from 0.6 to 10.7 mbgs.

The reported well test yields reflect the purpose of the wells (i.e., private residential supply) and do not necessarily reflect the maximum sustained yield that might be available from the shallow bedrock aquifers. Long-term groundwater yield in fractured bedrock will depend on the number and size of fractures, their connectivity, transmissivity, storage, and on the recharge properties of the fracture network in the wider aquifer. Gartner and McQuay (1980a) noted that groundwater resources within bedrock are limited to fractures, faults, and fissures making the occurrence of bedrock aquifers unpredictable.

The MOE water well records indicate that no potable water supply wells are known to exploit aquifers at typical repository depths in the Manitouwadge area or anywhere else in Northern Ontario.

4.4 Regional Groundwater Flow

In many shallow groundwater flow systems the water table is generally a subdued replica of the topography (AECOM, 2014). The variation of the water table elevation across an area reflects the changes in hydraulic head, the driving force within the flow system. However, the pattern of groundwater flow will also be influenced by horizontal and vertical variations in the hydraulic properties of the medium, for example associated with inter-bedding of sand and clay layers in overburden sediments and the presence of fracture networks in bedrock. As a general concept, shallow groundwater flow in Canadian Shield terrain will tend to be directed from areas of higher hydraulic head, such as highlands, towards areas of lower hydraulic head such as adjacent or nearby valleys and depressions. The extent of these localized flow systems are defined by local, topography-controlled, drainage divides across which flow will not readily occur. However, the geometry of shallow flow systems can be more complex in the presence of permeable fracture zones and more complex topography.

Within the Manitouwadge area, it is believed that groundwater flow divides mimic the boundaries of surface watersheds (Figure 2.4) due to the fact that large areas are characterized by the presence of bedrock at or near the surface. Groundwater recharge in these areas is through an interconnected fracture network present in the bedrock. Recharge can be rapid but is largely restricted to a near surface zone. Groundwater flow is directed toward flanking valleys and depressions where the bulk of the groundwater discharges either directly to waterways or into surficial deposits occupying the lower ground. Surficial deposits on the highland bedrock areas, most commonly till, are usually thin and relatively coarse-grained, allowing downward infiltration to the bedrock surface. These high relief areas can have higher hydraulic gradients that may impact the depth extent of shallow flow systems. Site specific, subsurface characteristics such as hydraulic conductivity and groundwater density variations, will also influence flow system geometry. No information was found in the available literature regarding groundwater recharge rates and temporal patterns in the Manitouwadge area; however, it is expected to be typical for the shield region with elevated recharge in spring and fall, reduced recharge in late summer, and essentially no recharge during frozen winter conditions.

Coarse-grained outwash deposits found along the major bedrock valleys in the Manitouwadge area (Figure 2.3) are recharged by overland and subsurface storm flow from the bedrock highlands and direct precipitation (rain and snow). Groundwater discharge from these deposits is as baseflow to streams and rivers which transect them. The presence of a shallow water table in many of the valley outwash deposits is suggested by the fact that the elevation of the dissecting waterway is often close to that of the surrounding ground surface.

The large glaciofluvial (esker) deposits that trend south and southwest across the area are also zones of significant groundwater recharge. Creeks and streams are generally lacking over these glaciofluvial systems; however, the water level in kettle lakes associated with these features indicates a generally shallow water table. The influence of regional bedrock structures, such as the mapped faults in the area, on the rate and volume of groundwater flow is not known at present.

There is little known about the hydrogeologic properties of the deep bedrock in the Manitouwadge area, as no deep boreholes have been advanced for this purpose. Experience from other areas in the Canadian Shield with similar rock types has shown that active groundwater flow in bedrock is generally confined to shallow fractured localized systems and is dependent on the secondary permeability associated with the fracture networks (Singer and Cheng, 2002). For example, in Manitoba's Lac du Bonnet batholith, groundwater movement is largely controlled by a fractured zone down to about 200 m depth (Everitt *et al*., 1996).

The low topographic relief of the Canadian Shield tends to result in low hydraulic gradients for groundwater movement in the shallow active region (McMurry *et al.*, 2003). In deeper regions, hydraulic conductivity tends to decrease as fractures become less common and less interconnected (Stevenson *et al*., 1996; McMurry *et al*., 2003). Increased vertical and horizontal stresses at depth tend to close or prevent fractures thereby reducing permeability and resulting in low groundwater movement and diffusion-dominated solute transport (Stevenson *et al*., 1996; McMurry *et al*., 2003). Rock mass hydraulic conductivity values measured at typical repository depths (500 m or greater) at the Whiteshell and Atikokan research areas range from approximately 10^{-10} to 10^{-15} m/s (Ophori and Chan, 1996; Stevenson *et al*., 1996). Another example is data reported by Raven *et al.* (1985) which shows that rock mass hydraulic conductivity of the East Bull Lake pluton decreases from an average near-surface value of 10^{-8} m/s to less than 10^{-12} m/s below a depth of 400 to 500 m.

As the fracture frequency in a rock mass tends to decline with depth, eventually the movement of ions becomes diffusion-dominated. However, fracture networks associated with deep faults and shear zones will influence advective groundwater flow around bodies of rock characterized by diffusion-controlled conditions. The orientation of these fracture networks relative to the *in situ* stress field may influence their hydraulic properties. For example, in the fractured crystalline rock at SKB's Forsmark site, Follin and Stigsson (2014) documented that the transmissivities of large-scale, fracture zones generally decreased with depth by four orders of magnitude from ground surface to nearly 800 m, but specifically-orientated fracture zone groupings tended to have different ranges of transmissivities. The sub-vertical fracture zones orientated at high angles (near perpendicular) to the northwest-southeast, maximum horizontal compressive stress direction tended to have a greater frequency of low transmissivities compared to sub-vertical fracture zones oriented at low angles to the maximum horizontal stress direction. Notably, the sub-horizontal fracture zones had even higher transmissivities regardless of depth, presumably because of the lower normal effective stresses acting across these zones as a result from their preferential orientation to the minimum vertical stress. Horizontal stress measurements from various locations in the Canadian Shield (Kaiser and Maloney, 2005; Maloney *et al.*, 2006) indicate that the axis of maximum horizontal stress is oriented predominantly in the west-southwest-trending direction. However, due to lack of data in the Manitouwadge area, caution is warranted in extrapolating the west-southwest stress orientations without site-specific data.

There is no site-specific information on the hydraulic characteristics of the dykes interpreted for the Manitouwadge area. Information from mines in the Canadian Shield (Raven and Gale, 1986) and other geological settings shows that dykes may act as either pathways or barriers for groundwater flow in a host rock. Their hydraulic characteristics depend on a wide range of factors that include their frequency and location within the host rock, their orientation with respect to the direction of groundwater flow, their mineralogical composition, degree of alteration and their potential association with brittle deformation structures (e.g., Ryan *et al*., 2007; Svensson and Rhén, 2010; Gupta *et al*., 2012; Holland, 2012), including both pre-existing structures and those developed as a result of dyke emplacement.

The exact nature of deep groundwater flow systems in the Manitouwadge area would need to be evaluated at later stages of the site evaluation process, through the collection of site-specific information.

4.5 Hydrogeochemistry

There is a lack of information or studies on groundwater hydrogeochemistry for the Manitouwadge area. Existing literature, however, has shown that groundwater within the Canadian Shield can be subdivided into two main hydrogeochemical regimes: a shallow, generally fresh groundwater flow system, and a deep, typically saline flow system (Singer and Cheng, 2002).

Gascoyne *et al*. (1987) investigated the saline brines found within several Precambrian plutons and identified a chemical transition at around 300 m depth marked by a uniform, rapid rise in total dissolved solids (TDS) and chloride. This was attributed to advective mixing above 300 m, with a shift to diffusion-controlled flow below that depth. It was noted that major fracture zones within the bedrock can, where present, extend the influence of advective processes to greater depths and hence lower the transition to the more saline conditions characteristic of deeper, diffusion-controlled conditions.

In the deeper regions, where groundwater transport in unfractured or sparsely fractured rock tends to be very slow, long residence times on the order of a million years or more have been reported (Gascoyne, 2000; 2004). Groundwater research carried out in AECL's Whiteshell Underground Research Laboratory (URL) in Manitoba found that crystalline rocks from depths of 300 to 1,000 m have TDS values ranging from 3 to 90 g/L (Gascoyne *et al*., 1987; Gascoyne, 1994; 2000; 2004). However, TDS exceeding 250 g/L have been reported in some regions of the Canadian Shield at depths below 500 m (Frape *et al*., 1984).

Site-specific conditions will influence the depth of transition from advective to diffusion-dominated flow, which may occur at a depth other than the typical 300 m reported by Gascoyne *et al.* (1987). Such conditions would need to be evaluated during subsequent site evaluation stages.

5. NATURAL RESOURCES – ECONOMIC GEOLOGY

Mining and exploration in the Manitouwadge area has historically focused on base metals within the Manitouwadge – Hornepayne greenstone belt. This is clearly illustrated by the distribution of active mining claims in the Manitouwadge area, the bulk of which are located over and adjacent to the nose of the greenstone belt in the area of the Town of Manitouwadge (Figure 5.1). The greenstone belt hosts the majority of mineral occurrences, historic mining operations and exploration activity (Figure 5.1).

There are currently no producing metallic mineral mines in the Manitouwadge area. However, past-producing zinc-copper-silver operations located within the Manitouwadge greenstone belt include the Big Nama, Geco, Will-Echo 1, 2 and 3, and Willroy mines (Figure 5.1). Total ore production from the Geco deposit was 55.9 Mt at a grade of 1.9% copper, 3.8% zinc and 47 g/t silver; combined production from the Willroy, Big Nama, and Will-Echo mines was 8.7 Mt with a grade of 0.9% copper, 4.9% zinc (Zaleski and Peterson, 1995). Of the six mines, only the Big Nama and Geco mines are classified as being without reserves.

Metallic mineral occurrences in the Manitouwadge area are numerous and include: copper; zinc-copper-silver; copper-nickel; and copper-zinc. The potential for economically exploitable base and, possibly, precious metal mineralization remains high, and mineral exploration is active (MNDM, 2013b).

5.1 Petroleum Resources

The Archean suites of felsic intrusive and metavolcanic rocks found in the Manitouwadge area are unfavourable host rocks for petroleum generation and/or containment. For this reason, there is negligible potential for hydrocarbon reserves in the area and no records exist of exploration for oil or gas.

5.2 Metallic Mineral Resources

Gold

In the 1930s exploration in the Manitouwadge area was focused on gold (Thomson, 1932). However, no significant discoveries resulted, and attention switched to other minerals. McKay (1994) noted that many of the known sulphide occurrences in the Manitouwadge area have low gold values and recommends that all such occurrences, especially those proximal to fault or shear zones, be evaluated for their gold potential. The existence of metamorphic amphibolite facies, pyritic, sericite-muscovite schists (Pye, 1960; Friesen *et al.*, 1982), similar to those hosting gold mineralization in the Hemlo area, indicates that the Manitouwadge area has the potential, albeit limited, to host gold mineralization.

Silver

In the Manitouwadge area, silver occurs as an accessory mineral associated with base metal mineralization (Johns and McIlraith, 2003). Signficant silver was produced from the Geco, Willroy, Big Nama and Willecho zinc-copper-silver deposits (McKay, 1994). Given the past production and geological setting of the Manitouwadge area, the potential for silver associated with base metal deposits is considered high.

Base metals

Williams and Breaks (1996) classified base metal sulphide mineralization in the Manitouwadge area as occurring in four lithostructural environments:

- Sporadically as veins and disseminations within mafic metavolcanic rocks;
  - Within the major mafic units that traverse the Manitouwadge area sulphide occurrences are numerous.
- Associated with ferruginous altered rocks, rich in garnet and amphibole, adjacent to contacts between mafic and intermediate metavolcanic rocks;
  - The Geco, Willroy, Big Nama Creek mines occur at or close to major lithologic boundaries that often have a highly schistose muscovite-rich rock present at the contact.
- Within metamorphosed layers of gabbroic to anorthositic plutons;
  - Outside the Manitouwadge synform, sulphides are present within plutons of gabbro, ultramafic rock and anorthosite mafic, as well as intermediate and felsic metavolcanic rocks.
- Within pegmatitic to appinitic segregations in ultramafic rock associated with homogeneous quartz diorite-tonalite plutons;
  - Hornblendite and melagabbroic bodies associated with the marginal portions of the late-stage dioritic bodies.

Other, less frequent, geologic settings noted by Williams and Breaks (1996) in the Manitouwadge area that host sulphide occurrences include:

- Highly strained gneiss developed at the contact zone between tonalite and anorthosite hosting molybdenite;
- Sporadic seams, layers and alteration patches within the migmatitic metasedimentary rocks of the Quetico Subprovince;
- Diopside and garnet-bearing pods, possibly representing altered mafic layers, in migmatitic metasedimentary rocks;

- Foliated mafic enclaves within tonalitic gneisses.

Given the past production and geological setting of the Manitouwadge area, the potential for base metal mineralization is considered high.

Rare earth metals

Rare earth elements (REE) mineralization has not been identified in the Manitouwadge area. The potential for such mineralization in granitic intrusions and pegmatites in the area is considered low, as workers in the Manitouwadge area have not recommended any areas for exploration (McKay, 1994 and references therein). However, Puumala *et. al.* (2014) have recommended exploration for REEs in the Quetico Subprovince in the Killala Lake area to the west.

Platinum Group Elements

Occurrences of platinum group element (PGE)-copper-nickel mineralization associated with gabbroic intrusions are reported in Cecil and Roberta townships (Johns and McIlraith, 2003). The possibility exists that additional PGE mineralization may occur in the Manitouwadge area, particularly in ultramafic volcanic and mafic-ultramafic intrusive rocks (McKay, 1994).

Uranium

No significant uranium mineralization has been identified within the Manitouwadge area, although, a uranium occurrence is reported approximately 5 km northwest of Manitouwadge on the margin of a small foliated tonalite body. McKay (1994) suggested there is potential for uraniferous pegmatites in the Manitouwadge area. Exploration results in the region surrounding the Manitouwadge area indicate that the potential for economic uranium deposits is low.

5.3 Non-metallic Mineral Resources

Sand and Gravel

The Ontario Ministry of Natural Resources records (MNR, 2013a) indicate that 18 sand and gravel pits are licensed under the *Aggregate Resources Act* in the Manitouwadge area. Nine of the pits are located within the Township of Manitouwadge with the others scattered across the Manitouwadge area where they are a source of material for the construction and maintenance of forestry roads. A number of small unpermitted sites, largely abandoned, have been developed along forestry roads and trails.

Sand and gravel operations largely developed in glaciofluvial material are utilized on an as-needed basis to meet demand. The majority of aggregate license owners are forestry companies with a lesser number held by local construction companies.

Aggregate – Crushed Stone

The Ontario Ministry of Natural Resources (MNR, 2013a) records indicate that there is one active quarry permit in the Manitouwadge area. The quarry, located 5 km west of Hillsport, mainly produces ballast rock for use in maintaining the CNR rail bed. Highway construction in the area has used the “cut and fill” method, whereby excavated rock along the right-or-way has been used as fill in lower areas.

Building Stone

The potential for a building stone extraction in the Manitouwadge area has been recognized, and regional investigations to investigate the bedrock have been conducted and reported on by the Ontario Geological Survey (Hinz *et al.*, 1994). The investigation focussed on a suite of felsic lithologies which are all considered “granite” in construction terminology. While the potential for a building stone quarry in the Manitouwadge area exists, past exploration and development activity has been limited.

Based on the appearance of the bedrock, Williams and Breaks (1996) highlighted the potential of the following bodies as dimension stone sources:

- Megacrystic granodiorite in the Loken Lake area;
- Massive hornblende-biotite quartz diorite in the Rawluk Lake area;
- Orange-pink quartz monzodioritic rocks in the Ice Cream Lake area;
- Tonalitic gneisses of the Black Pic batholith;
- Trondhjemite and hornblende-biotite in the McGraw Lake-Faries Lake area; and
- “Leopard rock” (plagioclase aggregates within a hornblende matrix) near Moshkinabi Lake.

Regionally, in the Marathon area to the south, a number of quarries have seen extractive activity; however, none are currently operating. Some of these quarries appear to have been developed to supply stone for the construction of the CPR railway. All quarries were developed in iron-rich syenite with the rock being described as black granite (Hinz *et al.*, 1994).

Diamonds (kimberlite)

To date, no reports of kimberlite intrusions, with which diamonds are associated, have been reported in the Manitouwadge area. The exploration for diamond-bearing intrusions along Highway 614, between Hemlo and Manitouwadge, has been recommended by Schnieders *et. al.* (2005). Sage (1982) suggested that a north-trending corridor to the west, between Marathon and Terrace Bay, is more prospective for diamond exploration.

Peat

No records of peat extraction exist for the Manitouwadge area. Organic deposits in the Manitouwadge area are generally of modest size and appear to hold limited potential for development (Monenco Ontario Limited, 1981). A regional evaluation of peat deposits to the north of the area was conducted by Dendron Resource Surveys Limited (1986). Their findings indicated that large peat deposits develop on poorly drained glaciolacustrine and till substrates; while such settings exist in the Manitouwadge area, the organic deposits are likely to be relatively thin and immature.

Other Industrial Minerals

The felsic intrusive bodies within and surrounding the Manitouwadge area are recognized as having three primary settings with potential for non-metallic/metallic mineralization (Springer, 1978). These are:

- Vein infillings - amethyst, barite, and fluorite mineralization;
- Migmatite contact zones – uranium, thorium mineralization;
- Pegmatitic zones - lithium, beryllium, cesium, molybdenum, and rare earth elements.

Occurrences of industrial minerals in the area include:

- Cordierite, garnet, and sillimanite along the southern limit of the Manitouwadge synform (Williams and Breaks, 1996);
- Two flake graphite occurrences, present within shear zones in areas underlain by migmatites and gneisses of the Quetico Subprovince, are located 12 km south-southwest and 17 km northwest of Hillsport (MNDM, 2013a).

6. GEOMECHANICAL AND THERMAL PROPERTIES

Geomechanical information including intact rock properties, rock mass properties and *in situ* stresses are needed to design stable underground openings, predict the subsequent behaviour of the rock mass around these openings and predict the response of the groundwater flow system. As such, geomechanical information associated with a potential host rock can be used when addressing several geoscientific, safety-related factors defined in the site selection process document (NWMO, 2010).

There is limited geomechanical information on the granitic intrusions in the Manitouwadge area. Table 6.1 summarizes available geomechanical information from the granitic intrusions elsewhere in the Canadian Shield with rock types similar to those of interest in the Manitouwadge area. These sites are the Lac du Bonnet granite at AECL's Underground Research Laboratory (URL) in Manitoba and the Eye-Dashwa granite near Atikokan, Ontario. The majority of the geomechanical characterization work for the URL in Pinawa, Manitoba, was conducted as part of AECL's Nuclear Fuel Waste Management Program in the 1990s. Data on intact rock strengths and elastic properties of gneissic rocks including paragneisses and orthogneisses are available from studies completed at the Chalk River Laboratories. The reported ranges of geomechanical properties may be representative of metasedimentary and foliated/gneissic rocks in the Manitouwadge area (Table 6.1).

Table 6-1: Summary of Intact Rock Properties for Selected Canadian Shield Rocks

Property	Lac du Bonnet Granite	Eye-Dashwa Granite	Chalk River Gneiss
Uniaxial Compressive Strength (MPa)	185 ±24[a]	212 ±26[b]	100-200[e]
Split Tension Strength (Brazilian) (MPa)	4 to 9[c]	NA	NA
Porosity (%)	0.35[a]	0.33[b]	NA
P-wave velocity (km/s)	3220 (±100) - 4885 (±190)[d]	NA	NA
S-wave velocity (km/s)	2160 (±55) - 3030 (±115)[d]	NA	NA
Density (Mg/m^3)	2.65[a]	2.65[a]	NA
Young's Modulus (GPa)	66.8[a]	73.9[a]	80-100[e]
Poisson's Ratio	0.27[a]	0.26[a]	0.2-0.3[e]
Thermal Conductivity (W/(m^{0}K))	3.4[a]	3.3[a]	NA
Coef. Thermal Expansion (x10^{-6}/^{0}C)	6.6[a]	15[a]	NA

NA = Not Available; [a]Stone *et al.*, 1989; [b]Szewcyk and West, 1976; [c]Annor *et al.*, 1979; [d]Eberhardt *et al.*, 1999; [e]Laroque and Annor (1985)

6.1 Intact Rock Properties

Intact rock properties tabulated in Table 6.1 are based on laboratory testing of rock core specimens from boreholes. The table includes basic rock properties such as density, porosity, uniaxial compressive strength and tensile strength for use in engineering design and structural analyses. These parameters feed into the rock mass classification schemes and *in situ* stress determination.

There is a general paucity of information on the geomechanical properties of the granitic intrusive bodies in the Manitouwadge area. A limited amount of construction and development has taken place in the area that required near surface investigation of the batholiths' engineering properties and no deep subsurface investigations have been conducted. No specific information is available for the metasedimentary rocks of the Quetico Subprovince, the Black-Pic batholith or the plutons present (e.g., Dotted Lake, Fourbay, Nama Creek, Loken Lake) within the Manitouwadge area.

At this stage of the site evaluation process, it is reasonable to assume that the geomechanical properties of intact rock in the Manitouwadge area may resemble those of similar rock types elsewhere in the Superior Province. The rock property values presented in Table 6.1 are consistent with the values selected for numerical modeling studies conducted to evaluate the performance of hypothetical repository designs in a similar crystalline rock environment (SNC-Lavalin Nuclear Inc., 2011; Golder Associates, 2012a; 2012b). Site-specific geotechnical assessment would need to be conducted during later stages of the site evaluation process.

6.2 Rock Mass Properties

Rock mass properties address the behaviour of a body of rock, including its fracture or joint network. The presence of fractures changes the strength and hydraulic behaviour of a rock mass compared to what would be measured on small intact samples of the rock. For example, the strength of a rock mass containing a network of joints will be lower than the uniaxial compressive strength of a core sample measured in a laboratory. One would also expect the permeability of a rock mass to be greater than what would be measured on an intact core sample.

Fracture spacing, orientation and condition (width or aperture, mineral fill, evidence of relative displacement, etc.) of the fractures tend to influence the overall mechanical response of the rock mass. There is no information available on rock mass properties of the granitic intrusions in the Manitouwadge area. However, it is known that crystalline rock of the Canadian Shield can have a spectrum of fracture conditions at a given site. In general, there will be a downward decreasing fracture density from highly fractured rocks in shallow horizons (ca. <300 m below ground surface) to sparsely fractured intact rock at greater depths as experienced at other shield sites (e.g., Everitt, 2002). Fractures observed on surface bedrock exposures may occur as well-defined sets of geological discontinuities, or as randomly oriented and variably-dipping features. Based on observations from other shield sites (e.g., Everitt, 2002) and stress measurement data (e.g., Maloney *et al*., 2006), one could infer that a shallowly-dipping to sub-horizontal fracture set may exist as a result of either strain releasing during the rebound from the last glacial cycle or the presence of pre-existing fabric anisotropy (e.g., bedding, tectonic foliation) in the rock structure. Rock mass properties for the Manitouwadge area would need to be determined at later stages of the assessment.

6.3 *In situ* stresses

Knowledge of the *in situ* stress at a site is required to model the stress concentrations around underground excavation designs. These stress concentrations are ultimately compared to the strength of a rock mass to determine if conditions are stable or if the excavation design needs to be modified. This is particularly important in a repository design scenario, where minimization of excavation induced rock damage is required.

No site-specific information is available regarding the *in situ* stress conditions within the Manitouwadge area; however, in eastern North America the current stress orientation is approximately east-northeast (Heidbach *et al*., 2008). Despite that horizontal stress conditions are difficult to estimate, over-coring or hydraulic fracturing methods can be used to determine the stresses on a plane at depth and resolve the horizontal *in situ* stress conditions (or resolve inclined principal stresses). A large set of such horizontal stress measurements is available from various locations in the Canadian Shield (Kaiser and Maloney, 2005; Maloney *et al*., 2006). These data are presented on Figure 6.1.

The nearest *in situ* stress measurements were taken in metasedimentary and /or metavolcanic rocks at depths of 1000 mbgs at the David Bell Mine located southwest of the Manitouwadge area at Marathon, Ontario (Kaiser and Maloney, 2005). The reported maximum principal stress data available from two sets of tests were 34.7 and 44.6 MPa oriented south, with the minimum principal stress being subvertical.

More extensive *in situ* stress testing was done in metavolcanic rocks at depths of 360 to 810 mbgs at the MacLeod Mine located to the southeast in the Municipality of Wawa. The minimum principal stress was vertical (Arjang and Herget, 1997). The reported maximum principal stress data available from 11 sets of tests ranged from 17.4 to 53.7 MPa with an average value of 32 MPa. The maximum principal stress was subhorizontal and oriented from the north-northwest to east-northeast (Kaiser and Maloney, 2005). The intermediate principal stress was also subhorizontal and comparable in magnitude to the maximum principal stress, suggesting a predominantly horizontally isotropic stress regime. Herget (1973) noted that some of the measured directions of maximum compressive stresses aligned with directions of maximum compression (north-northwest) deduced from kinematic analysis of slaty cleavage, transverse faults and fracture slickensides.

The observation that the stress state is neither constant nor linear (Maloney *et al*., 2006) suggests that variability should be expected in the Canadian Shield. Based on the available stress measurement data, Maloney *et al.* (2006) developed a conceptual model that describes the variable stress state in the upper 1500 m of the Canadian Shield. The conceptual model identifies a shallow stress-released zone from surface to a depth of 250 m, a transition zone from 250 to 600 m, and an undisturbed stress zone below 600 m. The undisturbed stress zone can be expected to be representative of far-field boundary stress conditions whereas stresses within the shallow zone tend to be lower as they have been disturbed through exhumation and influenced by local structural weaknesses such as faults (Maloney *et al*., 2006).

Typical repository depths of approximately 500 m fall within the transition zone, where the maximum principal stress may range from approximately 20 to 50 MPa (Maloney *et al*., 2006). The data presented by Maloney *et al.,* (2006) indicate an average southwest orientation for the maximum horizontal stress, which is consistent with the World Stress Map, although anomalous stress orientations have been identified in northwest Ontario including a 90° change in azimuth of the maximum compressive stress axis which was identified in the near surface of the Whiteshell area of Manitoba (Brown *et al.*, 1995). In addition, a roughly north-south orientation of maximum horizontal compressive stress was found for the Sioux Falls Quartzite in South Dakota (Haimson, 1990).

Local stress relief features such as faults and shear zones can be expected to locally affect stress regime. For example, thrust faults at AECL's URL were shown to be boundaries between significant changes in the magnitude and orientation of the principal stresses. Above a major thrust fault, located at depth of 270 m (referred to as Fracture Zone 2, or FZ2 at the site), the magnitude was close to the average value for the Canadian Shield and the orientation of the maximum horizontal stress was consistent with the average predicted by the World Stress Map (i.e., southwest) (Zoback, 1992). Below the same thrust fault, the stress magnitudes are much higher than the average data for the Canadian Shield, and the maximum principal stress rotates approximately 90° to a southeast orientation (Martino *et al*., 1997). The principal maximum horizontal stress magnitude below the Fracture Zone 2 thrust fault remains relatively constant around 55-60 MPa, which is more typical of the values found at greater depths. The southeast orientation of the maximum principal horizontal stress is consistent with the data presented by Herget (1980) for the area, which indicates maximum compression clustered in the southwest and southeast for the Canadian Shield.

In addition to loading history and geologic structure, *in situ* stress conditions are further influenced by rock mass complexity (i.e., jointing, heterogeneities, and mineral fabric). As such, local stresses may not resemble the average stress state for a region (Maloney *et al*., 2006). The conceptual model presented by Maloney *et al.* (2006) is considered appropriate for sub-regional modelling activities. Due to wide scatter in the data (Figure 6.1), site-specific measurements would be required during detailed site investigations for application to more detailed design activities.

6.4 Thermal Conductivity

Thermal conductivity values for potential host rocks provide information on how effectively the rock will transfer heat from the repository and dissipate it into the surrounding rock. The thermal conductivity of a rock is in part dependent on its mineral composition, with rocks containing higher quartz content generally having higher thermal conductivities. The thermal conductivity of quartz (7.7 W/(m˚K)) is greater than that of other common rock-forming minerals such as feldspars (1.5 to 2.5 W/(m˚K)) or mafic minerals (2.5 to 5 W/(m˚K)) (Clauser and Huenges,1995).

There are no site-specific thermal conductivity values or detailed quantitative mineral compositions for the Manitouwadge area. The mineralogy of the principal geologic units in the Manitouwadge area is described in Section 3.2.1. Available information indicates that the compositions of some of these potentially suitable geologic units range from granite and granodiorite to tonalite. The quartz mineral content of granite and granodiorite rock types can range from approximately 20% to 60% by volume (Streckeisen, 1976). The range of measured thermal conductivity values for granite, granodiorite and tonalite found in the literature are presented in Table 6.2; data for monzonite was not found. At this desktop stage of the investigation, there is additional uncertainty as to whether the existence of dykes will have a positive or negative impact on the thermal conductivity of the surrounding host rocks. The potential heterogeneity in thermal conductivity associated with the presence and nature of dykes is difficult to quantify at the desktop stage of the investigation and would need to be studied in further detail.

Table 6-2: Thermal Conductivity Values for Granite and Granodiorite

Rock type	Average thermal conductivity (W/(m˚K))	Minimum thermal conductivity (W/(m˚K))	Maximum thermal conductivity (W/(m˚K))
Granite[a,b,c,d,e,f,g]	3.15	2.60	3.63
Granodiorite[a,f,g]	2.69	2.44	2.86
Tonalite[h,i]	3.01	2.95	3.14

[a]Petrov *et al*., 2005; [b]Kukkonen *et al.*, 2011; [c]Stone *et al*., 1989; [d]Back *et al.*, 2007; [e]Liebel *et al*., 2010; [f]Fountain *et al*., 1987; [g]Fernandez *et al.*, 1986; [h]de Lima Gomes and Mannathal Hamza 2005; [i]Kukkonen *et al.*, 2007.

Although no thermal conductivity values are available for the Manitouwadge area, some useful comparisons are provided by Stone *et al.* (1989) in their summary of thermal conductivity values for two late Archean granitic intrusions of the Superior Province of the Canadian Shield, the Lac du Bonnet Batholith and the Eye-Dashwa Pluton (Table 6.1). Both intrusions were described by Stone *et al.* (1989) as having similar mineralogical compositions. The average thermal conductivity for the Eye-Dashwa Pluton was 3.3 W/(m˚K) based on 35 samples. The average thermal conductivity for the Lac du Bonnet Batholith was 3.4 W/(m˚K) based on 227 samples.

The above literature values for thermal conductivity are considered useful for general comparison purposes as part of this preliminary assessment. However, actual values would need to be determined at later stages of the assessment.

7. POTENTIAL GEOSCIENTIFIC SUITABILITY OF THE MANITOUWADGE AREA

7.1 Approach

The objective of the Phase 1 geoscientific preliminary assessment was to assess whether the Manitouwadge area contains general areas that have the potential to satisfy the geoscientific site evaluation factors outlined in NWMO's site selection process document (NWMO, 2010). The location and extent of general potentially suitable areas would be refined during the second phase of the preliminary assessment through more detailed assessments and field evaluations.

The repository is expected to be constructed at a depth of about 500 mbgs. The surface facilities will require a dedicated surface area of about 600 x 550 m for the main buildings and about 100 x 100 m for the ventilation exhaust shaft (NWMO, 2013). The actual underground footprint at any particular site would depend on a number of factors, including the characteristics of the rock, the final design of the repository and the inventory of used fuel to be managed. For the purpose of this preliminary assessment, it is assumed that the repository would require a footprint in the order of 2 x 3 km.

The geoscientific assessment of suitability was carried out in two steps. The first step (Section 7.2) was to identify general potentially suitable areas using the key geoscientific characteristics described below. The second step (Section 7.3) was to verify that identified general areas have the potential to meet all NWMO's geoscientific site evaluation factors (NWMO, 2010). The potential for finding general areas that are potentially suitable for hosting a deep geological repository was assessed using the following key geoscientific characteristics:

- **Geological Setting:** All areas of unfavourable geology identified during the initial screening (Geofirma Engineering Ltd., 2013a) were not considered. Such areas include rocks of the Manitouwadge greenstone belt and its detached fragments in the area, which were not considered suitable due to their heterogeneity, structural complexity and potential for mineral resources. Small plutons and gabbroic bodies spatially associated with the greenstone belt were not considered due to their small size which would limit their ability to host a repository. Metasedimentary rocks in the Quetico Subprovince, the Black-Pic batholith, and Fourbay Lake pluton in the Wawa Subprovince were considered as potentially suitable host rocks. Within these units, the geophysical data was examined (PGW, 2014), such that areas with "quiet" aeromagnetic signatures were favoured. These units were further evaluated on the basis of the subsequent considerations.

- **Structural Geology**: Areas within or immediately adjacent to regional faults and shear zones were considered unfavourable. The main structural feature in the Manitouwadge area is the Quetico-Wawa subprovince boundary, which cross-cuts the Manitouwadge area (Figure 3.4 and 7.1). It is characterized as a regional shear zone with a belt of deformation of about 15 km on either side (Williams *et al*., 1991). The thickness of potentially suitable units was also considered when identifying suitable areas. Metasedimentary rocks in the Quetico is estimated to be about 7.5 km thick. Although the thickness of the Black-Pic batholith and the Fourbay Lake pluton are unknown, both are expected to extend well below the planned respository depth of approximately 500 m. Hence depth was not a differentiating feature.

- **Lineament Analysis:** In the search for potentially suitable areas, there was a preference to select areas that have a relatively low density of lineaments, particularly a low density of longer lineaments as they are more likely to extend to greater depth than shorter lineaments (Section 3.2.3). For the purpose of this assessment, all interpreted lineaments (fractures and dykes) were conservatively considered as conductive (permeable) features. In reality, many of these interpreted features may be sealed due to higher stress levels at depth and the presence of infilling.
- **Overburden:** The distribution and thickness of overburden cover is an important site characteristic to consider when assessing amenability to site characterization of an area. For practical reasons, it is considered that areas covered by more than 2 m of overburden deposits would not be amenable for the purpose of structural mapping. This consideration is consistent with international practices related to site characterization in areas covered by overburden deposits (e.g., Andersson *et al*., 2007). At this stage of the assessment, preference was given to areas with greater bedrock exposures (Figure 2.3). Areas mapped as bedrock terrain are assumed to be covered, at most, with a thin veneer of overburden and are therefore considered amenable to geologic mapping.
- **Protected Areas:** Provincial parks and conservation reserves were excluded from consideration. Portions of two conservation reserves are present in the Manitouwadge area and occupy a combined total of less than 9 km^2 (Figures 1.1 and 7.1). The Isko Dewabo Lake Complex Conservation Reserve straddles the southern boundary of the area in the southwest corner, west of Highway 614. The 7.3 km^2 of the reserve which falls within the Manitouwadge area overlies the Black-Pic batholith. The North Thornhen Lake Moraine Conservation Reserve lies astride the northern boundary of the area, northeast of Hillsport. A small portion of this reserve, approximately 1.5 km^2, is within the Manitouwadge area and over lies the Quetico Subprovince. These two protected areas were eliminated from further consideration.
- **Natural Resources:** The potential for natural resources is shown in Figure 5.1. Areas with known exploitable natural resources were excluded from further consideration. As noted above, the Manitouwadge greenstone belt has known potential for exploitable natural resources and was not considered due to its unfavourable geology. Gabbroic plutons were also excluded from consideration based on their potential to host base metal and/or PGE mineralization. The mineral potential of the potentially suitable geological units identified above is considered to be low. At this stage of the assessment, areas of active mining claims located in geologic environments judged to have low mineral resource potential were not systematically excluded.
- **Surface Conditions**: Areas of obvious topographic constraints (e.g., density of steep slopes) and large water bodies (wetlands, lakes) were considered in the identification of potentially suitable areas. The Manitouwadge area is moderately rugged as bedrock dominated regions have a knobby topography with local areas of significant relief present across the area (Figure 2.2). The distribution of lakes is relatively uniform across the Manitouwadge area; only in a few areas of limited extent would the concentration or size of water bodies affect the placement of general potentially suitable areas. Wetlands occur in the central part of the Manitouwadge area, while those in the remainder of the region are mostly of limited size.

7.2 Potential for Finding General Potentially Suitable Areas

The consideration of the above geoscientific evaluation factors and constraints revealed that the Manitouwadge area contains at least four general areas that have the potential to satisfy NWMO`s geoscientific site evaluation factors. Two of these areas are located within the Black-Pic batholith, one in the metasedimentary rocks of the Quetico Subprovince and one in the Fourbay Lake pluton. Figure 7.1 shows features illustrating some of the key characteristics and constraints used to identify general potentially suitable areas, including bedrock geology' protected areas' areas of thick overburden cover' surficial and geophysical lineaments' existing road network' the potential for natural resources' and mining claims. Zoomed-in views of the suitable geologic units where potentially suitable areas where found are shown in Figures 7.2 to 7.4, these are the metasedimentary rocks of the Quetico Subprovince, the Black-Pic batholiths and the Fourbay Lake pluton, respectively. The legend of each figure includes a 2 km by 3 km box to illustrate the approximate extent of suitable rock that would be needed to host a repository. The zoomed in areas are also identified in the insets of Figures 7.2 to 7.4.

The following sections provide a summary of how the key geoscientific factors and constraints discussed above were applied to the various geological units within the Manitouwadge area to assess whether they contain general potentially suitable areas. At this early stage of the assessment, the boundaries of these general areas are not yet defined. The location and extent of general potentially suitable areas would be further refined during subsequent site evaluation stages.

7.2.1 Metasedimentary Rocks of the Quetico Subprovince, Northest Quetico Area (Figure 7.2)

The northern half of the Manitouwadge area is underlain by metasedimentary rocks and granite to granodiorite intrusions of the Quetico Subprovince (Figure 3.4) covering 1,740 km^2. The metasedimentary rocks of the Quetico Subprovince are mostly composed of metasedimentary gneisses and migmatites (i.e., highly metamorphosed sedimentary rocks that underwent partial melting). These metasedimentary rocks have an estimated thickness of at least 7.5 km (Percival, 1989), although the thickness of this geologic unit is interpreted to slightly decrease along the border of the Quetico and Wawa subprovinces (Percival, 1989). The deposition of the sedimentary rocks began approximately 2.698 Ga with the cessation of deposition constrained to approximately 2.688 Ga (Zaleski *et al*., 1999). The metasedimentary rocks are separated from the Black-Pic batholith by the Wawa-Quetico subprovince boundary that bisects the Manitouwadge area.

The metasedimentary rocks of the Quetico Subprovince have low potential for natural resources, and are mostly free of protected areas and significant surface constraints (i.e., topography and large water bodies). Therefore, identification of potentially suitable areas within the metasedimentary rocks of the Quetico Subprovince was mainly based on geological setting, structural geology (e.g., setback from the subprovince boundary), overburden cover, and lineament analysis.

The assessment of the key geoscientific characteristics identified one general potentially suitable area in the metasedimentary rocks in the northwest part of Quetico Subprovince (referred to herein as the northwest Quetico area). The potentially suitable area extends southward from the northern Manitouwadge area boundary to approximately 2 km south of Bishop Lake, between Ramsay Lake to approximately 5 km west of Lauri Lake (Figure 7.2). This potentially suitable area is mapped entirely as metasedimentary rock; however, interpretation of the geophysical data suggests some uncertainty regarding the lithological homogeneity (PGW, 2014). The magnetic signature over the northwest Quetico area is considered as being somewhat noisy; a detailed interpretation is hampered by the fact that the area is covered by a low resolution geophysical survey (805 m line spacing; Figures 3.6 and 3.7). The potentially suitable area is on the northern flank of a gravity high that occupies the central part of the metasedimentary rocks of the Quetico Subprovince in the Manitouwadge area (Figure 3.8). This gravity signature is not typical of the Quetico Subprovince; thus, it may suggest the presence of a higher metamorphic grade near the subprovince boundary (PGW, 2014). While no mapped faults are present in this general potentially suitable area, the Wawa-Quetico subprovince boundary lies 22 km to the south, and the Gravel River Fault lies 17 km to the northwest.

The identification of the northwest Quetico area was based, in part, on the analysis of interpreted lineaments (Figure 3.12) completed by SRK (2014). High resolution geophysical coverage is available for only the southern 60% of the metasedimentary rocks of the Quetico Subprovince resulting in a marked decrease in the number of identified geophysical lineaments in the northern part of the subprovince which includes the northwest Quetico area. Within the northwest Quetico area, magnetic lineaments shorter than 10 km in length are largely lacking (Figure 3.10), reflecting the low resolution of available aeromagnetic data. The sparseness of the magnetic lineaments is reflected in the fact that the distance between features ranges from 2 to 7 km, greater than in other parts of the Manitouwadge area. The dominant geophysical lineament orientation in the northwest Quetico area is northwest (SRK, 2014).

The assessment of potentially suitable areas within the metasedimentary rocks of the Quetico Subprovince also took into consideration interpreted surficial lineaments. The surficial lineaments, in contrast to the geophysical ones, have a relatively uniform distribution across the metasedimentary rocks of the Quetico Subprovince with the exception of the area around Hillsport where thicker overburden is present (Figure 3.9). The northwest Quetico area displays a low to moderate apparent surficial lineament density. At this desktop stage, it is uncertain whether surficial lineaments represent real bedrock structure and how far they extend to depth, particularly in the shorter lineaments.

Total lineament density as a function of lineament length is shown on Figures 3.15 to 3.17 for lengths greater than 1 km, 5 km, and 10 km, respectively. The density of lineaments across the metasedimentary rocks of the Quetico Subprovince and in the northwest Quetico siting area decreases only slightly with the filtering of the <1 km lineaments, due to their limited numbers (Figures 3.15). The subsequent filtering of the <5 km long lineaments (Figure 3.16) and the <10 km lineaments (Figure 3.17) lowers the density markedly. It is of note that the density of surficial and geophysical lineaments within the northwest Quetico area is low regardless of filtering (Figures 3.14).

The Manitouwadge area contains numerous mapped and interpreted dykes as it lies within regional dyke swarms. Although a large number of these dykes are identifiable in the geophysical data in the Manitouwadge area, there still remain some uncertainties regarding the distribution and structural impact of the dykes (Figure 3.12). The assessment revealed that that dykes tend to have well-defined orientations, consistent with the geological history of the area (SRK, 2014). However, there remain some uncertainties regarding the nature and distribution of the dykes. For example, the potential existence of thin dykes, which are too small to be identified with any confidence from the geophysical data, cannot be ruled out. Another aspect of uncertainty associated with the presence of dykes relates to understanding the extent of damage to the host rock as a result of dyke emplacement. It is well understood, but not easily quantifiable from geophysical data alone, that dyke propagation will induce damage to the host rock within an envelope around the dyke that varies with the size of the intrusion (e.g., Meriaux *et al*., 1999). Additional uncertainty exists with regard to the indigenous fracture pattern within and adjacent to each dyke and their effects on the bulk thermal conductivity of the bedrock.

The northwest Quetico area consists entirely of Crown Land (Figure 2.5), and does not contain any protected areas. The area contains no mineral occurrences and the potential for economic mineralization is considered low. The area is free of active mining claims (Figures 5.1 and 7.3) and contains no mineral occurrences. Approximately 45% of the northwest Quetico area is mapped as bedrock drift complex in which drift cover is thin and outcrops are expected to be common (Figure 2.3). The remainder of the area is covered by a veneer of ground moraine (till) that, while obscuring the bedrock, is believed to be relatively thin, although zones of thicker deposits can be expected. The northwest Quetico area is well-drained by several streams, rivers and lakes. The general potentially suitable area straddles the continental divide with the vast majority of the area (~95%) of area within Pic tertiary watershed that drains to Lake Superior (Figure 2.4). The remainder of the area is within Upper Kenogami tertiary watershed and drains to James Bay. Approximately 5% of the area is covered by water bodies (AECOM, 2014). Relief in the area is low to moderate, although bedrock knobs are found in areas of bedrock dominated terrain (Figure 2.3). Access to the northwest Quetico area is by logging roads running westward from the Caramat Industrial Road (Figure 1.1).

In summary, the general area located in the northwestern corner of the metasedimentary rocks of the Quetico Subprovince (Figures 3.4 and 7.2) appears to be potentially suitable based on its favourable geology, structural geology, and lineament density. The potentially suitable area is within an extensive area mapped as metasedimentary rocks, contains no mapped faults, has a low to moderate interpreted lineament density, and has low potential for economically exploitable natural resources. Approximately 45% of the area consist of bedrock outcrop or thin drift allowing for site characterization.

Inherent uncertainties remain in relation to the potential influence of the regional features, such as the Gravel River fault and subprovince boundary, the potential presence of fractures and smaller-scale dykes not identifiable on aeromagnetic data and the potential damage of the host rock due to dyke emplacement. In addition, uncertainty remains in relation to the litholithic homogeneity at a local scale, particularly the varying degree of metamorphism that the metasedimentary rocks may have experienced.

7.2.2 Black-Pic Batholith, South Central and Eastern Areas (Figure 7.3)

The Black-Pic batholith is a 2.720-2.689 Ga granitic intrusion covering the majority of the southern half of the Manitouwadge area where it occupies 1,607 km^2. As discussed in section 3.2.1.3, the batholith is a large multiphase intrusion that is predominantly composed of tonalite, with associated granite-granodiorite phases. In the area west and northwest of the Manitouwadge synform, it contains migmatized supracrustal rocks (Figure 3.4). 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 east-west trending Wawa-Quetico subprovince boundary separates the Black-Pic batholith from the metasedimentary rocks of the Quetico Subprovince to the north. Geophysical data for the Manitouwadge area indicate that highly magnetic horizons south of the subprovince boundary, likely associated with a zone of deformation, strike sub-parallel to the subprovince boundary.

The Black-Pic batholith has low potential for natural resources, and is mostly free of protected areas and significant surface constraints (i.e., topography and large water bodies). Identification of potentially suitable areas within this intrusion was mainly based on geological setting, structural geology (e.g., setback from the Wawa-Quetico subprovince boundary), lineament analysis, and overburden cover.

Two general potentially suitable areas were identified in the Black-Pic batholith. One potentially suitable area was identified in the south-central part of the batholith (Figure 7.1). Referred to herein as the south-central area, it extends from the north end of Kaginu Lake southward to the boundary of the Manitouwadge area, between Barehead Lake and Poshtar Lake (Figure 7.3). The other potentially suitable area in the Black-Pic batholith is positioned in the southeastern quadrant of the Manitouwadge area (Figure 7.1). Referred to herein as the eastern area, it is bounded by Macutagon Lake, Jembi Lake, Gum Creek and Bissonnette Lake (Figure 7.3). This area contains a granite-granodiorite intrusion that is shown on recent completion maps of the area (Figure 3.4); however, as discussed previously, this intrusion was not defined by field mapping conducted in the area (Giguere, 1972), and it does not have a geophysical signature. For these reasons its presence is highly suspect and it is believed the Black-Pic batholith underlies the area.

Both general potentially suitable areas have relatively good bedrock exposure and are removed from the subprovince boundary. The northern boundaries of the areas are proximal to portions of the Manitouwadge greenstone belt, but the lack of mineral occurrences, despite decades of exploration, suggests a low probably of economic resources. The south-central area contains several north-trending mapped faults of limited length along its northern boundary that extend into the Manitouwadge greenstone belt and one northeastern-trending fault parallel to, but east of, the Black Creek (Figure 7.3). The eastern area contains a single northwest-trending fault, although another fault outside the area parallels its western boundary.

The magnetic signature over the two general potentially suitable areas in the Black-Pic batholith is relatively quiet for the south-central area and moderately noisy for the eastern area (Figures 3.6 and 3.7). Subtle variations in magnetic responses and foliation across the potential suitable areas may suggest heterogeneity within the batholith.

A regional gravity low is present across the southern portion of the Black-Pic batholith (Figure 3.8), covering the majority of the general potentially suitable areas, suggesting that the intrusion may be somewhat thicker in this region (PGW, 2014).

Additional insight into the potential suitability of the two identified areas is provided by the analysis of interpreted lineaments (Figure 3.12), which is described in detail by SRK (2014). Thin overburden cover and areas of outcrop combined with the high resolution geophysics enabled a detailed assessment of the bedrock structure of the Black-Pic batholith. The two areas identified in the south-central and eastern portions of the Black-Pic batholith have a low to moderate density of geophysical lineaments, several of which are interpreted as dykes (Figures 3.10 and 7.3). Interpreted dykes within the two areas are generally consistent with those indicated on published maps (Figure 3.4). The spacing between the longer geophysical lineaments (i.e., >10 km) in the two general potentially suitable areas ranges between approximately 0.5 and 4 km; shorter lineaments have a closer spacing (SRK, 2014). The dominant orientation of longer geophysical lineaments in the batholith is northwest and northeast.

The assessment of potentially suitable areas within the Black-Pic batholith also took into consideration interpreted surficial lineaments. Figure 3.9 shows the surficial lineament density to be generally low to moderate throughout the batholith, including the south-central and eastern areas. However, surface lineament density is notably low in a northeast-trending band centred on Black Creek, likely due to thicker overburden cover, and in the eastern area north of Jembi Lake. At this desktop stage, it is uncertain whether surficial lineaments represent real bedrock structures and how far they extend to depth, particularly in the shorter lineaments.

The distribution of total lineament density as a function of lineament length is shown on Figures 3.15 to 3.17 for lengths greater than 1 km, 5 km, and 10 km, respectively. The figures show that the density of lineaments across the Black-Pic batholith decreases very slightly when the <1 km long lineaments are filtered out (Figure 3.15) and decrease notably when the lineaments <5 km are removed (Figure 3.16). There is another visible decrease in the lineament density from filtering out the <10 km long features (Figure 3.17).

As noted in the discussion of the metasedimentary rocks of the Quetico Subprovince, all of the Manitouwadge area, including the Black-Pic batholith, contains numerous mapped and interpreted dykes as the area is within regional dyke swarms (Figures 3.3, 3.4 and 3.12). The previously noted uncertainties regarding the identification, distribution and structural impact of the dykes would need to be assessed during subsequent site evaluation stages. Additional uncertainty exists with regard to the indigenous fracture pattern within and adjacent to each dyke and their effects on the bulk thermal conductivity of the bedrock.

The general potentially suitable areas identified in the Black-Pic batholith are mostly on Crown Land (Figure 2.5), and do not contain any protected areas. The areas are free of active mining claims as depicted on Figures 5.1 and 7.3. The south-central and eastern portions of the Black-Pic batholith are well-drained by numerous streams, rivers and lakes. The south-central area is within the Pic tertiary watershed which drains to Lake Superior and has permanent water bodies that occupy approximately 12% of the land surface (Figure 2.4). The eastern area straddles the continental divide with the northern and central parts of area being in the Nagagami tertiary watershed and draining northward. The remainder of the area is divided between the White and Pic tertiary watersheds and drains southward to Lake Superior. Approximately 18% of the area is covered by water bodies (AECOM, 2014). Relief in both general potentially suitable areas is modest; however, steep slopes of varying heights frequently occur in areas of bedrock dominated terrain. The Black-Pic batholith's south-central area is easily accessible by Highway 614 and numerous secondary roads and trails. Access to the potentially suitable eastern area in the batholith is via a major logging road and some trails (Figure 1.1).

In summary, the two general areas located in the Black-Pic batholith (Figures 3.4 and 7.3) appear to be potentially suitable based on their favourable geology, structural geology, and lineament density. The general potentially suitable areas are within a large granitic intrusion, contain few mapped faults, have a low to moderate interpreted lineament density, and have low potential for economically exploitable natural resources. In addition, the areas have good bedrock exposure making them amenable to site characterization.

The uncertainties associated with the two general areas identified in the Black-Pic batholith relate to the presence and nature of dykes and the potential effect that the Wawa-Quetico subprovince boundary may have on the structural geology and fracture network. In addition, the characteristics and potential impact of the mapped faults in the areas would require further assessment.

7.2.3 Fourbay Lake Pluton (Figure 7.4)

The Fourbay Lake pluton is located in the southwestern corner of the Manitouwadge area and covers 65 km^2 (Figure 3.4). The pluton is described by Milne (1968b) as consisting of pyroxene-hornblende-biotite granodiorite and by Beakhouse (2001) as a massive, compositionally uniform quartz monzodiorite. The pluton has been age dated at 2.678 Ga (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 pluton is completely surrounded by the Black-Pic batholith.

The Fourbay Lake pluton has low potential for natural resources, and is mostly free of protected areas and significant surface constraints (i.e., topography and large water bodies). Identification of potentially suitable areas within this intrusion was mainly based on geological setting, structural geology, lineament analysis, and overburden cover.

One general potentially suitable area was identified in the central portion of the Fourbay Lake pluton in an area centred between two northwest-trending mapped faults (Figures 3.4 and 7.4). The area is roughly 40 km south of the Wawa-Quetico subprovince boundary. The magnetic signature of the Fourbay Lake pluton presents a strong contrast with the surrounding gneissic tonalite of the Black-Pic batholith (Figures 3.6 and 3.7). The pluton is also associated with a weak gravity high and relatively high responses in three radioelements (PGW, 2014).

The identification of the Fourbay Lake potentially suitable area was based, in part, on the analysis of interpreted lineaments (Figure 3.12) using high resolution geophysical survey coverage and satellite data sets (SRK, 2014). The area has a low to moderate apparent geophysical lineament density (Figures 3.10 and 7.4) with the longer geophysical lineaments (i.e., >10 km) oriented northwest and northeast, having a spacing of approximately 5 km. The Fourbay Lake potentially suitable area also has a low to moderate apparent surficial lineament density. As is previously noted, there is a degree of uncertainty as to whether the surficial lineaments represent bedrock structures extending to depth.

The distribution of total lineament density for the Fourbay Lake pluton area as a function of lineament length is shown on Figures 3.15 to 3.17 for lengths greater than 1 km, 5 km, and 10 km, respectively. Lineament density is little changed with the removal of the <1 km features (Figure 3.15), but with the filtering of the lineaments <5 km in length the potentially suitable area becomes one of the lowest density areas in the Wawa Subprovince (Figure 3.16). This continues to be the case with the filtering of the <10 km lineament (Figure 3.17).

A number of northwest- and northeast-trending dykes have been interpreted as crossing the Fourbay Lake general potentially suitable area (Figure 3.12). The previously noted uncertainties regarding the identification, distribution, and structural impact of the dykes would need to be assessed during subsequent site evaluation stages. Additional uncertainty exists with regard to the indigenous fracture pattern within and adjacent to each dyke and their effects on

the bulk thermal conductivity of the bedrock. The ambiguity of the lithology (granodiorite or quartz monzodiorite) raises additional uncertainty concerning the thermal conductivity of the host rock.
The Fourbay Lake pluton potentially suitable area consists entirely of Crown Land (Figure 2.5). Also, it does not contain any protected areas, although the Isko Dewabo Lake Complex Conservation Reserve is adjacent to the southeast (Figure 1.1). The Fourbay Lake pluton is deemed to have low potential for natural resources as no mineral occurrences or mining claims are documented on or in the vicinity of the intrusion (Figure 5.1). The Fourbay Lake pluton potentially suitable area is free of active mining claims and contains no mineral occurrences (Figures 5.1 and 7.4). The Fourbay Lake pluton potentially suitable area is well-drained by streams, rivers, and lakes, is located within the Pic tertiary watershed and drains to Lake Superior (Figure 2.4). Approximately 5% of the area is covered by water bodies (AECOM, 2014). The terrain over the pluton is classified as bedrock-drift complex indicating that the overburden is generally thin and outcrops are common (Figure 2.3). The pluton has few significant surface constraints as the size, the density of lakes are low, and relief is generally moderate, although steep-walled bedrock valleys are common. Access to the pluton is by logging roads branching off of Highway 614 to the east and the Caramat Industrial Road to the north (Figure 1.1).

In summary, the Fourbay Lake pluton potentially suitable area, located in the southwestern corner of the Manitouwadge area (Figures 3.4 and 7.4), appears to be potentially suitable based on its favourable geology, structural geology, and lineament density. The potentially suitable area is within a massive intrusion of suitable lithology, contains sufficient area for a repository between mapped faults, has a low to moderate interpreted lineament density, and has low potential for economically exploitable natural resources. The terrain in the area consists of bedrock outcrop or thin drift allowing for site characterization.

Uncertainties associated with the general area in the Fourbay Lake pluton relate to its small size, the presence and nature of dykes, and the potential effect that the Wawa-Quetico subprovince boundary may have on the structural geology and fracture network. In addition, the characteristics and potential impact of the nearby northwest-trending mapped faults would require further assessment.

7.2.4 Other Areas

While the northwestern portion of the metasedimentary rocks of the Quetico Subprovince in the Manitouwadge area has a lower lineament density, the north-central and northeastern portions of the subprovince (i.e., east of the Caramat Industrial Road) may have general potentially suitable areas in areas of thin overburden. More detailed aeromagnetic surveys or field investigations may be required to address questions regarding lithological homogeneity (PGW, 2014) and to determine if this aspect of the rock would pose a significant concern to the siting of a deep geological repository for used nuclear fuel. It may also be possible to identify general potentially suitable areas in the Black-Pic batholith outside of those portions of the intrusion described in Section 7.2.2, specifically in zones of bedrock dominated terrain (Figure 2.3) with a lower lineament density relative to other parts of the Manitouwadge area (Figure 3.14).

Given the geographic extent of the Manitouwadge area, it may be possible to identify additional general potentially suitable areas. However, the four general areas identified are those judged to best meet the preferred geoscientific characteristics outlined in Section 7.1, based on available information.

7.2.5 Summary of Geoscientific Characteristics of the General Potentially Suitable Areas

Table 7.1 provides a summary of the key geoscientific descriptive characteristics of the general potentially suitable areas identified in the Manitouwadge area.

Table 7-1: Summary Characteristics of the General Potentially Suitable Areas – Manitouwadge Area

Geoscientific Descriptive Characteristic	**General Potentially Suitable Areas**			
	Metasedimentary rocks (northwest Quetico Subprovince)	**Fourbay Lake pluton**	**Black-Pic batholith (south-central area)**	**Black-Pic batholith (eastern area)**
Composition	Metasedimentary rocks: gneisses and migmatites	Granite-granodiorite Quartz monzodiorite	Foliated biotite-granodiorite gneiss	Foliated biotite-granodiorite gneiss
Age	ca. 2.700 to ca. 2.688 Ga	ca. 2.678 Ga	ca.2.720-2.689 Ga	ca.2.720-2.689 Ga
Inferred host rock thickness	Unknown; Likely of considerable thickness (up to ~7.5 km)	Unknown	Unknown; Likely of considerable thickness	Unknown; Likely of considerable thickness
Extent of geologic unit in the Manitouwadge area	1,740 km^2	65 km^2	1,607 km^2	1,607 km^2
Relative proximity to mapped structures (faults, shear zones, subprovince boundaries, etc.)	Wawa-Quetico Subprovince boundary 22 km to south Gravel River Fault – 17 km to northwest No mapped faults in area Nearest mapped fault – 6 km to east	Wawa-Quetico Subprovince boundary 39 km to north Gravel River Fault – 74 km to north Two northwest-trending mapped faults in area Nearest mapped fault – 3 km to southwest	Wawa-Quetico Subprovince boundary 28 km to north Gravel River Fault – 73 km to north Several short mapped faults: One northeast-trending mapped fault in area; Three north-trending mapped faults in area Nearest mapped fault – 5 km to southeast	Wawa-Quetico Subprovince boundary 21 km to north Gravel River Fault – 74 km to north One northwest-trending mapped fault in area Nearest mapped fault – 3 km to north
Structure: faults, foliation, dykes, joints	Low to moderate apparent surficial lineament density Low apparent geophysical lineament density No mapped faults in area Few mapped and geophysically interpreted dykes – well defined orientations	Low to moderate apparent surficial lineament density Low to moderate apparent geophysical lineament density Two northwest-trending mapped faults in area Few mapped and geophysically interpreted dykes – well defined orientations	Low to moderate apparent surficial lineament density Low to moderate apparent geophysical lineament density Several short mapped faults Few mapped and geophysically interpreted dykes – well defined orientations	Low to moderate apparent surficial lineament density Low to moderate apparent geophysical lineament density One northwest-trending mapped fault in area Few mapped and geophysically interpreted dykes – well defined orientations

Table 7-1: Summary Characteristics of the General Potentially Suitable Areas – Manitouwadge Area

Aeromagnetic characteristics and resolution	Noisy	Moderately noisy	Quiet	Moderately noisy
Terrain: topography, vegetation	Low to moderate relief, boreal forest; logged areas; bedrock-drift complex and ground moraine	Moderate relief, boreal forest; logged areas; bedrock-drift complex	Low to moderate relief, boreal forest; logged areas; bedrock-drift complex and glaciolacustrine terrain	Moderate relief, boreal forest; logged areas; bedrock-drift complex and glaciofluvial terrain
Access	An all weather road is within 1 km of the eastern side of area. Number of forest roads and trails	Limited number of logging roads in area. Power line transect area	Highway 614 roughly follows western boundary. Number of forest roads and trails	Logging road trend northward through area. Limited number of forest roads and trails
Resource potential	Low	Low	Low	Low
Overburden cover *	~56%	~3%	~29%	~16%
Drainage	Good; straddles continental divide	Good; drainage to north to Pic Creek	Good; drainage to southwest to Black Creek	Good; straddles continental divide

*Estimated percentage of area outside of bedrock terrain, as mapped on Figure 2.3.

7.3 Evaluation of the General Potentially Suitable Ares in the Manitouwadge Area

This section provides a brief description of how the identified potentially suitable areas were evaluated to verify whether they have the potential to satisfy the geoscientific safety functions outlined in NWMO's site selection process (NWMO, 2010). At this early stage of the site evaluation process, where limited geoscientific information is available, the intent is to assess whether there are any obvious conditions within the identified potentially suitable areas that would fail to satisfy the geoscientific safety functions. These include:

- ***Safe containment and isolation of used nuclear fuel**:* Are the characteristics of the rock at the site appropriate to ensuring the long-term containment and isolation of used nuclear fuel from humans, the environment and surface disturbances caused by human activities and natural events?
- ***Long-term resilience to future geological processes and climate change**:* Is the rock formation at the siting area geologically stable and likely to remain stable over the very long-term in a manner that will ensure the repository will not be substantially affected by geological and climate change process such as earthquakes and glacial cycles?
- ***Safe construction, operation and closure of the repository**:* Are conditions at the site suitable for the safe construction, operation and closure of the repository?
- ***Isolation of used fuel from future human activities:*** Is human intrusion at the site unlikely, for instance through future exploration or mining?

- ***Amenable to site characterization and data interpretation activities:*** Can the geologic conditions at the site be practically studied and described on dimensions that are important for demonstrating long-term safety?

The evaluation factors under each safety function are listed in Appendix A. An evaluation of the four general potentially suitable areas in the Manitouwadge area is provided in the following subsections.

7.3.1 Safe Containment and Isolation of Used Nuclear Fuel

The geological, hydrogeological, chemical and mechanical characteristics of a suitable site should promote long-term isolation of used nuclear fuel from humans, the environment and surface disturbances; promote long-term containment of used nuclear fuel within the repository; and restrict groundwater movement and retard the movement of any released radioactive material.

This requires that:

- The depth of the host rock formation should be sufficient for isolating the repository from surface disturbances and changes caused by human activities and natural events;
- The volume of available competent rock at repository depth should be sufficient to host the repository and provide sufficient distance from active geological features such as zones of deformation or faults and unfavourable heterogeneities;
- The hydrogeological regime within the host rock should exhibit low groundwater velocities;
- The mineralogy of the rock, the geochemical composition of the groundwater and rock porewater at repository depth should not adversely impact the expected performance of the repository multiple-barrier system;
- The mineralogy of the host rock, the geochemical composition of the groundwater and rock porewater should be favourable to retarding radionuclide movement; and
- The host rock should be capable of withstanding natural stresses and thermal stresses induced by the repository without significant structural deformations or fracturing that could compromise the containment and isolation functions of the repository.

The above factors are interrelated as they contribute to more than one safety function. The remainder of this section provides an integrated assessment of the above factors based on information that is available at the desktop stage of the evaluation.

As discussed in Section 3 and summarized in Table 7.1, available information reviewed as part of this preliminary assessment indicates that the thicknesses of the metasedimentary rocks of the Quetico Subprovince, Black-Pic batholith, and Fourbay Lake pluton in the Manitouwadge area are unknown but are estimated to be well in excess of 1 km. The metasedimentary rocks of the Quetico Subprovince may achieve a thickness of >7.5 km (Percival, 1989) away from the subprovince boundary. The Black-Pic batholith is believed to extend to a considerable depth based on its size and an understanding of the regional geologic history and structure. No information exists on the thickness of the Fourbay Lake pluton, but its areal extent and late stage emplacement suggest that it is likely to extend well below typical repository depth (approximately 500 m). Therefore, the depth of the rock in the four potentially suitable areas would contribute to the isolation the repository from human activities and natural surface events.

Analyses of lineaments interpreted during this preliminary assessment (Section 3.2.3 and 7.1) indicate that the four general potentially suitable areas in the Manitouwadge area warrant further consideration as they have the potential to contain rock volumes of sufficient size to host a deep geological repository. The existence of a high resolution magnetic/electromagnetic geophysical survey covering the majority of the Manitouwadge area and lack of widespread areas of thick overburden allowed a detailed assessment of lineament distribution. The distribution of lineament density as a function of lineament length over the potential host rocks shows that the variable density and spacing of shorter brittle lineaments is strongly influenced by geophysical data resolution and, to a lesser degree, by the amount of exposed bedrock (Figures 3.14 to 3.17). By classifying the lineaments according to length, this local bias is reduced and the spacing between lineaments increases as shorter lineaments are filtered out. Longer lineaments are more likely to extend to greater depth than shorter lineaments. All four general areas exhibit lineament spacing between longer lineaments (i.e., those longer than 10 km) on the order of 2 to ≥5 km, suggesting there is a potential for there to be sufficient volumes of structurally favourable rock at typical repository depth. All four general areas are located away from regional deformation zones, such as that associated with the Wawa-Quetico subprovince boundary. However, the potential impact of this deformation zone on the four potentially suitable areas needs to be further assessed.

The hydrogeological regime at repository depth should exhibit low groundwater velocities and retard the movement of any potentially released radioactive material. There is no information on the hydrogeologic properties of the deep crystalline bedrock in the Manitouwadge area. It is therefore not possible at this stage of the evaluation to predict the nature of the groundwater regime at repository depth in the two areas. The potential for groundwater movement at repository depth is, in part, controlled by the fracture frequency, the degree of interconnection and the extent to which the fractures are sealed due to higher stress levels and the presence of mineral infilling. Experience from other areas in the Canadian Shield indicates that ancient faults, similar to those in the Manitouwadge area, have been subjected to extensive periods of rock-water interaction resulting in the long-term deposition of infilling materials that contribute to sealing and a much reduced potential for groundwater flow at depth. Site-specific conditions that can influence the nature of deep groundwater flow systems in the Manitouwadge area would need to be investigated at later stages of the site evaluation process through site characterization activities that include drilling and testing of deep boreholes.

As discussed in Section 4.4, available information for other granitic intrusions (plutons and batholiths) within the Canadian Shield, indicates that active groundwater flow within structurally-bounded blocks tends to be generally limited to shallow fracture systems, typically less than 300 m. In deeper regions, hydraulic conductivity tends to decrease as fractures become less common and less interconnected (Stevenson *et al*., 1996; McMurry *et al*., 2003). Increased vertical and horizontal stresses at depth tend to close or prevent fractures thereby reducing permeability and resulting in diffusion-dominated groundwater movement (Stevenson *et al*., 1996; McMurry *et al.*, 2003). Hydraulic conductivity values measured at typical repository depths (500 m or greater) at the Whiteshell Research Area and Atikokan range from approximately 10^{-10} to 10^{-15} m/s (Stevenson *et al*., 1996; Ophori and Chan, 1996). Data reported by Raven *et al.* (1985) show that the hydraulic conductivity of the East Bull Lake pluton decreases from an average near-surface value of 10^{-8} m/s to less than 10^{-12} m/s below a depth of 400 to 500 m.

Information on other geoscientific characteristics relevant to the containment and isolation functions of a deep geological repository, such as the mineralogy of the rock, the geochemical composition of the groundwater and rock porewater, and the thermal and geomechanical properties of the rock is largely lacking for the Manitouwadge. The review of available information from other locations with similar geological settings did not reveal any obvious conditions that would suggest unfavourable mineralogical or hydrogeochemical characteristics for the metasedimentary and plutonic rocks characterizing the four areas identified within the Manitouwadge area (Sections 4.0 and 7.2). Mineralogical and hydrogeochemical characteristics, including pH, Eh, and salinity would need to be assessed during subsequent site evaluation stages. It is expected that the geomechanical and thermal characteristics of the granitic intrusions within the Manitouwadge area may resemble those of other granitic bodies (i.e., the Lac du Bonnet batholith) elsewhere in the Superior Province (Section 6.0) with no obvious unfavourable conditions known at present. These characteristics would need to be assessed during subsequent site evaluation stages.

Dykes associated with Matachewan, Biscotasing and Marathon dyke swarms have been mapped and/or were identified during the lineament analysis of the Manitouwadge area. At this desktop stage of the investigation, information about the hydraulic and thermal conductivity properties of dykes is lacking, and there is uncertainty as to whether the existence of dykes will have a positive or negative impact on the thermal conductivity of the surrounding host rocks. In addition, the potential existence of thin/narrow dykes, which are too small to be identified with any confidence from the geophysical data, or the presence of damage to the host rock (i.e., additional smaller lineaments) associated with dyke emplacement cannot be ruled out at this time. These aspects of uncertainty will need to be studied in further detail at later stages if the community remains in the site selection process.

In summary, the review of available geoscientific information, including completion of a lineament analysis and geophysical interpretation of the area, did not reveal any obvious conditions that would cause the rejection of any of the four identified areas on the basis of them not satisfying the containment and isolation requirements demanded of a repository. Potential suitability of these areas would have to be further assessed during subsequent site evaluation stages.

7.3.2 Long-term Resilience to Future Geological Processes and Climate Change

The containment and isolation functions of the repository should not be unacceptably affected by future geological processes and climate changes, including earthquakes and glacial cycles.

The assessment of the long-term stability of a suitable site would require that:

- Current and future seismic activity at the repository site should not adversely impact the integrity and safety of the repository system during operation and in the very long-term;
- The expected rates of land uplift, subsidence and erosion at the repository site should not adversely impact the containment and isolation functions of the repository;
- The evolution of the geomechanical, hydrogeological and geochemical conditions at repository depth during future climate change scenarios such as glacial cycles should not have a detrimental impact on the long-term safety of the repository; and
- The repository should be located at a sufficient distance from geological features such as zones of deformation or faults that could be potentially reactivated in the future.

A full assessment of the above factors requires detailed site-specific data that would be typically collected and analyzed through detailed field investigations. The assessment would include understanding how the site has responded to past glaciations and geological processes and would entail a wide range of detailed studies involving disciplines such as seismology, hydrogeology, hydrogeochemistry, paleohydrogeology and climate change. At this desktop preliminary assessment stage of the site evaluation process, the long-term stability factor is evaluated by assessing whether there is any evidence that would raise concerns about the long-term stability of the four general potentially suitable areas identified in the Manitouwadge area. The remainder of this section provides an integrated assessment of the factors listed above.

The Manitouwadge area is located in the Superior Province of the Canadian Shield, where large portions of land have remained tectonically stable for the last 2.5 billion years (Percival and Easton, 2007). Although a number of low magnitude seismic events (i.e., less than magnitude 3) have been recorded in the surrounding region, there are only two recorded earthquakes occurring in the Manitouwadge area (Figure 3.20).

Nearby regional features include the Gravel River fault (~17 km) and the Wawa-Quetico subprovince boundary, which is within the Manitouwadge area (Figure 3.3). As discussed in Section 3.1, the east-west-trending Wawa-Quetico subprovince boundary that transects the Manitouwadge area is characterized as a regional shear zone. However, the four identified general areas lie away from the subprovince boundary and its associated zone of deformation. A number of smaller faults are identified on the published bedrock geological maps covering the Manitouwadge area, including several mapped faults in the metasedimentary rocks of the Quetico Subprovince, the Black-Pic batholith, and the Fourbay Lake pluton (Figure 3.4). The structural geology of the Manitouwadge area and associated fracture network would require further assessment.

The geology of the Manitouwadge area is typical of the Canadian Shield, which has been subjected to numerous glacial cycles during the last million years. Glaciation is a significant past perturbation that could occur again in the future. However, findings from studies conducted in other areas of the Canadian Shield suggest that deep crystalline units, particularly plutonic intrusions, have remained largely unaffected by past perturbations such as glaciation (e.g., Laine, 1980, 1982; Bell and Laine 1985). Findings of a comprehensive paleohydrogeological study of the fractured crystalline rock at the Whiteshell Research Area, located within the Manitoba portion of the Canadian Shield (Gascoyne, 2004) indicated that the evolution of the groundwater flow system was characterized by periods of long-term hydrogeological and hydrogeochemical stability. Furthermore, there is evidence that only the upper 300 m shallow groundwater zone has been affected by glaciations within the last million years. McMurry *et al.* (2003) summarized several studies conducted in a number of plutons in the Canadian Shield and in the crystalline basement rocks of western Ontario. These various studies found that fractures below a depth of several hundred metres in the plutonic rock were ancient features. Subsequent geological processes such as plate movement and continental glaciation have typically caused reactivation of existing zones of weakness rather than the formation of large new zones of fractures.

The Manitouwadge area is still experiencing isostatic rebound following the end of the Wisconsinan glaciations. Current rates of isostatic uplift in the Manitouwadge area are not precisely known, although Lee and Southam (1994) estimate that the land is rising at a rate of 2.9 mm/a at Michipicoten, Ontario, some 150 km to the southeast. There is no site-specific information on erosion rates for the Manitouwadge area. However, as discussed in Section 3.1.6, the erosion rates from wind, water and past glaciations on the Canadian Shield are reported to be low, and are unlikely to affect the integrity of a deep geological repository in the Manitouwadge area in the long-term.

In summary, available information indicates that the identified areas in the Manitouwadge area have the potential to meet the long-term stability factor. The review did not identify any obvious conditions that would cause the performance of a repository to be substantially altered by future geological and climate change processes, or prevent the identified areas from remaining stable over the long-term. The long-term stability factor would need to be further assessed through detailed multidisciplinary site specific geoscientific and climate change site investigations.

7.3.3 Safe Construction, Operation and Closure of the Repository

The characteristics of a suitable site should be favourable for the safe construction, operation, closure and long-term performance of the repository.
This requires that:

- The available surface area should be sufficient to accommodate surface facilities and associated infrastructure;

- The strength of the host rock and *in-situ* stress at repository depth should be such that the repository could be safely excavated, operated and closed without unacceptable rock instabilities; and
- The soil cover depth over the host rock should not adversely impact repository construction activities.

There are few surface constraints that would limit the construction of surface facilities in the four general potentially suitable areas identified in the Manitouwadge area. These areas are characterized by moderate relief and each contains enough surface land outside protected areas and major water bodies to accommodate the required repository surface facilities.

From a constructability perspective, limited site-specific information is available on the local rock strength characteristics and *in-situ* stresses for the Manitouwadge area. However, there is abundant information at other locations of the Canadian Shield that could provide insight into what might be expected for the Manitouwadge area in general. As discussed in Section 6.0, available information suggests that granitic and gneissic crystalline rock units within the Canadian Shield generally possess good geomechanical characteristics that are amenable to the type of excavation activities involved in the development of a deep geological repository for used nuclear fuel (Arjang and Herget, 1997; Everitt, 1999; McMurry *et al*., 2003; Chandler *et al*., 2004). The conceptual model developed by Kaiser and Maloney (2005), based on available stress measurement data, describes the variable stress state in the upper 1,500 m of the Canadian Shield. Although this model can be used as an early indicator of average stress changes with depth, significant variations such as the principal horizontal stress rotation and the higher than average stress magnitudes found at typical repository depth (500 m) at AECL's URL (Martino *et al.*, 1997) could occur as a result of local variations in geological structure and rock mass complexity.

The four general potentially suitable areas are situated in areas having a reasonable amount of outcrop exposure. At this stage of the site evaluation process it is not possible to accurately determine the exact thickness of the overburden deposits in these areas due to the low resolution of available data. However, it is anticipated that overburden cover is not a limiting factor in any of the identified general areas.

In summary, the four general potentially suitable areas in the Manitouwadge area have good potential to meet the safe construction, operation, closure and long-term performance factors required of a repository.

7.3.4 Isolation of Used Fuel from Future Human Activities

A suitable site should not be located in areas where the containment and isolation functions of the repository are likely to be disrupted by future human activities.

This requires that:

- The repository should not be located within rock formations containing economically exploitable natural resources such as gas/oil, coal, minerals and other valuable commodities as known today; and
- The repository should not be located within geological formations containing groundwater resources at repository depth that could be used for drinking, agriculture or industrial uses.

In the Manitouwadge area, the Manitouwadge greenstone belt and gabbroic intrusions have the greatest mineral potential with exploration active in both of these geologic settings. No economic or significant mineralization has been identified to date in the metasedimentary rocks of the Quetico Subprovince, the Black-Pic batholith, or the Fourbay Lake pluton within the Manitouwadge area. A number of active mining claims exist in the central and eastern portions of the metasedimentary rocks of the Quetico Subprovince; however, only a few scattered mineral occurrences are recorded and, in general, the potential for economic mineralization is considered low.

The review of available information did not identify any groundwater resources at repository depth for the Manitouwadge area. As discussed in Section 4.0, water wells in the Manitouwadge area obtain water from overburden or shallow bedrock sources with well depths ranging from 4.6 to 119.2 m. Experience from other areas in the Canadian Shield has shown that active groundwater flow in crystalline rocks is generally confined to shallow fractured localized systems (Singer and Cheng, 2002). Records contained in the Ontario Ministry of Environment databases indicate that no potable water supply wells are known to exploit aquifers at typical repository depths in the Manitouwadge area or anywhere else in northern Ontario. Groundwater at such depths is generally saline and very low groundwater recharge at such depths limits potential yield, even if suitable water quality were to be found.

In summary, the potential for groundwater resources and economically exploitable natural resources at repository depth is considered low in the four identified general potentially suitable areas within the Manitouwadge area, although this conclusion will be subject to further confirmation if the community advances in the site selection process.

7.3.5 Amenability to Site Characterization and Data Interpretation Activities

In order to support the case for demonstrating long-term safety, the geologic conditions at a potential site must be amenable to site characterization and data interpretation. Factors affecting the amenability to site characterization include geological heterogeneity, structural and hydrogeological complexity, accessibility, and the presence of lakes or overburden with thickness or composition that could mask important geological or structural features.

As described in Section 3, the bedrock in the two general potentially suitable areas identified in the Black-Pic batholith are interpreted as foliated biotite-granodiorite gneiss with potential for homogeneitythat will not be difficult to characterize. A similar situation exists for the Fourbay Lake pluton as it is described as a uniform, massive pyroxene-hornblende-biotite granodiorite or quartz monzodiorite. While bedrock in the general potentiallu suitable area identified in the Quetico Subprovince is mapped entirely as metasedimentary, there is uncertainty on the lithological homogeneity based on interpretation of magnetic data. Also, lithological characteristics of the metasedimentary rocks in this area may be more complex due to the variable degree of metamorphism and migmatization they have experienced. However, at this stage of the assessment, such uncertainties are not considered to pose an impediment to site characterization.

As discussed in Section 7.1, interpreted lineaments represent the observable two-dimensional expression of three-dimensional features. The ability to detect and map such lineaments is influenced by topography, the character of the lineaments (e.g., their width, orientation, age, etc.), and the resolution of the data used for the mapping. Two factors significantly influenced the lineament interpretation for the Manitouwadge area: the majority of the area is covered by a high resolution geophysical survey and the bulk of the area has bedrock at or near surface. Together, these allow a detailed assessment of the lineament distribution and length. The fact that the northern edge of the Manitouwadge area has only lower resolution geophysical coverage is compensated, in part, by areas of outcrop and thin drift that enable the recognition of lineaments from satellite imagery and by the topographic data. The orientation of lineament features in three dimensions represents another degree of structural complexity that will require assessment through detailed site investigations in future phases of the site selection process.
In the Manitouwadge area, further mapping of geology and identification of geological structures would be strongly influenced by the extent and thickness of overburden cover and large lakes. Information on the thickness of overburden deposits within the Manitouwadge area is derived from a terrain evaluation (AECOM, 2014), data within the MOE's water well records and MNDM's diamond drill hole database. These data indicate that the majority of the Manitouwadge area has thin, but variable, drift cover. Extensive overburden deposits in the Manitouwadge area are mostly found in the northeast quadrant along the Pic-White Otter river system, and in the valleys hosting the Black Creek, Macutagon Creek, and Nama Creek. Additionally, a number of relatively narrow glaciofluvial deposits trend

north and/or northeast across the Manitouwadge area. The four identified general potentially suitable areas have fairly good bedrock exposure allowing site characterization.

Lakes in the Manitouwadge area, while frequent, are generally of a modest size although in a limited number of cases lake density is high within a local area. The identified potentially suitable areas contain sufficient areas with exposed bedrock and limited surface water cover which will allow for surface bedrock mapping as part of detailed site characterization.

All four general potentially suitable areas can be accessed via forest roads and trails. In the case of the northwestern part of the metasedimentary rocks of the Quetico Subprovince, this road network is within a kilometre of an all-weather road to the east of the area. The south-central part of the Black-Pic batholith has relatively well-developed road network, including Highway 614 along its western boundary. The eastern portion of the batholith is bisected by a northward-trending logging road.

The review of available information did not indicate any obvious conditions which would make the rock mass in the four identified general potentially suitable areas unusually difficult to characterize. All areas have good bedrock exposure allowing for detailed surface mapping to support site characterization. No conditions were identified that would make site characterization unusually difficult at any of the general potentially suitable areas.

8. GEOSCIENTIFIC PRELIMINARY ASSESSMENT FINDINGS

The objective of the Phase 1 geoscientific preliminary assessment was to assess whether the Manitouwadge area contains general areas that have the potential to satisfy the geoscientific site evaluation factors outlined in NWMO's site selection process document (NWMO, 2010).

The preliminary geoscientific assessment built on the work previously conducted for the initial screening (Geofirma Engineering Ltd., 2013a) and focused on the Township of Manitouwadge and its periphery, which are referred to as the "Manitouwadge area" in this report (Figure 1.1). The geoscientific preliminary assessment was conducted using available geoscientific information and key geoscientific evaluation factors that can be realistically assessed at this early stage of the site evaluation process. These include geology, structural geology, interpreted lineaments, distribution and thickness of overburden deposits, surface conditions, and the potential for economically exploitable natural resources. Where information for the Manitouwadge area was limited or not available, the assessment drew on information and experience from other areas on the Canadian Shield. The desktop geoscientific preliminary assessment included the following review and interpretation activities:

- Detailed review of available geoscientific information such as geology, structural geology, natural resources, hydrogeology and overburden deposits;
- Interpretation of available geophysical surveys (magnetic, electromagnetic, gravity, radiometric);
- Lineament studies using available satellite imagery, topography and geophysical surveys to provide information on the characteristics such as location, orientation and length of interpreted structural bedrock features;
- Terrain analysis studies to help assess overburden type and distribution, bedrock exposures, accessibility constraints, watershed and subwatershed boundaries, groundwater discharge and recharge zones; and
- The identification of general potentially suitable areas based on key geoscientific characteristics and the systematic application of NWMO's geoscientific site evaluation factors.

The desktop geoscientific preliminary assessment showed that the Manitouwadge area contains at least four general potentially suitable areas that have the potential to satisfy NWMO's geoscientific factors. Two of these potentially suitable areas are located within the Black-Pic batholith in the south central portion of the Manitouwadge area, one in the metasedimentary rocks of the Quetico Subprovince in the north, and one in the Fourbay Lake pluton in the southwest of the Manitouwadge area. Given the geographic extent of the Manitouwadge area, there may be additional areas that are also potentially suitable for hosting a deep geological repository.

The four general potentially suitable areas in the Manitouwadge area have a number of geoscientific characteristics that are favourable for hosting a deep geological repository. The geological units appear to have sufficient depth and lateral extent. The four areas identified have a low potential for natural resources, good bedrock exposure and limited surface water constraints, making the areas amenable to geological site characterization activities. In addition, three of the areas are covered by high resolution geophysical surveys.

While the identified general potentially suitable areas appear to have favourable geoscientific characteristics, there are inherent uncertainties that would need to be addressed during subsequent stages of the site evaluation process. The main uncertainties relate to the influence of regional structural features, the presence of numerous dykes, and the variable degree of metamorphism that the metasedimentary rocks experienced in the past.

The identified potentially suitable areas are located away from regional structural features, such as the Gravel River fault and Wawa-Quetico subprovince boundary. However, the potential impact of these regional features on the suitability of the areas needs to be further assessed. The Manitouwadge area contains numerous dykes. While the spacing between mapped and interpreted dykes appears to be favourable, the potential presence of smaller dykes not identifiable on geophysical data, the potential damage of the host rock due to the intrusion of dykes, and the hydraulic properties of the dykes would need to be assessed. In addition, uncertainty remains in relation to the lithological homogeneity at a local scale, particularly the varying degree of metamorphism that the metasedimentary rocks may have experienced.

Should the Township of Manitouwadge be selected by the NWMO to advance to Phase 2 study and remain interested in continuing with the site selection process, several years of progressively more detailed studies would be required to confirm and demonstrate whether the Manitouwadge area contains sites that can safely contain and isolate used nuclear fuel. This would include the acquisition and interpretation of higher resolution airborne geophysical surveys, detailed geological mapping and the drilling of deep boreholes.

9. REFERENCES

AECOM Canada Ltd., 2014. Phase 1 Geoscientific Desktop Preliminary Assessment, Terrain and Remote Sensing Study, Township of Manitouwadge, Ontario. Prepared for Nuclear Waste Management Organization (NWMO). NWMO Report Number: APM-REP-06144-0076.

Andersson, J., Ahokas, H., Hudson, J.A., Koskinen, L., Luukkonen, A., Löfman, J., Keto, V., Pitkänen, P., Mattila, J., A. Ikonen, T.K., Ylä-Mella, M. 2007. Olkiluoto Site Description 2006. POSIVA 2007-03.

Annor, A., Larocque, G. and Chernis, P. 1979. Uniaxial compression tests, Brazilian tensile tests and dilatational velocity measurements on rock specimens from Pinawa and Chalk River. CANMET Report No. MRP/MRL 79-60 (TR).

Arjang, B. 2004. Database on Canadian *in-situ* ground stresses. CANMET Division Report MMSL 01-029 (TR).

Arjang, B. and Herget, G. 1997. *In-situ* ground stresses in the Canadian hardrock mines: An update. International Journal of Rock Mechanics and Mining Science, Vol 34, Issue 3-4, P.15.e1-15.e16.

Back, P-E., Wrafter, J., Sundberg, J. and Rosén, L. 2007. R-07-47; Thermal properties Site descriptive modelling Forsmark – stage 2.2, SKB, 228p.

Baird, A. and McKinnon, S. D. 2007. Linking stress field deflection to basement structures in southern Ontario: results from numerical modeling; Tectonophysics, Vol. 432, p.89-100.

Barnett, P.J., Henry, A.P. and Babuin, D. 1991. Quaternary geology of Ontario, east-central sheet; Ontario Geological Survey, Map 2555, scale 1:1,000,000.

Barnett, P.J. 1992. Quaternary Geology of Ontario; *In:* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.1010–1088.

Beakhouse, G.P., 2001. Nature, timing and significance of intermediate to felsic intrusive rocks associated with the Hemlo greenstone belt and implications for the regional geological setting of the Hemlo gold deposit; Ontario Geological Survey, Open File Report 6020, 248p.

Bell, M. and E.P. Laine. 1985. Erosion of the Laurentide region of North America by glacial and glaciofluvial processes. Quaternary Research 23, p.154-175.

Berman, R.G., Easton, R.M. and Nadeau, L. 2000. A New Tectonometamorphic Map of the Canadian Shield: Introduction; The Canadian Mineralogist, v. 38, p.277-285.

Berman, R.G., Sanborn-Barrie, M., Stern, R.A. and Carson, C.J. 2005. Tectonometamorphism at *ca.* 2.35 and 1.85 Ga: in the Rae Domain, western Churchill Province, Nunavut, Canada: Insights from structural, metamorphic and *in situ* geochronological analysis of the southwestern Committee Bay Belt; The Canadian Mineralogist, v. 43, p.409-442.

Bleeker, W. and Hall, B. 2007. The Slave Craton: Geology and metallogenic evolution; *In:* Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of

Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p.849-879.

Boissonneau, A.N. 1965. Surficial Geology of Algoma-Cochrane; Ontario Department of Lands and Forests, Map S365, scale 1 inch to 8 miles.

Bostock, H.S. 1970. Physiographic subdivisions of Canada. *In:* Geology and Economic Minerals of Canada, Geological Survey of Canada, Economic Geology Report no. 1, p.11-30.

Breaks, F.W. 1991. English River Subprovince; *In:* Geology of Ontario. Ontario Geological Survey, Special Publication, v. 4, p.239-277.

Breaks, F.W. and Bond, W.D. 1993. The English River Subprovince – An Archean Gneiss Belt: Geology, geochemistry and associated mineralization; Ontario Geological Survey, Open File Report 5846, v. 1, 483p.

Brevic, E.C. and J.R. Reid, 1999. Uplift-based limits to the thickness of ice in the Lake Agassiz basin of North Dakota during the Late Wisconsinan; Geomorphology 32 2000. p.161–169

Brown A., Soonawala, N.M. Everitt R.A. and Kamineni, D.C. 1989. Geology and geophysics of the Underground Research Laboratory Site, Lac du Bonnet batholith, Manitoba. Can. J. Earth Sci. 26, 404-425.

Brown, A., Everitt, R.A., Martin C.D. and Davison, C.C. 1995. Past and future fracturing In AECL research areas in the Superior Province of the Canadian Precambrian Shield, with emphasis on the Lac Du Bonnet Batholith; Whiteshell Laboratories, Pinawa, Manitoba.

Buchan, K.L. and Ernst, R.E. 2004. Diabase dyke swarms and related units in Canada and adjacent regions; Geological Survey of Canada, Map 2022A, scale 1:5,000,000.

Buchan K.L., Halls, H.C. and Mortensen, J.K. 1996. Paleomagnetism, U-Pb geochronology, and geochemistry of Marathon dykes, Superior Province, and comparison with the Fort Frances swarm. Canadian Journal of Earth Sciences, vol. 33, p.1583-1595.

Card, K.D. 1990. A review of the Superior Province of the Canadian Shield, a product of Archean accretion. Precambrian Res, v.48, p.99-156.

Chandler, N., Guo, R. and. Read, R. (Eds). 2004. Special issue: Rock mechanics results from the underground research laboratory, Canada. International Journal of Rock Mechanics and Mining Science, Vol 41 (8), p.1221-1458.

Chown, E.H.M. 1957. The geology of the Wilroy property, Manitouwadge Lake, Ontario; MSc Thesis, University of British Columbia.

Clauser, C. and Huenges, E. 1995. Thermal conductivity of rocks and minerals; *In*: Ahrens, T. J. (Eds.), Rock Physics & Phase Relations: A Handbook of Physical Constants, American Geophysical Union, p.105-126.

Coates, M.E. 1967a. Kagiano Lake sheet, Thunder Bay District; Ontario Department of Mines, Map 2140, scale 1:63,360 or 1 inch to 1 mile.

Coates, M.E. 1967b. Stevens sheet, Thunder Bay District; Ontario Department of Mines, Map 2141, scale 1:63,360 or 1 inch to 1 mile.

Coates, M.E. 1970a. Vein Lake sheet, Thunder Bay District; Ontario Department of Mines, Map 2192, scale 63,360 or 1 inch to 1 mile.

Coates, M.E. 1970b. Geology of the Killala-Vein Lake area; Ontario Department of Mines, Geological Report 81, 35p.

Corfu, F. and Andrews, A. 1986. A U–Pb age for mineralized Nipissing diabase, Gowganda, Ontario; Canadian Journal of Earth Sciences, v.23, p.107–112.

Corfu, F. and Muir, T.L. 1989. The Hemlo-Heron Bay greenstone belt and Hemlo Au-Mo deposit, Superior Province, Ontario, Canada: 1. Sequence of igneous activity determined by zircon U-Pb geochronology. Chemical Geology, vol. 79, p.183-200.

Corfu, F., Stott, G.M. and Breaks, F.W. 1995. U-Pb geochronology and evolution of the English River Subprovince, an Archean low P – high T metasedimentary belt in the Superior Province; Tectonics, v.14, p.1220-1233.

Corfu, F. and Stott, G.M. 1996. Hf isotopic composition and age constraints on the evolution of the Archean central Uchi Subprovince, Ontario, Canada; Precambrian Research, v.78, p.53-63.

Corrigan, D., Galley, A.G. and Pehrsson, S. 2007. Tectonic evolution and metallogeny of the southwestern Trans-Hudson Orogen; *In:* Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p.881-902.

Davis, D.W., Schandl, E.S. and Wasteneys, H.A. 1994. U-Pb dating of minerals in alteration halos of Superior Province massive sulfide deposits: syngenesis versus metamorphism; Contributions to Mineralogy and Petrology, v.115, p.427-437.

Davis, D.W. and Stott, G.M. 2003. Geochronology of two Proterozoic mafic dike swarms in northwestern Ontario; Ontario Geological Survey, Open File Report 6120, p.12-1 to 12-7.

de Lima Gomes, A. J. and Mannathal Hamza, V. 2005. Geothermal Gradient and Heat Flow in the State of Rio de Janeiro. Revista Brasileira de Geofisicaisica, 23(4), p.325-347.

Dendron Resource Surveys Limited. 1986. Peat and Peatland Evaluation of the Longlac-Nakina Area, 7 Volumes (Summary Volume and Appendix Volumes A-F); Ontario Geological Survey, Open File Report 5542, 382p. 51 figures, 41 tables, 51 maps and 71 profiles.

Earthquakes Canada, 2013. Natural Resources Canada (NRCan), Geologic Survey of Canada, http://www.earthquakescanada.nrcan.gc.ca/historic-historique/caneqmap-eng.php

Easton, R.M. 2000a. Metamorphism of the Canadian Shield, Ontario, Canada. I. The Superior Province; The Canadian Mineralogist, v. 38, p.287-317.

Easton, R.M. 2000b. Metamorphism of the Canadian Shield, Ontario, Canada. II. Proterozoic metamorphic history; The Canadian Mineralogist, v. 38, p.319-344.

Easton, R.M., Hart, T.R., Hollings, P., Heaman, L.M., MacDonald, C. A. and Smyk, M. 2007. Further refinement to the timing of Mesoproterozoic magmatism, Lake Nipigon region, Ontario; Can Jour Earth Sci., 44(8), p.1055-1086.

Eberhardt, E., Stead, D. and Stimpson, B. 1999. Effects of sample disturbance on the stress-induced microfracturing characteristics of brittle rock; Can. Geotech. Jour., v.36, p.239-250.

Environment Canada. 2013. Water Survey of Canada, http://www.wateroffice.ec.gc.ca/index_e.html

Everitt, R. 1999. Experience gained from the geological characterisation of the Lac due Bonnet batholith, and comparison with other sparsely fractured granite batholiths in the Ontario portion of the Canadian Shield. Atomic Energy of Canada Limited. Ontario Power Generation Report No. 06819-REP-01200-0069-R00.

Everitt, R. 2002. Geological model of the moderately fractured rock experiment. Ontario Power Generation, Nuclear Waste Management Division, Report 06819-REP-01300-10048-R00. Toronto, Canada.

Everitt, R., McMurray, A., Brown, A., Davison, C. 1996. Geology of the Lac du Bonnet Batholith, Inside and Out: AECL's Underground Research Laboratory, Southeastern Manitoba – Field Trip Guidebook B5; Geological Association of Canada/Mineralogical Association of Canada Annual Meeting, Winnipeg, Manitoba, May 27-29, 1996.

Farrand, W.R. and Drexler, C.W. 1985. Late Wisconsinan and Holocene history of the Lake Superior basin; *In:* Quaternary Evolution of the Great Lakes, Geological Association of Canada, Special Paper 30, p.17-32.

Fernández, M., E. Banda and E. Rojas, 1986. Heat pulse line-source method to determine thermal conductivity of consolidated rocks; Rev. Sci. Instrum., 57, p.2832-2836.

Flint, R. 1947. Glacial Geology and the Pleistocene Epoch, J. Wiley and Sons, New York.

Follin, S. and S. Stigsson, 2014. A transmissivity model for deformation zones in fractured crystalline rock and its possible correlation to in situ stress at the proposed high-level nuclear waste repository site at Forsmark, Sweden. Hydrogeology Journal, 22, p. 299–311.

Fountain, D.M., Salisbury, M.H. and Furlong, K.P. 1987. Heat production and thermal conductivity of rocks from the Pikwitonei - Sachigo continental cross section, Central Manitoba: Implications for the thermal structure of Archean crust; Can. J. Earth Sci., 24, p.1583-1594.

Fralick P., Davis, D.W. and Kissin, S.A. 2002. The age of the Gunflint Formation, Ontario, Canada: single zircon U-Pb age determinations from reworked volcanic ash; Canadian Journal of Earth Sciences, v.39, p.1085-1091.

Frape, S.K., Fritz P. and McNutt, R.H. 1984. Water–Rock interaction and chemistry of groundwaters from the Canadian Shield. Geochimica et Cosmochimica Acta, v. 48, p.1617–1627.

Fraser, J.A. and Heywood, W.W. (editors) 1978. Metamorphism in the Canadian Shield; Geological Survey of Canada, Paper 78-10, 367p.

Friesen, R.G. Pierce, G.A. and Weeks, R.M. 1982. Geology of the Geco base metal deposit; *In:* Precambrian Sulphide Deposits, Geological Association of Canada, Special Paper 25, p.343-363.

Friske, P.W.B., Hornbrook, E.H.W., Lynch, J.J., McCurdy, M.W., Gross, H., Galletta, A.C. and Durham, C.C. 1991. National geochemical reconnaissance lake sediment and water data, northwestern Ontario; Geological Survey of Canada, Open File 2360.

Gartner, J.F. 1979. Steel Lake Area (NTS 42E/SE), District of Thunder Bay; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 44, 14p., Accompanied by Maps 5080, scale 1:100, 000.

Gartner. J.F. and McQuay. D.F. 1980a. Obakamiga Lake Area (NTS 42F/SW). Districts of Algoma and Thunder Bay; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 45, 16p., Accompanied by Map 5084, scale 1:100,000.

Gartner. J.F. and McQuay. D.F. 1980b. White River Area (NTS 42C/NW). Districts of Thunder Bay and Algoma; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 61, 18p., Accompanied by Maps 5094 and 5998, scale 1:100,000.

Gartner. J.F. and McQuay. D.F. 1980c. Taradale Area (NTS 42F/NW), Districts of Algoma, Cochrane and Thunder Bay; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 29, 15p., Accompanied by Map 5082, scale 1:100, 000.

Gascoyne, M. 1994. Isotopic and geochemical evidence for old groundwaters in a granite on the Canadian Shield. Mineralogical Magazine. v58A p319-320.

Gascoyne, M. 2000., Hydrogeochemistry of the Whiteshell research area. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10033-R00.

Gascoyne, M. 2004. Hydrogeochemistry, groundwater ages and sources of salts in a granitic batholith on the Canadian Shield, southeastern Manitoba. Applied Geochemistry, 19, p.519-560.

Gascoyne, M., Davison, C.C., Ross J.D. and Pearson, R. 1987. Saline groundwaters and brines in plutons in the Canadian Shield; *In* Saline water and gases in crystalline rocks, Editors: Fritz, P., and Frape, S.K.

Gascoyne, M, Ross, J.D. and Watson, R.L. 1996. Highly saline pore fluids in the rock matrix of a granitic batholith on the Canadian Shield. Proc 30th Int Geol. Congress. Beijing, China, p.4-14.

Geddes, R.S. and Kristjansson, F.J. 1984. Quaternary Geology of the Hemlo Area; Constraints on Mineral Exploration; Paper presented at 8th District 4 Meeting, Canadian Institute of Mining and Metallurgy, Thunder Bay, October, 1984.

Geddes. R.S., Bajc, A.F. and Kristjansson, F.J. 1985. Quaternary Geology of the Hemlo Region, District of Thunder Bay; *In:* Summary of Field Work, 1985, Ontario Geological Survey, Ontario Geological Survey, Miscellaneous Paper 126, p.151-154.

Geddes R.S. and Bajc, A.F. 1985. Quaternary Geology of the While Lake area, District of Thunder Bay; Ontario Geological Survey, Map P.2849, Geological Series-Preliminary Map. scale 1:50,000.

Geddes R.S. and Bajc, A.F. 2009. Quaternary Geology of the While Lake area, District of Thunder Bay; Ontario Geological Survey, Map 2683, Geological Series, scale 1:50,000.

GeoBase, 2011a. Canadian Digital Elevation Data: http://www.geobase.ca/

GeoBase, 2011b. GeoBase Orthoimage 2005-2010: http://www.geobase.ca/

Geofirma Engineering Ltd. 2013a. Initial screening for siting a deep geological repository for Canada's used nuclear fuel, Township of Manitouwadge, Ontario; Prepared for Nuclear Waste Management Organization, 37p., plus figures.

Geofirma Engineering Ltd. 2013b. Phase 1 Geoscientific Desktop Preliminary Assessment of Potential Suitability for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel Township of Hornepayne, Ontario; Prepared for Nuclear Waste Management Organization, NWMO Report Number: APM-REP-06144-0003, 80p., plus appendices and figures.

Giguere, J.F. 1972. Granitehill Lake area, Thunder Bay and Algoma districts; Ontario Department of Mines and Northern Affairs, Map 2219; scale 1:63 360 or 1 inch to 1 mile.

Golder Associates Ltd. 2012a. Thermo-mechanical analysis of a single level repository for used nuclear fuel. Prepared by Golder Associates Ltd. for the Nuclear Waste Management Organization. APM-REP-00440-0010.

Golder Associates Ltd. 2012b. Thermo-mechanical analysis of a multi-level repository for used nuclear fuel. Prepared by Golder Associates Ltd. for the Nuclear Waste Management Organization. APM-REP-00440-0019.

Golder Associates Ltd., 2014. Phase 1 Desktop Assessment of Potential Suitability, Environment Report – Township of Manitouwadge, Ontario. Prepared for the Nuclear Waste Management Organization (NWMO), NWMO Report Number APM-REP-06144-0074.

Gordon, R.G. and Jurdy, D.M. 1986. Cenozoic global plate motions, J. Geophys. Res., 91, p.12,389–12,406.

Government of Ontario, 2011. Conserving a Future for our Past: Archaeology, Land Use Planning & Development in Ontario.

Gupta, G., Erram, V., Kumar, S. 2012. Temporal geoelectric behavior of dyke aquifers in northern Deccan Volcanic Province, India. J. Earth Syst. Sci. 121, No. 3, June 2012, p.723-732.

Halls, H.C. 1982. The importance and potential of mafic dyke swarms in studies of geodynamic processes; Geoscience Canada, Vol. p.145-154.

Halls, H.C. 1991. The Matachewan dyke swarm, Canada: an early Proterozoic magnetic field reversal; Earth and Planetary Science Letters, 105 (1991), p.279-292.

Halls, H. C. and Davis, D. W. 2004. Paleomagnetism and U–Pb geochronology of the 2.17 Ga Biscotasing dyke swarm, Ontario, Canada: evidence for vertical-axis crustal rotation across the Kapuskasing Zone; Canadian Journal of Earth Sciences, v. 41, p.255–269.

Halls, H.C., Stott, G.M., Ernst, R.E. and Davis, D.W., 2006. A Paleoproterozoic mantle plume beneath the Lake Superior region; *In*: Institute on Lake Superior Geology, 52nd Annual Meeting Sault Ste Marie, Ontario, Part 1, Program and Abstracts, p.23-24.

Haimson, B. C. 1990. Stress measurements in the Sioux Falls quartzite and the state of stress in the Midcontinent; The 31st U.S. Symposium on Rock Mechanics (USRMS), June 18 - 20, 1990, Golden, Colorado.

Hajnal, Z., Stauffer, M.R., King, M.S., Wallis, P.F., Wang, H.F. and Jones, L.E.A. 1983. Seismic characteristics of a Precambrian pluton and its adjacent rocks; Geophysics, Vol. 48, No. 5, p. 569-581.

Hallet, B., 2011, Glacial Erosion Assessment; NWMO DGR-TR-2011-18.

Halls, H.C., Stott, G.M., Ernst, R.E. and Davis, D.W., 2006. A Paleoproterozoic mantle plume beneath the Lake Superior region; *In*: Institute on Lake Superior Geology, 52nd Annual Meeting Sault Ste Marie, Ontario, Part 1, Program and Abstracts, p.23-24.

Halls, H.C., Davis, D.W., Stott, G.M., Ernst R.E. and Hamilton, M.A. 2008. The Paleoproterozoic Marathon Large Igneous Province: new evidence for a 2.1 Ga long-lived mantle plume event along the southern margin of the North American Superior Province; Precambrian Research, Volume 162, p.327-353.

Hamilton M.A., David, D.W., Buchan, K.L. and Halls, H.C. 2002. Precise U-Pb dating of reversely magnetized Marathon diabase dykes and implications for emplacement of giant dyke swarms along the southern margin of the Superior Province, Ontario. Geological Survey of Canada, Current Research 2002-F6, 10p.

Hay, W.W., Shaw C.A. and Wold, C.N. 1989. Mass-balanced paleogeographic reconstructions. Geologishce Rundschau 78.

Hayek, S., Drysdale, J., Adams, J., Peci, V., Halchuk, S. and Street, P. 2011. Seismic activity in the Northern Ontario portion of the Canadian shield: Annual progress report for the period January 01 - December 31, 2010. Prepared by the Canadian Hazards Information Service, Geological Survey of Canada, Natural Resources Canada. NWMO TR-2011-26.

Heaman, L.M. 1997. Global magmatism at 2.45 Ga: Remnants of an ancient large igneous province?; Geology, Vol. 25, p.299-302.

Heaman, L.M., Easton, R.M., Hart, T.R., Hollings, P., MacDonald, C.A. and Smyk, M. 2007. Further refinement to the timing of Mesoproterozoic magmatism, Lake Nipigon Region, Ontario; Canadian Journal of Earth Sciences, v.44, no.8, p.1055-1086.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfess D. and Müller. B. 2008. The World Stress Map Based on the Database Release 2008, Equatorial Scale 1:46,000,000. Commission for the Geological Map of the World. Paris, France.

Herget, G., 1973. Variation of rock stresses with depth at a Canadian iron mine; Int. J. Rock Mech. Min Sci., Vol. 10, p.37-51.

Herget, G., 1980. Regional stresses in the Canadian Shield; *In:* Proceedings 13th Canadian Rock Mechanics Symposium, CIM 22, p.9-16, Can. Inst. Min. and Metall.

Hinz, P., Landry, R.M. and Gerow, M.C. 1994. Dimension stone occurrences and deposits in northwestern Ontario; Ontario Geological Survey, Open File Report 5890, 191p.

Holland, M. 2012. Evaluation of factors influencing transmissivity in fractured hard-rock aquifers of the Limpopo Province; Water SA Vol. 38, No. 3, International Conference on Groundwater Special Edition 2012.

Innes, D.G. and Ayres, L.D. 1971. Caramat-Pagwa River sheet, geological compilation series, Algoma, Cochrane and Thunder Bay districts; Ontario Department of Mines and Northern Affairs, Map 2202; scale 1:253,440.

Jackson, S.L. Beakhouse, G.P. and Davis, D.W. 1998. Geological Setting of the Hemlo Gold Deposit; an Interim Progress Report, Ontario Geological Survey, Open File Report 5977, 121p.

James, R.S., Grieve, R.A.F., and Pauk, L. 1978. The petrology of cordierite-anthophyllite gneisses and associated mafic and pelitic gneisses at Manitouwadge, Ontario; American Journal of Science, v.278, p.41-63

Johns, G.W., and McIlraith, S. 2003. Precambrian geology compilation series – Hornepayne sheet; Ontario Geological Survey, Map 2668, scale 1:250,000.

Johns, G.W., McIlraith, S. and Stott, G.M. 2003. Precambrian geology compilation series – Longlac sheet; Ontario Geological Survey, Map 2667, scale 1:250,000.

Johnson, M. D., Armstrong, D.K., Sanford, B.V., Telford, P.G. and Rutka, M.A. 1992. Paleozoic and Mesozoic geology of Ontario; *In:* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.907-1008.

Jolly, W.T. 1978. Metamorphic history of the Archean Abitibi Belt; *In:* Metamorphism in the Canadian Shield; Geological Survey of Canada, Paper 78-10, p.63-78.

Kamineni, D.C., Stone, D. and Peterman, Z.E. 1990. Early Proterozoic deformation in the western Superior Province, Canadian Shield; Geological Society of America Bulletin, v.102, p.1623-1634.

Karrow ,P F. and White, O.L. 2002. A history of neotectonic studies in Ontario; Tectonophysics, Volume: 353, Issue: 1-4, p.3-15.

Kaiser, P. K. and Maloney, S. 2005. Review of ground stress database for the Canadian Shield, Report No: 06819-Rep-01300-10107-R00, December 2005.

Kettles, I.M. and Way Nee, V. 1998. Surficial geology, Vein Lake, Ontario; Geological Survey of Canada, Map 1921A, scale 1:50,000.

Kraus, J. and Menard, T. 1997. A thermal gradient at constant pressure: Implications for low- to medium-pressure metamorphism in a compressional tectonic setting, Flin Flon and Kisseynew domains, Trans-Hudson Orogen, Central Canada; The Canadian Mineralogist, v. 35, p.1117-1136.

Kristjansson F.J. and R.S. Geddes, 2009. Quaternary geology of the Manitouwadge area, Northern Ontario; Ontario Geological Survey, 2000 Series Map M2684, Scale 1:50,000.

Kristjansson. F.J., and Geddes, R.S. 1986: Quaternary geology of the Manitouwadge area, District of Thunder Bay; Ontario Geological Survey, Map P.3055, Geological Series-Preliminary Map, scale 1:50,000.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenough, J.D. and Nakamura, E. 1987. Precise U–Pb isotopic ages of diabase dykes and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon; *In*: Mafic dyke swarms. Edited by H.C. Halls and W.F. Fahrig, Geological Association of Canada, Special Paper 34, p.147–152.

Kukkonen, I., Suppala, A., Korpisalo, T. and Koskinen, T. 2007. Drill Hole Logging Device TERO76 for Determination of Rock Thermal Properties. Posiva Oy, February 2007.

Kukkonen, I., Kivekäs, L., Vuoriainen, S. and Kääriä, M. 2011. Thermal properties of rocks in Olkiluoto: Results of laboratory measurements 1994-2011; Geological Survey of Finland, Working Report 2011 – 17, 96p.

Laine, E.P. 1980. New evidence from beneath western North Atlantic for the depth of glacial erosion in Greenland and North America. Quaternary Research 14, p.188–198.

Laine, E.P. 1982. Reply to Andrew's comment. Quaternary Research 17, p.125–127.

Liebel. H.T., Huber, K., Frengstad, B.S., Kalskin Ramstad, R. and Brattli, B. 2010. Rock core samples cannot replace thermal response tests - A statistical comparison based on thermal conductivity data from the Oslo Region (Norway); Zero emission buildings - Proceedings of Renewable Energy Conference 2010, Trondheim, Norway.

Land Information Ontario (LIO). 2013. OHN – Watercourse. https://www.appliometadata.lrc.gov.on.ca/geonetwork/srv/en/main.home

Larocque, G. and Annor, A.1985. An overview of rock mechanics and rock properties; *In*: The Geoscience Program, Proceedings of the Seventeenth Information Meeting of the Nuclear Fuel Waste Management Program, Volume I, Atomic Energy of Canada Ltd., Technical Record, TR-299, p.25-44.

Lee, D.H. and Southam, C.F. 1994. Effect and implications of differential isostatic rebound on Lake Superior's regulatory limits; Journal of Great Lakes Research, 20(2), p.407-415.

Lin, S. 2001. Stratigraphic and structural setting of the Hemlo Gold Deposit, Ontario, Canada; Economic Geology, v. 96, p.477–507.

Lin, S. and Beakhouse, G.P. 2013. Synchronous vertical and horizontal tectonism at late stages of Archean cratonization and genesis of Hemlo gold deposit, Superior craton, Ontario, Canada; Geology, v. 41; no. 3; p.359–362.

Mainville, A. and Craymer, M.R. 2005. Present-day tilting of the Great Lakes region based on water level gauges. GSA Bulletin, 117(7/8), p.1070-1080.

Maloney, S.M., Kaiser, P.K. and Vorauer, A. 2006. A re-assessment of *in-situ* stresses in the Canadian Shield. 41st U.S. Symposium on Rock Mechanics (USRMS): "50 Years of Rock Mechanics - Landmarks and Future Challenges", Golden, Colorado. ARMA/USRMS 06-1096.

Manson, M.L. and Halls, H.C. 1994. Post-Keweenawan compressional faults in the eastern Lake Superior region and their tectonic significance; Can. J. Earth Sciences, v.31, p.640-651.

Martino, J.B., Thompson, P.M., Chandler, N.A. and Read, R.S. 1997. The *in situ* stress program at AECL's Underground Research Laboratory, 15 years of research (1982-1997); Ontario Hydro Report No. 06819-REP-01200-0053 R00.

McFall, G.H., 1993. Structural elements and neotectonics of Prince Edward County, Southern Ontario; Géographie physique et Quaternaire, v. 47, p.303-312.

McFall, G.H. and Allam, A. 1990. Neotectonic investigations in southern Ontario: Prince Edward County-Phase I, Atomic Energy Control Board, Technical Report INFO-0343, 67p.

McKay, D.B. 1994. Mineral occurrences of the Manitouwadge area, Volumes 1-3; Ontario Geological Survey, Open File Report 5906, 566p.

McMurry, J., Dixon , D.A., Garroni, J.D., Ikeda, B.M., Stroes-Gascoyne, S., Baumgartner, P. and Melnyk, T.W.. 2003. Evolution of a Canadian deep geologic repository: Base scenario. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10092-R00, p.102-107.

Menard, T. and Gordon, T.M. 1997. Metamorphic P-T paths from the Eastern Flin Flon Belt and Kisseynew Domain, Snow Lake, Manitoba; The Canadian Mineralogist, v. 35, p. 1093-1115.

Meriaux, C., Lister, J.R., Lyakhovsky, V., Agnon, A. 1999. Dyke propagation with distributed damage of the host rock; Earth and Planetary Science Letters, 165 (1999), p.177-185.

Miles, W.F. 1998. An Interpretation of high resolution aeromagnetic data over the Manitouwadge greenstone belt, Ontario, Canada; MSc Thesis, Ottawa-Carleton Geoscience Centre and University of Ottawa, Ottawa, Canada, 250p.

Milne, V.G. 1963. Flanders Lake area, Thunder Bay and Algoma districts; Ontario Department of Mines, Map 2047, scale 1:63,360 or 1 inch to 1 mile.

Milne, V.G. 1967a. Barehead Lake sheet, Thunder Bay District; Ontario Department of Mines, Map 2143, scale 1:31,680 or 1 inch to ½ mile.

Milne, V.G. 1967b. Gowan Lake sheet, Thunder Bay District; Ontario Department of Mines, Map 2144, scale 1:31,680 or 1 inch to ½ mile.

Milne, V.G. 1967c, Agonzon Lake sheet, Thunder Bay District; Ontario Department of Mines, Map 2145, scale 1:31,680 or 1 inch to ½ mile.

Milne, V.G. 1968a. Dotted Lake sheet, Thunder Bay District; Ontario Department of Mines, Map 2146, scale 1:31,680 or 1 inch to ½ mile.

Milne, V.G. 1968b. Geology of the Black River area, District of Thunder Bay; Ontario Department of Mines, Geological Report 72, 68p.

Milne, V.G. 1969. Progress report on a field study of the Manitouwadge-area ore deposits; Canadian Mining and Metallurgical Bulletin, v.62, p.209.

Milne, V.G. 1974, Mapledoram-Gemmell, Thunder Bay District; Ontario Division of Mines, Map 2280, sacle 1:12,000 or 1 inch to 1000 feet.

Milne, V.G., Giblin, P.E., Bennett, G., Thurston, P.C., Wolfe, W.J., Giguere, J.F., Leahy, E.J. and Rupert, R.J. 1972. Manitouwadge-Wawa sheet, Geological Compilation Series, Algoma, Cochrane, Sudbury and Thunder Bay districts, Ontario Division of Mines, 2000 Series Map 2220, Scale 1:253,440.

Ministry of Natural Resources (MNR), 2013a. Licence and permit list. http://www.mnr.gov.on.ca/en/Business/Aggregates/2ColumnSubPage/STDPROD_091593.html

Ministry of Natural Resources (MNR), 2013b. Forest Management Plans. http://www.efmp.lrc.gov.on.ca/eFMP/home.do

Ministry of Northern Development and Mines (MNDM). 2013a. GeologyOntario. Internet Application. http://www.geologyontario.mndm.gov.on.ca/

Ministry of Northern Development and Mines (MNDM). 2013b. Geo-Claims Internet Application. http://www.mndm.gov.on.ca/mines/claimaps_e.asp.

Monenco Ontario Limited 1981: Evaluation of the Potential of Peat in Ontario; Ontario Ministry of Natural Resources, Mineral Resources Branch, Occasional Paper No. 7, 193p.

Muir, T.L. 2003. Structural evolution of the Hemlo greenstone belt in the vicinity of the world-class Hemlo gold deposit. Can. J. Earth Sci., v40, p.395-430.

Natural Resources Canada (NRCan). 2013. Geoscience Data Repository (GDR), http://www.earthquakescanada.nrcan.gc.ca/historic-historique/images/caneqmap_e.pdf

NWMO, 2005. Choosing a Way Forward. The Future Management of Canada's Used Nuclear Fuel. Nuclear Waste Management Organization Final Study Report. (Available at www.nwmo.ca).

NWMO. 2010. Moving Forward Together: Process for selecting a site for Canada's deep geological repository for used nuclear fuel, Nuclear Waste Management Organization, May 2010.

NWMO, 2014. Preliminary Assessment for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel - Township of Manitouwadge, Ontario - Findings from Phase One Studies. NWMO Report Number APM-REP-06144-0073.

Ojakangas, R.W., Morey, G.B and Southwick, D.L. 2001. Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America; Journal of Sedimentary Geology, Vol. 141-142, p.319-341.

Ontario Geological Survey (OGS). 1991. Bedrock geology of Ontario, east-central sheet. Ontario Geological Survey, Map 2543, scale 1:1,000,000.

Ontario Geological Survey (OGS). 1992. Tectonic assemblages of Ontario, east-central sheet. Ontario Geological Survey, Map 2577, 1:1,000,000.

Ontario Geological Survey (OGS). 1997. Quaternary geology, seamless coverage of the province of Ontario: Ontario Geological Survey, Miscellaneous Release-Data, Data Set 14.

Ontario Geological Survey (OGS), Ministry of Northern Development and Mines, and Northeast Science and Information Section, Ministry of Natural Resources. 2005. Digital Northern Ontario Engineering Geology Terrain Study (NOEGTS); Ontario Geological Survey, Miscellaneous Release Data 160.

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

Ontario Ministry of Environment (MOE). 2013. Water Well Database.

Ontario Ministry of Tourism and Culture, 2013: Ontario Heritage Trust, http://www.heritagetrust.on.ca/Home.aspx.

Ontario Parks, 2010. Provincial Park Profiles. http://www.ontarioparks.com/.

Ophori, D.U. and Chan, T. 1996. Regional Groundwater Flow in the Atikokan Research Area: Model Development and Calibration. AECL-11081, COG-94-183.

Ophori, D.U., Brown, A., Chan T., Davison, C.C., Gascoyne, M., Scheier, N.W., Stanchell, F.W. and Stevenson, D.R. 1996. Revised model of regional groundwater flow of the Whiteshell Research Area. Atomic Energy of Canada Limited Report, AECL-11435, COG-95-443, Pinawa, Manitoba, Canada.

Osmani, I.A. 1991. Proterozoic mafic dike swarms in the Superior Province of Ontario; *In:* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.661-681.

Pan, Z. and Fleet, H.M. 1992. Calc-silicate alteration in the Hemlo Gold deposit, Ontario: mineral assemblages, P-T-X constraints, and significance; Economic Geology, v.87, p.104-1120.

Pan, Y., Fleet, M.E., Williams, H.R. 1994. Granulite–facies metamorphism in the Quetico Subprovince, north of Manitouwadge, Ontario; Can J. Earth Sci. 31, p.1427–1439.

Pan, Y., Fleet, M.E. and Heaman, L.M. 1998. Thermo-tectonic evolution of an Archean accretionary complex: U-Pb geochronological constraints on granulites from the Quetico Subprovince, Ontario, Canada; Precambrian Research, v.92, p.117-128.

Paterson, Grant and Watson Ltd., 2014. Phase 1 Geoscientific Desktop Preliminary Assessment, Processing and Interpretation of Geophysical Data, Township of Manitouwadge, Ontario. Prepared for Nuclear Waste Management Organization (NWMO). NWMO Report Number: APM-REP-06144-0077.

Pease, V., Percival, J., Smithies, H., Stevens, G. and Van Kranendonk, M. 2008. When did plate tectonics begin? Evidence from the orogenic record; *In:* Condie, K.C. and Pease, V., eds., When Did Plate Tectonics Begin on Earth?, Geological Society of America Special Paper 440, p.199-228.

Peltier, W.R., 2002. On eustatic sea level history: Last Glacial Maximum to Holocene: Quaternary Science Reviews, v.21, p.377–396.

Percival, J.A. 1989. A regional perspective of the Quetico metasedimentary belt, Superior Province, Canada; Canadian Journal of Earth Sciences, Vol. 26, p.677-693.

Percival, J.A. and Sullivan, R.W. 1988. Age constraints on the Quetico belt, Superior Province, Ontario; *In*: Radiogenic and Isotope Studies: Report 2; Geological Survey of Canada, Paper 88-2, p.97-107.

Percival, J.A. and Williams, H.R. 1989. Late Archean Quetico accretionary complex, Superior Province, Canada; Geology, v.17, p.23-25.

Percival, J.A., and G.F. West, 1994. The Kapuskasing uplift: A geological and geophysical synthesis; Canadian Journal of Earth Sciences, Vol. 31, p.56–1286.

Percival, J.A. and Easton. R.M. 2007. Geology of the Canadian Shield in Ontario: an update. Ontario Power Generation, Report No. 06819-REP-01200-10158-R00.

Percival, J.A., Sanborn-Barrie, M., Skulski, T., Stott, G.M., Helmstaedt, H. and White, D.J. 2006. Tectonic evolution of the western Superior Province from NATMAP and Lithoprobe studies; Can. J. Earth Sciences v.43, p.1085-1117.

Petersen, E.U. 1984. Metamorphism and Geochemistry of the Geco Massive Sulphide Deposit and it's Enclosing Wall-Rocks; unpublished Ph.D. Thesis, University of Michigan, Ann Arbor, Michigan, 195p.

Peterson, V.L., and Zaleski, E.1999. Structural history of the Manitouwadge greenstone belt and its volcanogenic Cu-Zn massive sulphide deposits, Wawa subprovince, south-central Superior Province; Can. Jour. of Earth Sciences, V36, p.605-625.

Petrov, V.A., Poluektov, V.V., Zharikov, A.V., Nasimov, R.M., Diaur, N.I., Terentiev, V.A., Burmistrov, A.A., Petrunin, G.I., Popov, V.G., Sibgatulin, V.G. ,Lind, E.N., Grafchikov A.A. and Shmonov, V.M. 2005. Microstructure, filtration, elastic and thermal properties of granite rock samples: implications for HLW disposal; Geological Society, London, Special Publications, 240, p.237-253.

Piercey, Patricia. 2006, Proterozoic metamorphic geochronology of the deformed Southern Province, northern Lake Huron region, Canada; M.Sc. thesis, Ohio University, 67p.

Polat, A. 1998. Geodynamics of the Late Archean Wawa Subprovince greenstone belts, Superior Province, Canada; PhD Thesis, Department of Geological Sciences, University of Saskatchewan, Saskatoon, 249p.

Polat, A., 2009. The geochemistry of Neoarchean (ca. 2700 Ma) tholeiitic basalts, transitional to alkaline basalts, and gabbros, Wawa Subprovince, Canada: Implications for petrogenetic and geodynamic processes. Precambrian Research 168: p.83-105.

Polat, A., Kerrich, R. and Wyman, D.A. 1998. The late Archean Schreiber–Hemlo and White River–Dayohessarah greenstone belts, Superior Province: collages of oceanic plateaus, oceanic arcs, and subduction–accretion complexes. Tectonophysics, 289, p.295–326.

Powell, W.G., Carmichael, D.M. and Hodgson, C.J. 1993. Thermobarometry in a subgreenschist to greenschist transition in metabasites of the Abitibi greenstone belt, Superior Province, Canada; J. Metamorphic Geology, v.11, p.165-178.

Prest. V.K. 1970. Quaternary geology of Canada; *In:* Geology and Economic Minerals of Canada, Geological Survey of Canada, Economic Geology Report no. 1, Chapter XII, p.675-764, accompanied by map 1253A.

Puumala, M.A., Campbell, D.A., Tuomi, R.D., Debicki, R.L., Wilson, A.C., Moses, P. and Brunelle, M.R. 2014. Report of Activities 2013, Resident Geologist Program, Thunder Bay South Regional Resident Geologist Report: Thunder Bay South District; Ontario Geological Survey, Open File Report 6293, 71p.

Pye, E.G. 1957. Manitouwadge area, District of Thunder Bay, Ontario; Ontario Department of Mines, Map 1957-8, scale 1:31,680.

Pye, E.G. 1960. Geology of the Manitouwadge area; Ontario Department of Mines, Annual Report, Volume LXVI, part 8, (1957), p.1-114.

Rainbird, R.H., Heaman, L.M., Davis, W.J. and Simonetti, A. 2006. Coupled Hf and U–Pb isotope analysis of detrital zircons from the Paleoproterozoic Huronian Supergroup; Geological Society of America, Abstracts with Programs, Vol. 38(7), p.410.

Raven, K.G., Bottomley, D.J. Sweezey, R.A. Smedley, J.A. and Ruttan, T.J. 1985. Hydrogeological Characterization of the East Bull Lake Research Area. National Hydrology Research Institute Paper No. 31, Inland Water Directorate Scientific Series No. 160, Environment Canada, Ottawa.

Raven, K.G. and J.E. Gale, 1986. A Study of Surface and Subsurface Structural and Groundwater Conditions at Selected Underground Mines and Excavations; Atomic Energy of Canada Ltd, Report TR-177, Pinawa, Manitoba.

Roberts, B., Zaleski, E., Adam, E., Perron, G., Petrie, L., Darch, W., Salisbury, M.H., Easton, D. and Milkereit, B. 1997. Seismic exploration of the Manitouwadge greenstone belt, Ontario; *In*: Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration, Paper 56, p.451-454.

Rogala, B., Fralick, P.W., Heaman, L. M. and Metsaranta, R. 2007. Lithostratigraphy and chemostratigraphy of the Mesoproterozoic Sibley Group, northwestern Ontario, Canada; Canadian Journal of Earth Sciences, v.44(8), p.1131-1149.

Rona, P.A. and Richardson, E.S. 1978. Early Cenozoic global plate reorganization, Earth Planet. Sci. Letters, 40, p.1-11.

Ryan, M. P., Pierce, H. A., Johnson, C. D., Sutphin, D. M., Daniels, D. L., Smoot, J. P., Costain, J. K., Çoruh, C., and Harlow, G. E. 2007. Reconnaissance borehole geophysical, geological and hydrological data from the proposed hydrodynamic compartments of the Culpeper Basin in Loudoun, Prince William, Culpeper, Orange and Fairfax Counties, Virginia. [Version 1.0]: U.S. Geological Survey Open File Report 2006-1203.

Sado, E.V. and Carswell, B.F. 1987. Surficial geology of northern Ontario; Ontario Geological Survey, Map 2518, scale 1:1,200,000.

Sage, R.P. 1982. Mineralization in diatreme structures north of Lake Superior; Ontario Geological Survey, Study 27, 79p.

Santaguida, F. 2001. Precambrian geology compilation series – White River sheet; Ontario Geological Survey, Map 2666, scale 1:250,000.

Santaguida, F. 2002. Precambrian geology compilation series – Schreiber sheet; Ontario Geological Survey, Map 2665 -Revised, scale 1:250,000.

Sbar, M.L. and Sykes, L.R. 1973. Contemporary compressive stress and seismicity in eastern North America: An example of intra-plate tectonics: Geol. Soc. America Bull., v. 84, p.1861-1882.

Schandl, E.S., Davis, D.W., Gorton, M.P., and Wasteneys, Ii.A. 1991. Geochronology of hydrothermal alteration around volcanic-hosted massive sulphide deposits in the Superior Province; Ontario Geological Survey, Miscellaneous Paper 156, p.105-120.

Schnieders, B.R., Scott, J.F., Smyk, M.C. and O'Brien, M.S. 2000. Report of Activities 1999, Resident Geologist Program, Thunder Bay South Regional Resident Geologist Report: Thunder Bay South District; Ontario Geological Survey, Open File Report 6005, 50p.

Sella, G.F., Stein, S., Dixon, T.H., Craymer, M., James, T.S. Mazzotti, S. and Dokka, R.K. 2007. Observation of glacial isostatic adjustment in "stable" North America with GPS, Geophys. Res. Lett., 34, L02306, doi:10.1029/2006GL027081.

Shackleton, N.J., Berger, A. and Peltier, W.R. 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677; Transactions of the Royal Society of Edinburgh: Earth Sciences, 81, p.251-261.

Sims, P.K., Van Schmus, W.R., Schulz, K.J. and Peterman, Z.E., 1989. Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen; Can. J. Earth Sci., 26, p.2145–2158.

Singer, S.N. and Cheng, C.K. 2002. An assessment of the groundwater resources of northern Ontario, Ontario Ministry of the Environment, Environmental Monitoring and Reporting Branch, Toronto, 242p.

Skulski, T., Sandeman, H., Sanborn-Barrie, M., MacHattie, T., Hyde, D., Johnstone, S., Panagapko, D. and Byrne, D. 2002. Contrasting crustal domains in the Committee Bay belt, Walker Lake – Arrowsmith River area, central Nunavut; Geological Survey of Canada, Current Research 2002-C11, 11p.

SNC-Lavalin Nuclear Inc. 2011. APM Conceptual Design and Cost Estimate Update – Deep Geological Repository Design Report – Crystalline Rock Environment – Copper Used Fuel Container. Prepared by SNC-Lavalin Nuclear Inc. for the Nuclear Waste Management Organization. APM-REP-00440-0001.

Springer, Janet. 1978: Ontario Mineral Potential, Hornepayne Sheet, Districts of Algoma, Thunder Bay and Cochrane; Ontario. Geological Survey Preliminary Map P.1526, Mineral Deposits Ser., Scale 1:250,000.

SRK Consulting Inc., 2014. Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation, Township of Manitouwadge, Ontario. Prepared for Nuclear Waste Management Organization (NWMO). NWMO Report Number: APM-REP-06144-0078.

Stevenson, D.R., Kozak, E.T. Davison, C.C. Gascoyne, M. and Broadfoot, R.A. 1996. Hydrogeologic characterization of domains of sparsely fractured rock in the granitic Lac du Bonnet Batholith, Southeastern Manitoba, Canada. Atomic Energy of Canada Limited Report, AECL-11558, COG-96-117. Pinawa, Canada.

Stone, D., Kamineni, D.C., Brown, A. and Everitt, R. 1989. A comparison of fracture styles in two granite bodies of the Superior Province; Canadian Journal of Earth Sciences, 26 (2), p.387-403.

Stott, G.M. 2010. A revised terrane subdivision of the Superior Province in Ontario; Ontario Geological Survey, Miscellaneous Release—Data 278.

Stott, G.M., Corkery, M.T., Percival, J.A., Simard, M. and Goutier, J. 2010. A revised terrane subdivision of the Superior Province; *In:* Summary of Field Work and Other Activities 2010, Ontario Geological Survey, Open File Report 6260, p.20-1 to 20-10.

Streckeisen, A. L., 1976. Classification of the common igneous rocks by means of their chemical composition: a provisional attempt;. Neues Jahrbuch fr Mineralogie, Monatshefte, 1976 H. 1, p.1-15.

Sutcliffe, R.H. 1991. Proterozoic Geology of the Lake Superior Area; *In:* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.627-658.

Svensson, U. and Rhén, I. 2010. Groundwater flow modelling of the excavation and operational phases – Laxemar; SKB R-09-23, December, 2010.

Szewcyk, Z.J. and West, G.F. 1976. Gravity study of an Archean granitic area northwest of Ignace, Ontario; Canadian Journal of Earth Sciences 13, p.1119-1130.

Tilton, G.R. and Steiger, R.H. 1969. Mineral ages and isotopic composition of primary lead at Manitouwadge, Ontario; Journal of Geophysical Research, v. 74, p.2118-2132.

Thompson, J.E. 1932. Geology of the Heron Bay - White River area; Ontario Department of Mines, Annual Report, Volume XL, pt .2 (1931), p.34-47.

Thurston, P.C. 1991. Geology of Ontario: Introduction; *In:* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.3-25.

Tollo, R.P., Corriveau, L., McLelland, J. and Bartholomew, M.J. (eds.) 2004. Proterozoic tectonic evolution of the Grenville orogen in North America; Geological Society of America Memoir 197, 820p.

Tourout , K. and Richard, P. 2012. Water system treatment and distribution; Manitouwadge Public Works 2011 Annual Report, Presentation February 23, 2012, 82p.

Van Schmus, W. R. 1992. Tectonic setting of the Midcontinent Rift system; Tectonophysics, v. 213, p.1-15.

West, G.F. and Ernst, R.E. 1991. Evidence from aeromagnetics on the configuration of Matachewan dykes and the tectonic evolution of the Kapuskasing Structural Zone, Ontario, Canada; Canadian Journal of Earth Sciences, Vol. 28, p.797-1811.

Williams, H.R. 1989. Geological studies in the Wabigoon, Quetico and Abitibi-Wawa subprovinces, Superior Province of Ontario, with emphasis on the structural development of the Beardmore-Geraldton Belt. Ontario Geological Survey, Open File Report 5724, 189p.

Williams, H.R. 1991. The Quetico Subprovince; *In*: The Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.383-403.

Williams, H.R. and Breaks, F.W. 1989. Geological studies in the Manitouwadge-Hornepayne area; Ontario Geological Survey, Miscellaneous Paper 146, p.79-91.

Williams, H.R. and Breaks, F.W. 1990. Geology of the Manitouwadge - Hornepayne area, Ontario Geological Survey, Open File Map 142, Scale 1:50,000.

Williams, H.R. and F.W. Breaks, 1996. Geology of the Manitouwadge-Hornepayne region, Ontario; Ontario Geological Survey, Open File Report 5953, 138p.

Williams, H. R., Stott, G.M., Heather, K.B., Muir, T.L. and Sage, R.P. 1991. Wawa Subprovince; *In:* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.485-525.

Williams, H. R., Stott, G.M., Thurston, P.C., Sutcliffe, R.H., Bennett, G, Easton, R.M. and Armstrong, D.K. 1992. Tectonic evolution of Ontario: summary and synthesis; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.1255-1332.

White, W. 1972. Deep erosion by continental ice-sheets. Geological Society of America Bulletin 83, 1037–1056.

White, O.L., Karrow, P.F. and Macdonald, J.R. 1973. Residual stress release phenomena in southern Ontario. Proceedings of the 9th Canadian Rock Mechanics Symposium, Montreal, p.323-348.

Young, G.M., Long, D.G.F., Fedo, C.M., Nesbitt, H.W., 2001. Paleoproterozoic Huronian basin: Product of a Wilson cycle punctuated by glaciations and a meteorite impact. Sedimentary Geology, 141–142, p.233–254.

Zaleski, E. and Peterson, V.L. 1993a. Geology of the Manitouwadge greenstone belt, Ontario; Geological Survey of Canada, Open File 2753, scale 1:25,000.

Zaleski, E. and Peterson, V.L. 1993b. Lithotectonic setting of mineralization in the Manitouwadge greenstone belt, Ontario; preliminary results; *In:* Current Research, Part C, Geological Survey of Canada, Paper 93-1C, p.307-317.

Zaleski E. and Peterson, V.L. 1995. Depositional setting and deformation of massive sulfide deposits, iron-formation, and associated alteration in the Manitouwadge greenstone belt, Superior Province, Ontario; Economic Geology, Vol. 90(8), p.2244-2261.

Zaleski, E. and Peterson, V.L. 1996. Rare earth element geochemistry of the metamorphosed volcanogenic massive sulfide deposits of the Manitouwadge mining camp, Superior province, Canada: a potential exploration tool? – a discussion; Economic Geology, Vol. 91, p,469-473.

Zaleski, E. and Peterson, V.L. 2001. Geology of the Manitouwadge greenstone belt and the Wawa-Quetico subprovince boundary, Ontario; Geological Survey of Canada, Map 1917A, scale 1:25,000.

Zaleski, E., Peterson, V.L., and van Breemen, 0, 1994. Structure and tectonics of the Manitouwadge greenstone belt and the Wawa-Quetico subprovince boundary, Superior province, northwestern Ontario; *In:* Current Research 1994-C; Geological Survey of Canada, p.237-247.

Zaleski, E., Peterson, V.L., and van Breemen, 0, 1995. Geological and age relationships of the margins of the Manitouwadge greenstone belt and the Wawa-Quetico subprovince boundary, northwestern Ontario; *In:* Current Research 1995-C; Geological Survey of Canada, p.35-44.

Zaleski, E., van Breemen O. and Peterson, V.L. 1999. Geological evolution of the Manitouwadge greenstone belt and the Wawa-Quetico subprovince boundary, Superior Province, Ontario, constrained by U-Pb zircon dates of supracrustal and plutonic rocks; Canadian Journal of Earth Sciences, Vol. 36, p.945-966.

Zoback, M.L., 1992. First- and second-order patterns of stress in the lithosphere: the world stress map project; Journal of Geophysical. Research, 97, p.11,703-11,728.

Zoltai, S. C. 1965. Surficial geology of the Thunder Bay; Ontario Department of Lands and Forests, Map S265, scale 1 inch to 8 miles.

APPENDIX A
Geoscientific Factors

Safety Factors Performance Objectives Evaluation Factors to be Considered

Table 1: Safety Factors, Performance Objectives and Geoscientific Factors

Safety Factors	Performance Objectives	Evaluation Factors to be Considered
Containment and isolation characteristics of the host rock	1. The geological, hydrogeological and chemical and mechanical characteristics of the site should: • Promote long-term isolation of used nuclear fuel from humans, the environment and surface disturbances; • Promote long-term containment of used nuclear fuel within the repository; and • Restrict groundwater movement and retard the movement of any released radioactive material.	**1.1** The depth of the host rock formation should be sufficient for isolating the repository from surface disturbances and changes caused by human activities and natural events. **1.2** The volume of available competent rock at repository depth should be sufficient to host the repository and provide sufficient distance from active geological features such as zones of deformation or faults and unfavourable heterogeneities. **1.3** The mineralogy of the rock, the geochemical composition of the groundwater and rock porewater at repository depth should not adversely impact the expected performance of the repository multi-barrier system. **1.4** The hydrogeological regime within the host rock should exhibit low groundwater velocities. **1.5** The mineralogy of the host rock, the geochemical composition of the groundwater and rock porewater should be favourable to retarding radionuclide movement. **1.6** The host rock should be capable of withstanding natural stresses and thermal stresses induced by the repository without significant structural deformations or fracturing that could compromise the containment and isolation functions of the repository.

Table 1: Safety Factors, Performance Objectives and Geoscientific Factors

Long-term stability of the site	2. The containment and isolation functions of the repository should not be unacceptably affected by future geological processes and climate changes.	2.1 Current and future seismic activity at the repository site should not adversely impact the integrity and safety of the repository system during operation and in the very long term. 2.2 The expected rates of land uplift, subsidence and erosion at the repository site should not adversely impact the containment and isolation functions of the repository. 2.3 The evolution of the geomechanical, hydrogeological and geochemical conditions at repository depth during future climate change scenarios such as glacial cycles should not have a detrimental impact on the long-term safety of the repository. 2.4 The repository should be located at a sufficient distance from geological features such as zones of deformation or faults.
Repository construction, operation and closure	**3.** The surface and underground characteristics of the site should be favourable to the safe construction, operation, closure and long-term performance of the repository.	3.1 The strength of the host rock and in-situ stress at repository depth should be such that the repository could be safely excavated, operated and closed without unacceptable rock instabilities. 3.2 The soil cover depth over the host rock should not adversely impact repository construction activities. 3.3 The available surface area should be sufficient to accommodate surface facilities and associated infrastructure.
Human intrusion	4. The site should not be located in areas where the containment and isolation functions of the repository are likely to be disrupted by future human activities.	4.1 The repository should not be located within rock formations containing economically exploitable natural resources such as gas/oil, coal, minerals and other valuable commodities as known today. 4.2 The repository should not be located within geological formations containing exploitable groundwater resources (aquifers) at repository depth.
Site characterization	5. The characteristics of the site should be amenable to site characterization and site data interpretation activities.	5.1 The host rock geometry and structure should be predictable and amenable to site characterization and site data interpretation.

APPENDIX B
Geoscientific Data Sources

Table 1: Summary of Geophysical Mapping Sources for the Manitouwadge Area

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

Table 2: Summary of Geological Mapping Sources for the Manitouwadge Area

Map Product	Title	Author	Source	Scale	Date	Coverage	Comments
P.1526	Ontario Mineral Potential, Hornepayne Sheet, Districts of Algoma, Thunder Bay and Cochrane	Springer, Janet	Ontario Geological Survey	1:250,000	1978	Full	Mineral Deposits Series, Black/white
P.2849	Quaternary Geology of the While Lake area, District of Thunder Bay	Geddes R.S. and Bajc, A.F.	Ontario Geological Survey	1:50,000	1985	Partial	Geological Series-Preliminary Map
P.3055	Quaternary geology of the Manitouwadge area, District of Thunder Bay	Kristjansson F.J. and R.S. Geddes	Ontario Geological Survey	1:50,000	1986	Partial	Geological Series-Preliminary Map
P.3533	Geology, Tectonometamorphic map of Ontario, Canada and part of the United States of America	Easton, R.M. and Berman, R.G.	Ontario Geological Survey; also as Geological Survey of Canada Open File 1810	1:500,000	2004	Full	Large scale
Map 1917A	Geology of the Manitouwadge greenstone belt and the Wawa-Quetico subprovince boundary, Ontario	Zaleski, E. and Peterson, V.L.	Geological Survey of Canada	1:25,000	2001	Partial	Covers central part of area
Map 1921A	Surficial geology, Vein Lake, Ontario	Kettles, I.M. and Way Nee, V.	Geological Survey of Canada	1:50,000	1998	Partial	West-central fringe of area
Map 1957-8	Manitouwadge area, District of Thunder Bay	Pye, E.G.	Ontario Department of Mines	1:31,680	1957	Partial	Superceeded by later mapping
Map 2022A	Diabase dyke swarms and related units in Canada and adjacent regions	Buchan, K.L. and Ernst, R.E.	Geological Survey of Canada	1:5,000,000	2004	Full	Large scale
Map 2047	Flanders Lake area, Thunder Bay and Algoma districts	Milne, V.G.	Ontario Department of Mines	1:63,360	1963	Partial	Covers northeastern part of area
Map 2140	Kagiano Lake sheet, Thunder Bay District	Coates, M.E	Ontario Department of Mines	1:63,360	1967	Partial	Covers northwest side of area
Map 2141	Stevens sheet, Thunder Bay District	Coates, M.E	Ontario Department of Mines	1:63,360	1967	Partial	Covers, northwest side of area
Map 2143	Barehead Lake sheet, Thunder Bay District	Milne, V.G.	Ontario Department of Mines	1:63,360	1967	Partial	Covers southwestern part of area
Map 2144	Gowan Lake sheet, Thunder Bay District	Milne, V.G.	Ontario Department of Mines	1:63,360	1967	Partial	Covers southwestern part of area
Map 2145	Agonzon Lake sheet, Thunder Bay District	Milne, V.G.	Ontario Department of Mines	1:63,360	1967	Partial	Covers southwestern part of area
Map 2146	Dotted Lake sheet, Thunder Bay District	Milne, V.G.	Ontario Department of Mines	1:63,360	1968	Partial	Covers southwestern part of area

Table 2: Summary of Geological Mapping Sources for the Manitouwadge Area

Map 2192	Vien Lake sheet, Thunder Bay District	Coates, M.E	Ontario Department of Mines	1:63,360	1970	Partial	Covers southwest side of area
Map 2202	Caramat-Pagwa River sheet, , Algoma, Cochrane and Thunder Bay districts	Innes, D.G. and Ayres, L.D.	Ontario Department of Mines and Northern Affairs	1:253,440	1971	Full	Large scale, geological compilation series
Map 2219	Granitehill Lake area, Thunder Bay and Algoma districts	Giguere, J.F	Ontario Department of Mines and Northern Affairs	1:63 360	1972	Partial	Colour map, eastern side of area
Map 2220	Manitouwadge-Wawa sheet	Milne, V.G., Giblin, P.E., Bennett, G., Thurston, P.C., Wolfe, W.J., Giguere, J.F., Leahy, E.J. and Rupert, R.J.	Ontario Division of Mines	1:253,440	1972	Full	Geological Compilation Series
Map 2280	Mapledoram-Gemmell, Thunder Bay District	Milne, V.G.	Ontario Division of Mines	1:12,000	1974	Partial	Covers majority of Township of Manitouwadge
Map 2518	Surficial geology of northern Ontario	Sado, E.V. and Carswell, B.F.	Ontario Geological Survey	1:1,200,000	1987	Full	Large Scale map, basis of NOEGTS mapping
Map 2543	Bedrock geology of Ontario, east-central sheet	Ontario Geological Survey	Ontario Geological Survey	1:1,000,000	1991	Full	Geology of Ontario series
Map 2555	Quaternary geology of Ontario, east-central sheet	Barnett, P.J.,Henry,A.P. and Babuin,D.	Ontario Geological Survey	1:1 000,000	1991	Full	Based on compilation of NOEGTS maps
Map 2577	Tectonic assemblages of Ontario, east-central sheet	Ontario Geological Survey	Ontario Geological Survey	1:1,000,000	1992	Partial	Geology of Ontario series
Map 2665-revised	Precambrian geology compilation series – Schreiber sheet	Santaguida, F.	Ontario Geological Survey	1:250,000	202	Partial	Southwestern corner of area
Map 2666	Precambrian geology compilation series – White River sheet	Santaguida, F.	Ontario Geological Survey	1:250,000	2001	Partial	Southwest corner of area
Map 2667	Precambrian geology compilation series – Longlac sheet	Johns, G.W., McIlraith, S. and Stott, G.M.	Ontario Geological Survey	1:250,000	2003	Partial	Northwestern part of area
Map 2668	Precambrian geology compilation series - Hornepayne sheet	Johns, G.W., and McIlraith, S.	Ontario Geological Survey	1:250,000	2003	Partial	Covers majority of area
Map 2683	Quaternary Geology of the While Lake area, District of Thunder Bay	Geddes R.S. and Bajc, A.F.	Ontario Geological Survey	1:50,000	1985	Partial	Geological Series
Map 2684	Quaternary geology of the Manitouwadge area, Northern Ontario	Kristjansson F.J. and R.S. Geddes	Ontario Geological Survey	1:50,000	2009	Partial	Covers central portion of area
Map S265	Surficial geology of the Thunder Bay map area	Zoltai, S. C.	Ontario Department of Lands and Forests	1:506,880	1965	Full	Regional scale surficial map

Table 2: Summary of Geological Mapping Sources for the Manitouwadge Area

Map S365	Surficial Geology of Algoma-Cochrane	Boissonneau, A.N.	Ontario Department of Lands and Forests	1:506 880	1965	Full	Large scale
Map 5080	Northern Ontario Engineering Geology Terrain Study Data Base Map Steel Lake Area	Gartner, J.F.	Ontario Geological Survey	1:100,000	1980	Partial	Map accompanies Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 44
Map 5082	Northern Ontario Engineering Geology Terrain Study Data Base Map Taradale Area	Gartner. J.F. and McQuay. D.F.	Ontario Geological Survey	1:100,000	1980	Partial	Map accompanies Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 29
Map 5084	Northern Ontario Engineering Geology Terrain Study Data Base Map Obakamiga Lake Area	Gartner. J.F. and McQuay. D.F.	Ontario Geological Survey	1:100,000	1980	Partial	Map accompanies Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 45
Map 5094	Northern Ontario Engineering Geology Terrain Study Data Base Map White River Area	Gartner. J.F. and McQuay. D.F.	Ontario Geological Survey	1:100,000	1980	Partial	Map accompanies Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 61
OFM 142	Geology of the Manitouwadge - Hornepayne area	Williams, H.R. and Breaks, F.W.	Ontario Geological Survey	1:50,000	1990	Partial	Covers E-W belt across central part of area

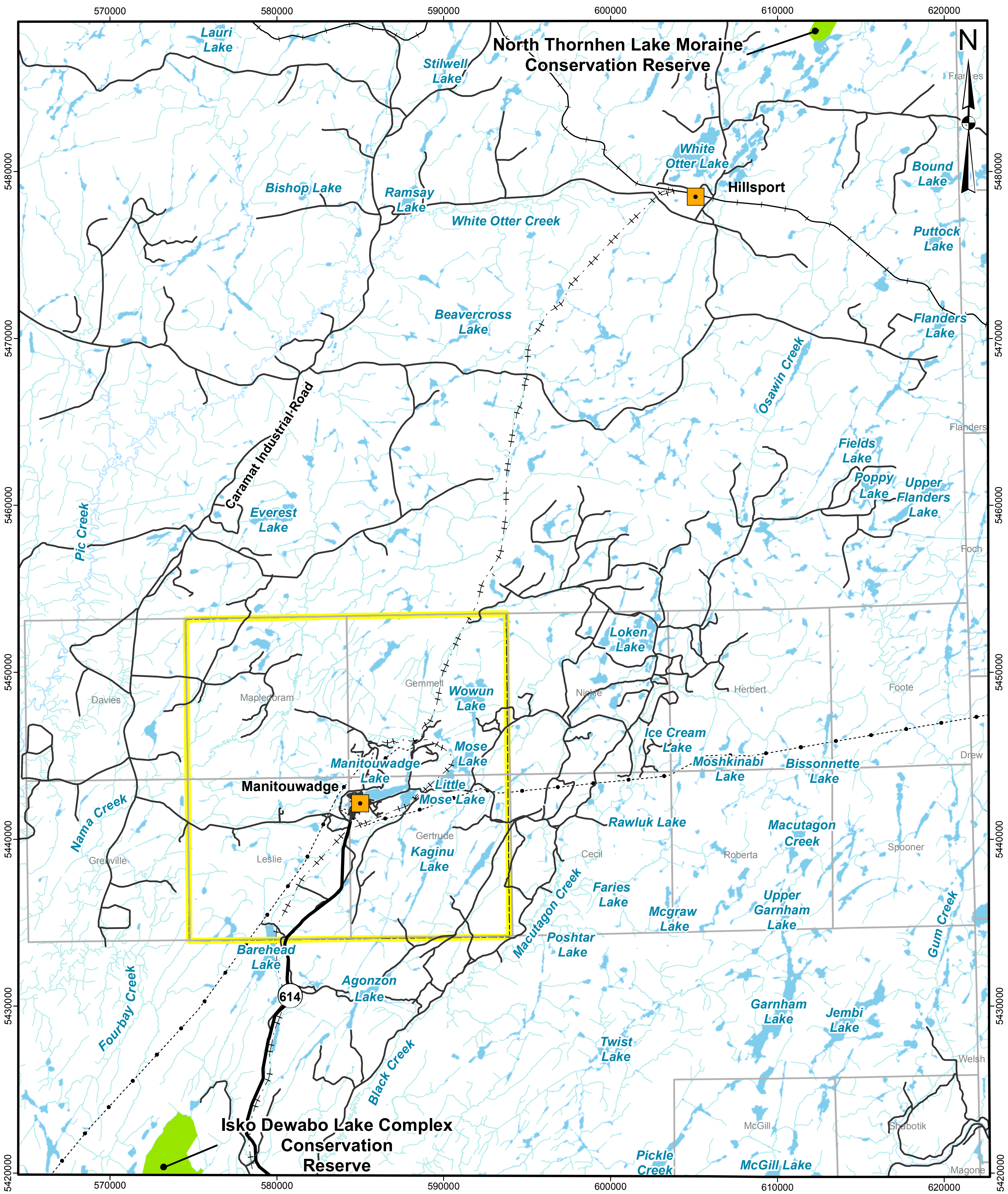
Table 3: Summary of Geoscientific Databases for the Manitouwadge Area

Database	Source / Description	Scale (Regional/Local)	Used? (Yes/No)
Abandoned Mines	Ministry of Northern Development and Mines. 2013. Ontario Ministry of Northern Development and Mines, Abandoned Mines Inventory (AMIS).	Regional	No
Aggregate Data	Ontario Ministry of Natural Resources, Licence and permit list, 2013.	Site	Yes
Bedrock Geology	Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release–Data 126 - Revision 1.	Site	Yes
Earthquake Data	Earthquakes Canada, 2013. Earthquake Search (On-line Bulletin). Natural Resources Canada, Geologic Survey of Canada	Regional	Yes
Exploration Data (Assessment Files)	Ministry of Northern Development and Mines. 2013. Assessment Files August 2013.	Site	Yes
Exploration Drill holes	Ministry of Northern Development and Mines. 2013, Diamond Drill Hole Database.	Site	Yes
Geochemical lake sediment and water data	Friske, P.W.B., Hornbrook, E.H.W., Lynch, J.J., McCurdy, M.W., Gross, H., Galletta, A.C. and Durham, C.C. 1991. National, northwestern Ontario; Geological Survey of Canada, Open File 2360.	Regional	Yes
Geochron	Geological Survey of Canada 2013. Geochron Database	Site	Yes
Geophysical Data	Natural Resources of Canada, 2013. Aeromagnetic and Electromagnetic data, Canadian Aeromagnetic Data Base, http://gdr.nrcan.gc.ca/aeromag/about_e.php	Regional	Yes
Geophysical Data	Ontario Geological Survey, 2013. Geophysical Atlas of Ontario,	Regional	Yes
Geoscience Data	Natural Resources Canada. 2013. Geoscience Data Repository (GDR),	Regional	Yes
Geotechnical Records	Ontario Ministry of Transportation, 2013. GeoCres Files; Downsview, Ontario	Site	No

Table 3: Summary of Geoscientific Databases for the Manitouwadge Area

In-situ ground stresses	Arjang, B. 2004. CANMET Division Report MMSL 01-029 (TR).	Regional	Yes
Lineament Data	Shirota, J. and Barnett, P.J., 2004. Lineament Extraction from Digital Elevation Model (DEM) for the Province of Ontario; Ontario Geological Survey, Miscellaneous Release - Data 142.	Regional	No
Mineral deposits	Ontario Geological Survey 2011. Mineral Deposit Inventory-2011; Ontario Geological Survey, Mineral Deposit Inventory, December 2011 release.	Site	No
Mining Claims (CLAIMaps)	Ministry of Northern Development and Mines. 2013. Ontario Ministry of Northern Development Mines. Mining Lands Section: Ontario Mining Land Tenure Spatial Data, August 2013.	Regional	Yes
Ontario Base Mapping	Land Information Ontario 2013. Ontario Ministry of Natural Resources	Regional	Yes
Quaternary Geology	Ontario Geological Survey, 1997. Quaternary Geology. Seamless coverage of the Province of Ontario: Ontario Geological Survey, Data Set 14.	Regional	No
Rock Geochemistry	Ontario Geological Survey. Miscellaneous Release—Data 250 Data from the PETROCH Lithogeochemical Database by M. Haus and T. Pauk	Site	Yes
Stream Flow Data	Environment Canada. 2013. Water Survey of Canada	Regional	No
Terrain Map	Ontario Geological Survey, Ministry of Northern Development and Mines, and Northeast Science and Information Section, Ministry of Natural Resources 2005. Digital Northern Ontario Engineering Geology Terrain Study (NOEGTS); Ontario Geological Survey, Miscellaneous Release Data 160.	Regional	Yes
Topographic Data	Natural Resources Canada. 2009. Canadian Digital Elevation Data, Government of Canada, Natural Resources Canada, Earth Sciences Sector, Centre for Topographic Information.	Regional	Yes
Water Information, Basemaps	Ministry of Natural Resources 2013. Land Information Ontario Date Warehouse.	Site	Yes
Water Well Data	Ontario Ministry of Environment. 2013. Water Well Information System (WWIS) Database.	Site	Yes

Figures

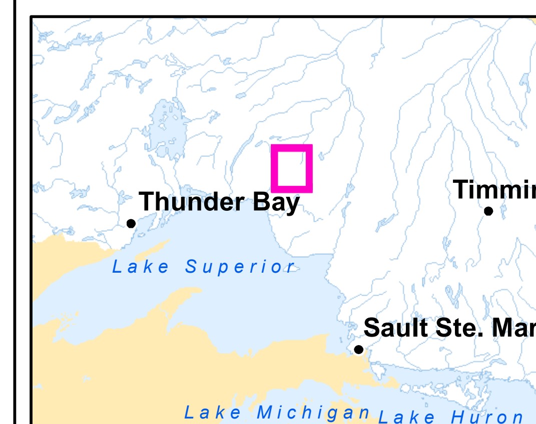


Legend

- 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

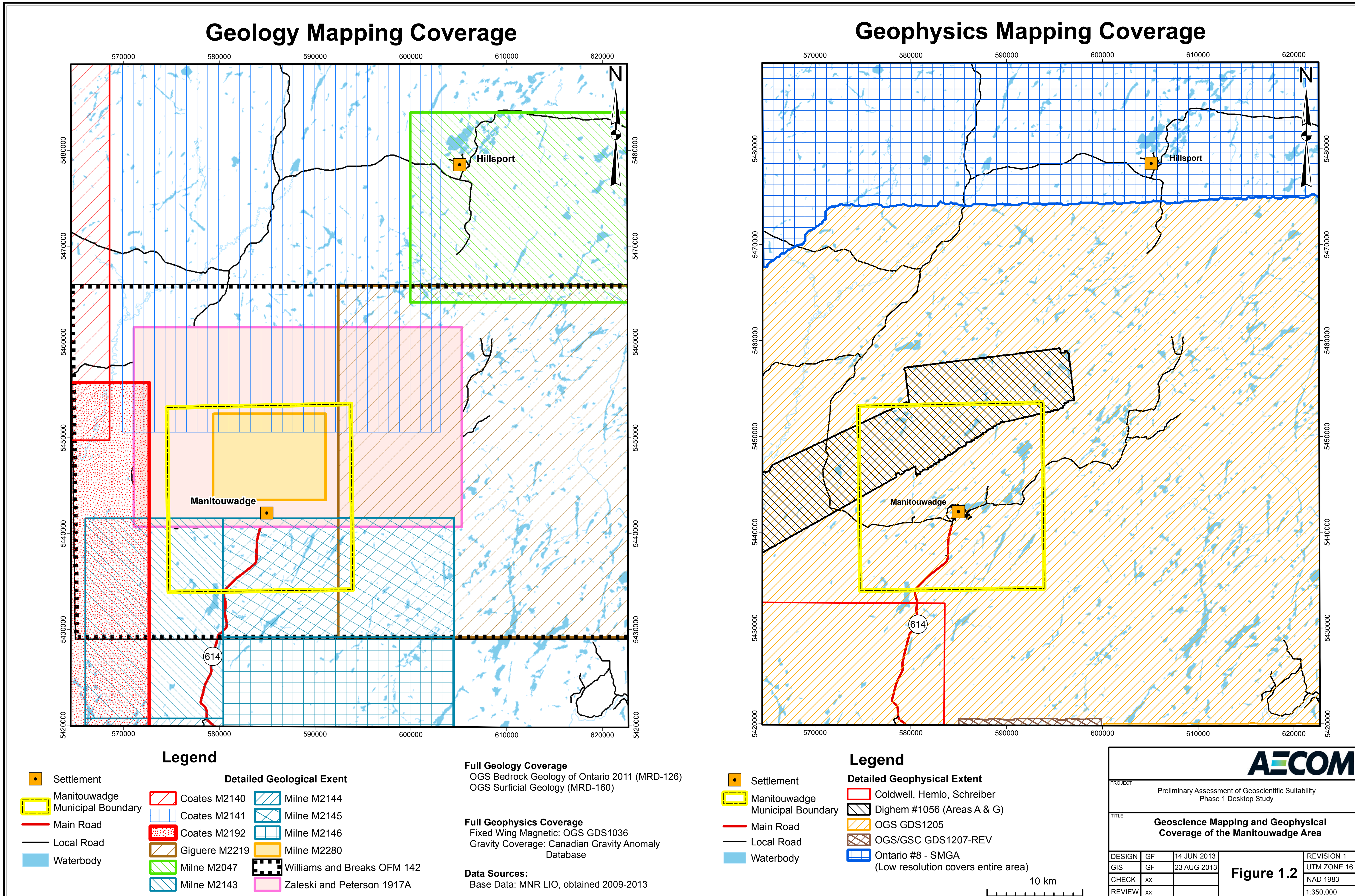
AECOM

PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

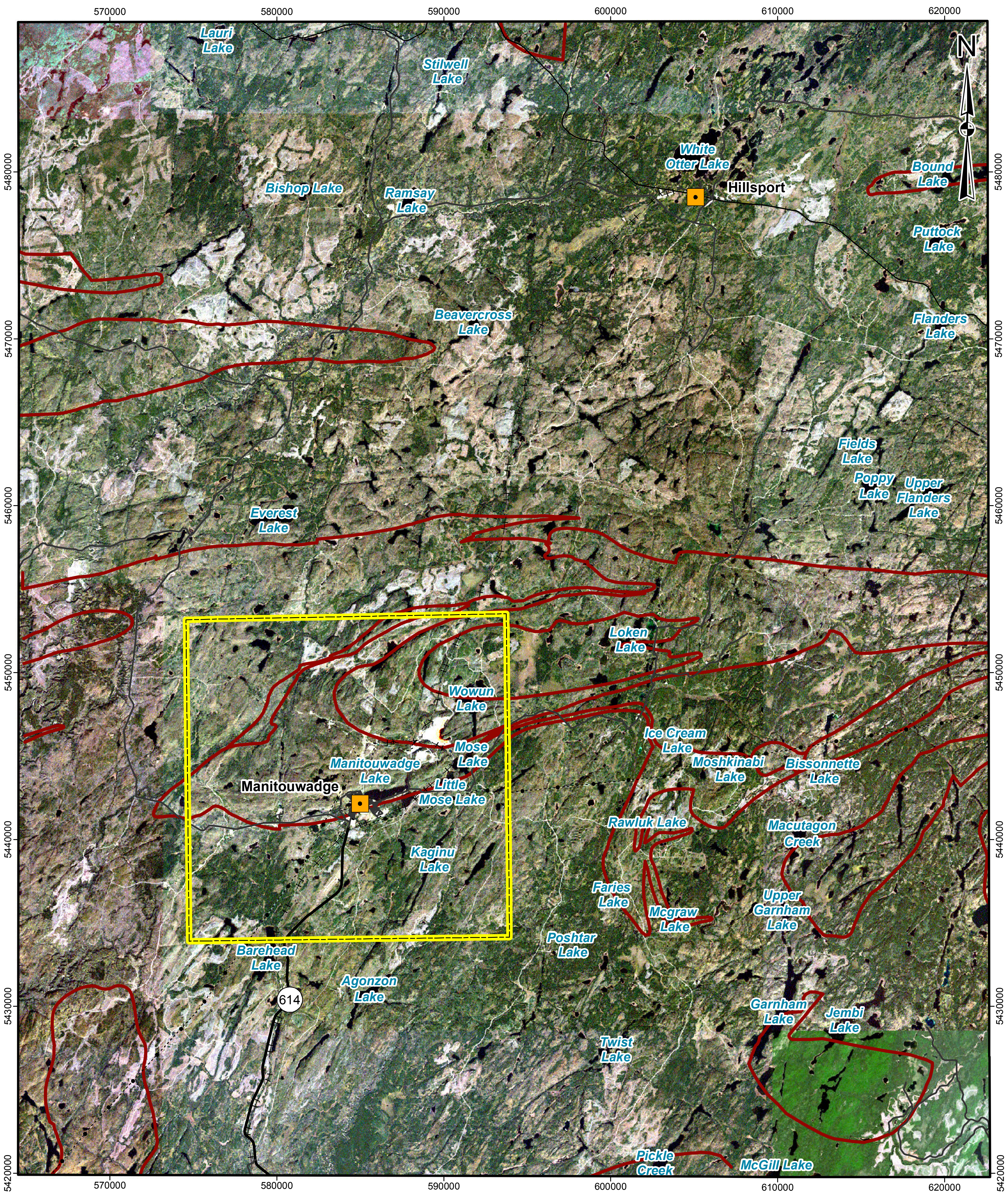
TITLE
Township of Manitouwadge and Surrounding Area

DESIGN	KR	14 JUN 2013	Figure 1.1	REVISION 1
GIS	KR	14 JUN 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 1.1 Township of Manitouwadge and Surrounding Area.mxd

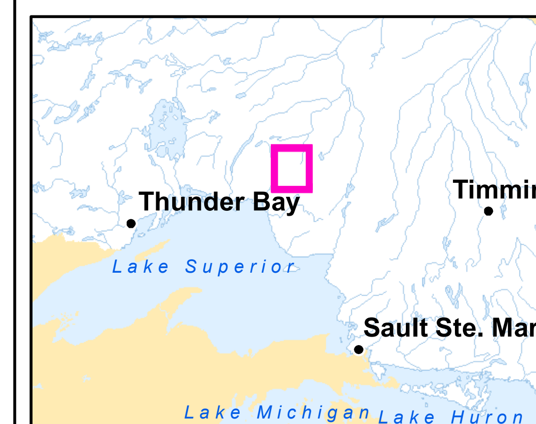


Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\Report\MXDs\Manitouwadge\60297733_Fig 1.2 - Geoscience Mapping and Geophysical Coverage of the Manitouwadge Area.mxd



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Hydro Line
- Bedrock Geology Contact



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Imagery: NRCAN CanImage - Landsat 7 Orthoimage
Composite of; Band 1 (Blue), Band 2 (Green), Band 3 (Red)
Obtained from GeoGratis (1:50,000)
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003

10 km

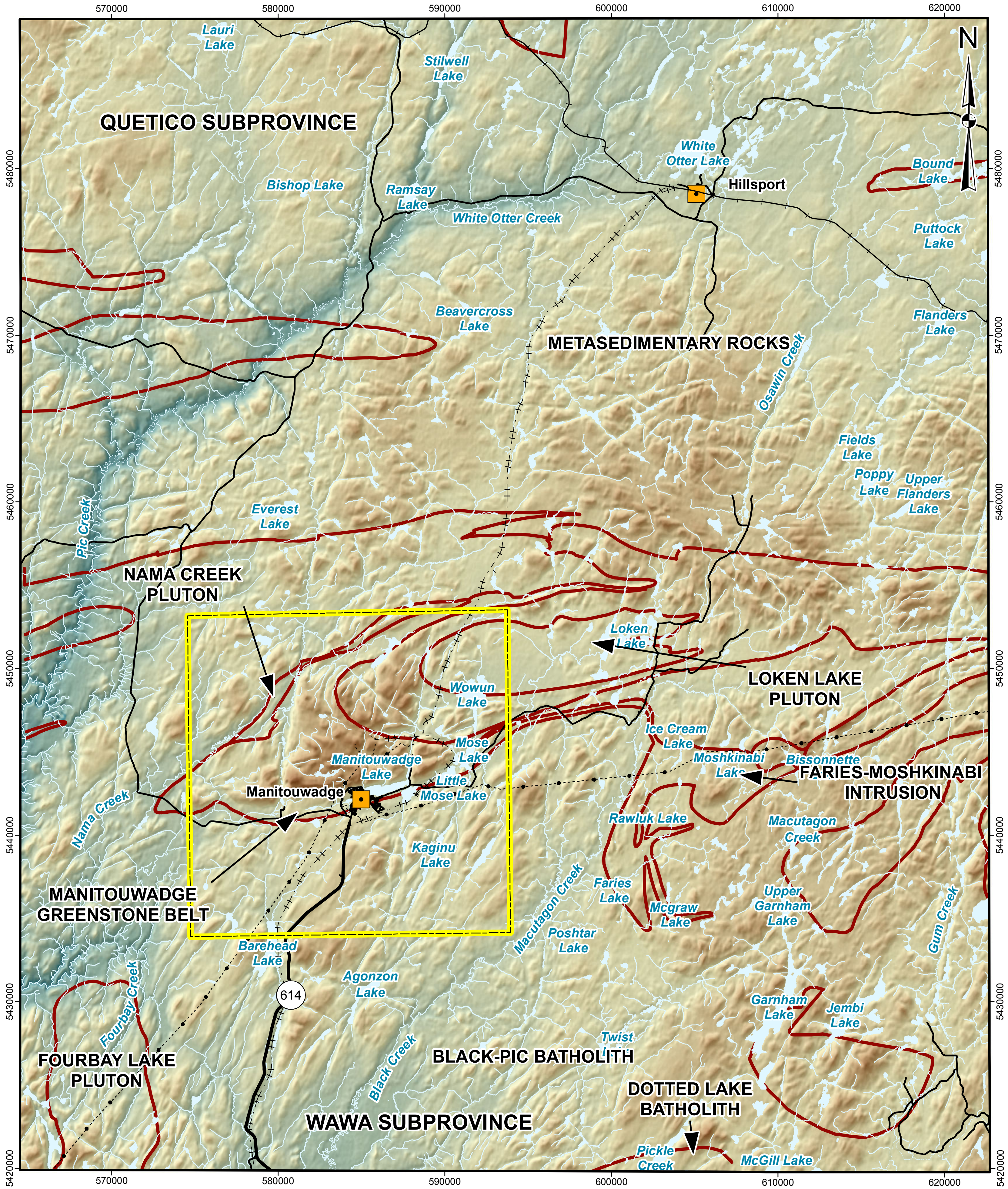
AECOM

PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Satellite Imagery of the Manitouwadge Area

DESIGN	GF	05 SEP 2013	Figure 2.1	REVISION 1
GIS	GF	06 JAN 2014		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 2.1 Satellite Imagery of the Manitouwadge Area.mxd



Legend

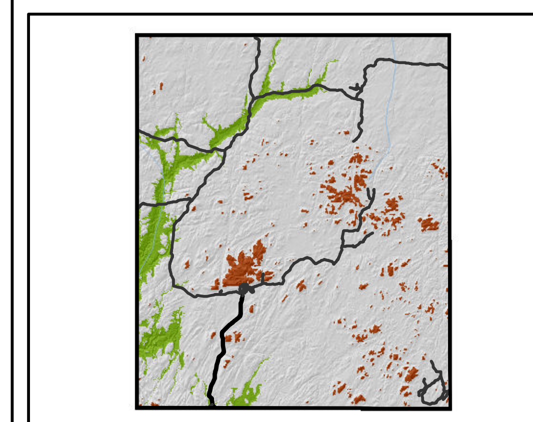
- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Hydro Line
- Waterbody
- Watercourse
- Bedrock Geology Contact

Elevation (masl)

High : 482

Low : 195

KEY TOPOGRAPHIC HIGHS AND LOWS



Elevation (m)

195 - 291 | 292 - 387 | 388 - 482

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Elevation and Slope: Ontario Ministry of Natural Resources
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003

10 km

AECOM

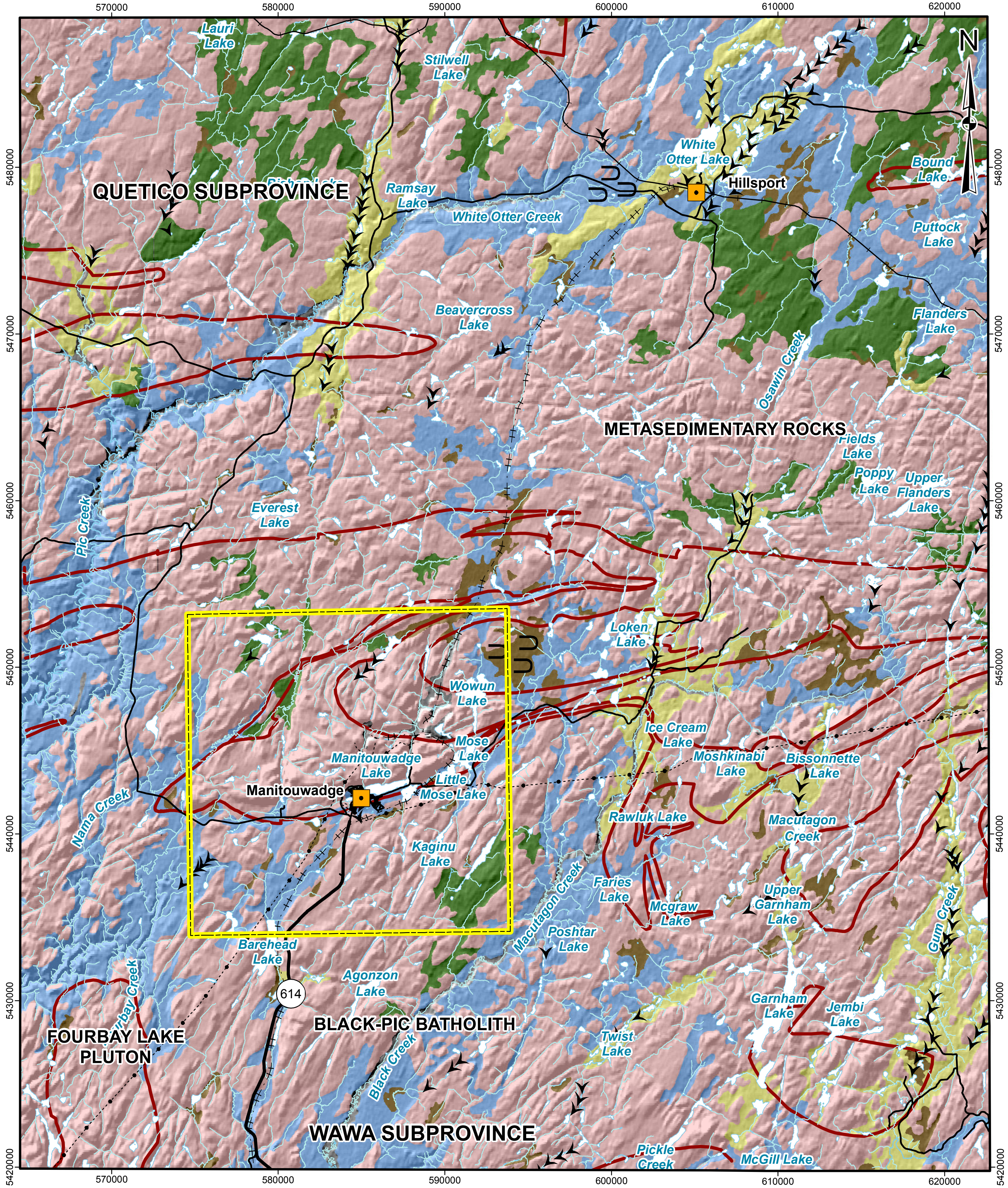
PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Elevation and Major Topographic Features of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 2.2**	REVISION 1
GIS	GF	05 SEP 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 2.2_Elevation and Major Topgraphic Features of the Manitouwadge Area.mxd

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 2.3 Terrain Features of the Manitouwadge Area.mxd



Legend

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

Surficial Geology

- Morainal Terrain
- Glaciofluvial Terrain
- Glaciolacustrine Terrain
- Bedrock Terrain
- Organic Terrain
- Sand Dunes
- Eskers

MAP OF SURFICIAL LANDFORMS AND WATERBODIES

Bedrock Geology Contact — Surficial/Water (39%) — Bedrock Terrain (61%)

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Overburden: OGS MRD-160, NOEGTS 2006
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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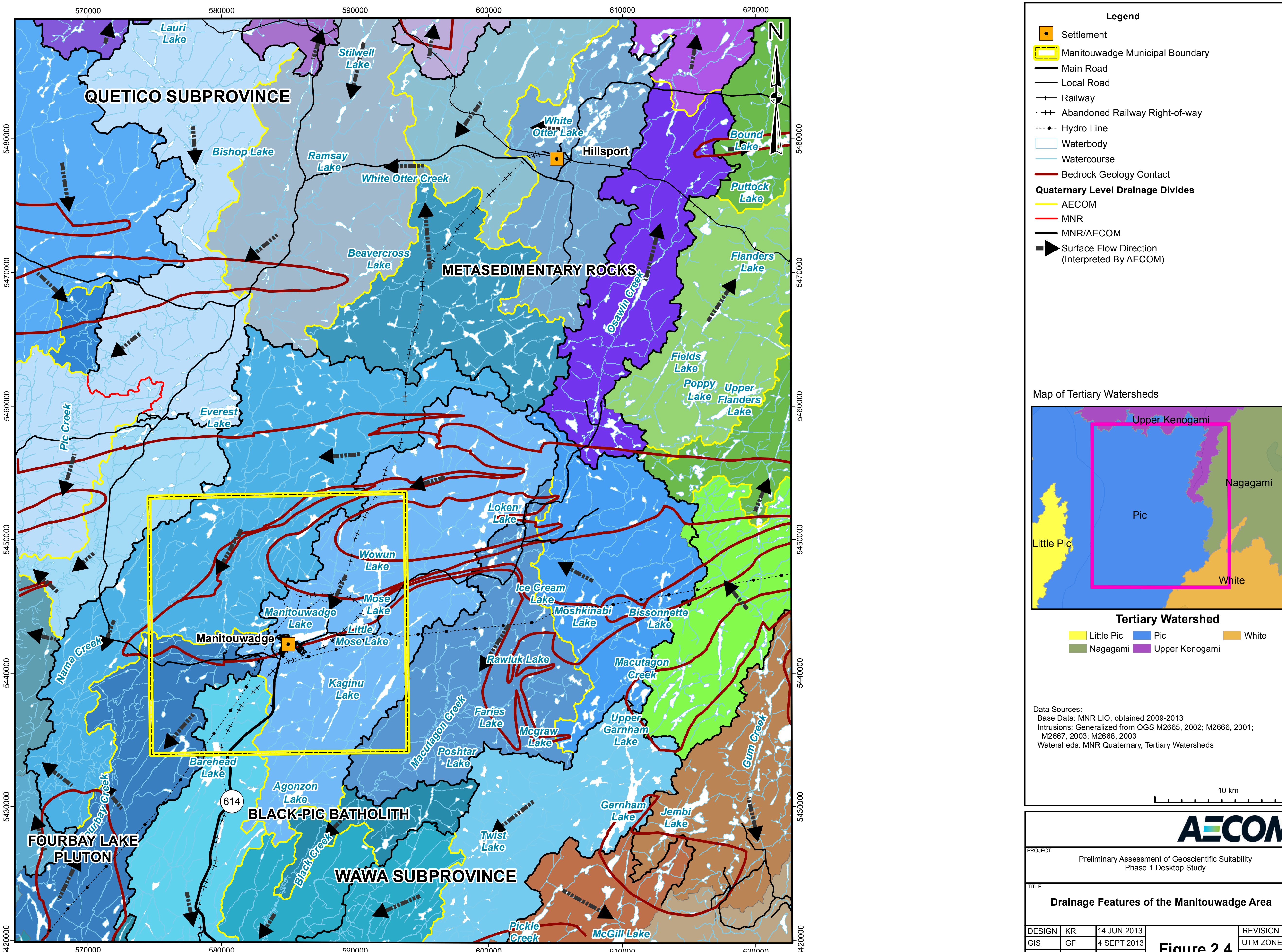
PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Terrain Features of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 2.3	REVISION 1
GIS	GF	06 SEP 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000



AECOM

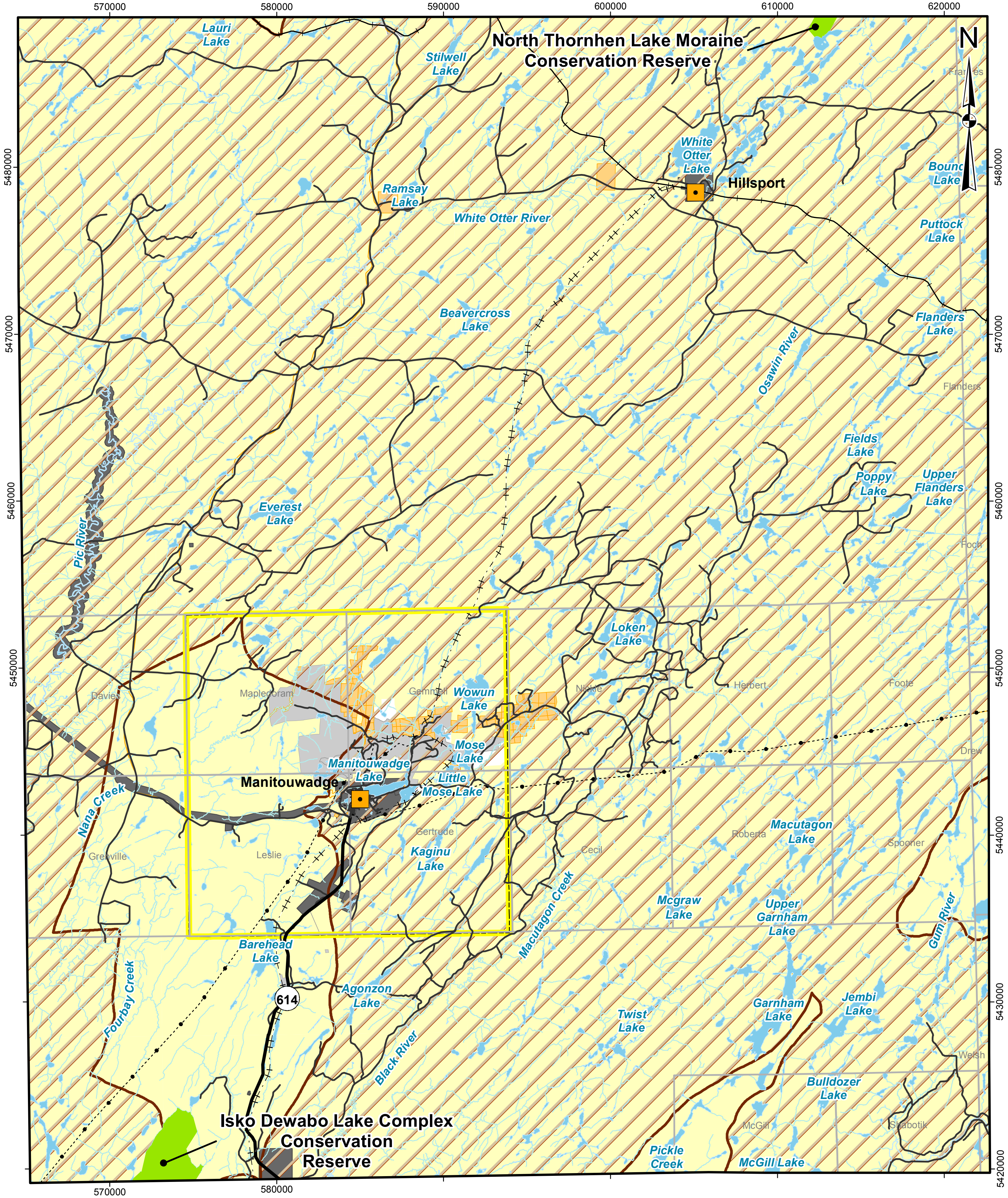
PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Drainage Features of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 2.4	REVISION 1
GIS	GF	4 SEPT 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

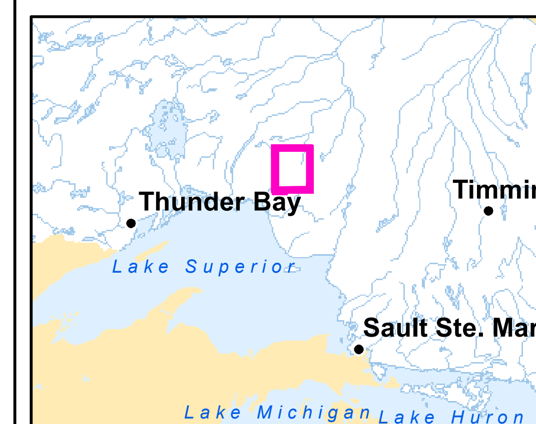
Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 2.4_Drainage Features of the_Manitouwadge Area.mxd

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\Report\MXDs\Manitouwadge\60297733_Fig 2.5 Land Disposition and Ownership within the Manitouwadge Area.mxd



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Township Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Hydro Line
- Waterbody
- Watercourse
- Conservation Reserve
- Regular Registered Trapline Area License
- Crown Land - Non-Freehold Dispositions Public
- Crown Reserves
- Crown Land - Unpatented Public Land
- Private Land



Data Sources:
Reproduced from Golder Associates Ltd. (2013)
Base Data: MNR LIO, obtained 2009-2013

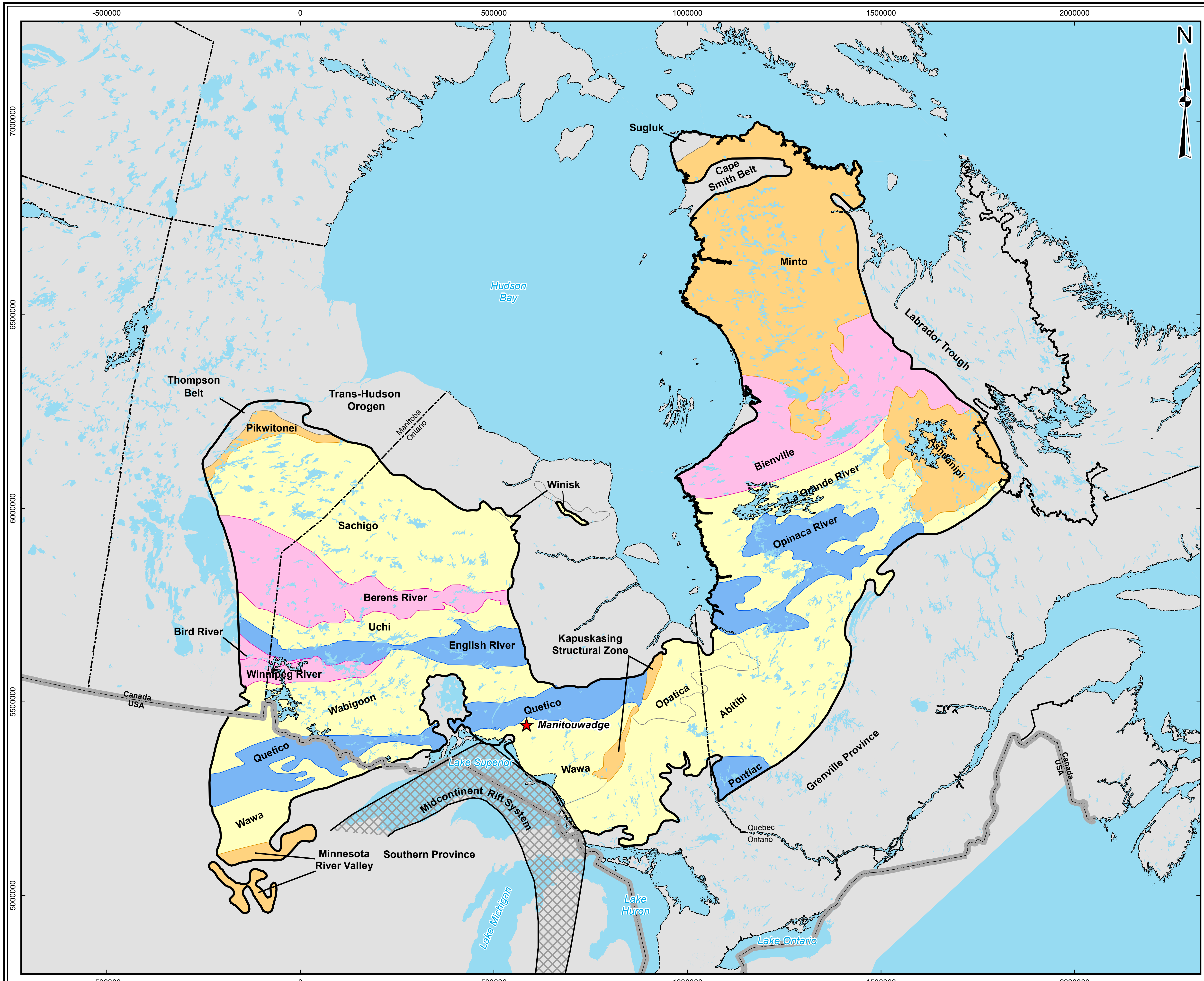
10 km

AECOM

PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Land Disposition and Ownerhsip within the Manitouwadge

DESIGN	PRM	05 JUL 2013	Figure 2.5	REVISION 1
GIS	GF	23 SEP 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

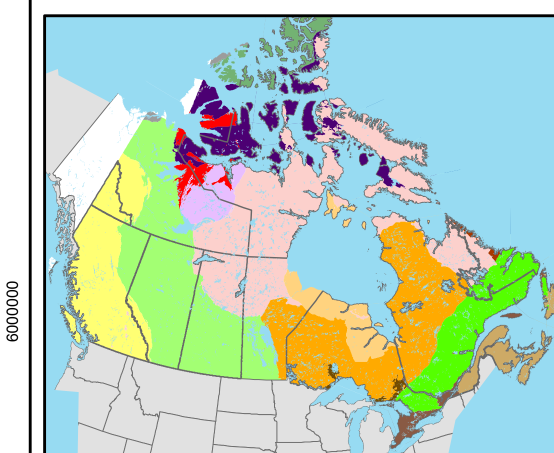


LEGEND

- City / Towns
- Provincial Boundary
- International Boundary
- Limit of Exposed Archean Rock

Superior Province (Archean)

- Subprovince Gneiss - Plutonic
- Subprovince Plutonic
- Subprovince Metasedimentary
- Subprovince Volcanic-Plutonic



Geological Regions of Canada

Appalachian Orogen	Cordilleran Orogen	Pacific Continental Shelf
Arctic Continental Shelf	Grenville Province	Slave Province
Arctic Platform	Hudson Bay Lowlands	Southern Province
Atlantic Continental Shelf	Innuitian Orogen	St. Lawrence Platform
Bear Province	Interior Platform	Superior Province
Churchill Province	Nain Province	Oceanic crust

Data Sources:
Produced by Golder Associates Ltd under licence from Ontario Ministry of Natural Resources, © Queens Printer 2009
Projection: Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 16
Base Data - MNR LIO, obtained 2009-2013, CANMAP v2006.4
Subdivisions of Superior Province - Thurston, P. C. 1991 Geology of Ontario: Introduction in Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.3-25
Geological Regions: Geological Map of Canada 1996, Map D1860A
Midcontinent Rift System: Sage, 1986

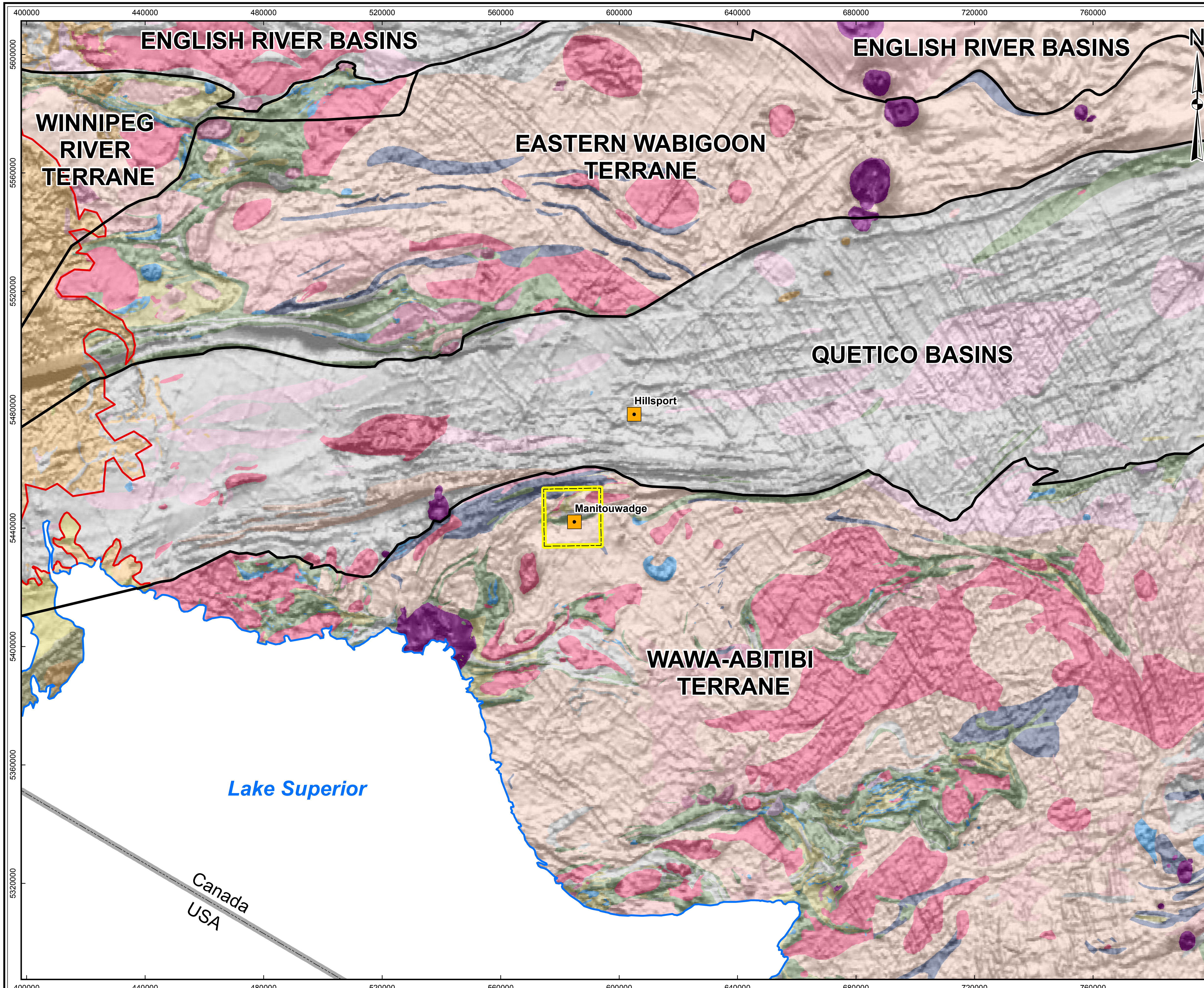
310 km

Golder Associates | AECOM

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Subdivision of the Superior Province of the Canadian Shield

DESIGN	PRM	30 Aug 2010	FIGURE 3.1	REVISION 3
GIS	GHF	24 Jan 2013		UTM ZONE 16
CHECK	CB	31 Jan 2013		NAD 1983
REVIEW	CB	31 Jan 2013		1:9,500,000



LEGEND

- Settlement
- Manitouwadge Municipal Boundary
- National Boundary
- Proterozoic Embayment
- Terrane Boundary

Bedrock Geology

- Alkalic Intrusive Suite and Carbonatite
- Mafic intrusive rocks (Keweenawan age)
- Osler Gp., Mamainse Point Fm., Michipicoten Island Fm.
- Sibley Gp.
- Animikie Gp.
- Hornblendite - nepheline syenite suite
- Massive granodiorite to granite
- Diorite-monzodiorite-granodiorite suite
- Muscovite-bearing granitic rocks
- Foliated tonalite suite
- Gneissic tonalite suite
- Mafic and ultramafic rocks
- Coarse clastic metasedimentary rocks
- Migmatized supracrustal rocks
- Metasedimentary rocks
- Felsic to intermediate metavolcanic rocks
- Mafic to intermediate metavolcanic rocks
- Mafic to ultramafic metavolcanic rocks
- Mafic metavolcanic and metasedimentary rocks
- Felsic to intermediate metavolcanic rocks

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Bedrock Geology: OGS, MRD 126 - Rev 1 (2011)
Terrane Divisions: MRD 278, Stott (2010)
Geophysical Underlay: #7 GSC, 800m Line Spacing

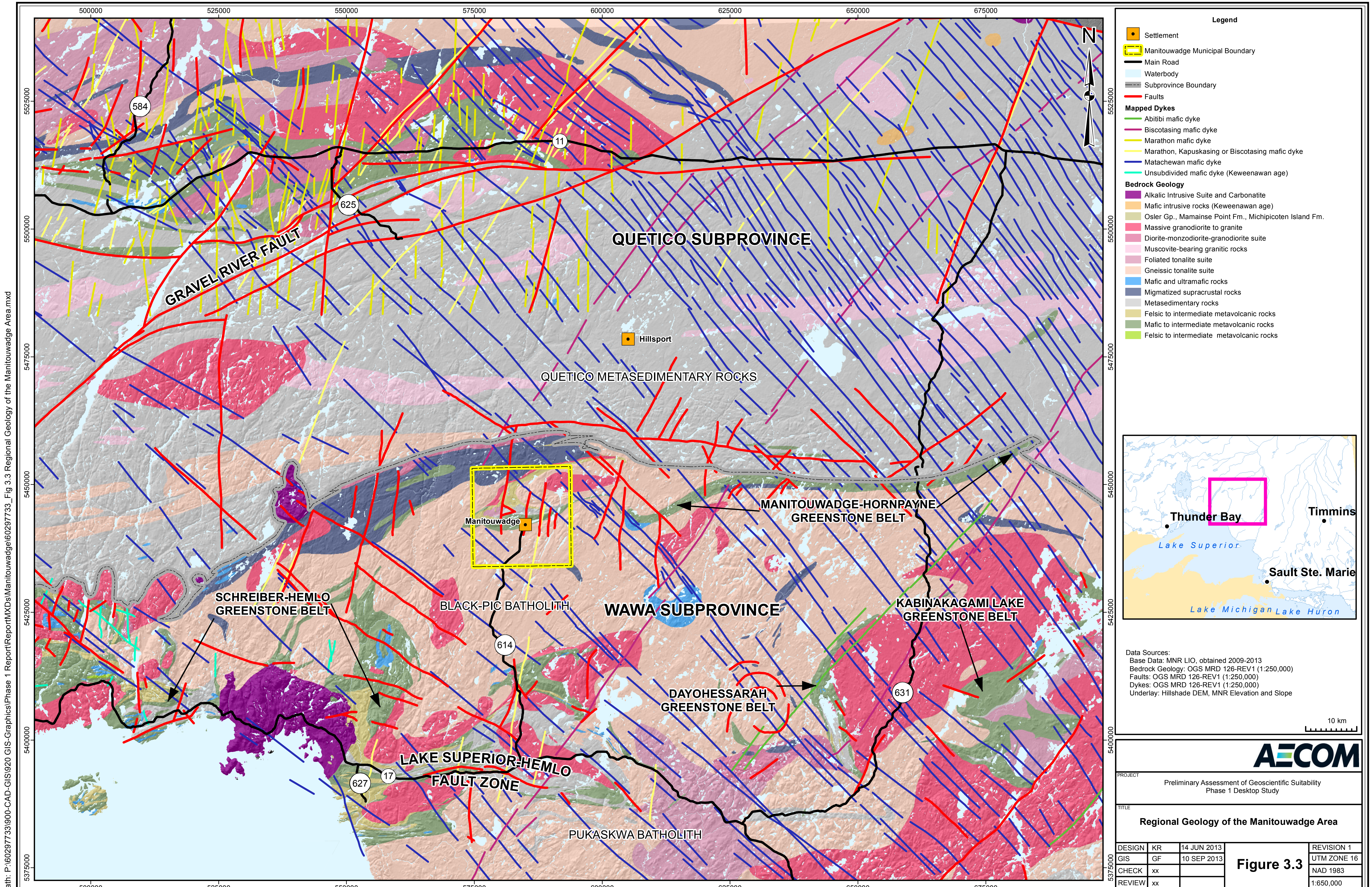
40 km

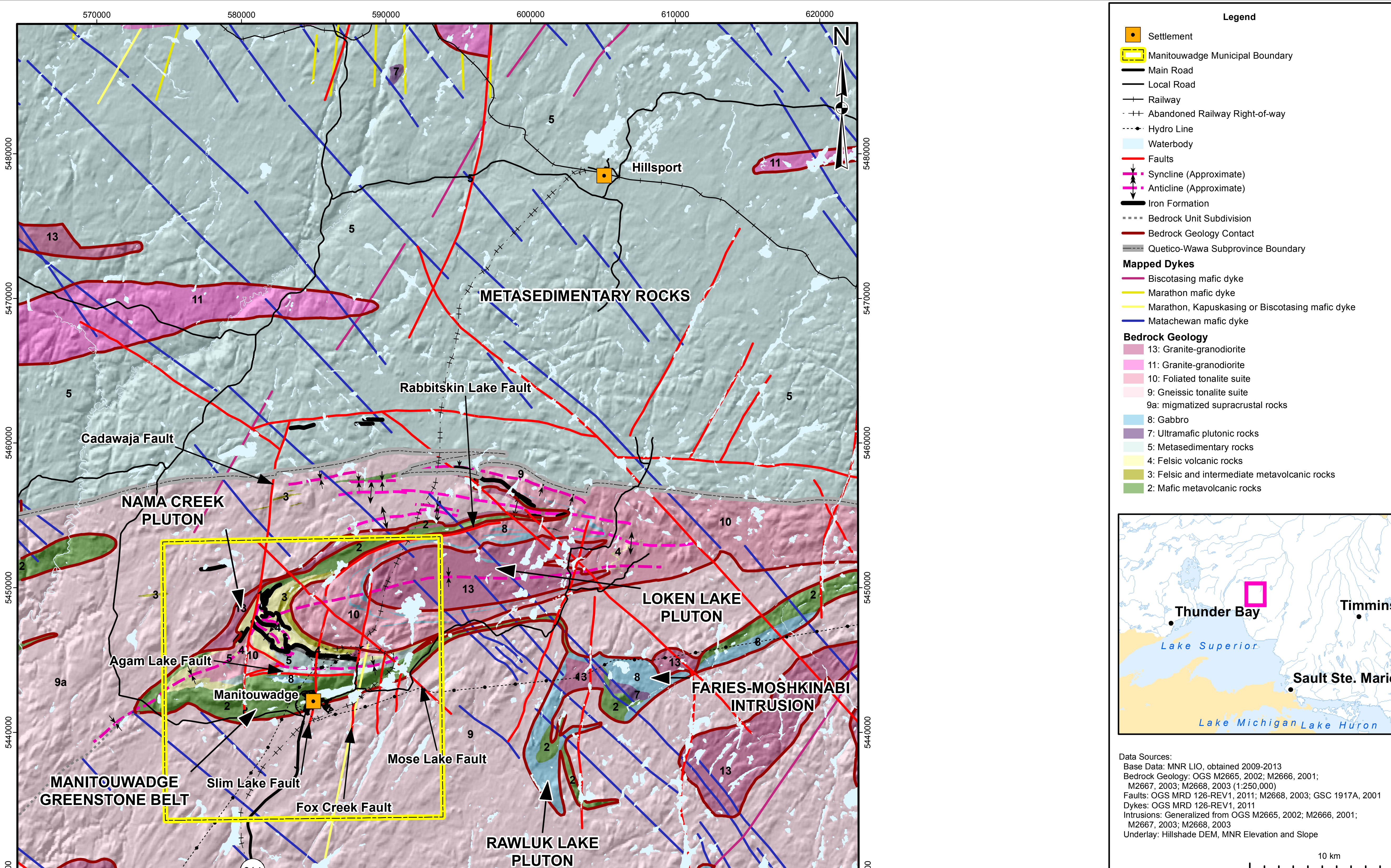
AECOM

PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Terrane Subdivision of North-Central Ontario

DESIGN	GHF	14 Aug 2012	**FIGURE 3.2**	REVISION 3
GIS	GHF	09 SEP 2013		UTM ZONE 16
CHECK	CB			NAD 1983
REVIEW	CB			1:1,250,000


Legend
Settlement
Manitouwadge Municipal Boundary
Main Road
Waterbody
Subprovince Boundary
Faults
Mapped Dykes
Abitibi mafic dyke
Biscotasing mafic dyke
Marathon mafic dyke
Marathon, Kapuskasing or Biscotasing mafic dyke
Matachewan mafic dyke
Unsubdivided mafic dyke (Keweenawan age)
Bedrock Geology
Alkalic Intrusive Suite and Carbonatite
Mafic intrusive rocks (Keweenawan age)
Osler Gp., Mamainse Point Fm., Michipicoten Island Fm.
Massive granodiorite to granite
Diorite-monzodiorite-granodiorite suite
Muscovite-bearing granitic rocks
Foliated tonalite suite
Gneissic tonalite suite
Mafic and ultramafic rocks
Migmatized supracrustal rocks
Metasedimentary rocks
Felsic to intermediate metavolcanic rocks
Mafic to intermediate metavolcanic rocks
Felsic to intermediate metavolcanic rocks
N
QUETICO SUBPROVINCE
GRAVEL RIVER FAULT
Hillsport
QUETICO METASEDIMENTARY ROCKS
Manitouwadge
MANITOUWADGE-HORNPAYNE GREENSTONE BELT
SCHREIBER-HEMLO GREENSTONE BELT
BLACK-PIC BATHOLITH
WAWA SUBPROVINCE
KABINAKAGAMI LAKE GREENSTONE BELT
DAYOHESSARAH GREENSTONE BELT
LAKE SUPERIOR-HEMLO FAULT ZONE
PUKASKWA BATHOLITH
584
11
625
614
631
627
17
500000
525000
550000
575000
600000
625000
650000
675000
5525000
5500000
5475000
5450000
5425000
5400000
5375000
Thunder Bay
Timmins
Lake Superior
Sault Ste. Marie
Lake Michigan
Lake Huron
Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Bedrock Geology: OGS MRD 126-REV1 (1:250,000)
Faults: OGS MRD 126-REV1 (1:250,000)
Dykes: OGS MRD 126-REV1 (1:250,000)
Underlay: Hillshade DEM, MNR Elevation and Slope
10 km
AECOM
PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study
TITLE
Regional Geology of the Manitouwadge Area
DESIGN KR 14 JUN 2013
GIS GF 10 SEP 2013
CHECK xx
REVIEW xx
Figure 3.3
REVISION 1
UTM ZONE 16
NAD 1983
1:650,000
Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Report\MXDs\Manitouwadge\60297733_Fig 3.3 Regional Geology of the Manitouwadge Area.mxd



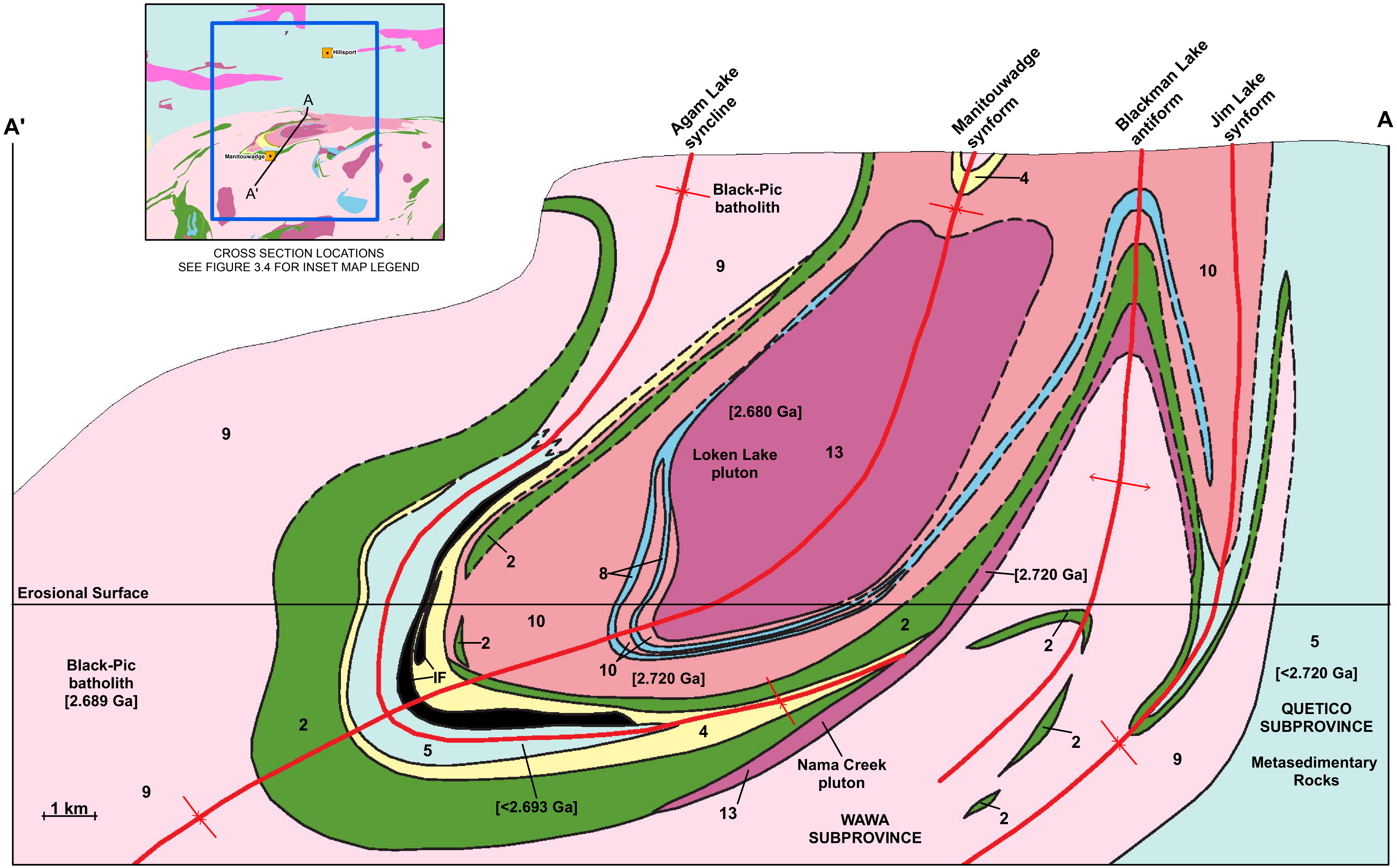
AECOM

PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Bedrock Geology of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 3.4	REVISION 1
GIS	GF	29 AUG 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.4 Local Bedrock Geology of the Manitouwadge Area.mxd



Data Sources - Inset Map:
Bedrock Geology: OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003 (1:250,000)

Data Sources - Cross-Section:
Modified from: OGS 2668, 2003
Original Source: Zaleski and Peterson, 2001

Legend for Cross Section

- 13: Granite-granodiorite
- 10: Foliated tonalite suite
- 9: Gneissic tonalite suite
- 8: Gabbro
- 5: Clastic sedimentary rocks
- 4: Felsic volcanic rocks
- 2: Mafic metavolcanic Rocks
- IF: Iron Formation
- Syncline
- Anticline

[2.680 Ga]: Age Date

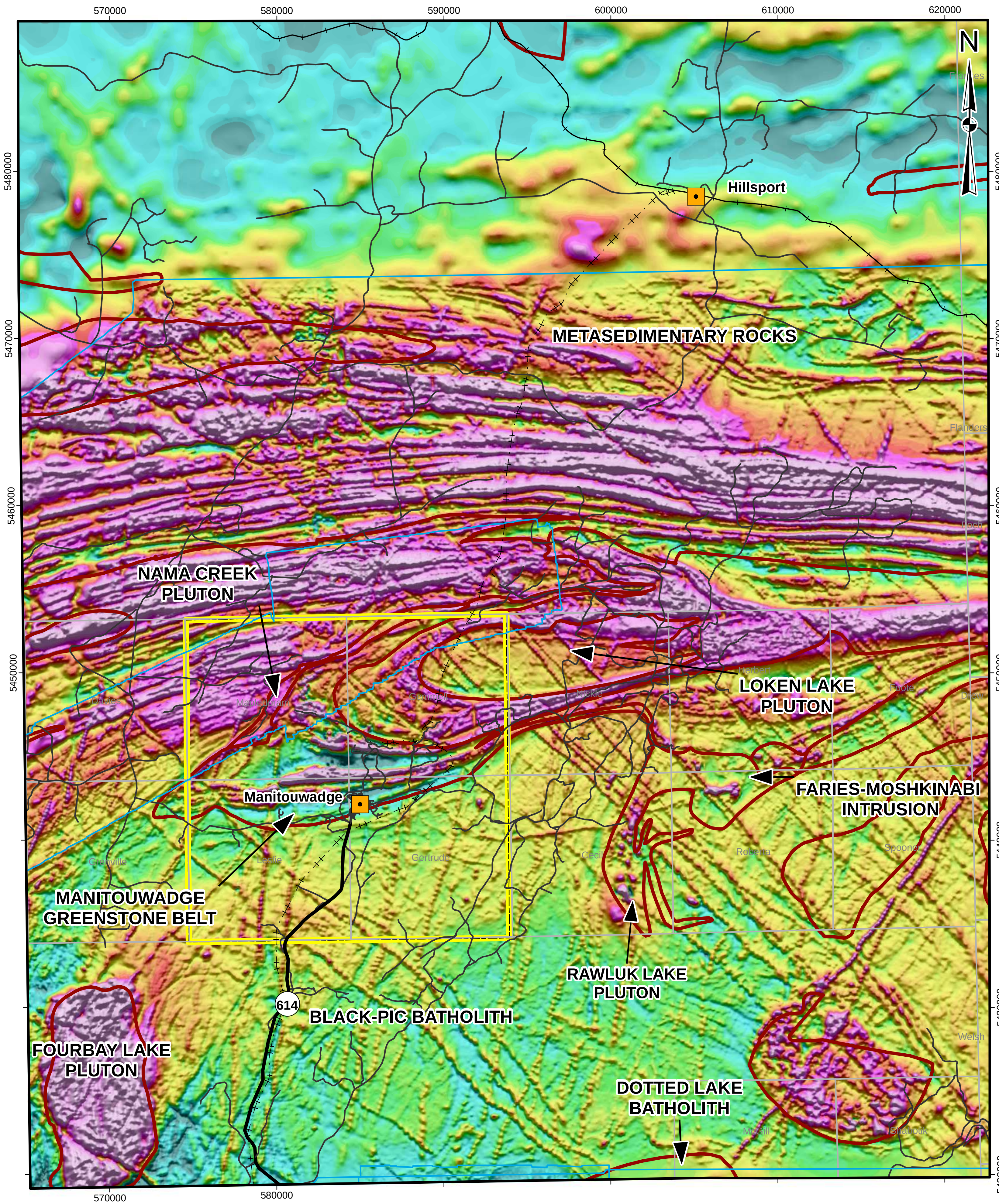
AECOM

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Manitouwadge Area Schematic Cross Section

DESIGN	GHF	14 Aug 2012	FIGURE 3.5	REVISION 2
GIS	GHF	10 Sep 2013		UTM ZONE 16
CHECK	CB			NAD 1983
REVIEW	CB			

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.5 - Manitouwadge Area Schematic Cross Section.mxd

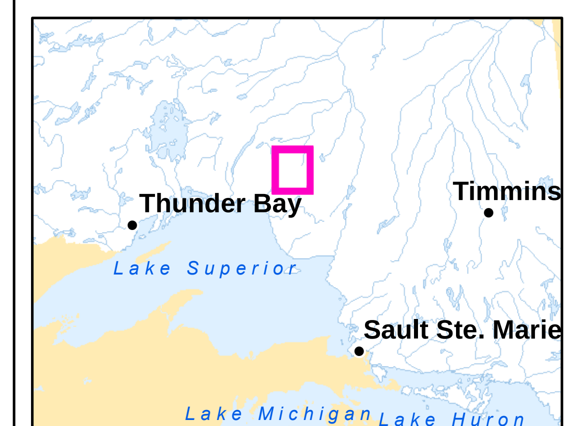


Legend

- Settlement
- Manitouwadge Municipal Boundary
- Township Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- 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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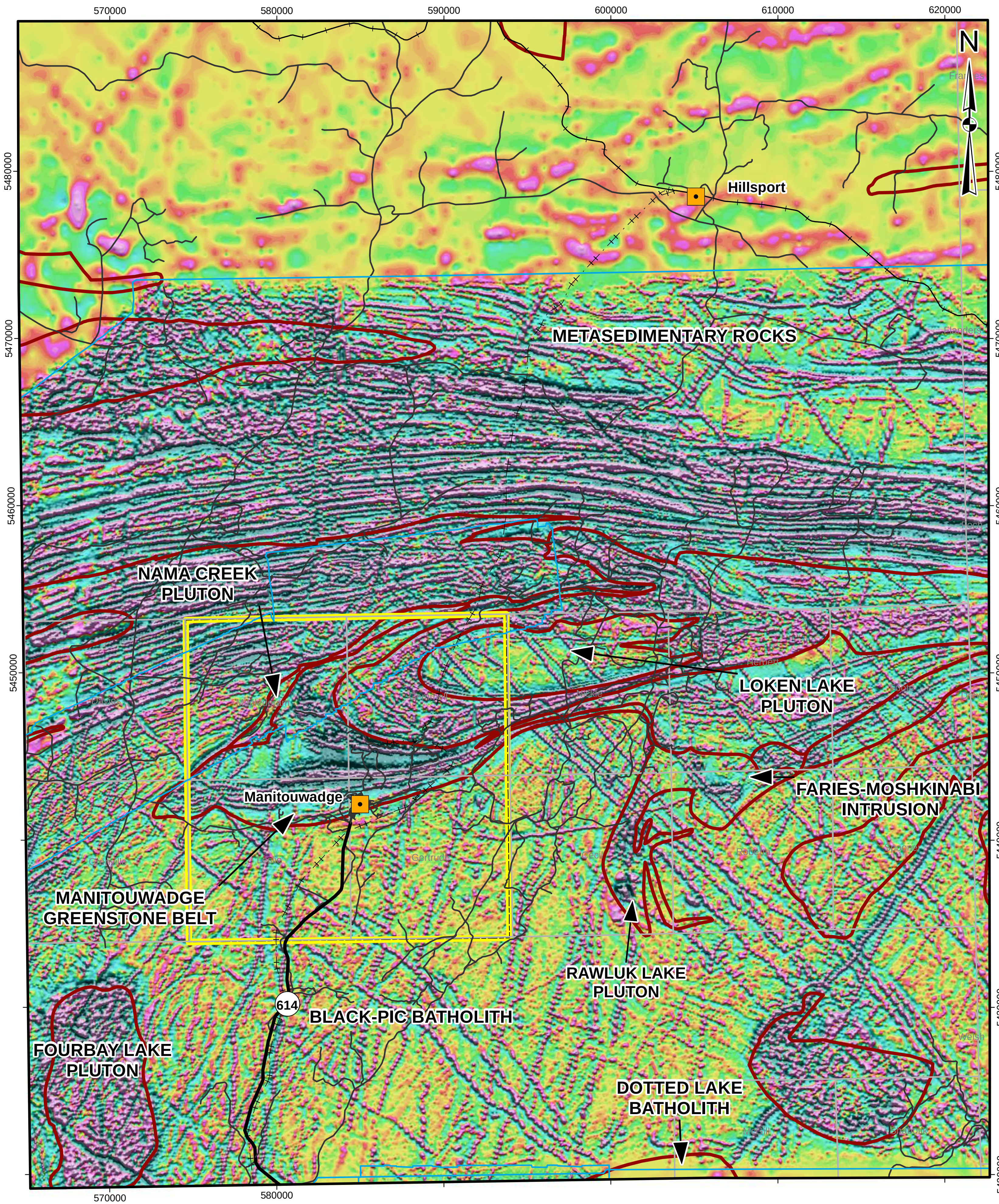
TITLE
Geophysical Data Analysis Reduced to Pole Residual Magnetic Field in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 3.6**	REVISION 2
GIS	WP	10 JAN 2014		UTM ZONE 16
CHECK	SR	19 JAN 2014		NAD 1983
REVIEW	CB	20 JAN 2014		1:275,000

Path: C:\Users\Stephen\PGW\2013-18\Proc\maps\ArcGIS\Aecom_maps_Jan_2014\Fig3.6_AECOM_Manitouwadge_Mag_RTP.mxd



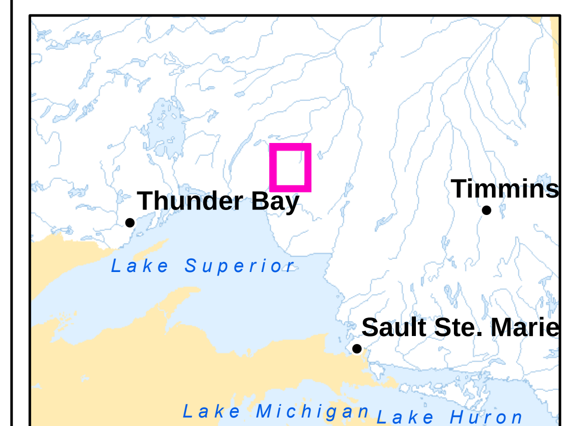
Path: C:\Users\Stephen\PGW\2013-18\Proc\maps\ArcGIS\Aecom_maps_Jan_2014\Fig3.7_AECOM_Manitouwadge_Mag_RTP1VD.mxd

Legend

- Settlement
- Manitouwadge Municipal Boundary
- Township Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- 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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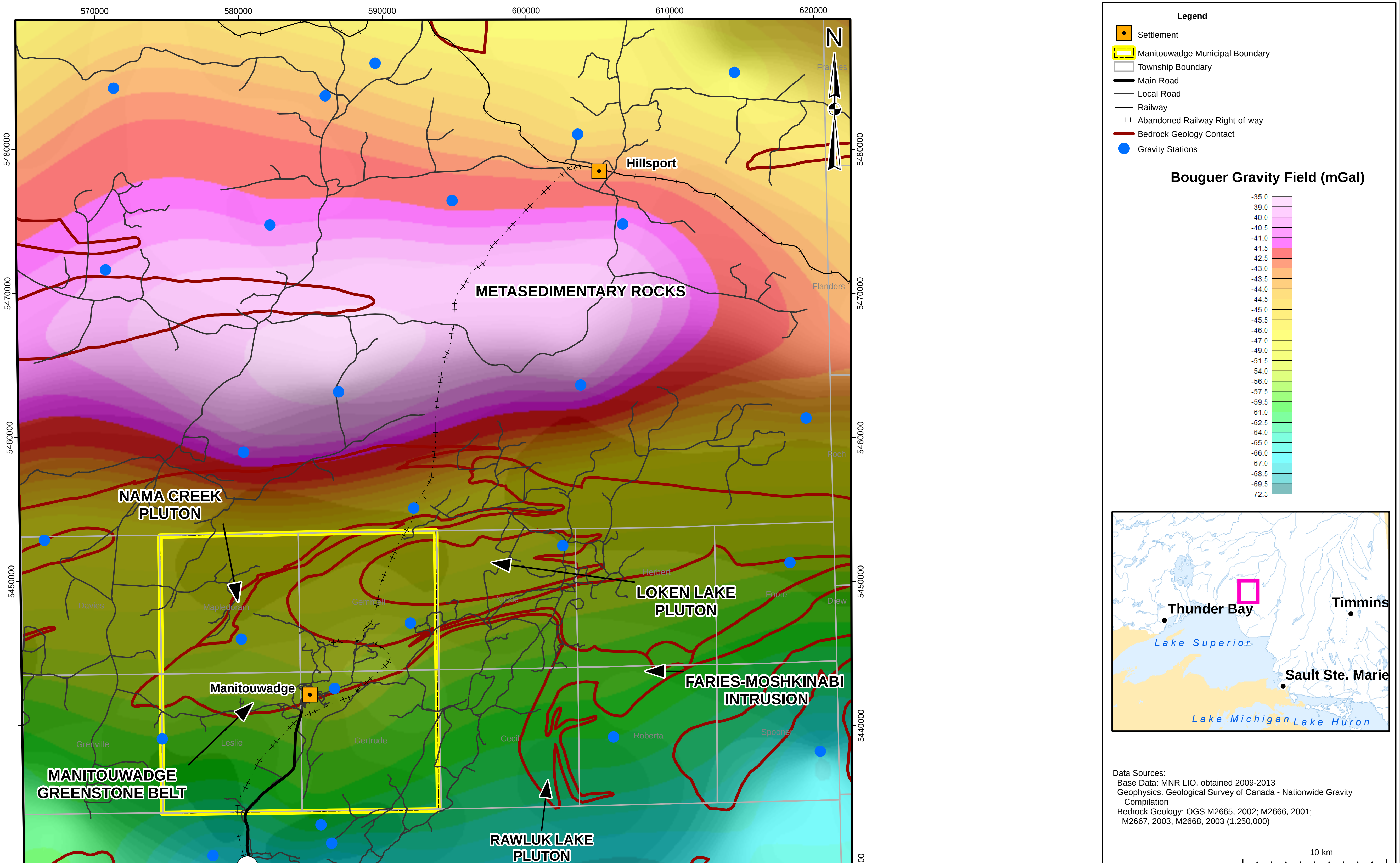
PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Geophysics Data Analysis First Vertical Derivative of Reduced to Pole Residual Magnetic Field in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 3.7**	REVISION 2
GIS	WP	10 JAN 2014		UTM ZONE 16
CHECK	SR	19 JAN 2014		NAD 1983
REVIEW	CB	20 JAN 2014		1:275,000



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)

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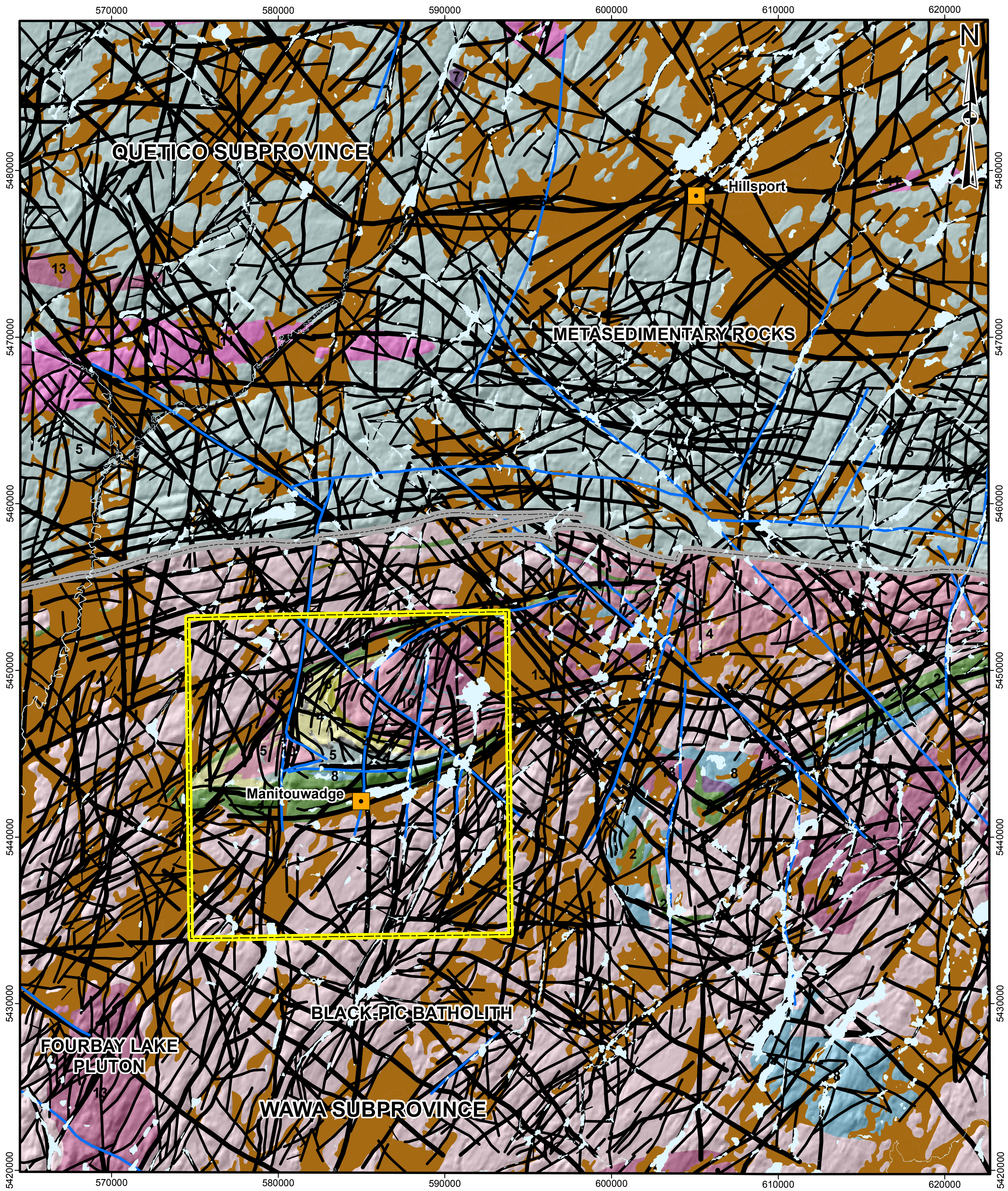
TITLE
Geophysical Data Analysis Bouguer Gravity Field with Station Locations in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 3.8	REVISION 2
GIS	WP	10 JAN 2014		UTM ZONE 16
CHECK	SR	19 JAN 2014		NAD 1983
REVIEW	CB	20 JAN 2014		1:275,000

Path: C:\Users\Stephen\PGW\2013-18\Proc\maps\ArcGIS\Aecom_maps_Jan_2014\Fig3.8_AECOM_Manitouwadge_Grav_Bouguer.mxd

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.9 Surficial Lineaments of the Manitouwadge Area.mxd



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Waterbody
- Mapped Fault

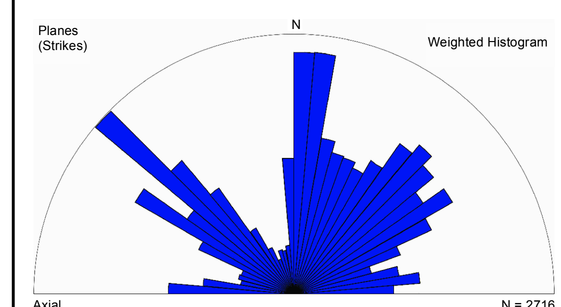
Surficial Lineaments (DEM and SAT)

- < 1 km
- 1 - 5 km
- 5 - 10 km
- > 10 km
- Quetico-Wawa Subprovince Boundary
- Overburden Cover

Bedrock Geology

- Granite-granodiorite
- Granite-granodiorite
- Foliated tonalite suite
- Gneissic tonalite suite
  migmatized supracrustal rocks
- Gabbro
- Ultramafic plutonic rocks
- Metasedimentary rocks
- Felsic volcanic rocks
- Felsic and intermediate metavolcanic rocks
- Mafic metavolcanic rocks

Manitouwadge Surficial Lineaments - Normalized Length in 5 Degree Azimuth Bins



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
Overburden: OGS MRD-160, NOEGTS 2006
Lineaments: SRK, 2014
Underlay: Hillshade DEM, MNR Elevation and Slope

10 km

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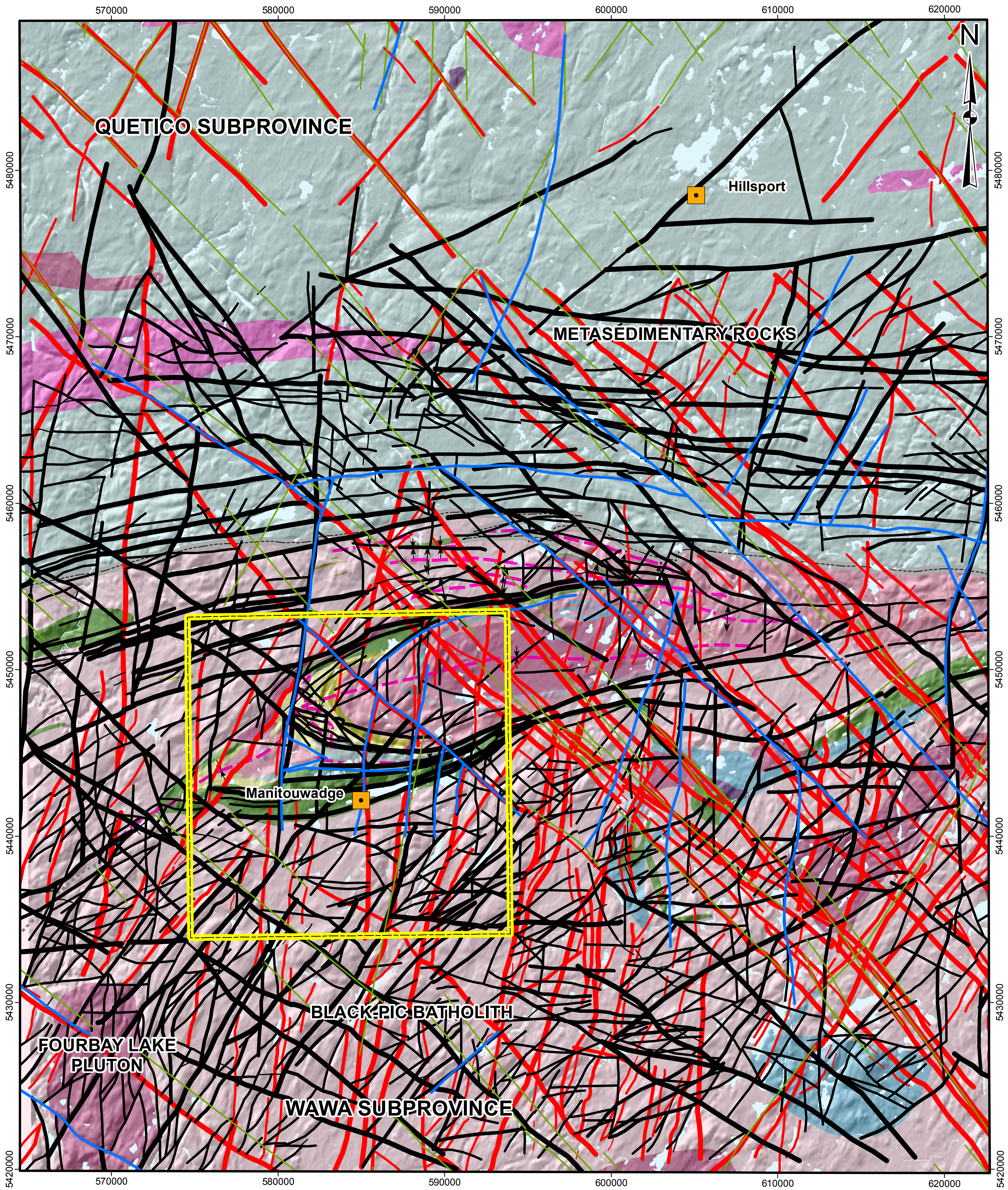
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Surficial Lineaments of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 3.9	REVISION 1
GIS	GF	29 AUG 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

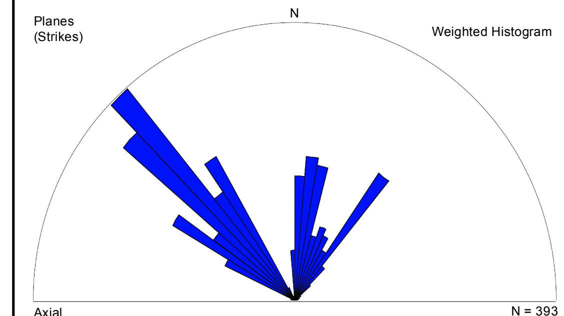


Legend

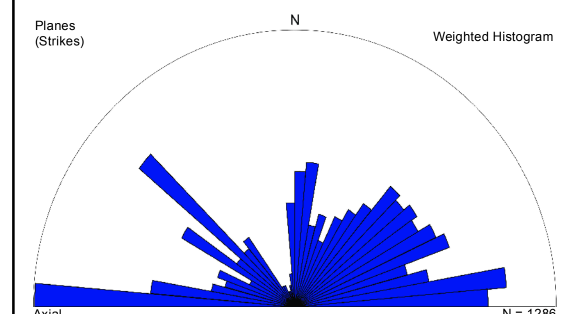
- Settlement
- Manitouwadge Municipal Boundary
- Waterbody
- Mapped Fault
- Mapped Dyke
- Syncline (Approximate)
- Anticline (Approximate)
- Bedrock Unit Subdivision
- Quetico-Wawa Subprovince Boundary

Fracture (length)	Dyke (length)
< 1 km	< 1 km
1 - 5 km	1 - 5 km
5 - 10 km	5 - 10 km
> 10 km	> 10 km

Manitouwadge Geophysical Dykes - Normalized Length in 5 Degree Azimuth Bins



Manitouwadge Geophysical Fractures - Normalized Length in 5 Degree Azimuth Bins



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
Lineaments: SRK, 2014
Underlay: Hillshade DEM, MNR Elevation and Slope

10 km

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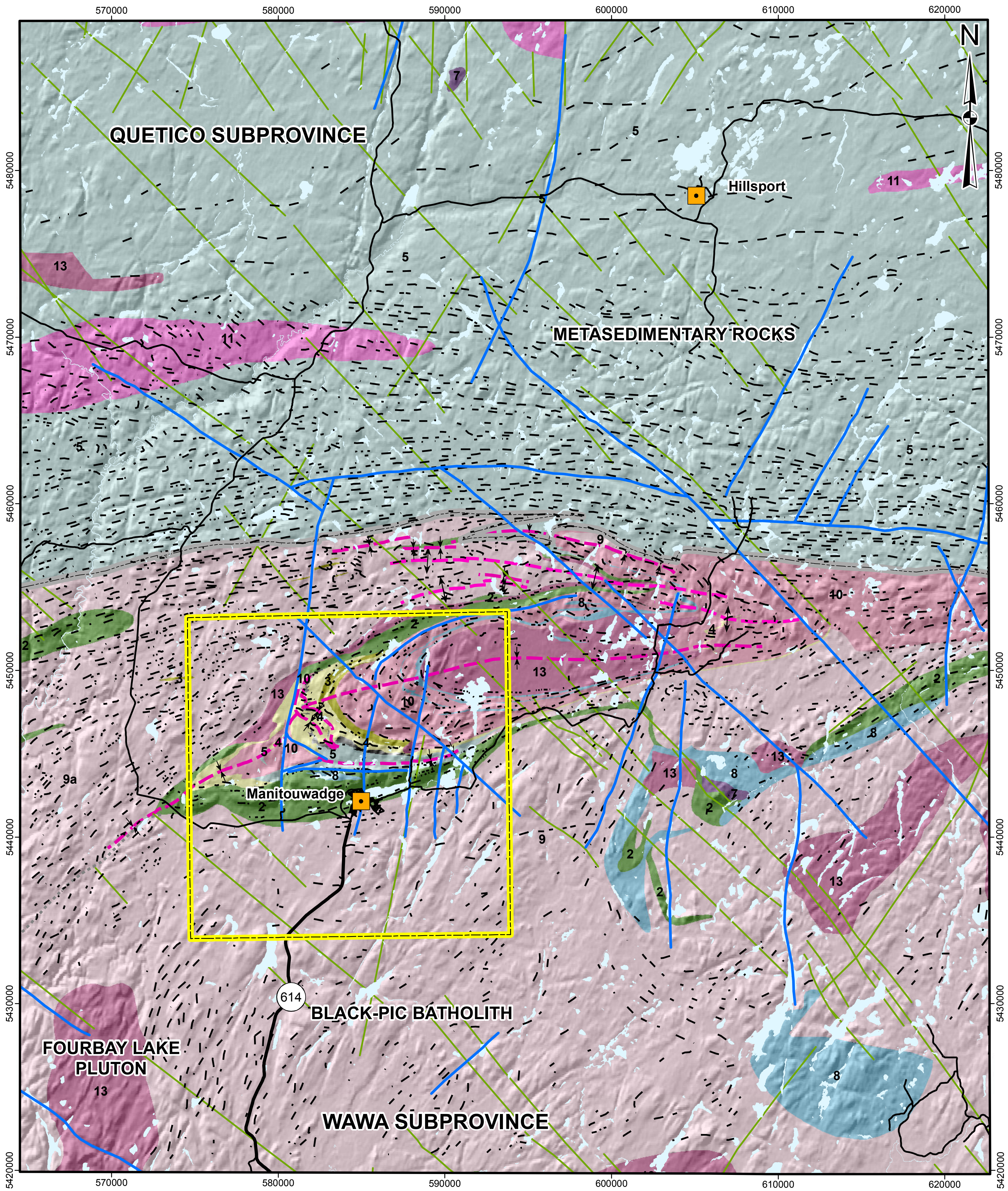
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Geophysical Lineaments of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 3.10**	REVISION 1
GIS	GF	29 AUG 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.10 Geophysical Lineaments of the Manitouwadge Area.mxd

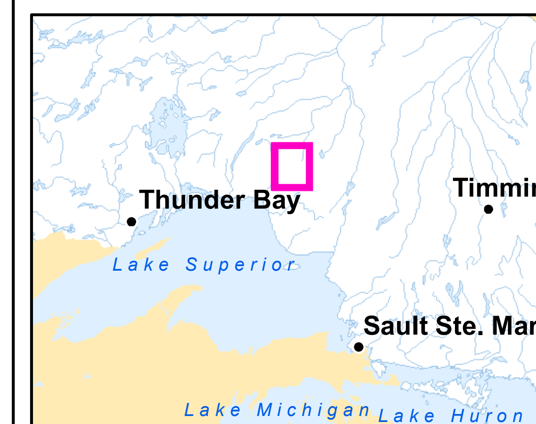


Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Waterbody
- Mapped Fault
- Mapped Dyke
- Syncline (Approximate)
- Anticline (Approximate)
- Bedrock Unit Subdivision
- Quetico-Wawa Subprovince Boundary
- Ductile Lineament

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
Ductile Lineament: SRK, 2013
Underlay: Hillshade DEM, MNR Elevation and Slope

10 km

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Preliminary Assessment of Geoscientific Suitability
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TITLE
Ductile Features of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 3.11	REVISION 1
GIS	GF	29 AUG 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

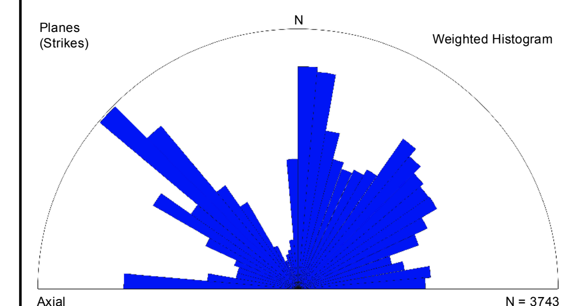
Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.11 Ductile Features of the Manitouwadge Area.mxd

Legend

- Settlement
- Manitouwadge Municipal Boundary
- Waterbody
- Syncline (Approximate)
- Anticline (Approximate)
- Quetico-Wawa Subprovince Boundary

Brittle Lineament Length	Dyke Lineament Length
< 1 km	< 1 km
1 - 5 km	1 - 5 km
5 - 10 km	5 - 10 km
> 10 km	> 10 km

Manitouwadge All Data -
Normalized Length in 5 Degree Azimuth Bins



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
Lineaments: SRK, 2014
Underlay: Hillshade DEM, MNR Elevation and Slope

10 km

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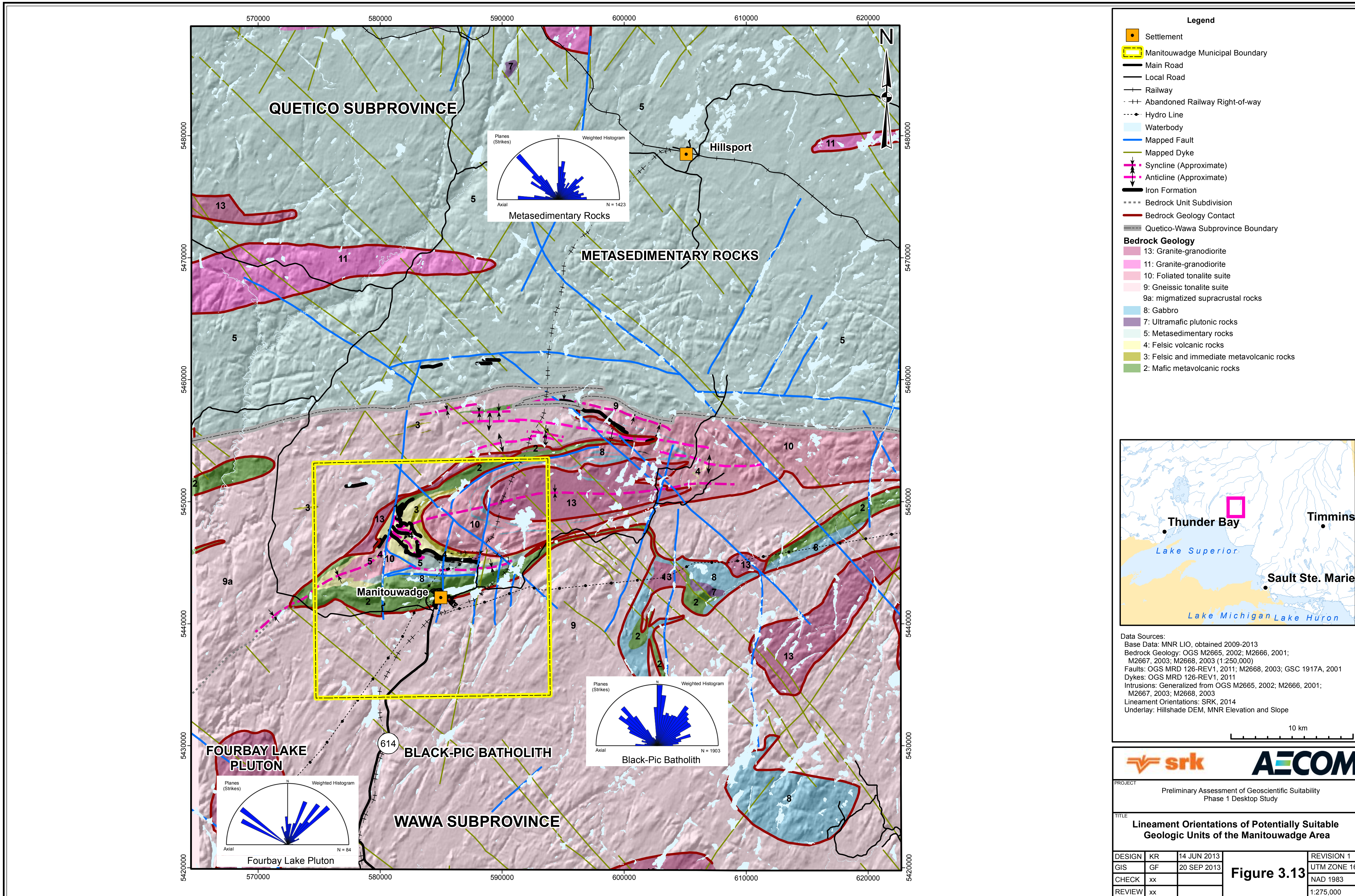
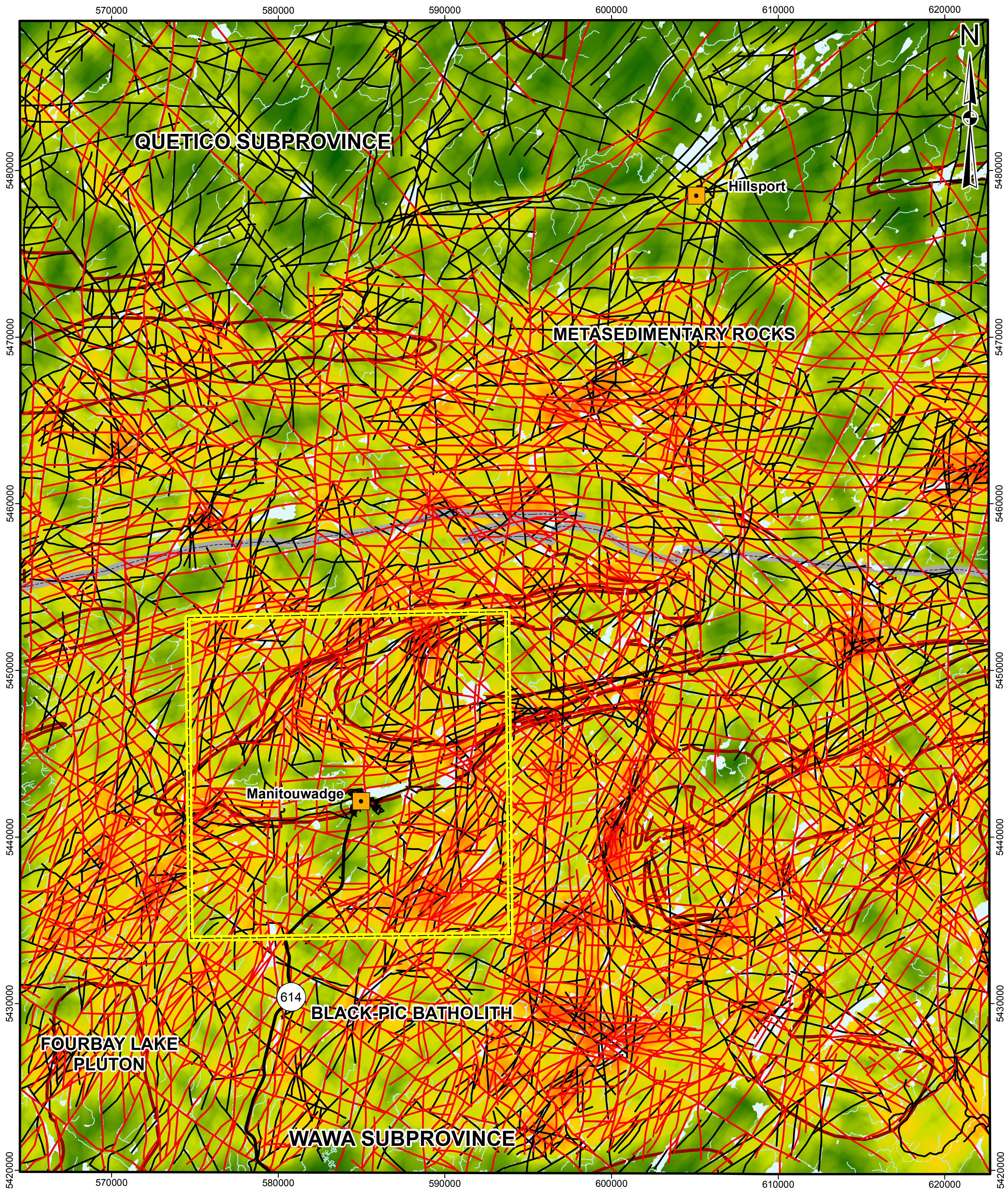
TITLE
Brittle and Dyke Lineaments of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 3.12**	REVISION 1
GIS	GF	07 OCT 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.12 Brittle and Dyke Lineaments of the Manitouwadge Area.mxd



Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.13 Lineament Orientations of Potentially Suitable Geologic Units of the Manitouwadge Area.mxd



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Waterbody
- Watercourse
- Bedrock Geology Contact
- Quetico-Wawa Subprovince Boundary

Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke

Lineament Density (km/km²)

7.0

0.0

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003
Lineaments: SRK, 2014

10 km

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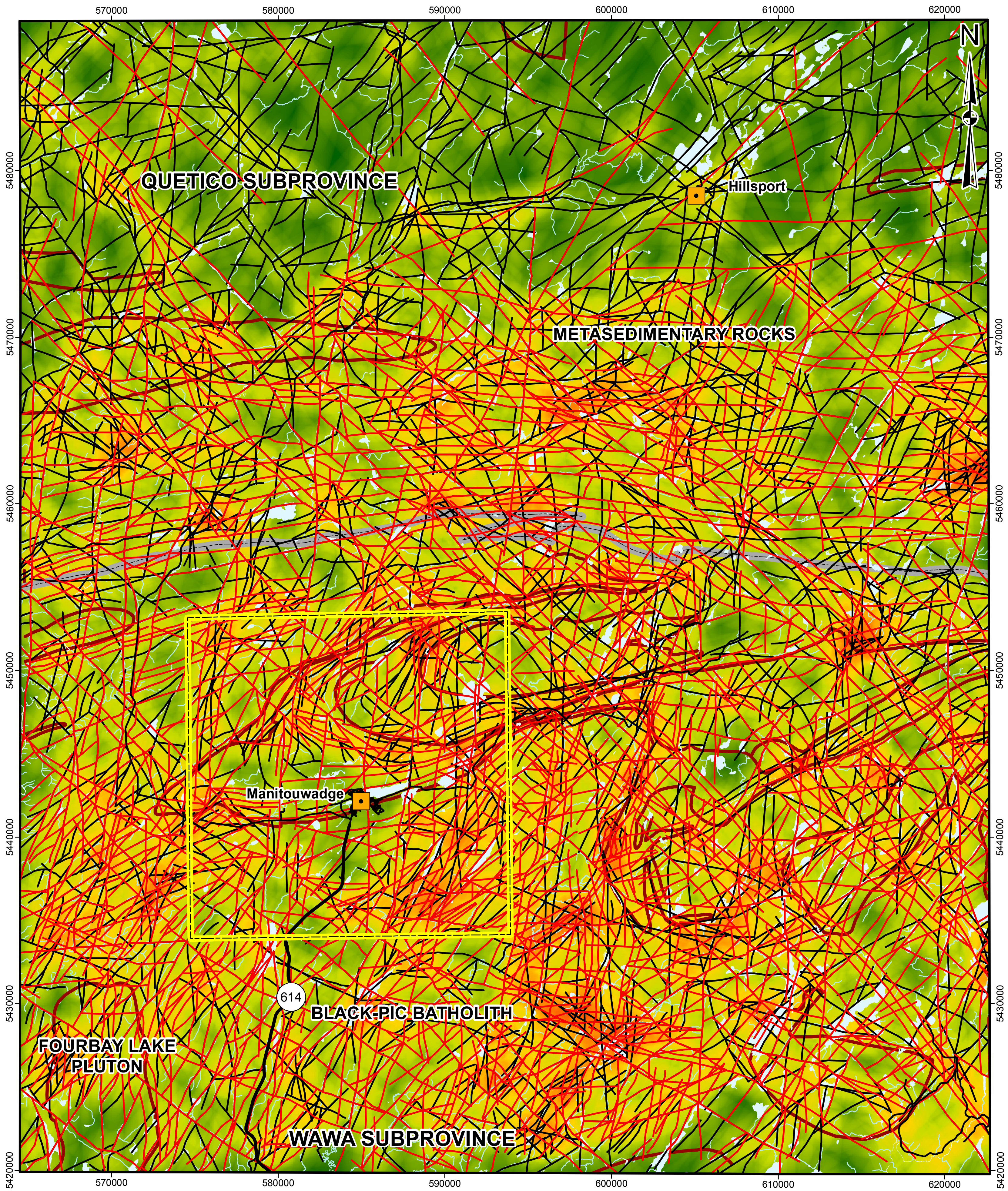
TITLE
Lineament Density Calculated for Lineaments in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 3.14**	REVISION 1
GIS	GF	07 OCT 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.14 Lineament Density Calculated for Lineaments in the Manitouwadge Area.mxd



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Waterbody
- Watercourse
- Bedrock Geology Contact
- Quetico-Wawa Subprovince Boundary

Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke

Lineament Density (km/km²)

7.0

0.0

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003
Lineaments: SRK, 2014

10 km

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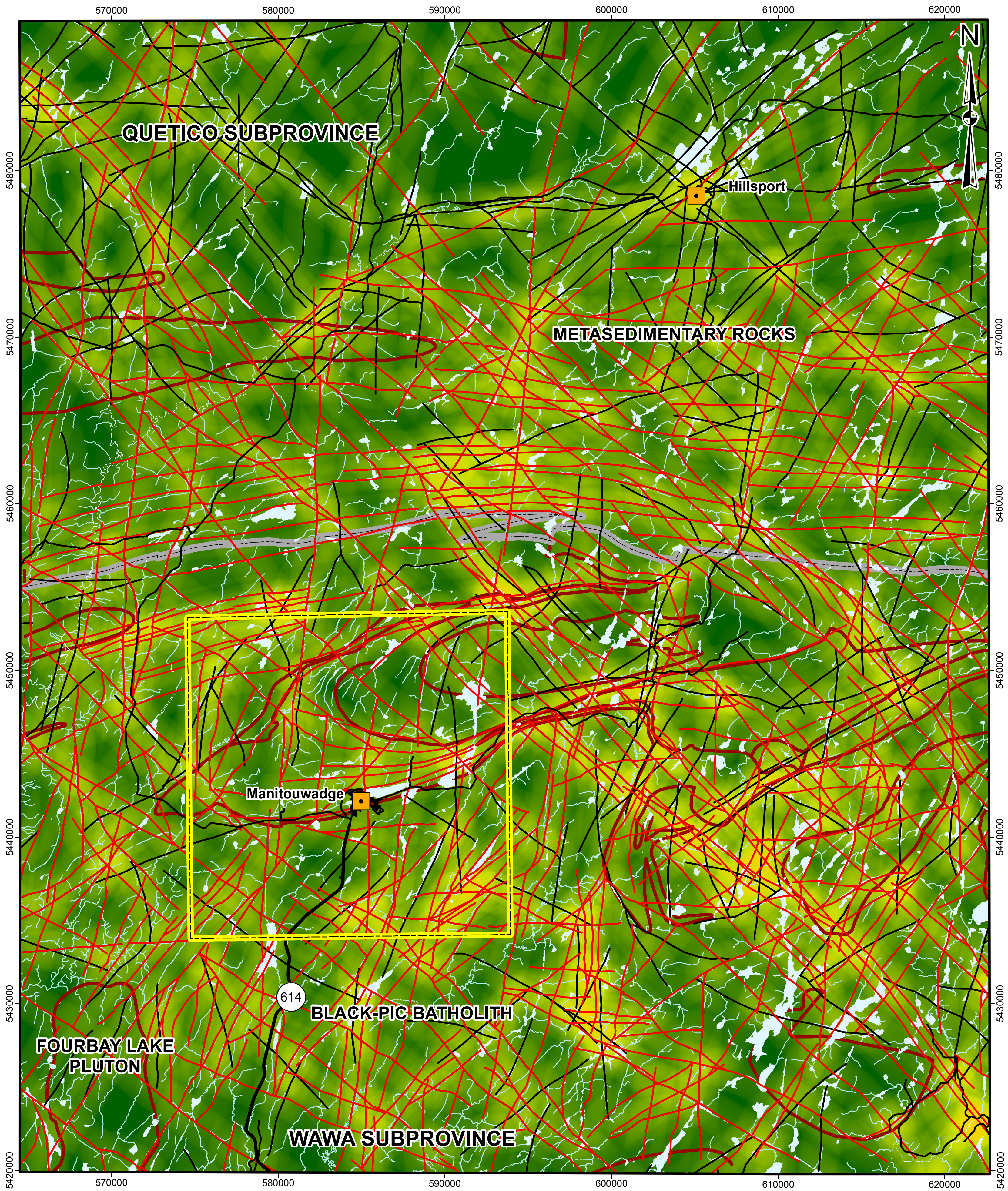
TITLE
Lineament Density Calculated for Lineaments (>1 km) in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 3.15**	REVISION 1
GIS	GF	07 OCT 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.15 Lineament Density Calculated for Lineaments 1km in the Manitouwadge Area.mxd



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Waterbody
- Watercourse
- Bedrock Geology Contact
- Quetico-Wawa Subprovince Boundary

Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke

Lineament Density (km/km²)

7.0

0.0

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003
Lineaments: SRK, 2014

10 km

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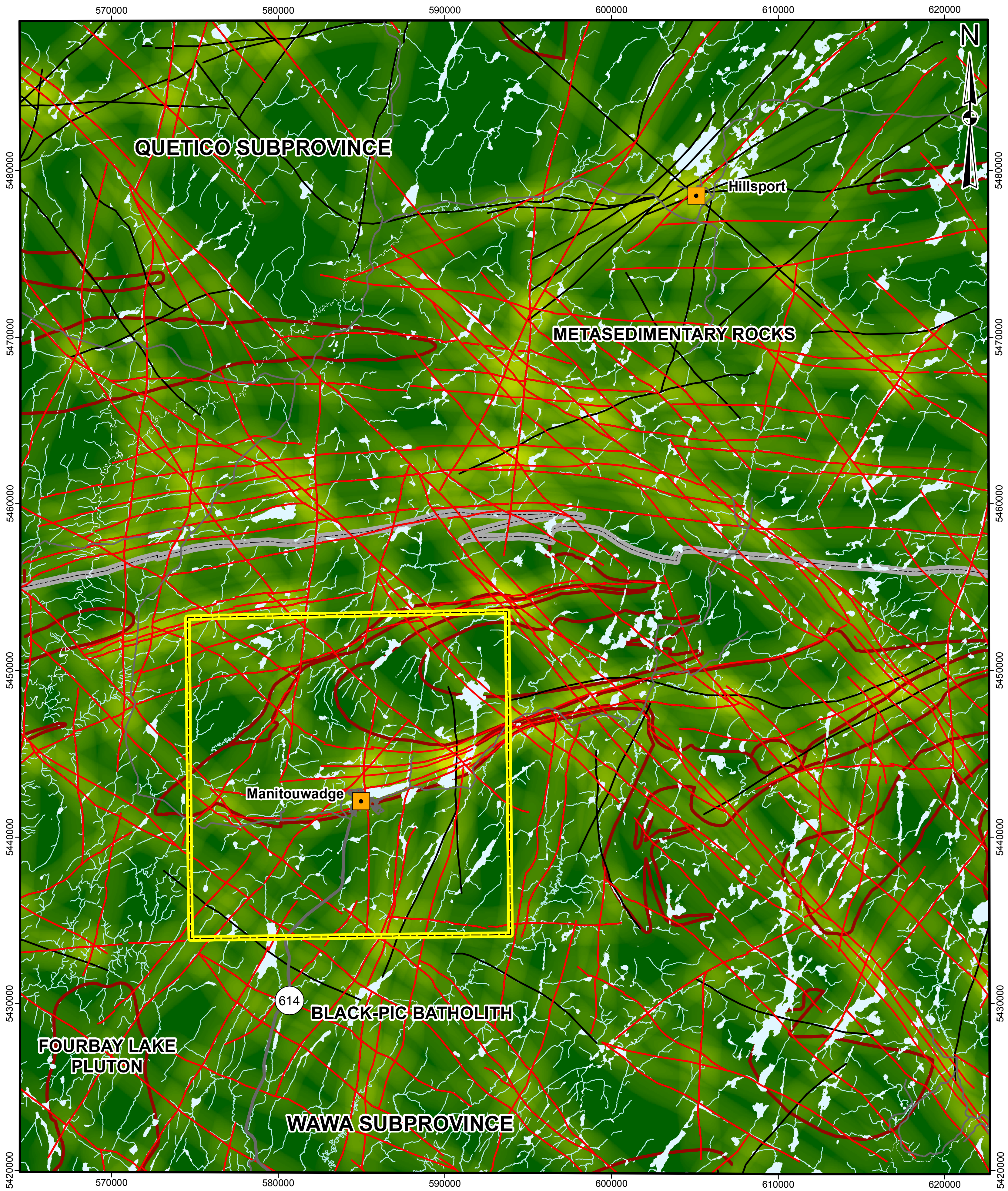
TITLE
Lineament Density Calculated for Lineaments (>5 km) in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 3.16	REVISION 1
GIS	GF	07 OCT 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\Report\MXDs\Manitouwadge\60297733_Fig 3.16 Lineament Density Calculated for Lineaments 5km in the Manitouwadge Area.mxd



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Waterbody
- Watercourse
- Bedrock Geology Contact
- Quetico-Wawa Subprovince Boundary

Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke

Lineament Density (km/km²)

7.0

0.0

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003
Lineaments: SRK, 2014

10 km

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TITLE
Lineament Density Calculated for Lineaments (>10 km) in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 3.17	REVISION 1
GIS	GF	07 OCT 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.17 Lineament Density Calculated for Lineaments 10km in the Manitouwadge Area.mxd

Legend

- Settlement
- Manitouwadge Municipal Boundary
- Waterbody
- Watercourse
- Mapped Fault
- Mapped Dyke
- Syncline (Approximate)
- Anticline (Approximate)
- Quetico-Wawa Subprovince Boundary
- Ductile Lineament

Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke
- Bedrock Unit Subdivision

Seismic Events (Magnitude)

- 2.1 - 3.0

*no events less than 2.0 and greater than 3 magnitude

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
Lineaments: SRK, 2014
Earthquake: NRCAN Earthquake Database (accessed Aug 15, 2013)
Underlay: Hillshade DEM, MNR Elevation and Slope

10 km

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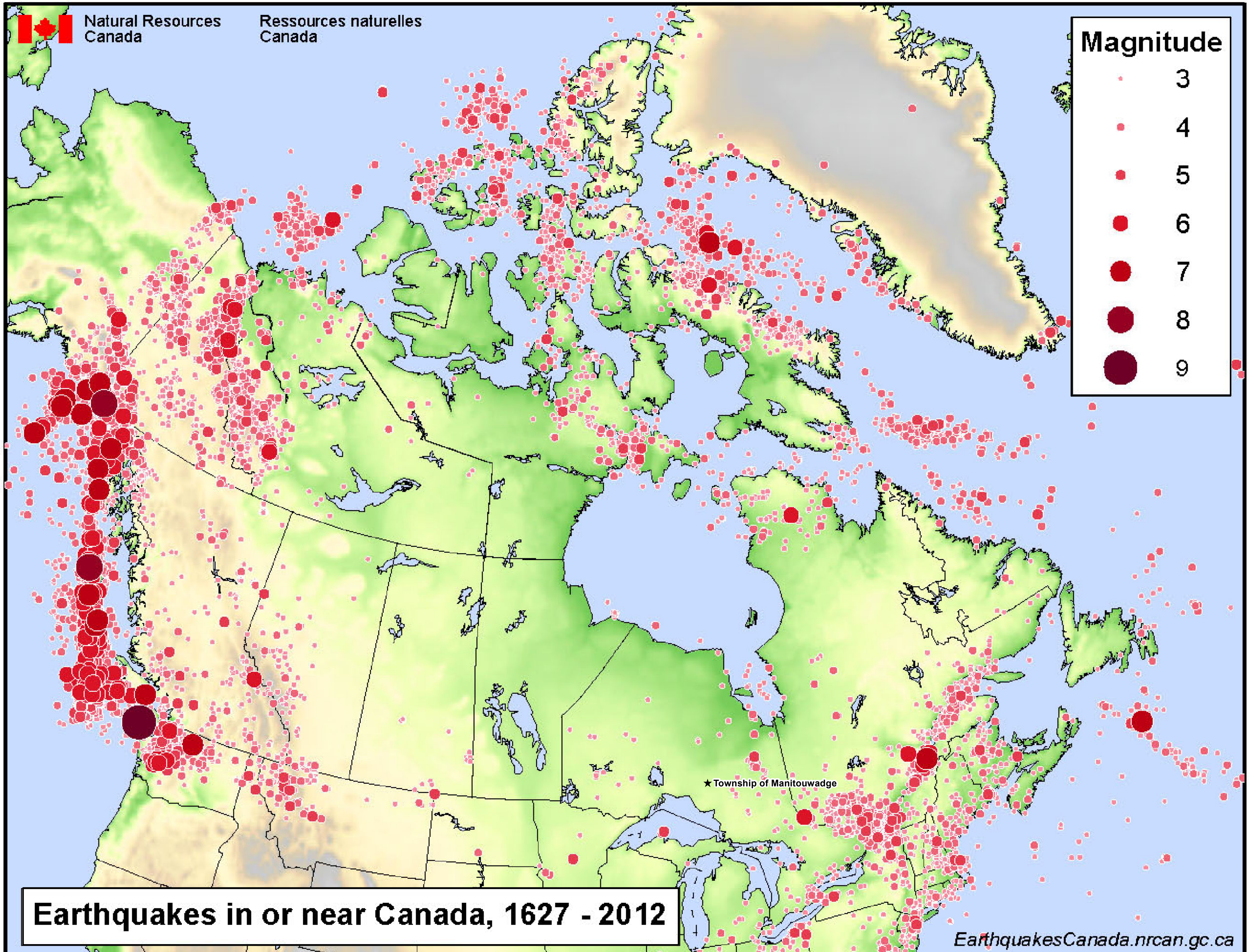
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Combined Structural Features of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 3.18**	REVISION 1
GIS	GF	20 SEP 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.18 Combined Structural Features of the Manitouwadge Area.mxd



LEGEND

★ Township of Manitouwadge

Data Sources:
Seismic: NRCAN, Earthquake Map of Canada 1627-2012

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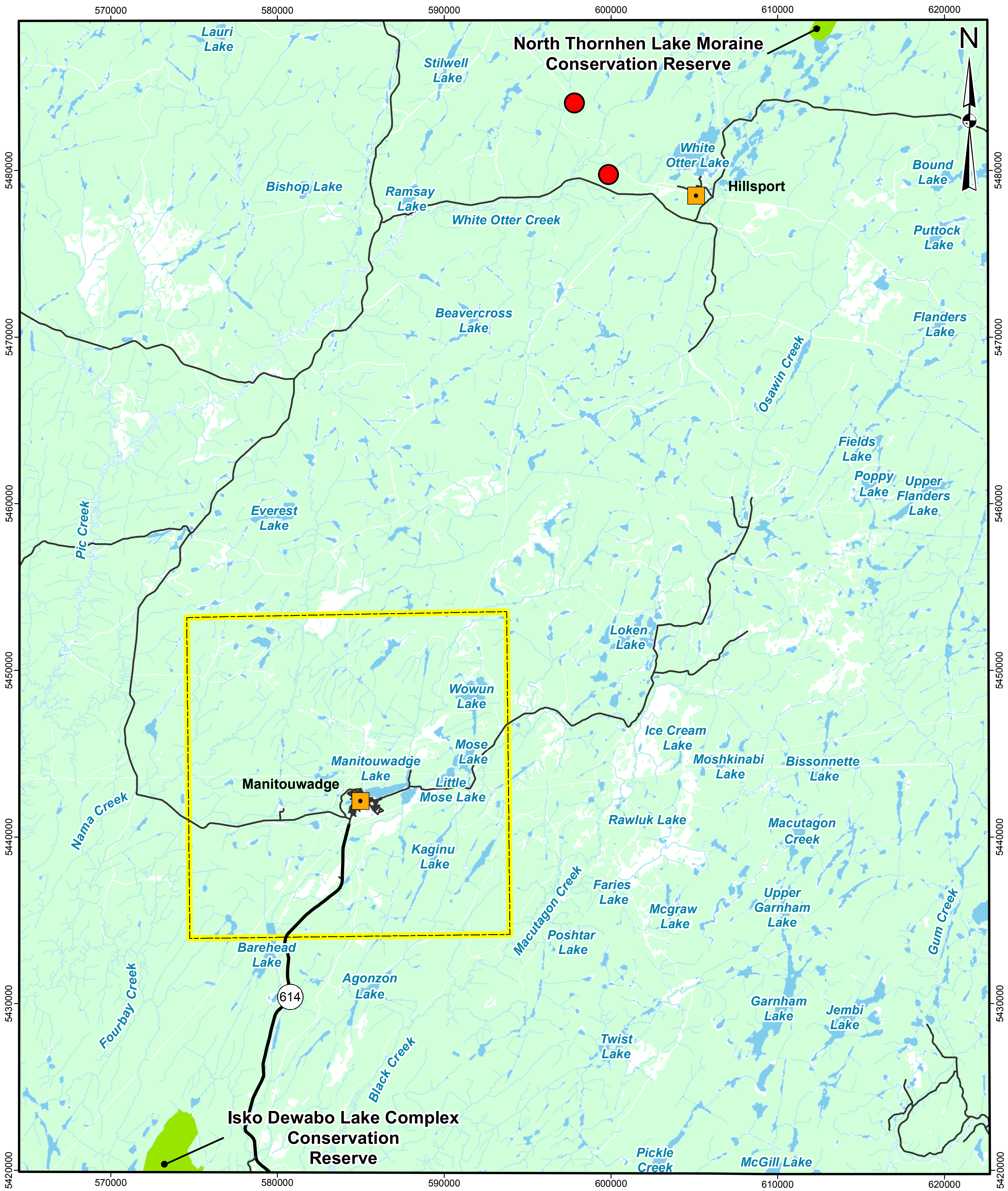
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Earthquakes Map of Canada 1627-2012

DESIGN	GHF	14 Aug 2012	**FIGURE 3.19**	REVISION 3
GIS	GHF	10 Sep 2013		Scale as Shown
CHECK	CB			
REVIEW	CB			

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.19 - Earthquake Map of Canada 1627-2012.mxd



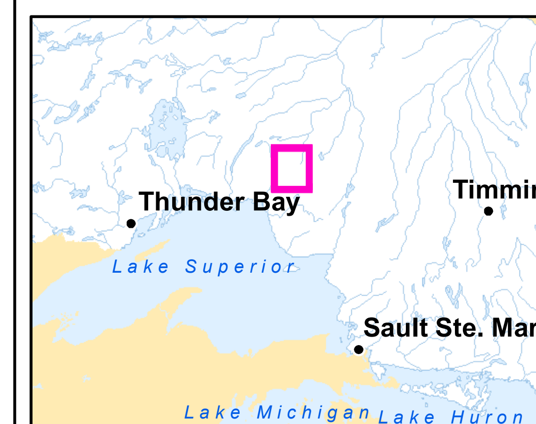
Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Waterbody
- Watercourse
- Wooded Area
- Conservation Reserve

Seismic Events (Magnitude)

- 2.1 - 3.0

*no events less than 2.0 and greater than 3 magnitude



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Earthquake: NRCAN Earthquake Database (accessed Aug 15, 2013)

10 km

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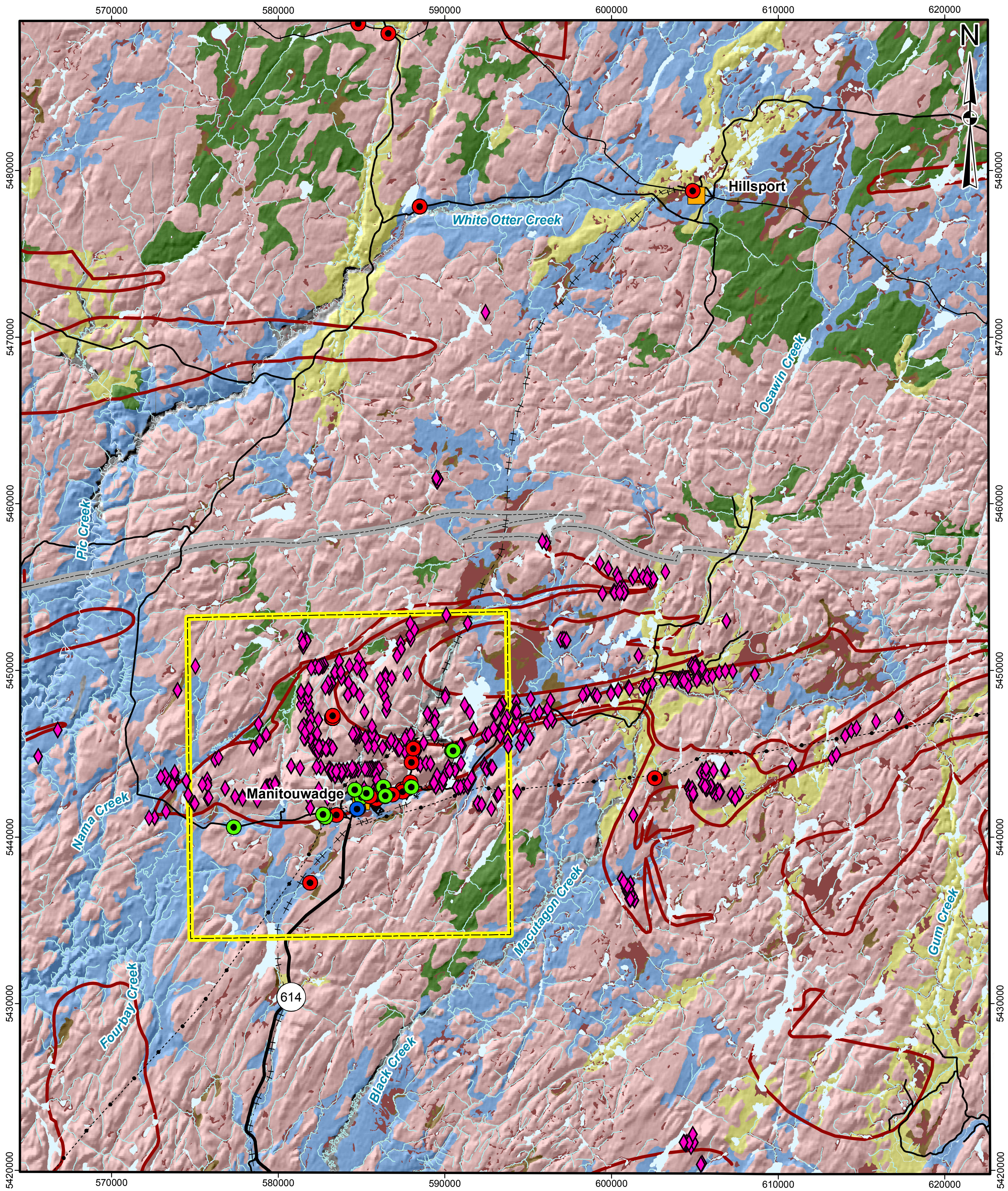
PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Historical Earthquake Records of the Manitouwadge Area 1985-2013

DESIGN	GF	21 AUG 2013	Figure 3.20	REVISION 1
GIS	GF	21 AUG 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 3.20 - Historical Earthquake Locations in the Region Surrounding Manitouwadge.mxd

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 4.1 Groundwater Well within the Manitouwadge Area.mxd



Legend

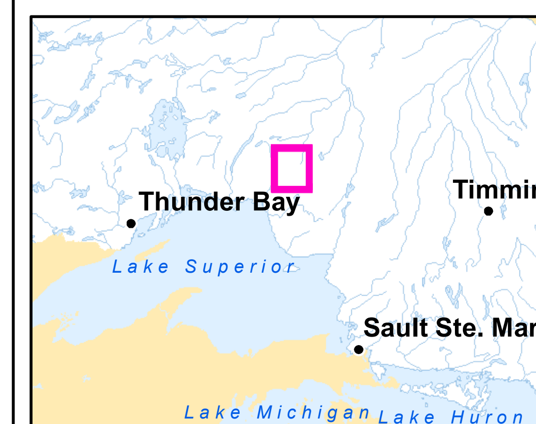
- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Hydro Line
- Wetlands
- Waterbody
- Watercourse
- Bedrock Geology Contact
- Quetico-Wawa Subprovince Boundary
- Diamond Drill Holes

Water Well (MOE)

- Reached Bedrock
- Ends in Overburden
- Monitoring Nest

Surficial Geology

- Morainal Terrain
- Glaciofluvial Terrain
- Glaciolacustrine Terrain
- Organic Terrain
- Bedrock Terrain



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Overburden: OGS MRD-160, NOEGTS 2006
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003
Water Well: MOE Water Well Information System
Diamond Drill Holes: Diamond Drill Hole Database, accessed September 2013
Underlay: Hillshade DEM, MNR Elevation and Slope

10 km

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Preliminary Assessment of Geoscientific Suitability
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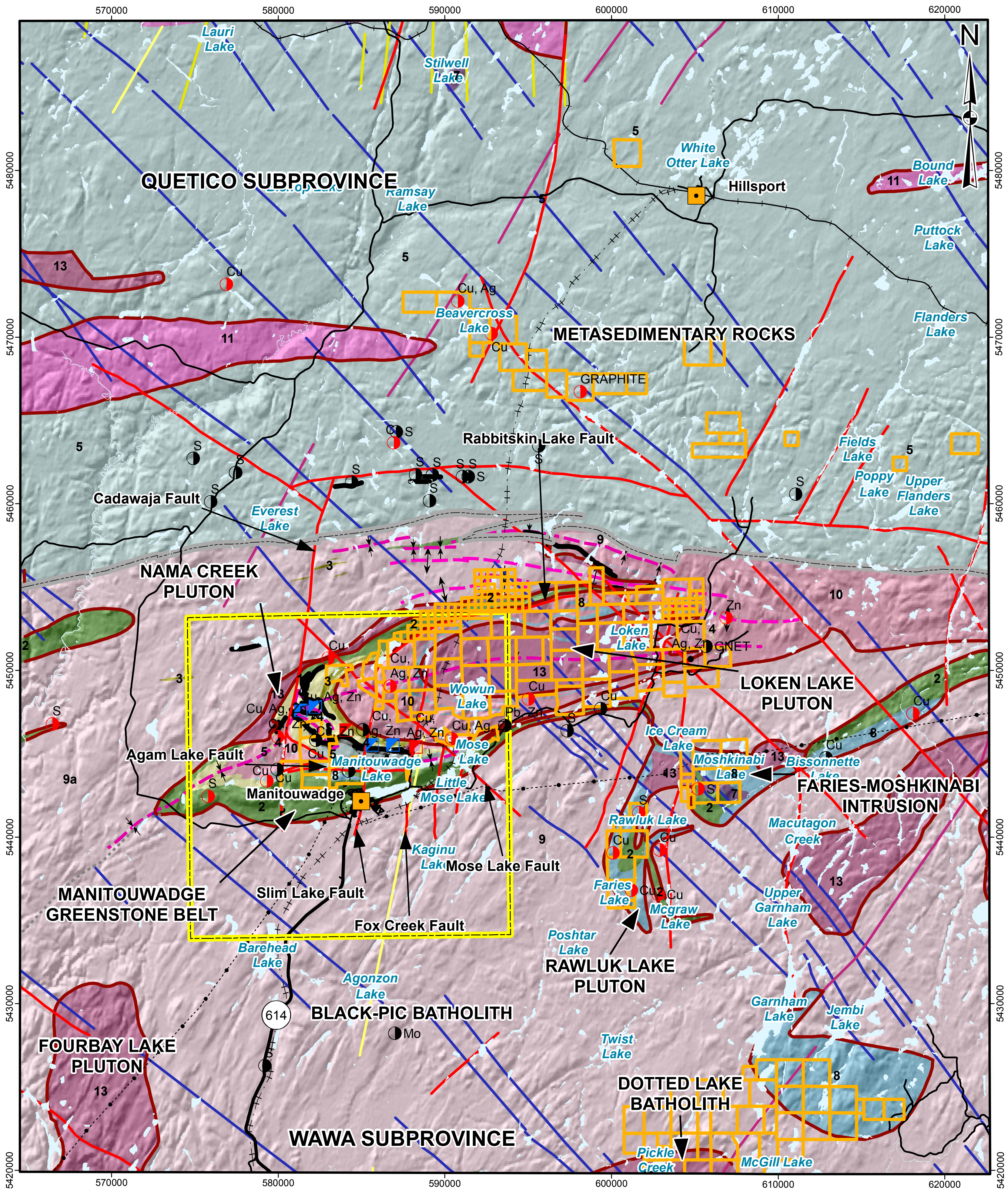
TITLE
Groundwater Wells and Exploration Drill Holes Within the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 4.1	REVISION 1
GIS	GF	06 SEP 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Hydro Line
- Waterbody
- Discretionary Occurrence
- Mineral Occurrence
- Past Producing Mine With Reserves
- Past Producing Mine Without Reserves
- Prospect
- Faults
- Syncline (Approximate)
- Anticline (Approximate)
- Iron Formation
- Mining Claims
- Bedrock Unit Subdivision
- Bedrock Geology Contact
- Quetico-Wawa Subprovince Boundary

Dykes

- Biscotasing mafic dyke
- Marathon mafic dyke
- Marathon, Kapuskasing or Biscotasing mafic dyke
- Matachewan mafic dyke

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
Active Mining Claims: MNDM, accessed July 15, 2013
Mineral Inventory: OGS MDI-2011
Underlay: Hillshade DEM, MNR Elevation and Slope

10 km

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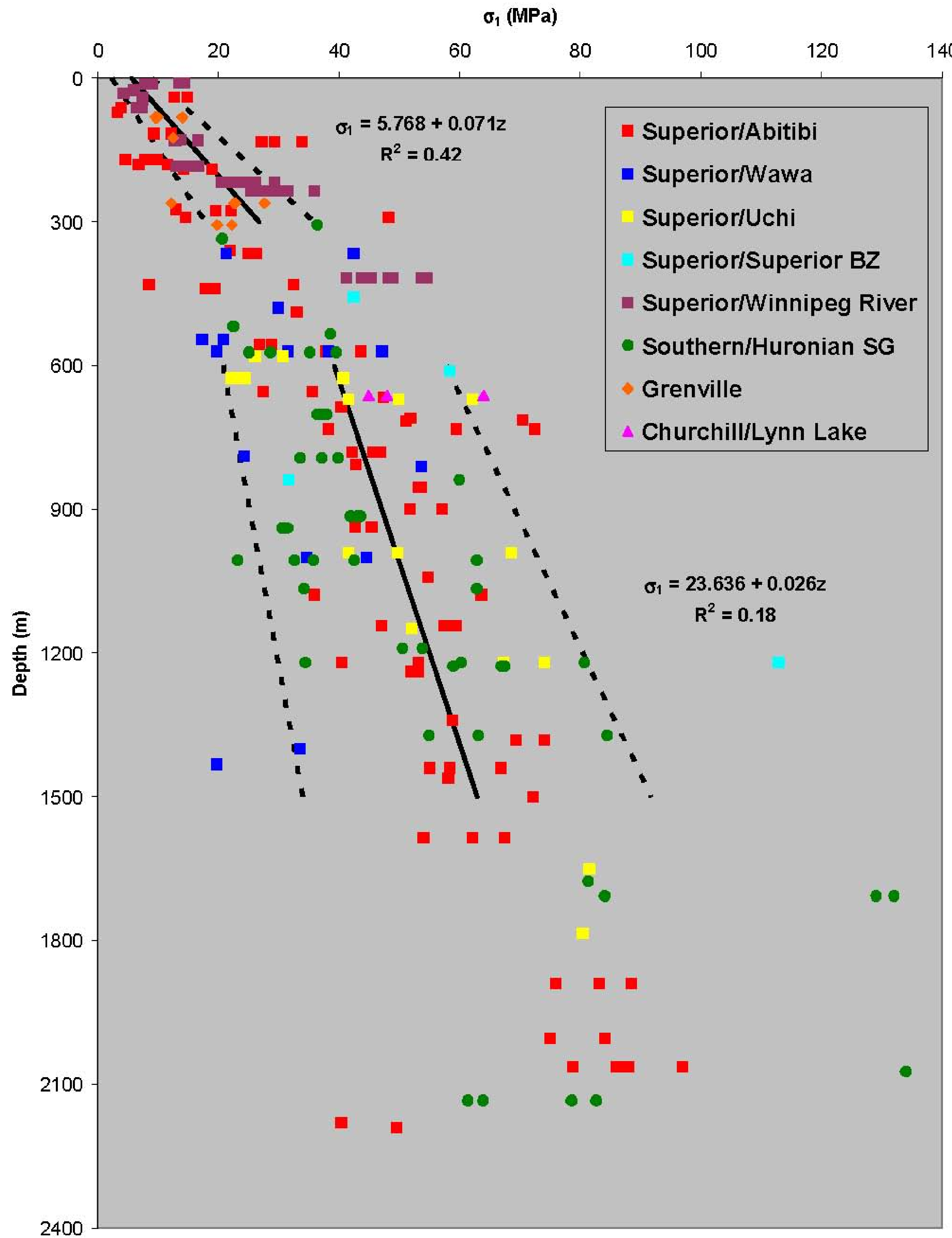
TITLE
Mineral Showings and Dispositions of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 5.1**	REVISION 1
GIS	GF	29 AUG 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 5.1 Mineral Showing and Dispositions of the Manitouwadge Area.mxd



Data Sources:
Maloney, Kaiser, and Vorauer, 2006

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Preliminary Assessment of Geoscientific Suitability
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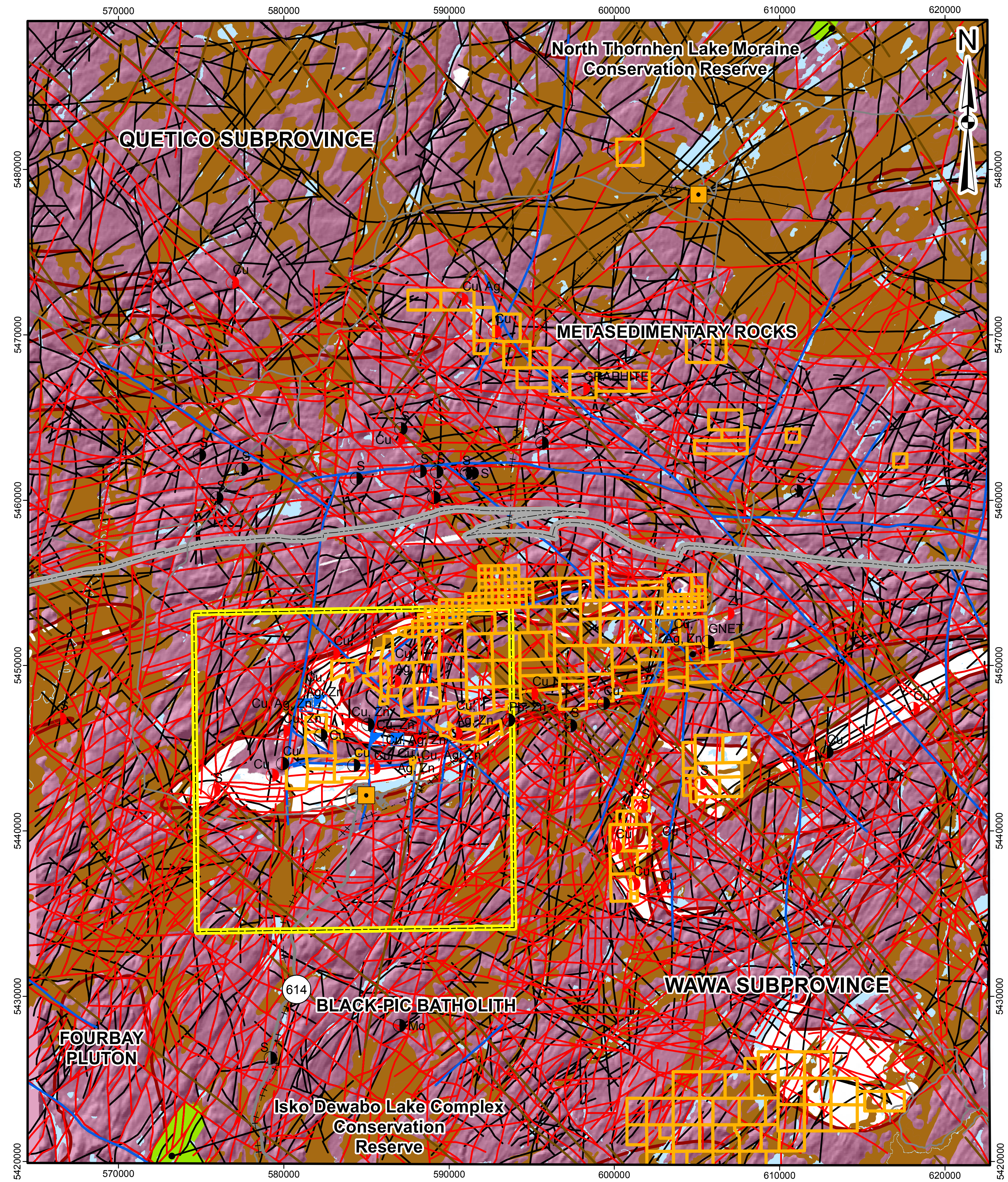
TITLE
Maximum Horizontal In Situ Stresses Typically Encountered in Crystalline Rock of the Canadian Shield

DESIGN	GHF	14 Aug 2012	**FIGURE 6.1**	UTM ZONE 16
GIS	GHF	17 Sep 2013		NAD 1983
CHECK	CB			
REVIEW	CB			



Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Waterbody
- Protected Areas
- Discretionary Occurrence
- Mineral Occurrence
- Past Producing Mine With Reserves
- Past Producing Mine Without Reserves
- Prospect
- Mining Claims
- Mapped Faults
- Mapped Dykes (MRD 126)
- Bedrock Geology Contact
- Overburden Cover
- Unfavourable Geology
- Favourable Geology (exposed or thinly covered)
- Quetico-Wawa Subprovince Boundary

Brittle Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke

Approximate Size of Repository Footprint

2 km
3 km

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
Overburden: OGS MRD-160, NOEGTS 2006
Active Mining Claims: MNDM, accessed July 15, 2013
Lineaments: SRK, 2014
Mineral Inventory: OGS MDI-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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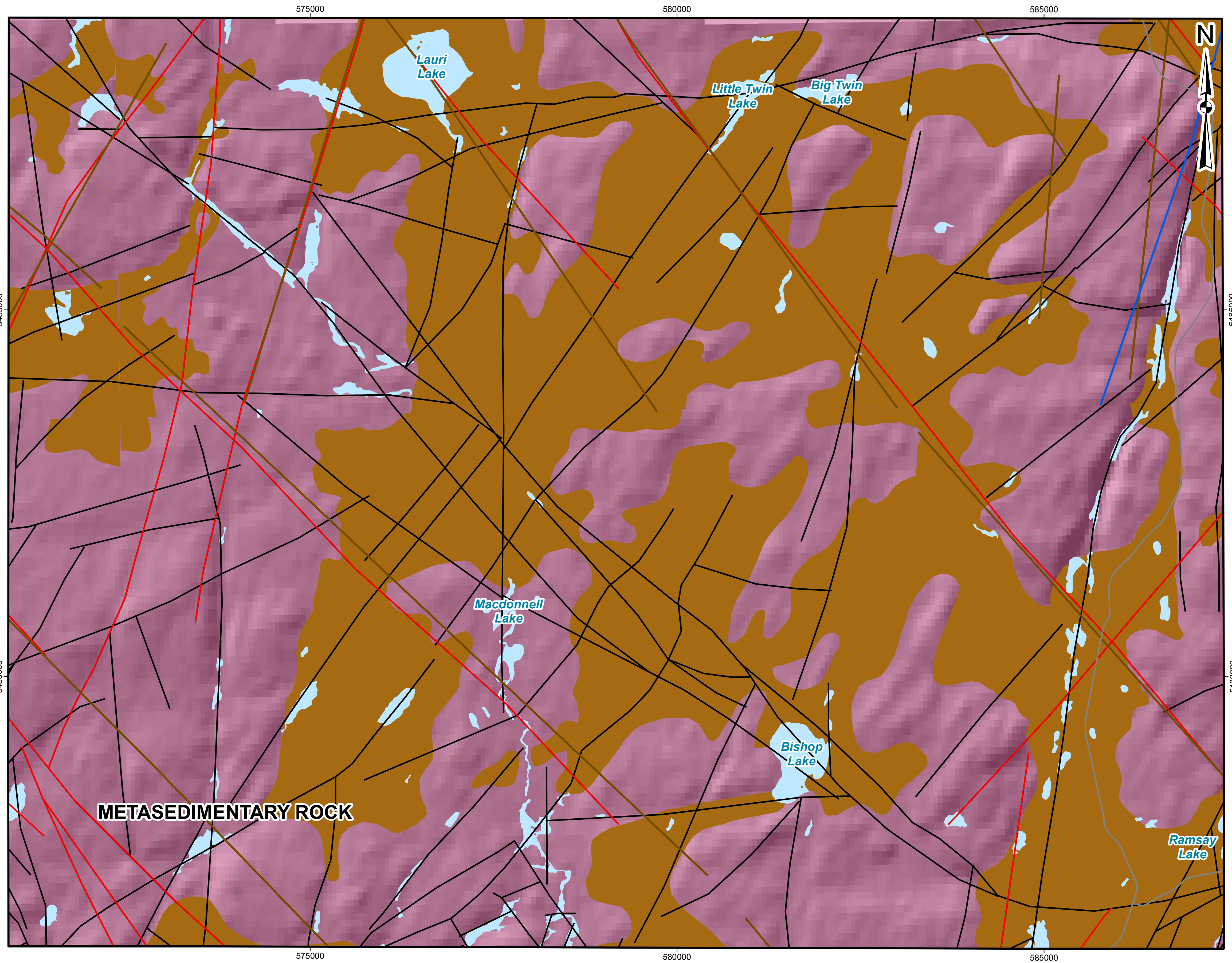
TITLE
Key Geoscientific Characteristics of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 7.1**	REVISION 1
GIS	GF	07 OCT 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:275,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 7.1 Key Geoscientific Characteristics of the Manitouwadge Area.mxd

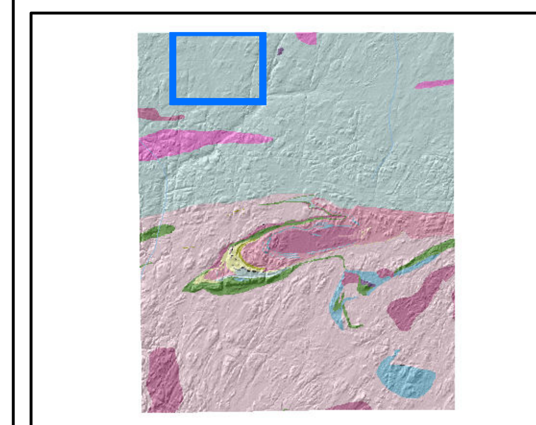


Legend

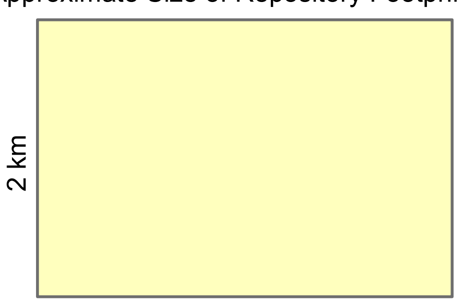
- Local Road
- Waterbody
- Mapped Faults
- Mapped Dykes (MRD 126)
- Overburden Cover
- Favourable Geology (exposed or thinly covered)

Brittle Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke



Approximate Size of Repository Footprint



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Bedrock Geology: OGS M2667, 2003; M2668, 2003 (1:250,000)
Faults: OGS MRD 126-REV1, 2011; M2668, 2003; GSC 1917A, 2001
Dykes: OGS MRD 126-REV1, 2011
Overburden: OGS MRD-160, NOEGTS 2006
Lineaments: SRK, 2014
Underlay: Hillshade DEM, MNR Elevation and Slope

2 km

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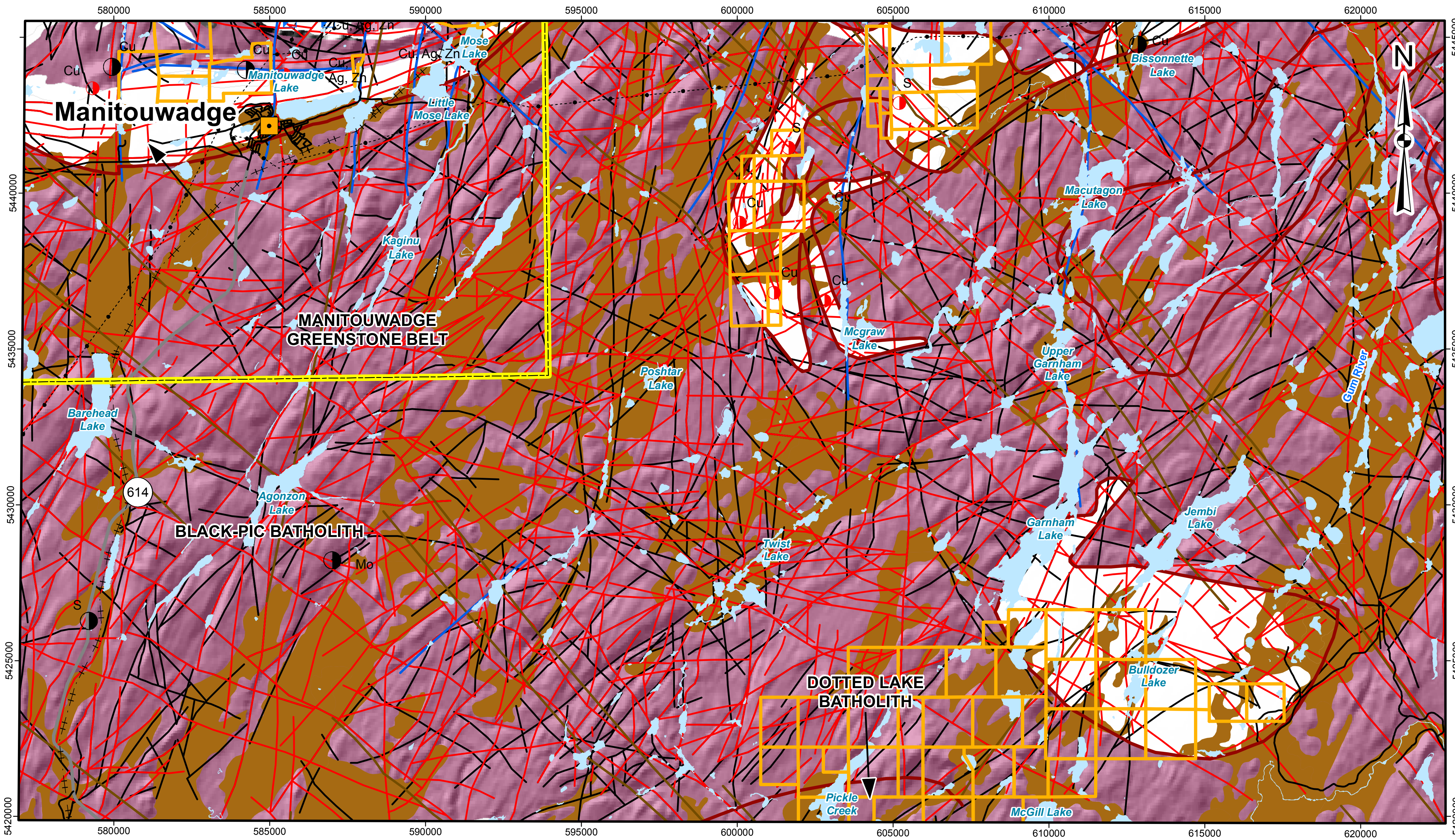
PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Key Geoscientific Characteristics of the Quetico Metasedimentary Rocks of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 7.2**	REVISION 1
GIS	KR	18 SEP 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:55,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 7.2 Potential Siting Area Quetico Metasedimentary Rocks.mxd

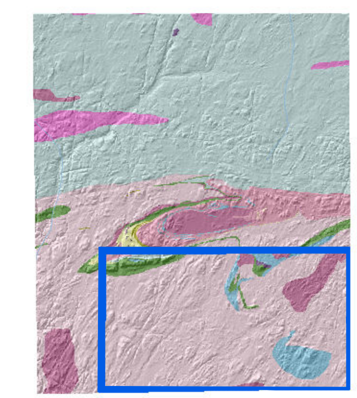


Legend

- Settlement
- Manitouwadge Municipal Boundary
- Main Road
- Local Road
- Abandoned Railway Right-of-way
- Waterbody
- Discretionary Occurrence
- Mineral Occurrence
- Past Producting Mine With Reserves
- Past Producting Mine Without Reserves
- Mining Claims
- Mapped Faults
- Mapped Dykes (MRD 126)
- Bedrock Geology Contact
- Overburden Cover
- Unfavourable Geology
- Favourable Geology (exposed or thinly covered)

Brittle Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke



Approximate Size of Repository Footprint

2 km × 3 km

Data Sources:
Base Data: MNR LIO, obtained 2009-2013
Bedrock Geology: OGS M2666, 2001; M2668, 2003 (1:250,000)
Faults: OGS MRD 126-REV1, 2011; M2668, 2003; GSC 1917A, 2001
Dykes: OGS MRD 126-REV1, 2011
Overburden: OGS MRD-160, NOEGTS 2006
Lineaments: SRK, 2014
Mineral Inventory: OGS MDI-2011
Active Mining Claims: MNDM, accessed July 15, 2013
Intrusions: Generalized from OGS M2666, 2001; M2668, 2003
Underlay: Hillshade DEM, MNR Elevation and Slope

2 km

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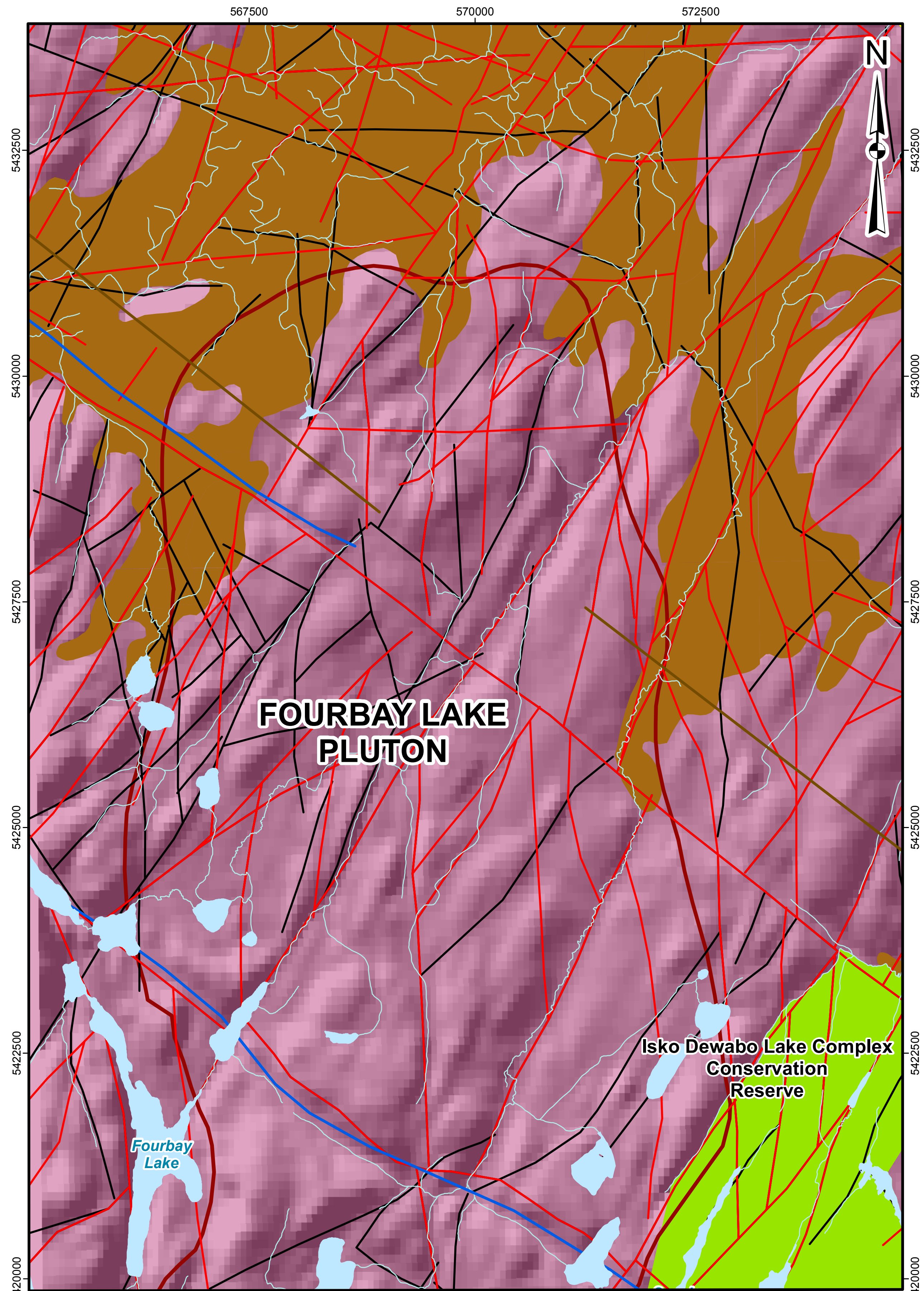
PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Key Geoscientific Characteristics of the Black-Pic Batholith in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 7.3	REVISION 1
GIS	KR	18 SEP 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:150,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 7.3 Siting Areas Black-Pic Batholith.mxd

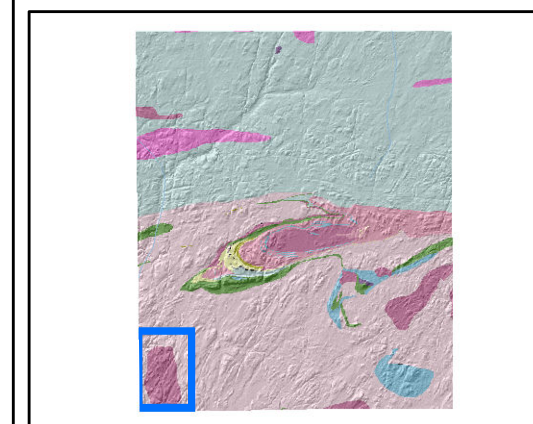


Legend

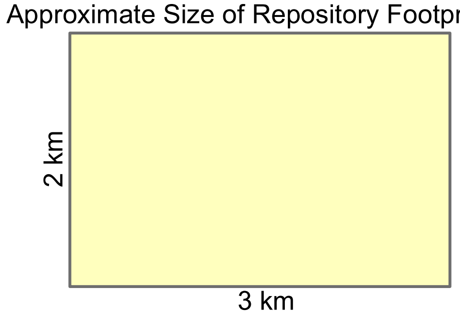
- Waterbody
- Watercourse
- Mapped Faults
- Mapped Dykes (MRD 126)
- Bedrock Geology Contact
- Protected Areas
- Overburden Cover
- Favourable Geology (exposed or thinly covered)

Brittle Lineaments

- Geophysical - Fracture and Dyke
- Surficial - Fracture and Dyke



Approximate Size of Repository Footprint



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
Overburden: OGS MRD-160, NOEGTS 2006
Lineaments: SRK, 2014
Intrusions: Generalized from OGS M2665, 2002; M2666, 2001; M2667, 2003; M2668, 2003
Underlay: Hillshade DEM, MNR Elevation and Slope

2 km

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PROJECT
Preliminary Assessment of Geoscientific Suitability
Phase 1 Desktop Study

TITLE
Key Geoscientific Characteristics of the Fourbay Lake Pluton in the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 7.4	REVISION 1
GIS	KR	18 SEP 2013		UTM ZONE 16
CHECK	xx			NAD 1983
REVIEW	xx			1:60,000

Path: P:\60297733\900-CAD-GIS\920 GIS-Graphics\Phase 1 Report\ReportMXDs\Manitouwadge\60297733_Fig 7.4 Potential Siting Area Fourbay Lake Pluton.mxd