NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation

TOWNSHIP OF MANITOUWADGE, ONTARIO

APM-REP-06144-0078

NOVEMBER 2014

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Phase 1 Geoscientific Desktop Preliminary Assessment

Lineament Interpretation

Township of Manitouwadge, Ontario

Report Prepared for:

AECOM Canada Ltd.

&

Nuclear Waste Management Organization
NWMO Report Number: APM-REP-06144-0078

Report Prepared by:

SRK Consulting (Canada) Inc.

SRK Project Number: 3CA041.001

October, 2014

Lineament Interpretation

Township of Manitouwadge, Ontario

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Executive Summary

In March, 2013, the Township of Manitouwadge in northwestern Ontario expressed interest in continuing to learn more about the Nuclear Waste Management Organization's (NWMO) nine-step site selection process, 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 a successful completion of an initial screening conducted during Step 2 of the site selection process.

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

This report presents the findings of a lineament investigation study completed as part of the desktop geoscientific preliminary assessment of the Manitouwadge area (AECOM 2014a). The lineament assessment focused on identifying surficial and geophysical lineaments and their attributes using publicly-available digital data sets, including geophysical (aeromagnetic with the support of electromagnetic) and surficial (satellite imagery, digital elevation) data sets for the Manitouwadge area in Northwestern Ontario. The assessment of interpreted lineaments in the context of identifying general areas that have the potentially to meet NWMO's geoscientific site evaluation factors is provided in the desktop preliminary geoscientific assessment report (AECOM 2014a). The lineament investigation interprets the location and orientation of potential bedrock structural features (e.g., individual fractures or fracture zones) within the context of the local and regional geological setting. The approach undertaken in this desktop lineament investigation is based on the following:

- Lineaments were interpreted from multiple, readily-available data sets (aeromagnetic, electromagnetic where available, CDED, Landsat and SPOT);
- Lineament interpretations were made by documented specialist observers and using a standardized workflow;
- Lineament interpretations were analyzed based on an evaluation of the quality and limitations of the available data sets;
- Interpreted lineaments were separated into three categories (ductile, brittle, dyke) based on their character;
- Lineament interpretations were analyzed using reproducibility tests, particularly the coincidence of lineaments extracted by different observers, coincidence of lineaments extracted from different data sets, relative ages and/or documentation in literature; and
- Final classification of the lineament interpretation was done based on length and reproducibility.

The distribution of lineaments in the Manitouwadge area reflects the bedrock structure, resolution of the data sets used, and surficial cover. Lineament density, as demonstrated in this study, is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures, and with the resolution of the interpreted data sets. Surface lineament density throughout the Manitouwadge area is fairly uniform, but does show local variation. The greatest density of lineaments occurs in areas underlain by the Manitouwadge greenstone belt. Other zones of high lineament density occur throughout the Manitouwadge area, and commonly correlate with high density clusters of dyke lineaments.

A total of 3336 brittle lineaments were interpreted in the Manitouwadge area. These lineaments exhibit four dominant orientations. North, northwest, and east-west trends are sharply defined, while a northeasterly trend exhibits a diffuse pattern. In addition, a total of 407 dyke lineaments were interpreted in the Manitouwadge area. Although the lineament density in the Manitouwadge area is generally high,

several areas with a relatively low density of lineaments were identified. These are restricted to select zones within the Black-Pic batholith, the Quetico Subprovince, and the Fourbay Lake pluton.

On the basis of the structural history of the Manitouwadge area, a framework was developed to constrain the relative age relationships of the interpreted lineaments.

Important Notice

AECOM Canada Ltd. (AECOM), on behalf of the Nuclear Waste Management Organization (NWMO), commissioned SRK Consulting (Canada) Inc. (SRK) to compile a structural lineament interpretation of remote sensing data for the Manitouwadge area in Ontario. The opinions expressed in this report have been based on the information supplied to SRK by AECOM and NWMO. These opinions are provided in response to a specific request from NWMO, and are subject to the contractual terms between SRK and AECOM. SRK has exercised all due care in reviewing the supplied information. Whilst SRK has compared key supplied data with expected values, the accuracy of the results and conclusions from the review are entirely reliant on the accuracy and completeness of the supplied data. SRK does not accept responsibility for any errors or omissions in the supplied information and does not accept any consequential liability arising from commercial decisions or actions resulting from them. Opinions presented in this report apply to the site conditions and features as they existed at the time of SRK's investigations, and those reasonably foreseeable. These opinions do not necessarily apply to conditions and features that may arise after the date of this report.

All title and beneficial ownership interests to all intellectual property, including copyright, of any form, including, without limitation, discoveries (patented or otherwise), software, data (hard copies and machine readable) or processes, conceived, designed, written, produced, developed or reduced to practice pertaining to this study shall vest in and remain with NWMO. For greater certainty, (a) ownership of all rights, title and interest, including intellectual property, in the work or deliverables are owned by NWMO and (b) ownership of all intellectual property created, developed or reduced to practice in the course of conducting this study and creating this report are exclusively owned by NWMO. SRK hereby grants NWMO a fully paid up irrevocable licence for all such intellectual property for its own non-commercial use.

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1 Introduction

In March, 2013, the Township of Manitouwadge expressed interest in continuing to learn more about the Nuclear Waste Management Organization's (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 a successful completion of an initial screening conducted during Step 2 of the site selection process.

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1.1 Scope of Work and Work Program

The scope of work includes the completion of a desktop structural lineament interpretation of remote sensing (AECOM 2014b) and geophysical (PGW 2014) data for the Manitouwadge area in northwestern Ontario (Figure 1).

The Manitouwadge area used for the interpretation is approximately 400 square kilometres (km^2) and was provided by NWMO as a shape file for a rectangular area (Figure 1).The southeast corner and eastern boundary of the study area are bounded by the northwest extent of the White River lineament interpretation area (AECOM 2014c) and the western boundary of the Hornepayne lineament interpretation area (Geofirma Engineering Ltd. 2013), respectively.

The lineament investigation interprets the location and orientation of possible individual faults or fracture zones and helps to evaluate their relative timing relationships within the context of the local and regional geological setting. For the purposes of this report, a lineament was defined as, 'an extensive linear or arcuate geologic or topographic feature'. The approach undertaken in this desktop lineament investigation is based on the following:

- Lineaments were mapped from multiple, readily-available data sets that include aeromagnetic geophysical survey data, satellite imagery (LandSAT; SPOT), and digital elevation models (Canadian Digital Elevation Data; CDED);

- Lineament interpretations from each source data type were made by two specialist observers for each data set using a standardized workflow;
- Lineaments were identified as brittle, dyke or ductile features by each observer;
- Lineaments were analyzed based on an evaluation of the quality and limitations of the available data sets;
- Lineaments were evaluated using: age relationships, reproducibility tests, particularly the coincidence of lineaments extracted by different observers, coincidence of lineaments extracted from different data sets, and comparison to literature; and
- Classification was applied to indicate the significance of lineaments based on length and reproducibility.

These elements address the issues of subjectivity and reproducibility normally associated with lineament investigations and their incorporation into the methodology increases the confidence in the resulting lineament interpretation.

At this desktop stage, the interpreted features were classified into three general categories based on a working knowledge of the structural history and bedrock geology of the Manitouwadge area. These categories include ductile, brittle and dyke lineaments, described as follows:

- **Ductile lineaments**: Features which were interpreted as being associated with the internal fabric of the rock units (including sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation) were classified as ductile lineaments. This category also includes recognizable penetrative shear zone fabric.
- **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**: Features which were interpreted, on the basis of their distinct character, e.g., scale and composition of fracture in-fill, orientation, geophysical signature and topographic expression, were classified as dykes. Dyke interpretation is largely made using the aeromagnetic data set, and is often combined with pre-existing knowledge of the bedrock geology of the area.

1.2 Qualifications of SRK and SRK Team

The SRK Group comprises of more than 1,400 professionals, offering expertise in a wide range of resource engineering disciplines. The independence of the SRK Group is ensured by the fact that it holds no equity in any project it investigates and that its ownership rests solely with its staff. These facts permit SRK to provide its clients with conflict-free and objective recommendations on crucial issues. SRK has a proven track record in undertaking independent assessments of mineral resources and mineral reserves, project evaluations and audits, technical reports and independent feasibility evaluations to bankable standards on behalf of exploration and mining companies, and financial institutions worldwide. Through its work with a large number of major international mining companies, the SRK Group has established a reputation for providing valuable consultancy services to the global mining industry.

The following is a brief description of the qualifications and roles of this assignment's team members.

Mr. Simon Craggs, MSc is a Senior Consultant (Structural Geology) with SRK who has a broad background in geoscience and specializes in regional mapping and detailed analysis of fracture/fluid flow mechanics and the structural controls on epithermal ore deposit formation. Mr. Craggs holds a bachelor's degree in Geological Science from the University of Leeds, UK, and a master's degree in Structural Geology from the University of New Brunswick, Canada. In this study, Mr. Craggs was the lead interpreter.

Dr. Julia Kramer Bernhard is a Senior Consultant (Structural Geology) with SRK who has more than 16 years of experience in regional- to deposit-scale field mapping and remote sensing data interpretation for the analysis of structurally controlled, polyphasely deformed mineralized deposits. Dr. Kramer Bernhard has conducted numerous regional and detailed-scale structural satellite image interpretations in Switzerland, South Africa, Kyrgyzstan, Peru, Chile, and China, on projects involving gold and PGE-copper-nickel deposits. Dr. Kramer Bernhard holds a PhD from the University of Basel, Switzerland, and an MSc from the University of Karlsruhe, Germany. In this study, Dr. Kramer was a second interpreter.

Mr. Carl Nagy, MSc is a Consultant (Structural Geology) with SRK who specializes in regional bedrock mapping and structural analysis in complex tectonic environments. He has recently completed a structural analysis of crustal-scale shear zones in the Himalaya and regional bedrock mapping of poly-deformed terranes in southwest USA and northern Canada. Mr. Nagy holds a bachelor's degree in Geological Sciences from McGill University, Canada, and a master's degree in Structural Geology from Queen's University, Canada. In this study, Mr. Nagy was also a second interpreter, and the primary author on the report.

Dr. James Siddorn, PGeo is a Practice Leader and Principal Consultant (Structural Geology) with SRK who has a broad background in geoscience. Dr. Siddorn specializes in building 4D deposit- to district-scale models to evaluate the structural controls on ore distribution, rock stability, and hydrogeology, and is highly proficient in computer based 2D/3D GIS and geological modelling. He has more than 18 years of experience in the consulting field, including the management of a number of high profile and multidisciplinary projects. He has managed and completed numerous studies involving the structural and geological interpretation of remote sensing data in Northern Ontario for mineral exploration and geotechnical/hydrogeological studies. Dr. Siddorn holds a bachelor's degree in Geology from the University of Durham, UK, a master's degree in Geology and a doctoral degree in Structural Geology from the University of Toronto. In this study, Dr. Siddorn supervised all work completed and reviewed drafts of this report prior to their delivery to AECOM and NWMO as per SRK internal quality management procedures.

Mr. Jason Adam is an Associate Consultant (GIS) who has a broad experience in GIS. Mr. Adam provided GIS support for the study, mainly for the preparation of figures, under the direction of Mr. Nagy.

1.3 Acknowledgements

SRK would like to thank Mr. Cam Baker and Mr. Bob Leech from AECOM and Mr. Stephen Reford from Paterson, Grant and Watson (PGW) for a fruitful collaboration on this project.

1.4 Report Organization

The report is organized into sections that describe the geological setting of the Manitouwadge area, the methodology used in identifying lineaments, the findings of the lineament interpretation, and a discussion of the results in the context of the local and regional geological framework.

Section 1 of this report includes an introduction and background for the completed structural lineament investigation.

Section 2 provides an overview of the geological setting of the Manitouwadge area and documents its structural history on the basis of available literature. A brief outline of the physical geography, Quaternary geology, and land use in the Manitouwadge area are also included in this section.

Section 3 documents the methodology applied for the lineament investigation for the Manitouwadge area. The source data used for the lineament interpretation are outlined and the interpretation workflow for the subsequent steps of the investigation is described.

Section 4 documents the findings of the lineament investigation in the Manitouwadge area. This includes a description of interpreted lineaments by data set and describes the classification of the integrated data set by major geological unit.

Section 5 discusses lineament length, density, and reproducibility, as well as their relative age relationships and fit with mapped features.

Section 6 is a brief summary of the main findings of this investigation.

2 Summary of Physical Geography and Geology

2.1 Physical Geography

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

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

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

The orientation of the drainage network within the study area is largely controlled by bedrock structural features (faults and lineaments) and the irregular topography of the terrain. Due to this control, the majority of waterways, including lakes, have, in order of dominance, a northeast, north, or northwest orientation. While the overall drainage in the Atlantic and Arctic watersheds are southwest and northeast, respectively, the catchment areas of individual lakes within the watersheds have stream segments with multiple flow directions (Figure 4).

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

The numerous lakes within the study area occupy approximately 4.6 percent (181.8 square kilometres) of the land surface and occur with an even distribution (Figure 4). In general, the lakes are of a modest size with the majority having a surface area of less than 1.0 square kilometre. 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.

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

The elevation difference within the Manitouwadge area is moderate with a maximum range of approximately 287 metres above sea level (masl; Figure 6). The highest point of land within the area, 482 masl, occurs approximately 5 kilometres west of the settlement area of Manitouwadge, and the lowest point (195 masl) is in the Nama Creek valley where it intersects the western project area boundary, approximately 21 kilometres southwest of the settlement area of Manitouwadge.

2.2 Bedrock Geology

The Manitouwadge area is within the Archean Wawa and Quetico subprovinces of the Superior Province which developed ca. 3.0 to 2.6 billion years ago (Ga) (Figures 2 and 3). The Wawa Subprovince is composed of well-defined greenstone belts of metamorphosed komatiite, basalt, dacite and rhyolite, and associated metasedimentary rocks, separated by granitoid plutons and batholiths. The metasedimentary rocks include turbiditic wacke, minor conglomerate and iron formation. Stratigraphic and structural relationships between these units of volcanic and sedimentary rocks are usually unclear and commonly masked by later shearing (Williams et al., 1991). The granitoids that separate the greenstone belts comprise 20 to 30 percent of the landmass and consist of massive, foliated and gneissic tonalite-granodiorite, which is cut by massive to foliated granodiorite and granite. The majority of the granitoids were intruded during or after the deposition of the greenstone belts with which they are associated (Williams et al., 1991).

The Quetico Subprovince, occurring in the northern portion of the area (Figures 2 and 3), 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).

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. 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 (Figures 2 and 3).

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 (Figures 2 and 3). 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 (e.g., Zaleski and Peterson, 2001; Johns and McIlraith, 2003) of the region surrounding Manitouwadge indicate a number of faults that range in length from a few kilometres to several tens of kilometres (Figures 2 and 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 (Figures 2 and 3). 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 greenstone belt and the Quetico Subprovince, and the folding of the latter together with the metavolcanic rocks argue for correlation of the sedimentary sequence across the subprovince boundary (Zaleski and Peterson, 2001). Williams et al. (1991) reported that the contact zone along the Wawa-Quetico Subprovince boundary in the Manitouwadge area contains foliated to gneissic intrusive sheets of tonalite-granodiorite that are highly strained.

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 produced a zone of highly sheared rocks that extends approximately 15 km 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 Mid-continent rifting event (Van Schmus, 1992). Additional fault movement may also have occurred as a result of Phanerozoic tectonism; however, no tectonic activity attributed to this event is evident in the area.

2.2.1 Metasedimentary Rocks of the Quetico Subprovince

Metasedimentary rocks of the Quetico Subprovince occupy the northern third of the Manitouwadge area and have a southern boundary approximately 6 kilometres north of the Township (Figure 3). These ca. 2.700 to 2.688 Ga clastic metasedimentary rocks have undergone various degrees of metamorphism (Percival, 1989; Zaleski et al., 1999). The Quetico Subprovince is understood to be an accretionary prism of an Archean volcanic island-arc system, which developed where the Wawa and Wabigoon belts form converging arcs (Percival and Williams, 1989). The timing of the Quetico-Wawa belt accretion has been constrained to between ca. 2.689 Ga and 2.684 Ga (Percival, 1989).

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

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

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

2.2.2 Granite – Granodiorite of the Quetico Subprovince

A number of largely east-west-trending granite-granodiorite intrusions have been mapped in the Quetico Subprovince in the Manitouwadge area (Figure 3). The largest of these, located approximately 15 km north of the Township of Manitouwadge, is described by Coates (1970b) as migmatitic, and consisting of biotite-quartz-feldspar gneisses and hornblende-biotite-quartz-feldspar gneisses; Percival (1989) in turn described it as pink biotite leucogranite. In general, granitic rocks in the Quetico Subprovince are typically medium- to coarse-grained and massive to rarely foliated (Percival, 1989). Information on the depth or age of the intrusions in the Manitouwadge area is not available.

2.2.3 Black-Pic Batholith

The Black-Pic batholith is a large, regionally-extensive intrusion that encompasses an area of approximately 3,000 km^2 and forms the bedrock for the majority of the southern half of the Manitouwadge area (Figure 3). 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 crosscutting 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 initial 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). 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), and another mapped, but unsubstantiated pluton toward the east of the Manitouwadge area (Figure 3). 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). Although depicted on a compilation map of the area (Johns and McIlraith, 2003), field geologic mapping of the area by Giguere (1972) could not confirm its existence.

2.2.4 Loken Lake Pluton

The Loken Lake pluton extends eastward from the northeastern portion of the Township of Manitouwadge and occupies the innermost area of the Manitouwadge synform (Figure 3). The surficial expression of the pluton, dated at ca. 2.687 Ga (Jackson et al., 1998), forms an ellipse approximately 16.5 kilometres across and 4 kilometres 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 kilometres (Roberts et al., 1997).

2.2.5 Foliated Tonalite Suite

A foliated tonalite intrusion that surrounds the Loken Lake pluton, between the arms of the Manitouwadge greenstone belt (Figure 3), 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 kilometres east-west and 6 kilometres 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 kilometres (Roberts et al., 1997).

2.2.6 Nama Creek Pluton

The Nama Creek pluton is located within the northwest quadrant of the Township of Manitouwadge (Figure 3). It is considered a distinct phase of the Black-Pic batholith and forms an approximately 33 kilometre long and typically less than 1 kilometre wide sinuous body along the contact with the Manitouwadge greenstone belt (Zaleski et al., 1999). It consists of foliated biotite-hornblende monzonite to monzodiorite, characterized by 1 to 5 cm K-feldspar phenocrysts. Compositionally, the Nama Creek pluton is similar to the Loken Lake pluton, albeit with a greater abundance of mafic minerals and less quartz. The pluton has been dated by Zaleski et al. (1999) at 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.

2.2.7 Fourbay Lake Pluton

The Fourbay Lake pluton is located in the southwest corner of the Manitouwadge area (Figure 3). The pluton is described by Milne (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 extend to greater than ca. 500 m depth 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.

2.2.8 Dotted Lake Batholith

The Dotted Lake batholith lies within the southeast corner of the Manitouwadge area (Figure 3). The surficial expression of the batholith is approximately 20 kilometres long and 15 kilometres 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.

2.2.9 The Manitouwadge Greenstone Belt

The Manitouwadge-Hornepayne greenstone belt (herein referred to as the Manitouwadge greenstone belt), together with the Faries-Moshkinabi intrusion (Williams and Breaks, 1990; 1996), is part of a semi-continuous supracrustal and mafic intrusive suite (Manitouwadge–Hornepayne assemblage, Williams et al., 1991) situated along the northern margin of the volcano-plutonic Wawa Subprovince (Figure 3).

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

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

2.2.10 Gabbroic Intrusion

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 kilometres to the east of the Township of Manitouwadge (Figure 3). 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 kilometre long and typically less than 2 kilometre thick elongate body. No data are available on the age of this intrusion.

The Faries-Moshkinabi intrusion is a layered pluton with a maximum thickness of 700 metres (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 kilometre by >6 kilometre north-south trending elliptical intrusion located east of the Township of Manitouwadge boundary and west of the Faries-Moshkinabi intrusion (Figure 3). 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 kilometre by 10 kilometre ellipsoid gabbroic intrusion in the southeast corner of the Manitouwadge area (Figure 3). The extent of the intrusion is defined by the boundary of a magnetic anomaly observed in an OGS shaded relief total magnetic survey (as seen in OGS Map 2666; Santaguida, 2001). No additional information on this pluton, including its depth, was documented in the reviewed literature.

2.2.11 Mafic Dykes

Several diabase dyke swarms crosscut the Manitouwadge area (Figure 3), 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 metres 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). This is a result of the combination of various datasets within the OGS database and does not reflect a geological boundary. The dykes vary in orientation from northwest to northeast, and occur as steep to subvertical sheets, typically a few metres to tens of metres thick, but occasionally up to 75

metres thick (Hamilton et al., 2002). The Marathon dykes comprise quartz diabase (Osmani, 1991) dominated by equigranular to subophitic clinopyroxene and plagioclase;

- Northeast-trending Biscotasing dykes (ca. 2.167 Ga; Hamilton et al., 2002). Locally, Marathon dykes also trend northeast and cannot be separated with confidence from the Biscotasing Suite dykes. On occasion, Biscotasing dykes appear to deflect at intersections with Matachewan-aged dykes; this is thought to be due to a rheological contrast between the Matachewan-aged dykes and the surrounding country rock.

2.2.12 Faults

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). 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 metres 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 metres (Miles, 1998). Miles (1998) noted that the southern limb to the east of the fault has significantly higher magnetic intensity and a more continuous anomaly pattern, and suggested that there may also be some vertical displacement along this fault. The northwest-trending faults are subparallel and adjacent to the similarly oriented Matachewan dykes. A complex history of brittle deformation is evidenced, in part, by offset of the Matachewan dykes by younger episodes of faulting (e.g., Miles, 1998).

Within the Quetico metasedimentary rocks a number of northeast-trending faults are indicated on the geological maps of the Manitouwadge area (Zaleski and Peterson, 2001; Johns and McIlraith, 2003; OGS, 2011). These faults are of modest length, ranging from approximately 5 to 20 kilometres (Figure 3).

2.2.13 Metamorphism

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

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

A widespread Paleoproterozoic tectonothermal event, the ca. 1.9 to 1.7 Ga Penokean Orogeny, involved volcanism, sedimentation, plutonism and deformation that affected the Churchill Province through northernmost Ontario, western Manitoba, northern Saskatchewan and Nunavut (e.g., Skulski et al., 2002; Berman et al., 2005). This event was associated with ca. 1.84 to 1.8 Ga collisional convergence of the Archean Hearne domain and Superior Province (Kraus and Menard, 1997; Menard and Gordon, 1997; Corrigan et al., 2007). Associated metamorphism at moderate to high temperatures and low to moderate pressures resulted in amphibolite facies metamorphism that overprinted Archean metamorphic signatures in Archean rocks of the Churchill Province, and a complex brittle overprint in Archean rocks of the Superior Province (e.g., Kamineni et al., 1990)

Along the eastern flank of the Canadian Shield, the Grenville Province records a complex history of episodic deformation and subgreenschist to amphibolite and granulite facies metamorphism, from ca. 1.300 Ga to 950 Ma (Easton, 2000b; Tollo et al., 2004 and references therein). Lower greenschist metamorphism was documented along faults in the vicinity of Lake Nipigon and Lake Superior and is inferred to be the result of ca. 1.0 Ga far-field reactivation during the Grenville Orogeny (Manson and Halls, 1994).

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

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

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

2.3 Structural History

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

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

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

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

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

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

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

Details of structural features associated with the D_5 and D_6 deformation events are limited in the literature to brittle and brittle-ductile faults of various scales and orientations (Lin, 2001; Muir, 2003). Within the Hemlo greenstone belt, Muir (2003) suggested that local D_5 and D_6 faults offset the Marathon and Biscotasing dyke swarms (all ca. 2.2 Ga), and as such, suggested that in the Hemlo region D_5 and D_6 faults propagated after 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-2.673 Ga timeframe that may include many periods of re-activation attributable to any of several post-Archean tectonic events, as summarized in Table 1.

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

Approximate Time period (years before present)	Geological Event
2.89 to 2.77 Ga	Progressive growth and early evolution of the Wawa-Abitibi terrane by collision, and ultimately accretion, of distinct geologic terranes
2.770 – 2.673 Ga	- ca. 2.720 Ga: Volcanism and subordinate sedimentation associated with the formation of the Manitouwadge greenstone belt - ca. <2.693: Deposition of sedimentary rocks in the Manitouwadge greenstone belt and the Quetico Subprovince - ca. 2.720-2.678 Ga: Inferred emplacement of granitoid intrusions in the Manitouwadge area. - Emplacement of the Pukaskwa and Black-Pic gneissic complexes at ca. 2.72 Ga - Emplacement of Loken Lake pluton (ca. 2.687 Ga), Nama Creek pluton (2.680 Ga), and Fourbay Lake pluton (ca. 2.678 Ga) - ca. 2.719 to 2.673 Ga: Four periods of ductile-brittle deformation (D_1-D_4) - D_1: ca. 2.719 – 2.691 Ga - D_2: ca. 2.691 – 2.683 Ga - D_3: ca. 2.682 – 2.679 Ga - D_4: ca. 2.679 – 2.673 Ga
2.675 to 2.669 Ga	Peak metamorphism of the Manitouwadge greenstone belt
2.666 to 2.650 Ga	Peak metamorphism of the Quetico Subprovince
2.5 to 2.100 Ga	- ca. 2.5 Ga: Supercontinent fragmentation and rifting in Lake Superior area. Development of the Southern Province - ca. 2.473 Ga: Emplacement of the Matachewan dyke swarm - ca. 2.167 Ga: Emplacement of Biscotasing dyke swarm - ca. 2.121 Ga: Emplacement of the Marathon dyke swarm
1.9 to 1.7 Ga	Penokean Orogeny in Lake Superior and Lake Huron areas; possible deposition and subsequent erosion in the Manitouwadge area
1.150 to 1.090 Ga	Rifting and formation of the Midcontinent Rift structure. - ca. 1.1 Ga
540 to 355 Ma	Possible coverage of the area by marine seas and deposition of carbonate and clastic rocks subsequently removed by erosion.
145 to 66 Ma	Possible deposition of marine and terrestrial sediments of Cretaceous age, subsequently removed by erosion
2.6 to 0.01 Ma	Periods of glaciation and deposition of glacial sediments

2.4 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 (30,000 to 10,000 years ago). The Quaternary (i.e., surficial) geology of the area has been mapped at a regional scale (>1:100,000) by several authors, including Boissonneau (1965), Zoltai (1965), Sado and Carswell (1987), and Barnett et al. (1991) and at a higher resolution (1:100,000) by Gartner (1979) and Gartner and McQuay (1980a, b, c). The area covered by the Manitouwadge, White Lake and Vein Lake NTS map sheets has been mapped at a scale of 1:50,000 by Kristjansson and Geddes (1986; 2009), (Geddes and Bajc, 1985; 2009) and Kettles and Way Nee (1998), respectively. Quaternary deposits and landforms in the area are thought to have formed during the latter stages of ice cover.

Kristjansson and Geddes (1986) reported that glacial striae in the Manitouwadge area indicate the last direction of glacial movement was toward the south-southwest with little deviation from a general orientation of 210° to 220°. Geddes and Bajc (1986) noted that in the southern portion of the area a weakly developed, presumed older, striation direction is recognized that reflects a more southerly direction of ice flow. For the large parts of the Manitouwadge area, drift thickness over bedrock is limited and the ground surface reflects the bedrock topography (Kristjansson and Geddes, 1985). Over the majority of the area, bedrock outcrops are common and the terrain is classified, for surficial purposes, as a bedrock-drift complex, i.e., thin drift cover that only locally achieves thicknesses that mask or subdue the bedrock topography (Figure 4). Valleys and lowland areas typically have extensive and thicker surficial deposits that frequently have a linear outline.

The remote sensing and terrain evaluation completed as part of the Phase 1 preliminary assessment (AECOM, 2014b) provides a more detailed assessment of the type, distribution and thickness of surficial deposits in the Manitouwadge area (Figure 4).

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 metres (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 area, and as such the ICSD feature trend south and southwest (Figure 4). 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 metres (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 4). Locally, the outwash plains are heavily kettled and pitted indicating the deposition of sediment over buried ice blocks. The thickness of the outwash deposits is likely to be variable, but may be substantial where they are proximal to ICSD features. Deposits are generally well-sorted and consist predominantly of stratified sand, with a low clast content; however, locally they are coarser grained and gravel-rich (Kristjansson and Geddes, 1986).

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

Glaciolacustrine sediments occur across the area, with extensive deposits occurring on the eastern and western sides of the Township of Manitouwadge and in the northeast quadrant of the area (Figure 4). The highest glacial lake level in the Manitouwadge area was approximately 340 metres (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 metres (Kettles and Way Nee, 1998).

Organic-rich alluvial deposits, consisting of sand, silt and clay, are present along water courses across the area (Figure 4). 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.

2.5 Land Use

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

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

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

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

3 Methodology

3.1 Source Data Descriptions

The lineament interpretation of the Manitouwadge area was based on publicly available remote sensing data sets, including airborne geophysical (aeromagnetic with the support of electromagnetic), topographic (CDED elevation models), and satellite imagery data (SPOT and Landsat).

Available data were assessed for quality, processed, and reviewed before use in the lineament interpretation (PGW, 2014). The geophysical data were used to evaluate deeper bedrock structures and proved invaluable to identifying potential bedrock structures beneath areas of surficial cover and aiding in establishing the age relationships among the different lineament sets. Topography (CDED) and satellite imagery (SPOT and Landsat) data sets were used to identify surficial lineaments expressed in the topography, drainage, and vegetation. Comparing surficial lineaments to aeromagnetic lineaments allows for the comparison of subsurface and surficial expressions of the bedrock structure. Throughout this study, the best resolution data available was used for the lineament interpretation.

During the data review process it was noted that three seismic profiles were available for the study area. The seismic data were acquired by the Geological Survey of Canada in collaboration with Noranda Inc. in 1995, and were documented by Roberts et al. (2003). The three seismic profiles were acquired
across the Manitouwadge synform, with two lines providing north-south profiles, sub-perpendicular to the axial trace of the synform, and one line providing an east-west profile, sub-parallel to the axial trace of the synform. One of the north-south profiles extended north in to the Quetico Subprovince. The seismic profiles are of low resolution, and are therefore of limited use to the lineament interpretation. In addition, brittle faults identified in the study area are typically strike slip faults (e.g. Peterson and Zaleski 1999, and Miles 1998), and as such are likely to be steeply dipping structures that produce weak reflection coefficients. As a result of the above factors, the seismic data was not used in the lineament interpretation.

Table 2 provides a summary of the source data sets, including their resolution, coverage, and acquisition dates that were used for the lineament interpretation. The geophysical surveys listed were acquired from variably oriented survey flight lines (details available in PGW 2014).

The lineament interpretation was built in two-dimensions in ArcGIS™ in UTM NAD83, Zone 16 North. Each data set used in the interpretation required manipulation in ErMapper™, including creating ErMapper (.ecw) compressed raster images as end products for each data set prior to import into ArcGIS.

Table 2: Source Data Information for the Lineament Interpretation, Manitouwadge Area

Data Set	Product	Source	Resolution	Coverage	Acquired
Geophysics	Single master gravity and aeromagnetic data for Ontario (SMGA; GDS 1036)	Ontario Geological Survey	805 m line spacing; Sensor height 305 m	Entire study area	1959 (reprocessed in 1999)
	Ontario airborne geophysical surveys, magnetic and electromagnetic data (GDS1205)	Ontario Geological Survey	150 and 200 m line spacing; Sensor height 45 m	All but northern portion of study area	1989 (published in 2002)
	Dighem #1056 (Areas A and G)	Geological Survey of Canada	150 m line spacing; Sensor height 45 m	West central portion of study area	1988
	GDS 1207-REV Hemlo	Ontario Geological Survey	100 m line spacing; Sensor height 55 m	Southern edge of study area	1983 (published in 2002)
	Coldwell, Hemlo, Schreiber*	Geological Survey of Canada	1000 m line spacing; Sensor height 121 m	Southwest part study area	1990
DEM	Canadian Digital Elevation Data (CDED); 1:50,000 scale	Geobase	8-23 m (0.75 to 3 arc seconds) depending on latitude	Entire study area	1995 (published in 2003)
Satellite Imagery	SPOT 4/5; Orthoimage, multispectral/ panchromatic	Geobase	10 m (panchromatic) 20 m (multispectral)	Entire study area	2005-2010
	Landsat 7 orthorectified imagery	Geobase	30 m (multispectral)	Entire study area	2001

* Not used in final mosaic of aeromagnetic data due to low resolution.

3.1.1 Geophysical Data

Paterson Grant & Watson (PGW) identified and evaluated all available geophysical data sets for the area of Manitouwadge (PGW, 2014). This evaluation highlighted the presence of the high-resolution geophysical data set GDS1205, which compiled 13 separate data sets into one high resolution data set covering approximately 75 percent of the study area. The remaining approximately 25 percent of the study area is located in the northern extent of the study area and is covered by the lower-resolution single master gravity and aeromagnetic data for Ontario (SMGA - GDS1036).

For the lineament investigation, gridded data for total magnetic field and several filters including first vertical derivative and tilt filters, both reduced to the pole (RTP) were used (PGW 2014). From these gridded data, a series of compressed raster images was created for the total magnetic intensity (RTP), first vertical derivative (RTP), and tilt derivative (RTP), including colour-draped and shaded images. Figure 5 shows the first vertical derivative of combined aeromagnetic data for the area of Manitouwadge.

For the majority of the study area, gridded aeromagnetic data was derived from the high-resolution GDS1205 data set. Additional high resolution aeromagnetic coverage was provided by the Dighem #1056 (areas A and G) survey in the central-west portion of the study area, and the OGS/GSC GDS 1207-REV survey along the central-southern boundary of the study area. For the northern portion of the study area not covered by the high-resolution data, gridded aeromagnetic data was derived from the single master gravity and aeromagnetic data for Ontario survey (GDS1036). The Coldwell,

Hemlo, Schreiber survey provided coarse resolution aeromagnetic data, and was not used in producing the final aeromagnetic mosaic. Source data information for all data sets is included in Table 2.
A frequency domain electromagnetic survey was also collected from the high resolution GDS1205 survey. PGW provided grids and raster images for three different frequencies (900 Hz, 7200 Hz, or 56000 Hz) for the electromagnetic data. The extent of the high resolution survey from which the electromagnetic data was collected covered approximately 75 percent of the study area. No electromagnetic data was available for the remaining area. As a consequence of a lack of coverage, electromagnetic data was only used in support of the aeromagnetic data, and was not interpreted as a separate data set.

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 metre line spacing; 30-metre grid cells) and covers approximately 75 percent of the Manitouwadge area (Figure 5). The majority of the remainder of the study area is covered by the lower resolution SMGA (GDS1036) data set (805-metre line spacing; 200-metre 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.

A summary of survey acquisition parameters for the geophysical surveys used during the lineament study is provided in Table 3.

Table 3: Geophysical Survey Acquisition Parameters for the Lineament Interpretation

Survey	Flight Line Spacing (m)	Grid Cell Size (m)	Sensor Height (m)	Flight Line Azimuth (0-359°)
Single master gravity and aeromagnetic data for Ontario (SMGA; GDS1036)	805	200	305	0°
Ontario airborne geophysical surveys, magnetic and electromagnetic data, Manitouwadge area (GDS1205)	150-200	30	45	Various orientations (north to northwest)
Dighem #1056 (Areas A and G)	150	35	45	173°/155°
GDS 1207-REV Hemlo	100	25	55	0°
Coldwell, Hemlo, Schreiber*	1000	200	121	0°

* Not used in final mosaic of aeromagnetic data due to low resolution.

3.1.2 Surficial Data

Canadian Digital Elevation Data (CDED)

CDED served as an important data source for analyzing and interpreting lineaments in the Manitouwadge area. The digital elevation model (DEM) used for this study was constructed by the Ontario Ministry of Natural Resources (MNR). The source data were acquired through the Ontario Base Mapping program, which was a major photometric program conducted across Ontario between 1978 and 1995. Four main data sets were used: contours, spot heights, stream networks, and lake elevations derived using spot heights and water features. CDED data sets are provided in geographic coordinates, referenced horizontally using North American Datum 1983 (NAD83) and vertically based on the Canadian Geodetic Vertical Datum 1928 (CGVD28). Ground elevations are recorded in metres relative to mean sea level. It was determined that the resolution of the DEM data set was sufficient to undertake the lineament interpretation.

The CDED topography data for the Manitouwadge area, including a reasonable buffer zone (greater than 15 kilometres) extending in all directions outside the study area, is available in 24 USGS DEM format individual tiles, each tile covering approximately 1200 square kilometres. A summary of the CDED tiles used in the lineament interpretation is provided in Table 4.

These files are accurate to within five metres and a resolution of 0.75 arc seconds (Table 4), which is equivalent to approximately 16 to 23 metres in the Manitouwadge area. The 24 individual tiles were merged, levelled, and a colour mosaic, shaded digital elevation model was created in ErMapper and saved as a compressed raster image. The DEM for the Manitouwadge area is shown in Figure 6.

Table 4: 1:50,000 scale CDED Tiles Used for Lineament Interpretation

Identifier	NTS Tiles	East/West Coverage	Ground Resolution (arc sec.)
042c13_0100_deme	042c/ 13	East	0.75
042c13_0100_demw	042c/ 13	West	0.75
042c14_0100_deme	042c/ 14	East	0.75
042c14_0100_demw	042c/ 14	West	0.75
042d16_0100_deme	042d/ 16	East	0.75
042d16_0100_demw	042d/ 16	West	0.75
042e01_0100_deme	042e/ 01	East	0.75
042e01_0100_demw	042e/ 01	West	0.75
042e08_0100_deme	042e/ 08	East	0.75
042e08_0100_demw	042e/ 08	West	0.75
042e09_0100_deme	042e/ 09	East	0.75
042e09_0100_demw	042e/ 09	West	0.75
042f03_0100_deme	042f/ 03	East	0.75
042f03_0100_demw	042f/ 03	West	0.75
042f04_0100_deme	042f/ 04	East	0.75
042f04_0100_demw	042f/ 04	West	0.75
042f05_0100_deme	042f/ 05	East	0.75
042f05_0100_demw	042f/ 05	West	0.75
042f06_0100_deme	042f/ 06	East	0.75
042f06_0100_demw	042f/ 06	West	0.75
042f11_0100_deme	042f/ 11	East	0.75
042f11_0100_demw	042f/ 11	West	0.75
042f12_0100_deme	042f/ 12	East	0.75
042f12_0100_demw	042f/ 12	West	0.75

Systeme Pour l'Observation de la Terre (SPOT) and Landsat Imagery

SPOT multispectral and panchromatic orthoimagery was used for identifying surficial lineaments and exposed bedrock within the Manitouwadge area. SPOT multispectral data consist of several bands, each band recording the reflected radiation within a particular spectral range, displayed with a radiometry of 8-bits (or a value ranging from 0 to 255). SPOT 4 and 5 images were acquired using a high resolution geometric (HRG) sensor. Each image covers an area of approximately 8,500 square kilometres.

For quality control, Natural Resources Canada (NRCan) provides images that have a maximum of 5 percent snow and ice cover, 5 percent cloud cover and a maximum viewing angle of 15 degrees. NRCan orthorectified the SPOT images using three data sources: 1:50,000 scale Canadian Digital Elevation Data (CDED), National Road Network (NRN), and Landsat 7 orthoimagery. The orthoimages are provided in GeoTIFF format and projected using Universal Transverse Mercator (UTM) projection referenced to the North American Datum 1983 (NAD83).

The SPOT 4/5 Geobase OrthoImage for the Manitouwadge area, including a reasonable buffer zone (minimum 7 kilometres, typically greater than 15 kilometres) extending in all directions outside the study area, is available as six tiles (Table 5). Each tile contains five Geotiff images representing spectral bands B1, B2, B3, MIR, and a panchromatic band. A natural colour image was created for this tile in ErMapper and saved as a compressed raster image.

Table 5: SPOT Imagery Scenes Used for the Lineament Interpretation

Scene ID	Satellite	Date of Image
s4_08622_4925_20080909_m20_utm16	SPOT 4	5-December-2008
s5_08456_4925_20060911_m20_utm16	SPOT 5	17-March-2008
s5_08509_4857_20060911_m20_utm16	SPOT 5	16-September-2008
s5_08539_4925_20070503_m20_utm16	SPOT 5	18-December-2007
s5_08551_4857_20060901_m20_utm16	SPOT 5	23-March-2007
s5_08632_4857_20080813_m20_utm16	SPOT 5	15-January-2009

The Landsat 7 orthorectified image for the Manitouwadge area, including a reasonable buffer zone extending in all directions outside the study area (minimum 4 kilometres, typically greater than 15 kilometres), is available as one individual tile from the Canadian Council of Geomatics (http://www.geobase.ca; Table 6). The tile contains ten Geotiff images representing spectral bands 1 through 8 (two versions of band 6) and a multispectral image with bands 7, 4, and 3 combined. The individual tile covers an area of approximately 75,000 square kilometres. A natural colour image (Landsat bands 3, 2 and 1), false colour image (Landsat bands 4, 3 and 2) and image combining Landsat bands 7,4 and 1 were created for this tile in ErMapper and saved as compressed raster images. The Landsat 7-4-1 multispectral image was used as the main reference for the lineament interpretation from satellite imagery (Figure 7). Different materials reflect and absorb solar radiation differently at different wavelengths and therefore have varying intensities within each of the Landsat bands. When bands 7, 4 and 1 are combined into a single image, the colour assignment enhances the presence of major geological units and topographical features.

Table 6: Landsat 7 Imagery Scenes Used for the Lineament Interpretation

Scene ID	Date of Image
023026_0100_001010_l7	6-November-2001

The SPOT satellite, Landsat satellite, and CDED topography data cover the entire Manitouwadge area with a good resolution (e.g., SPOT, 20-metre resolution). However, the bedrock structural information available from these three data sets is limited in in various sectors of the study area due to Quaternary cover (Figure 4). The sectors of the study area where bedrock structures are concealed by Quaternary cover include the northernmost quarter of the study area and an approximately 10 kilometres wide linear zone trending northeast in the central south sector of the study area (Figure 4). The total area of Quaternary cover where the satellite (SPOT and Landsat) and CDED topography data were of limited use is approximately 200 square kilometres or 5 percent of the Manitouwadge area (Figure 4). In addition, the majority of the area affected by Quaternary cover (i.e., the northern extent of the study 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.

3.2 Lineament Interpretation Workflow

Lineaments were interpreted using a workflow designed to address issues of subjectivity and reproducibility that are inherent to any lineament interpretation. The workflow follows a set of detailed guidelines using the publicly available surficial (DEM, SPOT) and geophysical (aeromagnetic and electromagnetic) data sets described above. The interpretation guidelines involved three steps:

- Step 1: Independent lineament interpretation by individual interpreters for each data set and assignment of certainty level (1, 2, or 3);
- Step 2: Integration of lineament interpretations for each individual data set and determination of reproducibility and first determination of reproducibility (RA_1; Figure 9,10, and 11); and
- Step 3: Integration of lineament interpretations for all data sets and determination of coincidence (RA_2; Figure 12).

Each identified lineament feature was classified in an attribute table in ArcGIS. The description of the attribute fields used is included in Table 7. Fields 1 to 9 are populated during Step 1. Fields 10 and 11 are populated during Step 2. Fields 12 to 19 are populated during Step 3, the final step. In addition, ductile geophysical lineaments (Figure 8) were interpreted using the aeromagnetic geophysical survey data by two specialist observers.

A detailed description of the three workflow steps is provided below. This includes the methodology for populating the associated attribute field for an interpreted lineament.

Table 7: Attribute Table Fields Populated for the Lineament Interpretation

ID	Attribute	Brief Description
1	Rev_ID	Reviewer initials
2	Feat_ID	Feature identifier
3	Data_typ	Data set used (MAG, CDED, SAT)
4	Feat_typ	**Type of feature used to identify each lineament** **Satellite Imagery:** A. Lineaments drawn along straight or curved lake shorelines; B. Lineaments drawn along straight or curved changes in intensity or texture (i.e., vegetation); C. Lineaments drawn down centre of thin rivers or streams; D. Lineaments drawn along a linear chain of lakes; or E. Other (if other, define in comments). **Digital Elevation Model:** A. Lineaments drawn along straight or curved topographic valleys; B. Lineaments drawn along straight or curved slope walls; or C. Other (if other, define in comments). **Airborne Geophysics (magnetic and electromagnetic data):** A. Lineaments drawn along straight or curved magnetic high; B. Lineaments drawn along straight or curved magnetic low; C. Lineaments drawn along straight or curved steep gradient; or D. Other (if other, define in comments).
5	Name	Name of feature (if known), includes names of dyke swarms
6	Certain	Value describing the interpreters confidence in the feature being related to bedrock structure (1-low, 2-medium or 3-high)
7	Length*	Length of feature is the sum of individual lengths of mapped polylines (not end to end) and is expressed in kilometres
8	Width**	**Width of feature. This assessment is categorized into 5 bin classes:** A. < 100 m B. 100 – 250 m C. 250 – 500 m D. 500 – 1,000 m E. > 1,000 m
9	Azimuth	Lineament orientation expressed as degree rotation between 0 and 180 degrees
10	Buffer_RA_1	Buffer zone width for first reproducibility assessment
11	RA_1	Feature value (1 or 2) based on first reproducibility assessment
12	Buffer_RA_2	Buffer zone width for second reproducibility assessment
13	RA_2	Feature value (1, 2 or 3) based on second reproducibility assessment (i.e., coincidence)
14	Geoph	Feature identified in geophysical data set (Yes or No)
15	DEM	Feature identified in topography data set (Yes or No)
16	SAT	Feature identified in satellite data set (Yes or No)
17	F_Width	Final interpretation of the width of feature
18	Rel_age	Relative age of feature, in accord with regional structural history
19	Comment	Comment field for additional relevant information on a feature
20	Unique_ID	Unique identification code for each lineament, written as: “data set (CDED, MAG, SAT) - initials of interpreter (CN, JK, SC) - lineament type (F for fault, and D for dyke) – Feature_ID (1, 2, 3 …)” For example, “MAG-SC-F-124” corresponds to the lineament number 124 interpreted from the magnetic data set by Simon Craggs as a fault

*The length of each interpreted feature is calculated based on the sum of all segment lengths that make up that lineament.

**The width of each interpreted feature is determined by expert judgment and utilization of a GIS-based measurement tool. Width determination takes into account the nature of the feature as assigned in the Feature type (Feat_typ) attribute.

3.2.1 Step 1: Lineament Interpretation and Certainty Level

To accommodate the generation of the best possible, unbiased lineament interpretation, two individual interpreters followed an identical process for structural lineament analysis during Step 1. The first step of the lineament interpretation was to have each individual interpreter independently produce GIS lineament maps, and detailed attribute tables, for each of the three data sets. The following components were addressed in the order specified:

- Magnetic Data
  - Throughout the interpretation of magnetic data sets, priority was given to the highest resolution data set available (Figure 5). For this study, this was the Ontario airborne geophysical surveys, magnetic and electromagnetic data set (GDS1205). Where this data set was not available, the single master gravity and aeromagnetic data for Ontario (GDS1036) data set was used. The interpretation of magnetic data included two steps:
    - Interpretation of Ductile Lineaments
      - Drawing of stratigraphic and structural form lines using first vertical derivative and tilt derivative magnetic data. 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 granitoid 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).
      - For this study, form lines were drawn using the Ontario airborne geophysical surveys, magnetic, and electromagnetic data set (GDS1205) first vertical derivative and the tilt derivative data. Where the Manitouwadge area was not covered by the GDS 1205 data set, form lines were interpreted from the low-resolution single master gravity and aeromagnetic data for Ontario (GDS1036).
    - Interpretation of Structural Lineaments
      - This part of the interpretation involved the drawing of lineaments, representing all interpreted faults regardless of interpreted age, style (e.g., brittle versus ductile) or kinematics. Evidence for interpreted brittle lineaments was derived from several sources in the magnetic data, including discontinuities between form lines (as outlined above), offset of magnetic units, or the presence of linear magnetic lows. Lineaments were drawn using the first vertical derivative image, with the tilt derivative image for validation and enhancement.
- Electromagnetic Data
  - In the Manitouwadge area, electromagnetic data are only available from the region covered by the Ontario airborne geophysical surveys, magnetic and electromagnetic data set (GSD1205). Consequently, electromagnetic data was only used to support lineaments identified in the aeromagnetic data, and was not interpreted as a separate data set. When a lineament was observed in electromagnetic data, typically along discontinuities and linear zones of low resistivity, it was noted in the “comments” column of the attribute table.
- CDED Topography Data
  - The lineament interpretation of topography data involved the drawing of lineaments along topographic valleys, slope walls or escarpments, drainage patterns and abrupt changes in topography that were visible in a colour mosaic constructed from the CDED

topography data. Attention was paid to not draw lineaments associated with glacial features.

- Satellite Imagery
  - The lineament interpretation of satellite imagery involved the drawing of lineaments along linear features including changes in bedrock colour (changing lithology), vegetation cover, and drainage patterns, such as rivers and streams, and linear chains of lakes that were visible in Landsat (primary dataset) and SPOT (supplementary dataset) satellite image data. Attention was paid to not draw lineaments associated with glacial features.

All lineaments were drawn up to a maximum of 10 kilometres outside the Manitouwadge area boundary, to express their full extent, or in the case of longer lineaments, to better estimate their maximum length around the Manitouwadge area. Lineaments displayed on maps are truncated at the boundary of the margins of the Manitouwadge area; however, the full length of the lineaments was included in the attribute table (Length; Table 7).

The higher resolution of the topography and satellite imagery data sets helped identify a greater density of smaller scale lineaments that were not evident in the geophysical data sets.

The Step 1 lineament analysis resulted in the generation of one interpretation for each data set, including magnetic (supported by electromagnetic), satellite imagery (Landsat and SPOT) and topography (CDED) for each interpreter, resulting in a total of six individual GIS layer-based interpretations. Within these data sets, crosscutting relationships between individual lineaments were assessed. Following this assessment, based on the expert judgment of each interpreter, lineament segments were merged, resulting in lineament length corresponding to the sum of all parts.

During Step 1, identified lineaments were attributed with Fields 1 to 9 as listed in. For attribute Field 6, each interpreter assigned a certainty/uncertainty descriptor (attribute field ‘Certain’ = 1-low, 2-medium or 3-high) to each lineament feature in their interpretation based on their judgment concerning the clarity of the lineament within the data set. Where a surface lineament could be clearly seen on exposed bedrock, it was assigned a certainty value of 3. Where a lineament represented a bedrock feature that was inferred from linear features, such as orientation of lakes or streams or linear trends in texture, it was assigned a certainty value of either 1 or 2. For geophysical lineaments, a certainty value of 3 was assigned when a clear magnetic susceptibility contrast could be discerned and a certainty value of either 1 or 2 was assigned when the signal was discontinuous or more diffuse in nature. The certainty classification for all three data sets ultimately was based on expert judgment and experience of the interpreter.

In the determination of azimuth, SRK used ET^{TM} EasyCalculate 10, an add-in extension to ArcGIS. This add-in provides a function (polyline_GetAzimuth.cal) that calculates the azimuth of each polyline at a user-specified point and populates an assigned attribute field. SRK used the mid-point of each interpreted lineament to calculate the azimuth.

It is understood that some of the lineament attributes (e.g., relative age) will be further refined as more detailed information becomes available in subsequent stages of characterization, should the community be selected by the NWMO and remain interested in advancing in the site selection process.

3.2.2 Step 2: Reproducibility Assessment 1 (RA_1)

During Step 2, individual lineament interpretations produced by each interpreter were compared for each data set (Figure 9, 10, and 11). This included a reproducibility assessment (RA_1) based on the coincidence, or lack thereof, of interpreted lineaments within a data set-specific buffer zone. For example, if a lineament was identified by both interpreters within an overlapping buffer zone, then it was deemed coincident. The two individual lineament interpretations for each data set were then integrated to provide a single interpretation for the aeromagnetic (Figure 9), topographic (Figure 10) and satellite (Figure 11) data that included the results of the first stage reproducibility assessment (RA_1). A discussion of the parameters used during this step follows.

Buffer Size Selection

Buffer sizes for lineaments in each data set were initially based on the (grid) resolution of each data set. It was determined using trial-and-error over a selected portion of the lineament interpretation that buffer sizes of five times the grid cell resolution of each data set provided a balanced result for assessing reproducibility.

A buffer of 150 metres (either side of the lineament) was generated for the area covered by high-resolution magnetic data, which represents approximately 77 percent of the Manitouwadge area. This value is equivalent to five times the data set grid cell resolution (30 metres) of the Ontario Airborne Geophysical Surveys, Magnetic and Electromagnetic data set (GDS1205). A buffer of 1000 metres (either side of the lineament) was generated for the area covered by low-resolution magnetic data. This value is equivalent to five times the data set grid cell resolution (200 metres) of the single master gravity and aeromagnetic data for Ontario (GDS1036).

A buffer of 150 metres (either side of the lineament) was generated for the satellite data. This value is equivalent to five times the resolution of the Landsat data (30 metres), which is the coarser of the two available satellite data sets.

A buffer of 125 metres (either side of the lineament) was generated for the topographic data. This value is approximately equivalent to five times the resolution of the CDED topographic data (23 metres).

The buffers were used as an initial guide to determine coincidence between lineaments, with the expert judgement of the interpreter ultimately determining which lineaments were coincident. The buffer size widths were included in the attribute fields of each interpretation file (Table 7).

Reproducibility Assessment

The generation of an integrated lineament interpretation for each data set, including the reproducibility assessment, utilized a three step process to combine the first interpreter’s lineaments (lead interpretation) and second interpreter’s lineaments, as follows:

- Lineament buffers, described above, were overlain on top of the lead interpretation data set. The second interpreter’s lineaments were overlain on top, and all lineaments that occurred within overlapping buffers were carried forward and copied into a new file for the next step. These lineaments were attributed with a reproducibility value (RA_1; Table 7) of two in the Step 2 attribute table.

- The remaining lineaments of the lead interpreter's Step 1 interpretation were then manually analyzed by both interpreters on the basis of the available imagery for each data set. In some instances, this included adapting the shape and extent of individual lineaments to increase the accuracy of spatial location or length of the lineament, and carrying the adapted lineament forward into the Step 2 interpretation file. These lineaments were attributed a RA_1 value of one in the Step 2 attribute table.
- Finally, the remaining lineaments of the second interpreter's Step 1 interpretation were then manually analyzed by both interpreters on the basis of the available imagery for each data set. In some instances, this included adapting the shape and extent of individual lineaments to increase the accuracy of spatial location or length of the lineament, and carrying the adapted lineament forward into the Step 2 interpretation file. These lineaments were attributed a RA_1 value of one in the Step 2 attribute table.

The decision on whether or not to adapt the shape and extent of an individual lineament and (or) whether the lineament was carried forward to the next step was based on expert judgement. The following guidelines were applied:

- If a lineament was drawn continuously by one interpreter but as individual, spaced, or disconnected segments by the other interpreter, a single continuous lineament was carried forward to the Step 2 interpretation with a RA_1 value of 2, if expert judgement deemed the continuous lineament to be more correct.
- If more than two thirds of a lineament were identified by one interpreter compared to the other interpreter, the lineament was carried forward to the Step 2 interpretation with a RA_1 value of 2. If less than two thirds of a lineament were identified by one interpreter compared to the other interpreter, the longer lineament was segmented, and each portion was attributed with RA_1 values accordingly.

The resulting Step 2 interpretations for each data set (magnetics, topography, and satellite imagery) were then refined using expert judgement to avoid any structurally inconsistent relationships. This included adapting the lineaments within the limits of the assigned buffer zone to avoid any mutually crosscutting relationships, and updating the attribute fields.

3.2.3 Step 3: Coincidence Assessment 2 (RA_2)

During Step 3, the integrated lineament interpretations for each data set were amalgamated into one final interpretation, as shown in Figure 12, following a similar methodology as described above in Stage 2. In this second assessment, reproducibility (RA_2) is based on the coincidence, or lack thereof, of interpreted lineaments between different individual data sets within an assigned buffer zone (Buffer_RA_2). A discussion of the parameters used during this step follows below.

Geophysical data supply vital information about structures in the subsurface, whereas surficial data only provide information about the surface expression of structures and may include lineaments that may not be related to the bedrock structural framework (e.g., lineaments related to glacial features). Since high resolution geophysical data is available over the majority of the Manitouwadge area, it was determined that for this step of the interpretation, the lineaments derived from geophysical data would be given precedence over lineaments derived from surficial data.

On this premise, all lineaments derived from the magnetic data were included in the final interpretation. A buffer (200 metres either side) was generated around these lineaments, which was used for comparison with lineaments derived first from topographic, and then from satellite data. This buffer size was included as an attribute field for all interpreted lineaments (Buffer RA_2; Table 7). As part of this comparison, coincident lines were identified and attributed. Next, non-coincident lineaments were evaluated against the magnetic data by both interpreters, and if required, were adapted and carried forward to the final Step 3 data set. During this process, each lineament was attributed with a text field highlighting in which data sets it was identified. This resulted in a combined interpretation with lineaments derived from geophysical and surficial data (topography and satellite).

The following rules were applied for determining reproducibility between the data set-specific lineament maps:

- If any coincidence of lineaments occurred between two lineament data sets, the longest lineament was carried forward to the Step 3 interpretation and attributed as derived from two (or more) data sets, regardless of the length of overlap between the lineaments. This meant that if any part of a lineament derived from one data set was identified in another data set, it was considered that this lineament was reproduced.
- In the case that a lineament derived from topographic or satellite imagery data was longer than a coincident lineament derived from geophysical data, the former lineament was cut and the non-coincident portion was carried forward into the final Step 3 interpretation as a single entity. Both the lineament in the geophysical data and the non-coincident portion derived from another data set were then attributed accordingly in terms of reproducibility.
- A lineament derived from topographic and (or) satellite imagery data that would fall within the buffer of a lineament derived from geophysical data would be attributed as reproduced in the relevant data sets if the orientation of the lineaments did not deviate significantly.
- Short (less than 500 metres) discontinuous topographic and satellite imagery data lineaments that are at low angles to geophysical data lineaments but extending outside the geophysical lineament buffer were considered to be coincident.
- Short (less than 500 metres) topographic and satellite imagery data lineaments that are at high angles to geophysical data lineaments, largely overlapped with the buffer zone from the geophysical data lineament, and had no further continuity (i.e., singular elements), were not carried forward to the final interpretation. This was done on the basis that these short segments represent a subsidiary lineament that is related to a broader fault zone already included as a brittle lineament in the final interpretation based on identification in the geophysical data.

The final reproducibility value (RA_2; Table 7) was then calculated as the sum of the number of data sets in which each lineament was identified (i.e., a value of 1-3).

The resulting lineament framework interpretation, representing the integration of all data sets, was then evaluated and modified (within the limits of relevant buffers) in order to develop a final lineament interpretation that is consistent with the interpreted structural history of the Manitouwadge region. This included defining the age relationships of the interpreted lineaments on the basis of crosscutting relationships between different generations of brittle lineaments and populating attribute field for each lineament for the relative age (Rel_Age; Table 7). This incorporated a working knowledge of the structural history of the Manitouwadge area, combined with an understanding of the fault characteristics in each brittle lineament population (e.g., brittle versus ductile). The structural history of the area is defined in Section 2.3.

The interpreted crosscutting and age relationships between different families of brittle lineaments and within individual families of brittle lineaments were refined using the available data. Crosscutting relationships were evaluated based on the through-going nature and termination of brittle lineaments and evaluated against the regional structural history as described below.

- D_1 deformation:
  - Development of S_1 compositional layering and localized isoclinal (overturned) F_1 folds and associated D_1 thrust faults in greenstone rocks; and
  - Not recognized in lineament analysis.
  - Constrained to before ca. 2691 Ga, as discussed below
- D_2-D_4 Deformation:
  - Represents protracted north-south to northwest-southeast compression and transpression;
  - Brittle-ductile structures constrained between ca. 2.691 Ga and ca. 2.673 Ga; and
  - Interpreted to form foliations, D_2-D_3 isoclinal folds, D_2-D_4 thrust faults and D_4 kink folds.
- D_5 Deformation:
  - Present in greenstone and granitic supracrustal rocks;
  - Only described in literature as "post-D_4 brittle structures subparallel to S_2 foliation in the Hemlo greenstone belt" (Lin 2001);
  - Muir (2003) suggested that in the Hemlo region, D_5 occurred after emplacement of granites and Proterozoic dykes (post ca. 2.121 Ga), however absolute age constraints are not available for this phase; and
  - Interpreted to form brittle faults.
- D_6 Deformation:
  - Present in greenstone and granitic supracrustal rocks;
  - Only described in literature as "post-D_4 southeasterly trending dextral strike-slip faults in the Hemlo greenstone belt" (Lin 2001);
  - Absolute age constraints are not available/ambiguous for this phase; and
  - Interpreted to form brittle faults.

Interpreted lineaments were amended by applying this structural framework where required. This resulted in a cohesive interpretation representing a clearly-defined, consistent lineament network for the Manitouwadge area.

Finally, following the amendment of selected lineaments, the azimuth and length attribute fields were recalculated. Since no information is available on the width of the known faults in the Manitouwadge area, the attribute field for the final interpretation of the width of each lineament (F_Width; Table 7) remains unpopulated.

Additional analyses described further below in this report were carried out using the final interpretation. The final lineament interpretation shows a dense network of lineaments throughout the majority of the Manitouwadge area (Figures 12, 13 and 14). This interpretation is preliminary and would need to be verified by field investigations.

4 Findings

4.1 Description of Lineaments by Data Set

4.1.1 Geophysical Data

Interpretation of geophysical data allows for the distinction between lineaments associated with ductile fabrics, dykes, and brittle faults. Features interpreted as ductile lineaments from the aeromagnetic geophysical data set are shown on Figure 8. Features interpreted as brittle and dyke lineaments from geophysical data sets are shown on Figure 9. The ductile features are included primarily to provide context for the discussion of interpreted brittle and dyke features in the following paragraphs.

A total of 1679 lineaments comprise the data set (RA_1) of merged lineaments identified by the two interpreters from the aeromagnetic data (Figure 9). Of the 1679 lineaments, 1286 are interpreted as brittle lineaments, and 393 as dyke lineaments. The length of the aeromagnetic lineaments ranges from 200 metres up to 83.5 kilometres, with a geometric mean length of 4.6 kilometres and a median length of 2.70 kilometres. Azimuth data, weighted by length, for the aeromagnetic lineaments interpreted as brittle lineaments exhibit four dominant orientations trending to the northeast, north, northwest and east-west. Of these orientations, the north, northwest, and east-west trending brittle lineaments are sharply defined, and the northeast trending brittle lineaments exhibit a diffuse pattern (Figure 9 inset). Lineaments interpreted as dykes exhibit three sharply defined orientations trending to the northwest, north, and northeast (Figure 9 inset). Of these lineament orientations, the northwest trending dyke lineaments are the most dominant, and the north and northeast trending dyke lineaments are less dominant. Each orientation of dyke lineament likely corresponds to a separate suite of dykes.

Of the brittle lineaments interpreted from aeromagnetic data, 625 (49 percent) lineaments were assigned the highest level of certainty (certainty = 3), while 149 (11 percent) and 512 (40 percent) were given certainty values of 2 and 1, respectively. For lineaments interpreted as dykes, 275 (70 percent) were assigned a certainty value of 3, while 45 (11 percent) and 73 (19 percent) were given certainty values of 2 and 1, respectively. The reproducibility assessment identified coincidence for 325 brittle lineaments (25 percent; RA_1 = 2) and a lack of coincidence for 961 of the interpreted brittle lineaments (75 percent; RA_1 = 1). The reproducibility assessment identified coincidence for 272 of the interpreted dykes (69 percent; RA_1 = 2) and a lack of coincidence for 121 of the interpreted dykes (31 percent; RA_1 = 1).

On the basis of their orientation, the 393 interpreted dyke lineaments were divided into three groups:

- 129 dyke lineaments are interpreted to belong to the northwest-trending Matachewan dyke swarm (ca. 2.473Ga; Buchan and Ernst 2004);
- 83 dyke lineaments are interpreted to belong to the northeast-trending Biscotasing dyke swarm (ca. 2.167 Ga; Hamilton et al., 2002); and
- 181 dyke lineaments are interpreted to belong to the north-trending Marathon dyke swarm, which in the Manitouwadge area trend slightly east of north (ca. 2.121Ga; Buchan et al., 1996; Hamilton et al., 2002).

Regional mapping by the Ontario Geological Survey identified several northeast-trending dykes of the Abitibi dyke swarm (ca. 1.14 Ga; Krogh et al., 1987) in the region surrounding the Manitouwadge study area, but not within the study area itself. It is therefore possible that some of the northeast-trending dykes interpreted as members of the Biscotasing dyke swarm (ca. 2.167 Ga) are actually members of the Abitibi dyke swarm. However, this could not be determined from the lineament analysis and therefore all northeast-trending dykes are interpreted as members of the Biscotasing dyke swarm.

4.1.2 Surficial Data (CDED topography and satellite imagery)

Interpreted brittle and dyke lineaments from the CDED topography and satellite imagery data sets are shown on Figure 10 and Figure 11, respectively. Very few dykes were initially interpreted from surficial data. 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 following paragraphs provide an overview of these surface-based interpretations.

A total of 2060 lineaments comprise the data set (RA_1) of merged lineaments identified by the two interpreters from the CDED topography data (Figure 10). Of the 2060 lineaments, 1914 are interpreted as brittle lineaments and 146 as dyke lineaments. These lineaments range in length from 230 metres to 83.5 kilometres, with a geometric mean length of 3.8 kilometres and a median length of 2.2 kilometres. Azimuth data, weighted by length, for the CDED lineaments interpreted as brittle lineaments exhibit three dominant orientations trending to the northwest, north and northeast, and one less dominant orientation trending east-west. 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 (Figure 10 inset). Lineaments interpreted as dykes exhibit three sharply defined orientations trending to the northwest, northeast and north (Figure 10 inset). Of these lineament orientations, the northwest trending dyke lineaments are the most dominant, and the north and northeast trending dyke lineaments are slightly less dominant. Each orientation of dyke lineament likely corresponds to a separate suite of dykes.

Of the brittle lineaments interpreted from the CDED topography data, 959 (50 percent) lineaments were assigned the highest level of certainty (certainty = 3), while 282 (15 percent) and 673 (35 percent) were given certainty values of 2 and 1, respectively. For lineaments interpreted as dykes, 110 (75 percent) were assigned a certainty value of 3, while 14 (10 percent) and 22 (15 percent) were given certainty values of 2 and 1, respectively. The reproducibility assessment identified coincidence for 673 brittle lineaments (35 percent; RA_1 = 2) and a lack of coincidence for 1241 of the interpreted brittle lineaments (65 percent; RA_1 = 1). The reproducibility assessment identified coincidence for 99 of the interpreted dykes (68 percent; RA_1 = 2) and a lack of coincidence for 47 of the interpreted dykes (32 percent; RA_1 = 1).

On the basis of their orientation, the 146 dyke lineaments were divided into three groups:

- 44 dyke lineaments are interpreted to belong to the northwest-trending Matachewan dyke swarm (ca. 2.473Ga; Buchan and Ernst 2004);
- 37 dyke lineaments are interpreted to belong to the northeast-trending Biscotasing dyke swarm (ca. 2.167 Ga; Hamilton et al., 2002); and
- 65 dyke lineaments are interpreted to belong to the north-trending Marathon dyke swarm (ca. 2.121 Ga; Buchan et al., 1996; Hamilton et al., 2002).

A total of 1590 lineaments comprise the data set (RA_1) of merged lineaments identified by the two interpreters from the satellite (Landsat/SPOT) data (Figure 11). Of the 1590 lineaments, 1491 are interpreted as brittle lineaments and 99 as dyke lineaments. These lineaments range in length from 400 metres to 83.5 kilometres, with a geometric mean length of 4.2 kilometres and a median length of 2.5 kilometres. Azimuth data, weighted by length, for the satellite imagery lineaments interpreted as brittle lineaments exhibit three dominant orientations trending to the northwest, north and northeast, and one less dominant orientation trending east-west. 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 (Figure 11 inset). Lineaments interpreted as dykes exhibit three sharply defined orientations trending to the northwest, northeast and north (Figure 10 inset). Of these lineament orientations, the northwest trending dyke lineaments are the most dominant, and the north and northeast trending dyke lineaments are less dominant. Each orientation of dyke lineament likely corresponds to a separate suite of dykes.

Of the brittle lineaments interpreted from the satellite data, 544 (36 percent) lineaments were assigned the highest level of certainty (certainty = 3), while 295 (20 percent) and 652 (44 percent) were given certainty values of 2 and 1, respectively. For lineaments interpreted as dykes, 78 (79 percent) were assigned a certainty value of 3, while 9 (9 percent) and 12 (12 percent) were given certainty values of 2 and 1, respectively. The reproducibility assessment identified coincidence for 597 brittle lineaments (40 percent; RA_1 = 2) and a lack of coincidence for 894 of the interpreted brittle lineaments (60 percent; RA_1 = 1). The reproducibility assessment identified coincidence for 77 of the interpreted dykes (78 percent; RA_1 = 2) and a lack of coincidence for 22 of the interpreted dykes (22 percent; RA_1 = 1).

On the basis of their orientation, the 99 dyke lineaments were divided into three groups:

- 35 dyke lineaments are interpreted to belong to the northwest-trending Matachewan dyke swarm (ca. 2.473 Ga; Buchan and Ernst 2004);
- 22 dyke lineaments are interpreted to belong to the northeast-trending Biscotasing dyke swarm (ca. 2.167 Ga; Hamilton et al., 2002); and
- 42 dyke lineaments are interpreted to belong to the north-trending Marathon dyke swarm (ca. 2.121Ga; Buchan et al., 1996; Hamilton et al., 2002).

4.2 Description and Classification of Integrated Lineament Coincidence (RA_2)

The integrated lineament data set produced by merging all lineaments interpreted from the geophysical (aeromagnetic with the support of electromagnetic), CDED topography, and satellite imagery data is presented on Figure 12 and Figure 13. Figure 12 displays the lineament classification based on Coincidence Assessment 2 (RA_2). Figure 13 displays the lineament classification based on length of interpreted lineaments. The merged lineaments were classified by length using four length bins: >10 kilometres, 5-10 kilometres, 1-5 kilometres and <1 kilometre. These length bins were provided by NWMO.

The merged lineament data set contains a total of 3743 lineaments (3336 brittle and 407 dyke) that range in length from 200 metres to 83.5 kilometres. The geometric average length of these lineaments is 3.6 kilometres and the median length is 2.6 kilometres. Of all merged lineaments, 218 lineaments are greater than 10 kilometres in length (6 percent), 406 lineaments are between 5-10 kilometres in length (11 percent), 2647 lineaments are between 1-5 kilometres in length (71 percent), and 472 lineaments are less than 1 kilometre in length (12 percent).

Azimuth data, weighted by length, for the merged lineaments data set exhibit three dominant orientations trending to the northwest, north and northeast, and one less dominant orientation trending east-west. Of these orientations, the northwest, north and east-west trending brittle lineaments are sharply defined, and the northeast trending brittle lineaments exhibit a diffuse pattern (Figure 12 inset).

Results from the Reproducibility Assessment 2 (RA_2), shown in Figure 12, for the merged lineament data set (brittle and dyke) show 357 lineaments (9.5 percent) were identified and coincident in all three data sets (RA_2 = 3), and 858 lineaments (23 percent) were coincident with a lineament from one other data set (RA_2 = 2). A total of 2528 lineaments (67.5 percent) lacked a coincident lineament from the other data sets (RA_2 = 1). A total of 652 lineaments observed in aeromagnetic data were coincident with a mapped interpreted surficial lineament (represents 39 percent of all geophysical lineaments). A total of 933 surficial lineaments were coincident in both CDED topography and satellite imagery data (represents 34 percent of all surficial lineaments).

Of all lineaments interpreted to represent brittle lineaments (Figure 12), 278 (8 percent) of the total 3336 brittle lineaments were identified and coincident in all data sets (RA_2 = 3), and 786 brittle lineaments (24 percent) were coincident with a brittle lineament from one other data set (RA_2 = 2). A total of 2272 brittle lineaments lacked a coincident brittle lineament from the other data sets (RA_2 = 1).

Of the total 407 interpreted dyke lineaments, 256 (63 percent) lineaments (Figure 12) have reproducibility values of 1 (RA_2 = 1), as they were only observed in the aeromagnetic data. A total of 72 dyke lineaments (18 percent) were coincident with a lineament from one other data set (RA_2 = 2), and a total of 79 dyke lineaments (19 percent) were coincident in all three data sets (RA_2 = 3). The 407 interpreted dyke lineaments include 132 Matachewan Suite dykes, 184 Marathon Suite dykes, and 91 Biscotasing Suite dykes.

4.3 Description of Lineaments by Lithological units in the Manitouwadge Area

The following subsections describe the characteristics of the interpreted lineaments for each of the select lithological units/areas (as described in section 2.2), including the Quetico Subprovince, the Black-Pic batholith, and the Fourbay Lake pluton. Rose diagrams for interpreted lineaments for select lithological units/areas are presented on Figure 14.

Quetico Subprovince

A total of 1423 lineaments (1332 brittle, 91 dyke) were interpreted in the Quetico Subprovince, an area that covers the upper half of the Manitouwadge area. This includes all lineaments that are contained within and crosscutting the boundary of the Quetico Subprovince. Of the 1332 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 kilometres.

Brittle lineaments trend predominantly northwest, northeast, and east-west (Figure 14). 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. East-west trending lineaments are only observed as brittle lineaments and not as dyke lineaments. The presence of brittle east-west trending lineaments appears to be more abundant with increasing proximity to the east-west oriented subprovince boundary.

Black-Pic Batholith

A total of 1903 lineaments (1629 brittle and 274 dyke) were interpreted in the Black-Pic batholith, an area that covers the majority of the lower half of the Manitouwadge area. 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.

Brittle lineaments exhibit a predominantly trend towards the northwest, north and northeast, and a very minor east-west trend (Figure 14). 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.

Fourbay Lake Pluton

A total of 84 lineaments (78 brittle, 6 dyke) were interpreted in the Fourbay Lake pluton, an approximately 14 kilometre long by 6 kilometre wide pluton in the southwest-most corner of the Manitouwadge area. These lineaments include all lineaments that are contained within and crosscutting the boundary of the pluton. The interpreted lineaments within the Black-Pic batholith range in strike length from 460 m to 38.6 kilometres. Of the 78 brittle lineaments, 18 are interpreted as D_5 faults and 60 as D_6 faults.

Brittle lineaments exhibit a predominantly trend towards the northwest and northeast, and a minor north trend (Figure 14). Dyke lineaments trend northwest and northeast. Northwest trending dykes are interpreted as members of the Matachewan dyke swarm, and northeast trending dykes as members of the Biscotasing dyke swarm.

5 Discussion

The following sections are provided to discuss the results of the lineament interpretation in terms of lineament density, reproducibility and coincidence, and lineament length, the relationship between mapped faults and interpreted lineaments, and the relative age relationships of the interpreted lineaments.

5.1 Lineament Density

The density of all interpreted lineaments in the Manitouwadge area was determined by examining the statistical density of individual lineaments using ArcGIS Spatial Analyst. A grid cell size of 50 metres and a search radius of 1.25 kilometres (equivalent to half the size of the longest boundary of the minimum area size of a potential siting area) were used for this analysis. The spatial analysis used a circular search radius examining the lengths of polylines intersected within the circular search radius around each grid cell, following this equation:

$$\text{Density} = (L1 + L2) / (\text{area of circle})$$

Where L1 represents the length of Line 1 within the circle and L2 represents the length of Line 2 in the circle, assuming that only two lineament polylines intersect the circle search radius.

The density of lineaments in the Manitouwadge area is relatively uniform and high, with the exception of the northern portion of the study area within the Quetico Subprovince (Figures 12, 13 and 14). Lineament density is low in the northern sector of the Manitouwadge area probably due to low resolution geophysical data and extensive Quaternary cover (Figure 4), which decreases the density of lineaments interpreted from geophysical (Figure 5) and surficial (Figures 10 and 11) data sets, respectively.

The greatest density of lineaments occurs in areas underlain by the Manitouwadge greenstone belt. Other zones of high lineament density occur throughout the Manitouwadge area, and commonly correlate with high density clusters of dyke lineaments.

Despite a relatively high density of lineaments throughout the majority of the Manitouwadge area, multiple low density zones can be identified visually (e.g., Figure 12). Some of these zones are the result of a low number of interpreted surficial lineaments due to Quaternary cover. Examples of this include the centre of the Manitouwadge synform and an approximately 10-kilometre wide northeast trending corridor of Quaternary cover between the central-southern boundary of the Manitouwadge area and the Manitouwadge greenstone belt. Other zones of low density are interpreted as bedrock with a low density of structures. These most significant zones of low lineament density not related to Quaternary cover are located in the Black-Pic batholith in the central southern portion of the Manitouwadge area, and the Fourbay Lake pluton in the southwest corner of the Manitouwadge area (Figures 12, 13 and 14).

5.2 Lineament Reproducibility and Coincidence

Reproducibility values assigned to the lineaments provide a measure of the significance of the bedrock structures expressed in the different data sets. The approach used to assign reproducibility values involved checking whether lineament interpretations from different interpreters (RA_1), and from different data sets (RA_2), were coincident within a specified buffer zone radius. Reproducibility values are discussed in detail in Sections 4.1 and 4.2.

The findings from the reproducibility assessment RA_1 indicate that approximately 35 percent of the total surficial lineaments were identified by both interpreters (see Figures 10 and 11). Importantly, longer lineaments with higher certainty values were identified more often by both interpreters. The reproducibility assessment of the geophysical lineaments shows that approximately 35 percent of the lineaments (includes both brittle and dyke lineaments combined) were also identified by both interpreters (see Figure 9). As with the surficial lineaments, longer geophysical lineaments with higher certainty values were also recognized more often by both interpreters.

There are some differences in the individual Step 1 lineament interpretations. These differences can be explained by two main factors: 1) the person carrying out the interpretation, and 2) the lineament information that can be derived from specific data sets. The lineament interpretations carried out by two different interpreters is subjective and, in part, may be affected by the interpreter's experience. The lineament information that can be derived from each data set may have a strong impact on the quality and resolution of an interpretation. As discussed earlier in this report, topographic and satellite data only provide information about the potential surficial expressions of lineaments. However, these data sets may include lineaments that are related to erosional features, such as glacial features, that do not have a structural origin. It can be challenging to distinguish such features from structural features, and careful evaluation, combined with a working knowledge of the glacial history of the area is required. For the final lineament interpretation in the Manitouwadge area, lineaments that were interpreted during Step 1 and Step 2 that strike roughly northeast (i.e., parallel to the ice flow direction), with relatively short lengths and discontinuous in nature, were considered as suspect and likely to represent glacial features that were incorrectly interpreted as structural features. Therefore, these lineaments were not included in the final Step 3 interpretation.

Coincidence between features identified in the various data sets was evaluated for the second reproducibility assessment (RA_2). Of the 2716 lineaments observed on surficial data sets (2553 brittle and 163 dyke), 933 lineaments (34 percent) 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. For example, a lineament drawn along a stream channel shown on the satellite imagery is expected to be coincident with a lineament that captures the trend of the associated topographic valley expressed in the digital elevation data. 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.

Of the 1679 lineaments observed in aeromagnetic data, 652 lineaments (39 percent) were reproduced in at least one surficial data set. The lack of coincidence between the aeromagnetic 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, certain structural features may not possess a magnetic susceptibility contrast with the host rock.

The resolution of each available data set has a strong impact on the reproducibility and number of interpreted lineaments. The Ontario airborne geophysical surveys magnetic and electromagnetic data (GDS 1205) has a high resolution (30-metre grid cells) and covers most of the area. The SPOT satellite, Landsat satellite, and CDED topography data cover the entire Manitouwadge area with a 30-metre (and less) grid cell resolution. The higher resolution of the surficial data sets over the entire study area may explain why a larger number of lineaments are identified from the combination of these data sets compared to the geophysical data sets.

The bedrock structural information available from surficial data sets (topography and satellite data) is limited in the northern portion of the Manitouwadge area and in several areas throughout the Manitouwadge greenstone belt and the Black-Pic batholith, due to the presence of relatively thick glaciolacustrine cover. In addition, in the northern portion of the study area, no high resolution geophysical data are available, limiting the ability to complete a suitable structural lineament interpretation in this area. In all other areas obscured by glaciolacustrine cover, high resolution geophysical data are present, which provide the required information to complete a suitable structural lineament interpretation. The absence of thick or extensive bedrock cover sequences elsewhere in the Manitouwadge area facilitates the practical interpretation of lineaments from surficial data.

SRK infers that the resolution and distribution of the data sets used, in combination with the final interpretation originating from two individual interpreters, formed a suitable basis to conduct a robust lineament interpretation in the Manitouwadge area. Regardless of the degree of coincidence, the observed overlap in dominant lineament orientation between all data sets (see insets on Figures 9, 10, and 11) suggests that all data sets are identifying the same regional sets of structures.

For these reasons, it is necessary to objectively analyze the results of the RA_2 assessment with the understanding that RA_2 = 1 does not necessarily imply a low degree of confidence that the specified lineament represents a true geological feature (i.e., a fracture). The true nature of the interpreted features will need to be investigated further during subsequent stages of the site evaluation process, if the community is selected by the NWMO, and remains interested in continuing with the site selection process.

5.3 Lineament Length

There is no information available on the depth extent of the lineaments interpreted for the Manitouwadge area. In the absence of available information, the interpreted length may be used as a proxy for the depth extent of the identified structures (Figure 13). A preliminary assumption may be that the longer interpreted lineaments in the Manitouwadge area may extend to greater depths than the shorter interpreted lineaments.

As discussed in Section 5.2, longer interpreted lineaments generally have higher certainty and reproducibility values. Although the existence of interpreted lineaments would need to be confirmed through field observations, certainty and reproducibility values provide a preliminary indication that the longer features are related to bedrock structures.

Although the existence of all interpreted lineaments would need to be confirmed through field observations, certainty and reproducibility values provide a preliminary indication of the higher confidence that the longer features identified are related to bedrock structures. Figure 13 shows the interpreted lineaments classified by lineament length. Four lineament length bins (0-1 kilometres, 1-5 kilometres, 5-10 kilometres, > 10 kilometres) were used for this analysis, and a length-weighted frequency rose diagram indicates the dominant lineament orientations (inset of Figure 13). Azimuth data, weighted by length, for the merged lineaments data set exhibit three dominant orientations trending to the northwest, north and northeast, and one less dominant orientation trending east-west. Of these orientations, the northwest, north and east-west trending brittle lineaments are sharply defined, and the northeast trending brittle lineaments exhibit a diffuse pattern (Figure 13 inset).

5.4 Fault and Lineament Relationships

As discussed, 3743 brittle and dyke lineaments were interpreted in the Manitouwadge area. Regional geological maps (Figure 3) identified multiple (approximately 25) northeast, northwest, and north trending faults, and one east-west trending fault in the Manitouwadge area. The east-west fault parallels the greenstone belt and is likely related to early D_1-D_4 ductile deformation, or a reactivated structure along this orientation (Peterson and Zaleski 1999). The additional mapped faults, such as the Nama Creek, Cadawaja, Slim Lake, and Fox Creek faults offset stratigraphy by up to 500 metres (Miles 1998) and are likely related to the D_5-D_6 brittle deformation.

All mapped (and named) faults shown on Figure 3 were reproduced to some degree during the lineament analysis. Certain 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. Where a dyke was interpreted to be coincident with a fault, a single dyke lineament was drawn, and a comment stating it was coincident with a fault was documented in the "comment" column of the attribute table. For most mapped faults, the dominant segment reproduced during the lineament analysis carried a reproducibility rating (RA_2) of three, indicating that at least a segment of the fault was observed in all three data sets.

The principal neotectonic stress orientation in central North America is generally oriented approximately east-northeast (63 degrees ± 28 degrees; Zoback 1992) although anomalous stress orientations have also been reported in the mid-continent that include a 90-degree change in azimuth of the maximum compressive stress axis (Brown et al. 1995) and a north-south maximum horizontal compressive stress (Haimson 1990). Local variations, and other potential complicating factors involved in characterizing crustal stresses, including the effect of shear stress by mantle flow at the base of the lithosphere (Bokelmann 2002; Bokelmann and Silver 2002), the degree of coupling between the North American plate and the underlying mantle (Forte et al. 2010), the effects of crustal depression and Holocene rebound, and the influence of the thick lithospheric mantle root under the Canadian Shield, make it premature to correlate the regional neotectonic stress orientation with the orientation of mapped lineaments at the desktop stage.

However, it is possible to broadly speculate on the potential behavior of the identified lineaments if they were to be reactivated by the regional east-northeast neotectonic stress regime. Four orientations of lineaments were interpreted: north, northeast, northwest, and east-west. Should the identified lineaments be reactivated under the current stress regime, the northeast oriented lineaments will likely reactivate as strike-slip faults, the northwest oriented lineaments likely as reverse dip-slip faults, and the north and east-west oriented lineaments likely as oblique-slip faults.

5.5 Relative Age Relationships

The structural history of the Manitouwadge area, outlined in Section 2.3, 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 area. The lineament interpretation is fairly consistent with regional observations, however, the D_5 and D_6 events interpreted from the lineament analysis differ from the D_5 and D_6 events described in the literature.

As stated 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 between ca. 2.691 and ca. 2.673 Ga. 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 Senneterre, 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 developed 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-2.673 Ga timeframe that may include many periods of re-activation attributable to any of several post-Archean tectonic events.

The 3743 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, 1190 D_5 lineaments, and 2026 D_6 lineaments. D_2-D_4 brittle lineaments are interpreted as Archean brittle-ductile faults. D_5 and D_6 brittle lineaments are interpreted as brittle faults. 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. As such, it is thought 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. However, 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 kilometre average length, 2.4 kilometre median length), followed by D_2-D_4 faults (3.8 kilometre average length, 2.1 kilometre median length), and D_5 faults (2.8 kilometre average length, 2.1 kilometre median length).

6 Summary

This report documents the source data, workflow, and results from a lineament interpretation of publicly-available digital data sets, including geophysical (aeromagnetic with the support of electromagnetic) and surficial (satellite imagery, topography) data sets for the Manitouwadge area (4,000 square kilometres) in northwestern Ontario.

The lineament analysis provides an interpretation of the location and orientation of possible individual brittle features and dykes on the basis of remotely sensed data, and helps to evaluate their relative timing relationships within the context of the regional geological setting. The three step process involved a workflow that was designed to address the issues of subjectivity and reproducibility.

The distribution of lineaments in the Manitouwadge area reflects the bedrock structure, resolution of the data sets used, and surficial cover. Lineament density, as demonstrated in this study, is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures, and with the resolution of the interpreted data sets. Surface lineament density throughout the Manitouwadge area is fairly uniform, but does show local variation. The greatest density of lineaments occurs in areas underlain by the Manitouwadge greenstone belt. Other zones of high lineament density occur throughout the Manitouwadge area, and commonly correlate with clusters of high density dyke lineaments.

Although the lineament density in the Manitouwadge area is generally high, several areas with a relatively low density of lineaments were identified. Areas of low lineament density interpreted to represent a low density of bedrock structures (i.e., areas not obscured by Quaternary cover or interpreted from low resolution data sets) were few in number and restricted to select areas within the Black-Pic batholith, the Fourbay Lake pluton, and the informally termed Bulldozer Lake pluton. Low lineament densities were also observed within areas of high bedrock exposure in the Quetico Subprovince, however these areas were not covered by high resolution geophysics. Within areas of exposed bedrock or thin drift, further investigations of bedrock formations and potential structures could be conducted through outcrop mapping and rock mass characterizations.

In terms of reproducibility, longer interpreted lineaments generally have higher certainty and reproducibility values. Comparison between the various data sets (RA_2) indicates that 39 percent of lineaments observed from aeromagnetic data were reproduced on at least one surficial data set and have an RA_2 value greater than 1. Of all lineaments observed on surficial data sets, 34 percent of lineaments were coincident in both CDED topography and satellite imagery data, and 24 percent of lineaments were observed in the geophysical data set. Regardless of the degree of coincidence, an observed overlap in dominant lineament orientation between all data sets suggests that all data sets are identifying the same regional sets of structures.

Azimuth data, weighted by length, for the merged lineaments data set exhibit three dominant orientations trending to the northwest, north and northeast, and one less dominant orientation trending east-west. Of these orientations, the northwest, north and east-west trending brittle lineaments are sharply defined, and the northeast trending brittle lineaments exhibit a diffuse pattern (Figure 12 inset). On the basis of the structural history of the Manitouwadge area, a framework was developed to constrain the relative age relationships of the interpreted lineaments.

A total of 3743 brittle lineaments were interpreted in the Manitouwadge area, representing three main generations: 527 D_2-D_4 lineaments, 1190 D_5 lineaments, and 2026 D_6 lineaments. In addition, a total of 407 dyke lineaments have been interpreted, including 132 Matachewan Suite dykes, 184 Marathon Suite dykes, and 91 Biscotasing Suite dykes.

Brittle lineaments interpreted as D_2-D_4 structures occur primarily along an east-west trend within and adjacent to the Manitouwadge greenstone belt. D_2-D_4 lineaments are interpreted to have formed between ca. 2.719 Ga and 2.673 Ga. Brittle structures representing D_5 and D_6 lineaments are interpreted to be younger than ca. 2.673 Ga, and represent a broad north-, northeast- and northwest-trending lineament network. Relationships between D_5 and D_6 and emplacement of the Marathon Suite dykes (ca. 2.1 Ga) are ambiguous. Therefore, no absolute age constraints exist for these stages of deformation.

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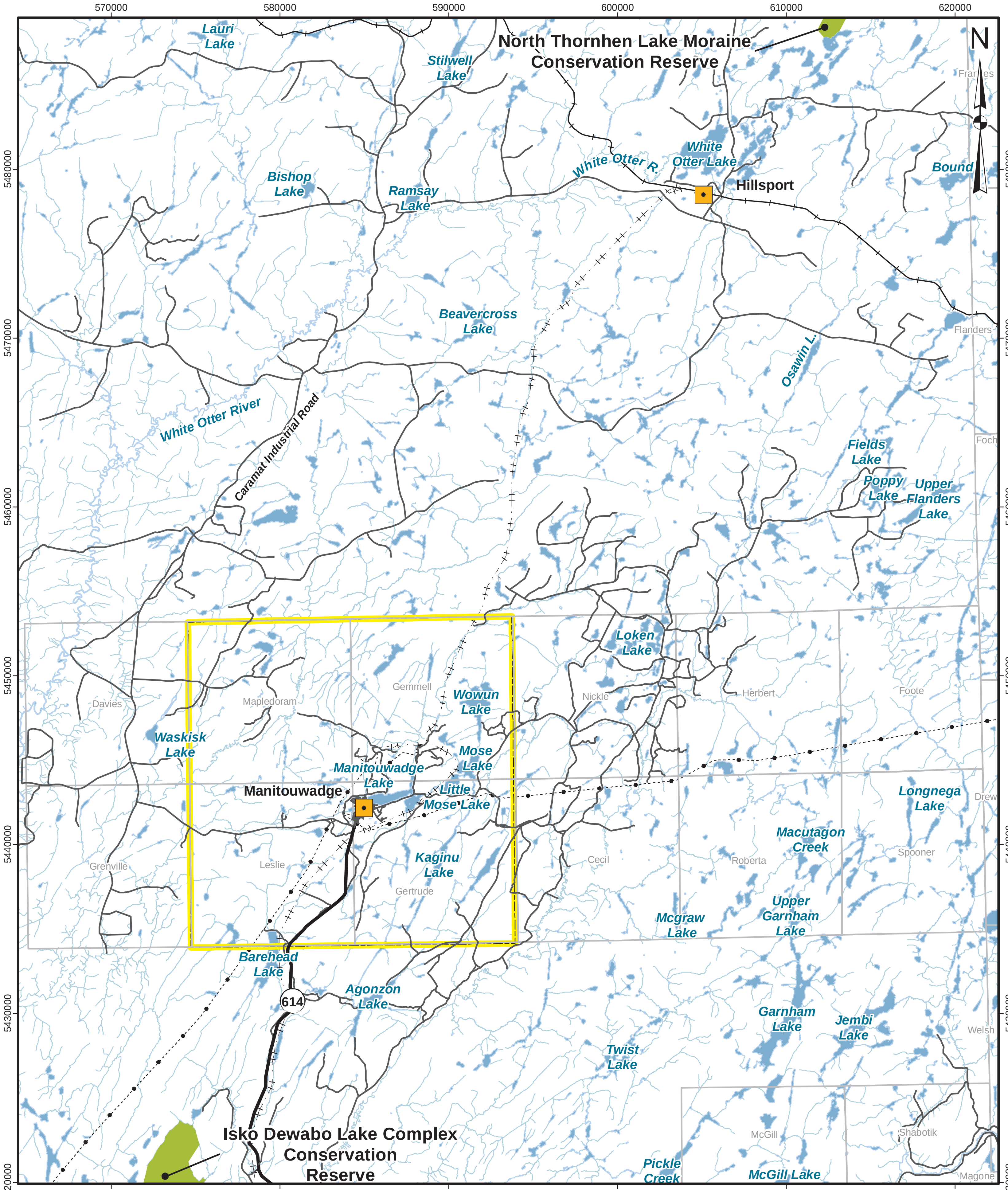
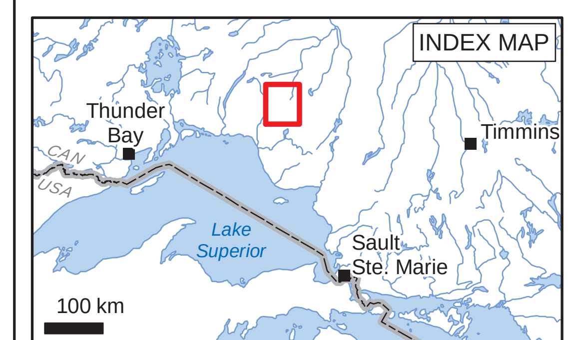


Legend

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

Protected Areas

- Conservation Reserve



Data Sources:
Base Data: MNR LIO, obtained 2009-2013
- Cities/Towns: 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

From Aecom (2014a)

10 km

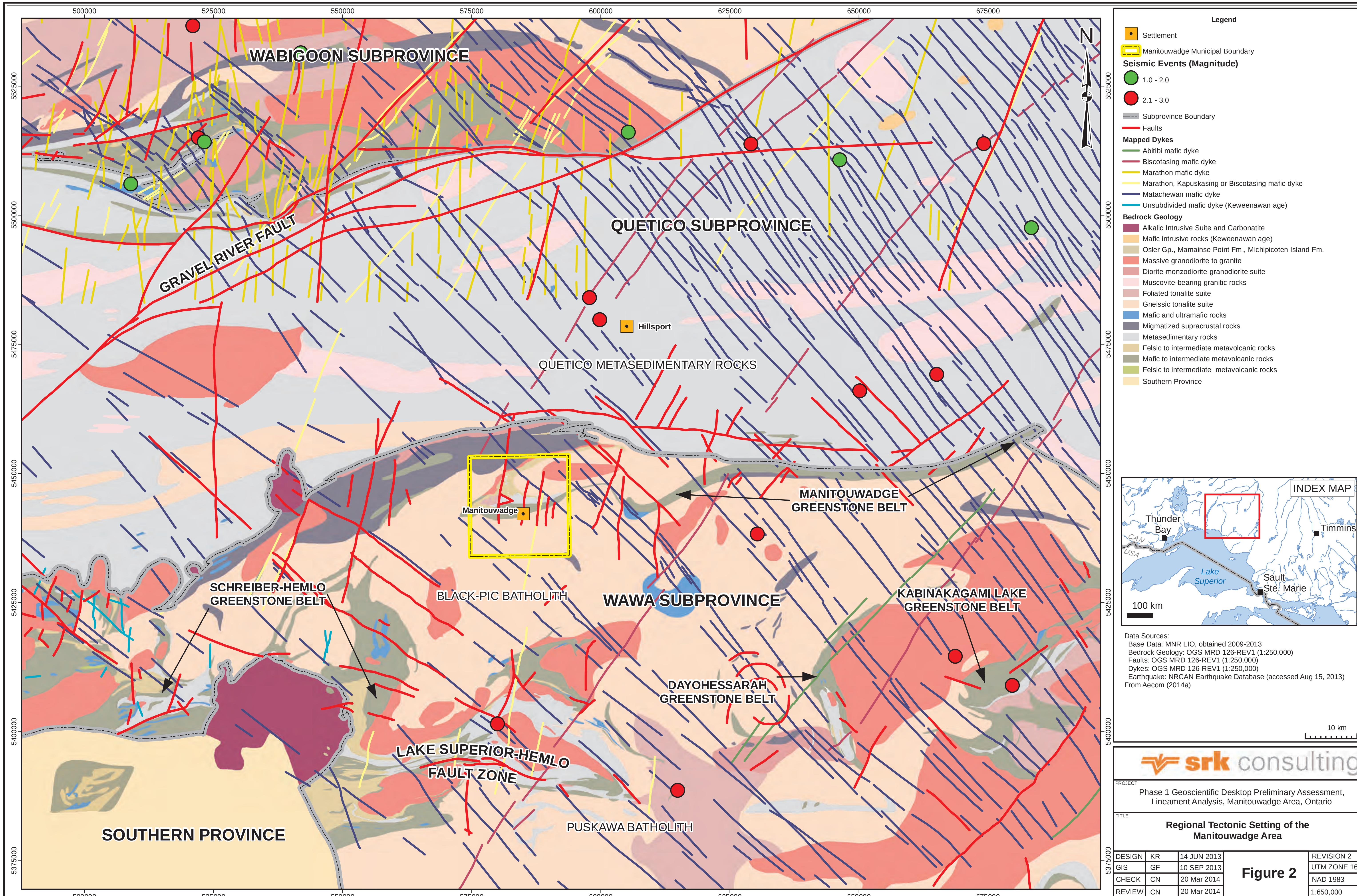
srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

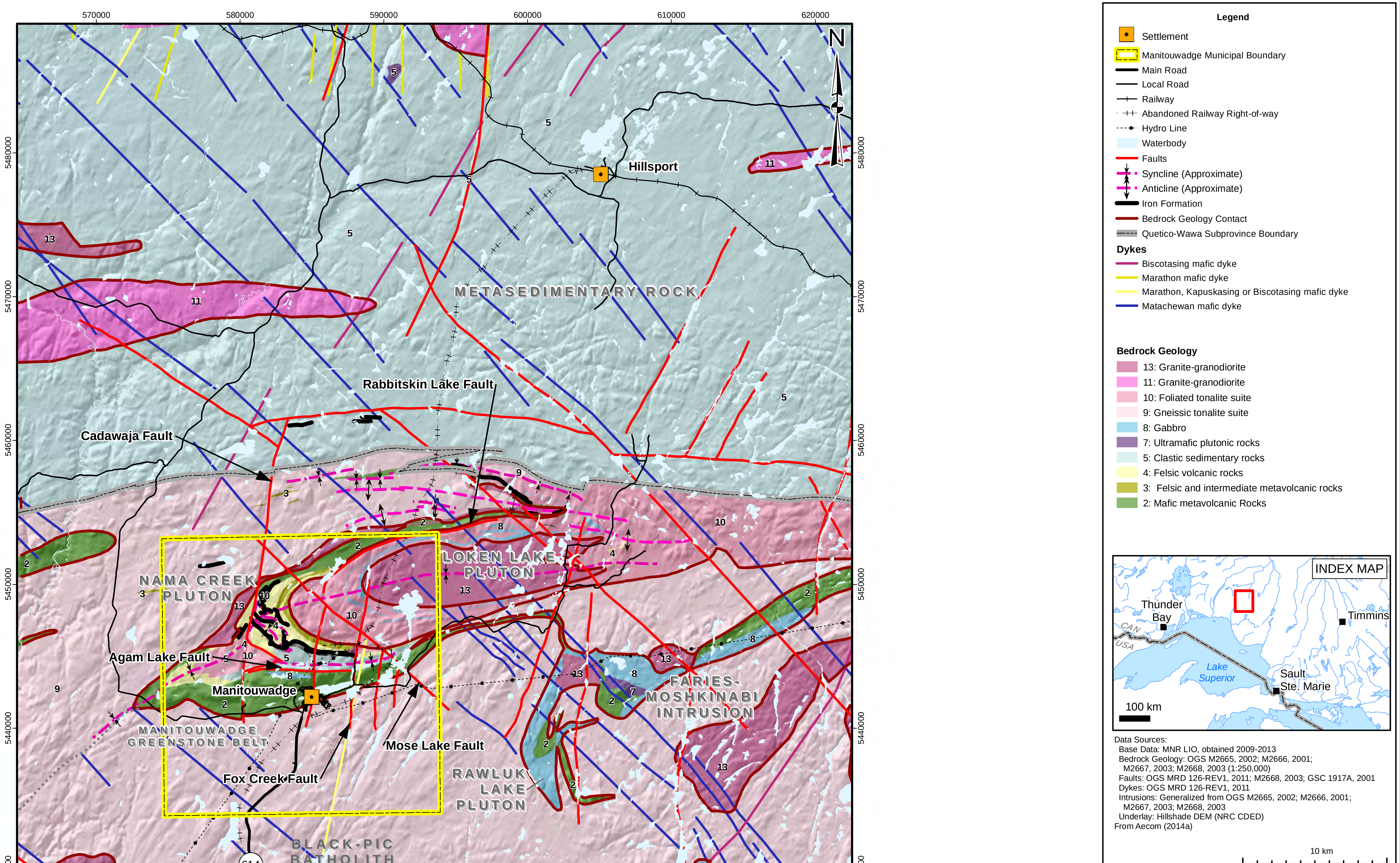
TITLE
Location and Overview of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 1**	REVISION 2
GIS	KR	20 Mar 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

File: aecom_Fig 1 - Township of Manitouwadge and Surrounding Area



File: aecom_Fig 2 - Regional Tectonic Setting of the Manitouwadge and Surrounding Area_Rev2



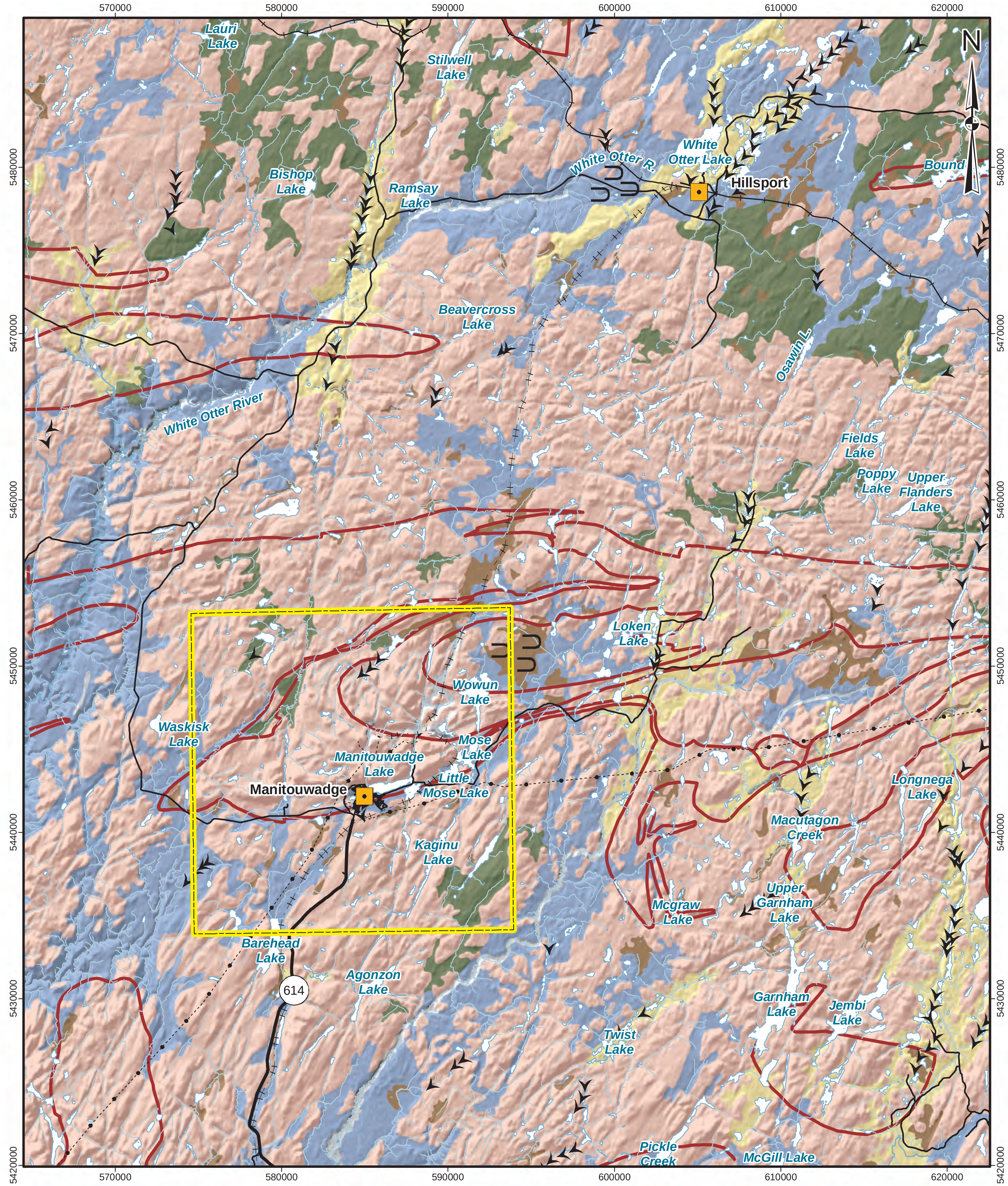
srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Bedrock Geology of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	**Figure 3**	REVISION 2
GIS	GF	29 AUG 2013		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

File: aecom_Fig 3 - Local Bedrock Geology of the Manitouwadge Area



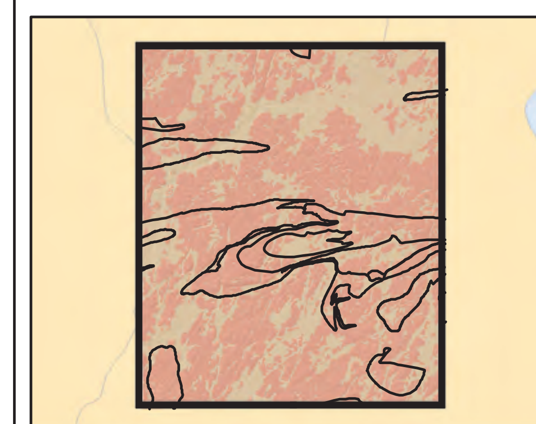
Legend

- 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 (NRC CDED)
From Aecom (2014a)

10 km

srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Surficial Geology of the Manitouwadge Area

DESIGN	KR	14 JUN 2013	Figure 4	REVISION 2
GIS	GF	06 SEP 2013		UTM ZONE 16
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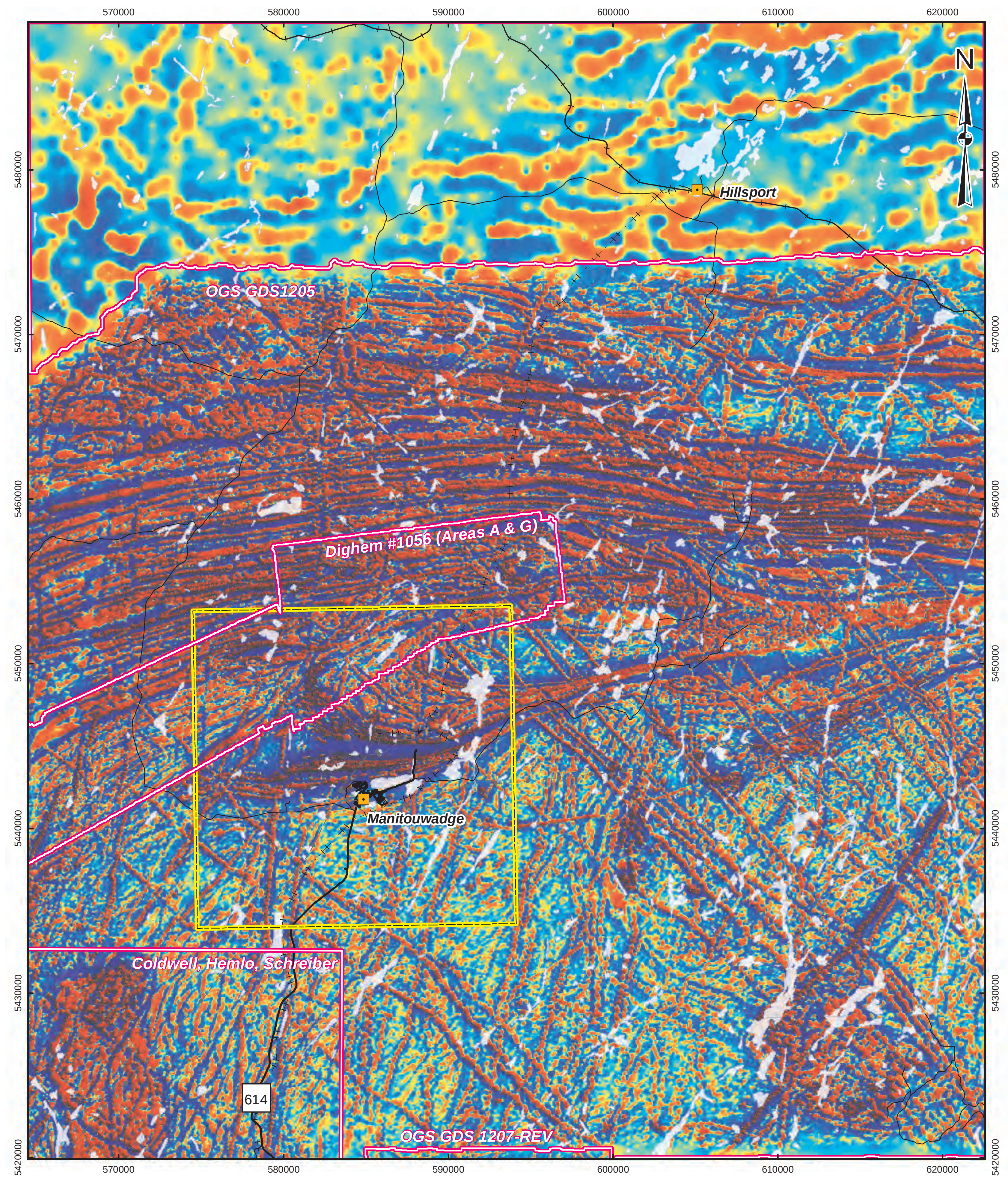
REVIEW	CN	20 Mar 2014		1:275,000

File: aecom_Fig 4 - Terrain Features of the Manitouwadge Area

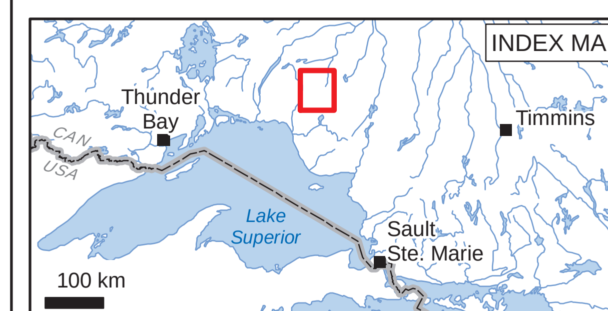


LEGEND

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

Residual Total 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



REFERENCE

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

10 km

srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

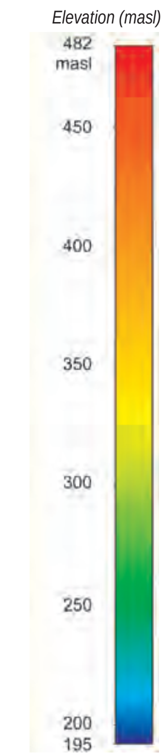
TITLE
Pole Reduced Magnetic Data (First Vertical Derivative) for the Manitouwadge Area

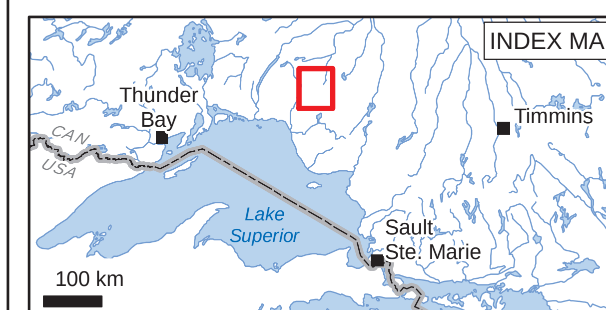
DESIGN	PRM	11 May 2012	Figure 5	REVISION 3
GIS	JA	15 Jan 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

Name: SRK_NWMO_MAN_Fig05_MAG.mxd

LEGEND

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





REFERENCE

Base Data: MNR LIO, obtained 2009-2013
NRC CDED Topography Data

10 km

srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

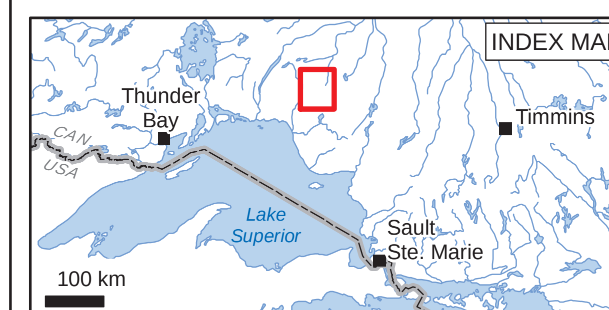
TITLE
CDED Digital Elevation Model for the Manitouwadge Area

DESIGN	PRM	11 May 2012	Figure 6	REVISION 3
GIS	JA	15 Jan 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

Name: SRK_NWMO_MAN_Fig06_DEM.mxd

LEGEND

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



REFERENCE

Base Data: MNR LIO, obtained 2009-2013
NRC LandSAT 7 OrthoImage (CanImage)

10 km

srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment,
Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Satellite Imagery Data (Landsat 7-4-1)
for the Manitouwadge Area

DESIGN	PRM	11 May 2012	Figure 7	REVISION 3
GIS	JA	15 Jan 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

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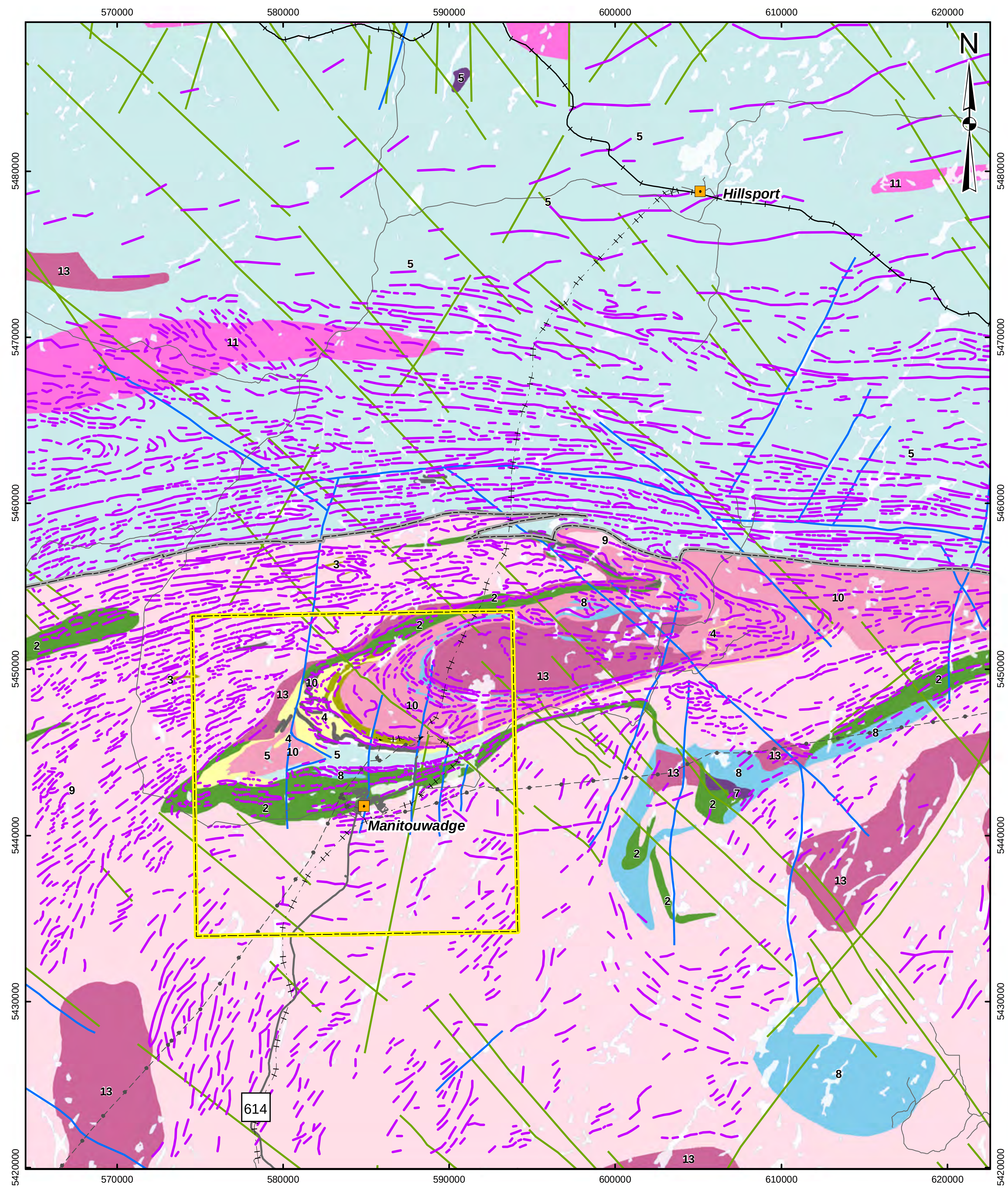
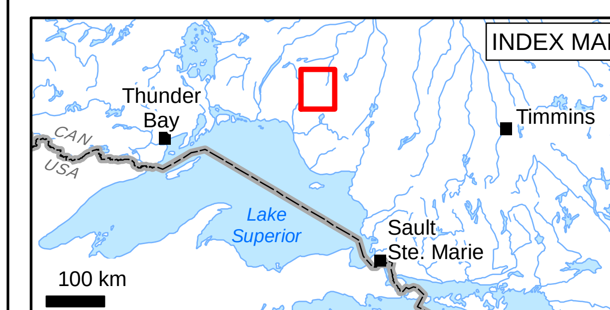


LEGEND

- Manitouwadge Municipal Boundary
- Settlement
- Main Road
- Local Road
- Railway
- Abandoned Railway Right-of-way
- Hydro Line
- Waterbody
- Mapped Fault
- Iron Formation
- Quetico - Wawa subprovince boundary
- Mapped Dyke
- Ductile Lineament

Bedrock Geology

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



REFERENCE

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

10 km

srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Ductile Lineaments of the Manitouwadge Area

DESIGN	PRM	11 May 2012	Figure 8	REVISION 3
GIS	JA	15 Jan 2014		UTM ZONE 16
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REVIEW	CN	20 Mar 2014		1:275,000

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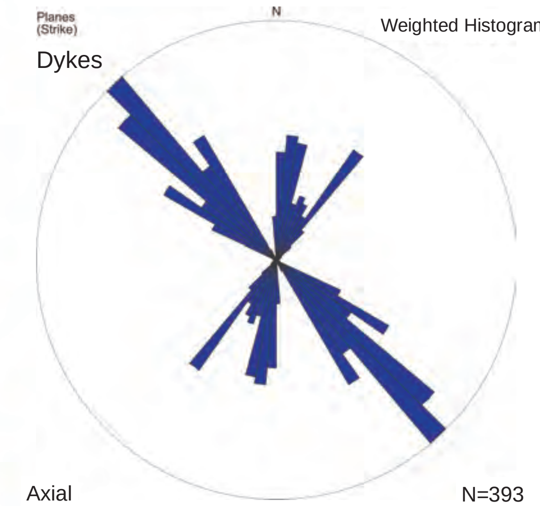
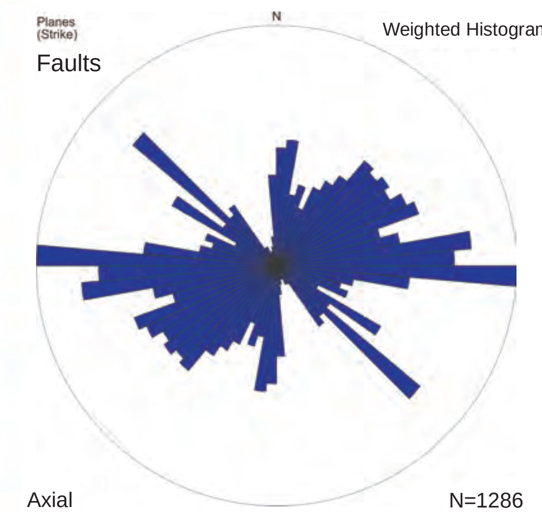




LEGEND

Manitouwadge Municipal Boundary

Settlement

Waterbody

Dyke (RA_1)

1

2

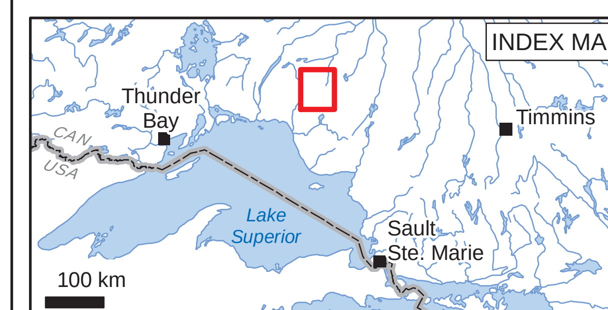
Fault (RA_1)

1

2

Residual Total 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



REFERENCE

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

10 km

srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Aeromagnetic Data
Reproducibility Assessment (RA_1)
for the Manitouwadge Area

DESIGN	PRM	11 May 2012	Figure 9	REVISION 4
GIS	JA	15 Jan 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

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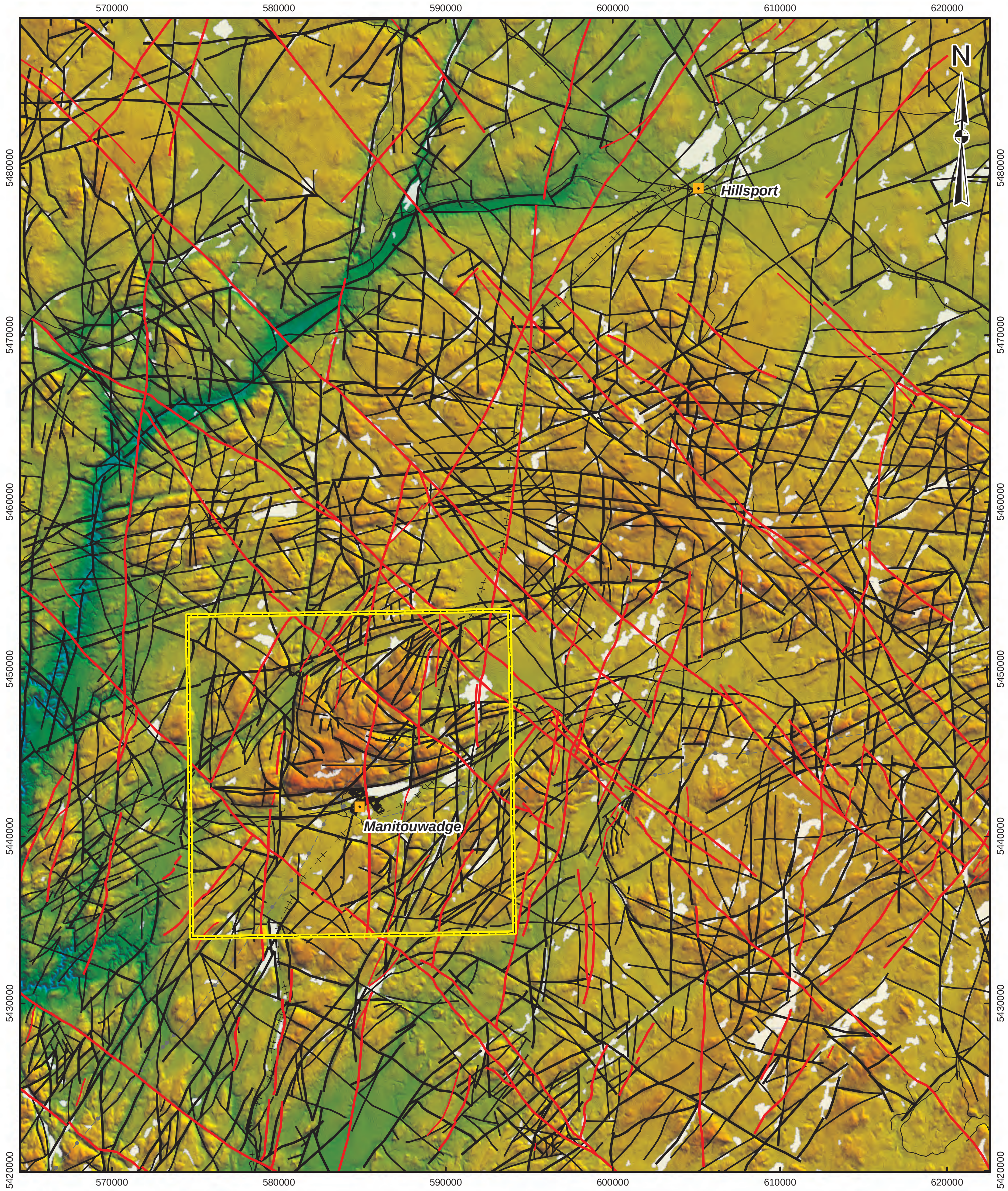
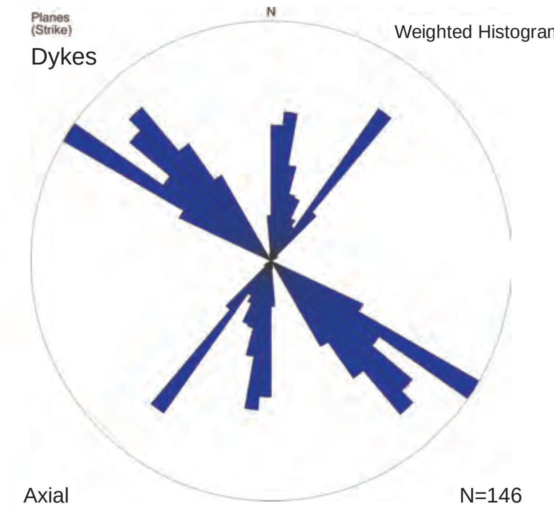
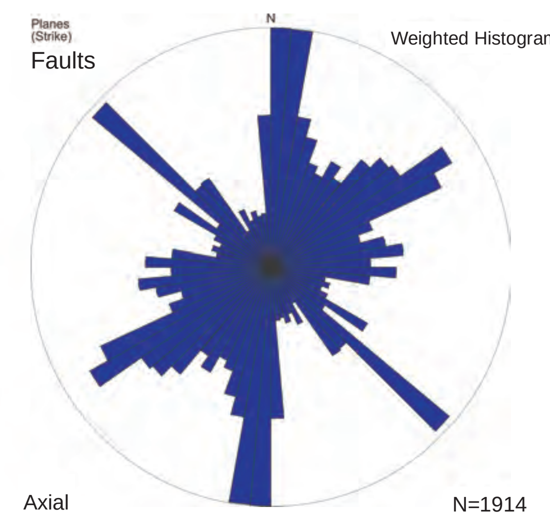






LEGEND

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

Dyke (RA_1)

- 1
- 2

Fault (RA_1)

- 1
- 2

Elevation (masl)

482 masl
450
400
350
300
250
200
195

REFERENCE

Base Data: MNR LIO, obtained 2009-2013
NRC CDED Topography Data

10 km

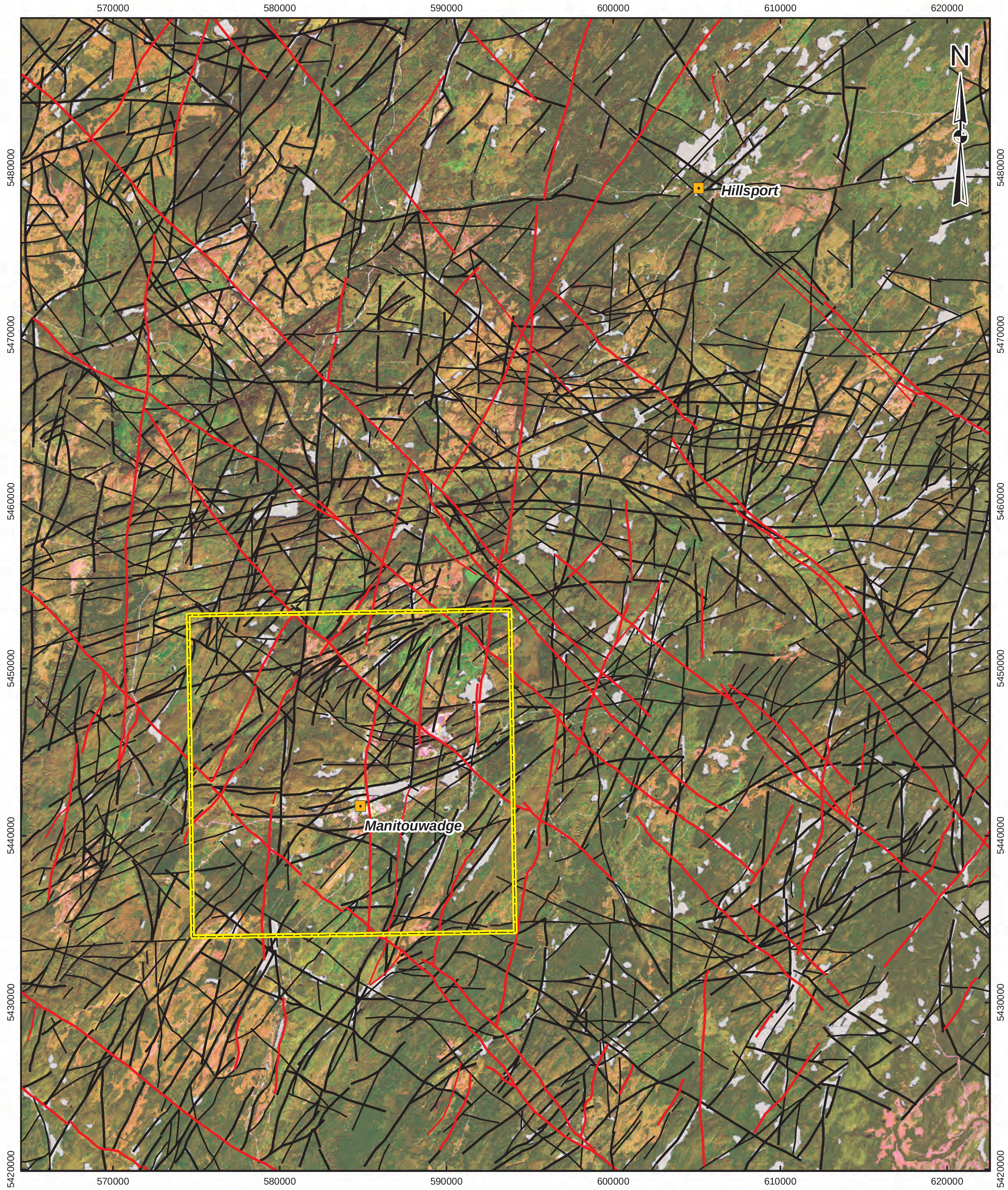
srk consulting

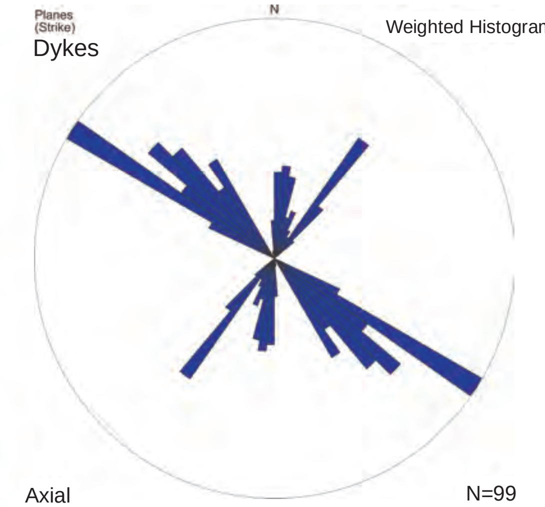
PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

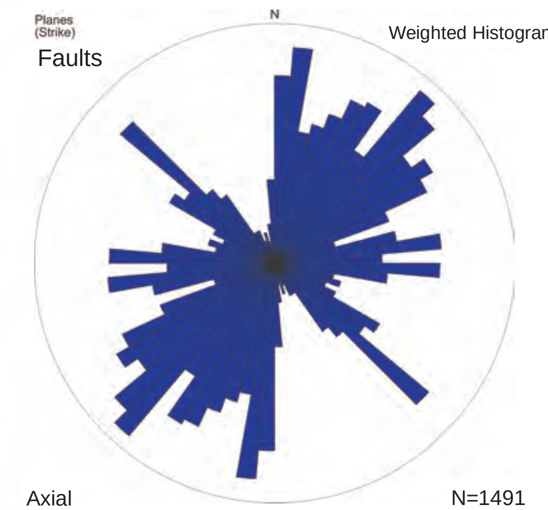
TITLE
CDED Topography
Reproducibility Assessment (RA_1)
for the Manitouwadge Area

DESIGN	PRM	11 May 2012	Figure 10	REVISION 4
GIS	JA	15 Jan 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

Name: SRK_NWMO_MAN_Fig10_DEM_ra1.mxd





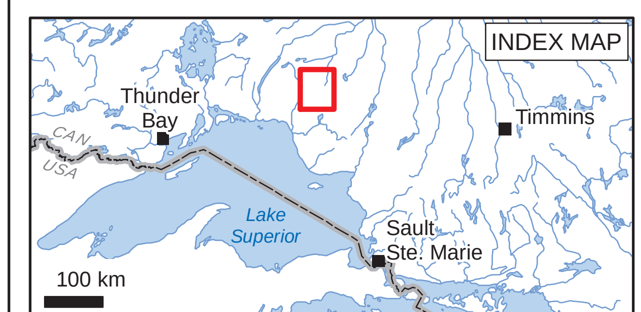


LEGEND

Manitouwadge Municipal Boundary
Settlement
Waterbody

Dyke (RA_1)
1
2

Fault (RA_1)
1
2



REFERENCE

Base Data: MNR LIO, obtained 2009-2013
NRC LandSAT 7 OrthoImage (CanImage)

10 km

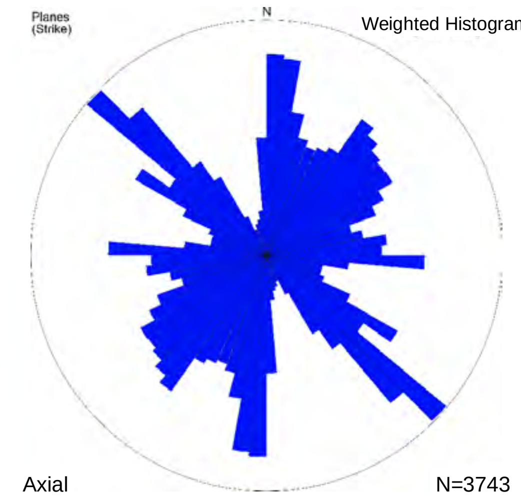
srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Satellite Imagery (Landsat) Reproducibility Assessment (RA_1) for the Manitouwadge Area

DESIGN	PRM	11 May 2012	Figure 11	REVISION 4
GIS	JA	15 Jan 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

Name: SRK_NWMO_MAN_Fig11_SAT_ra1.mxd



Length-weighted rose diagram of interpreted lineaments in the Manitouwadge area

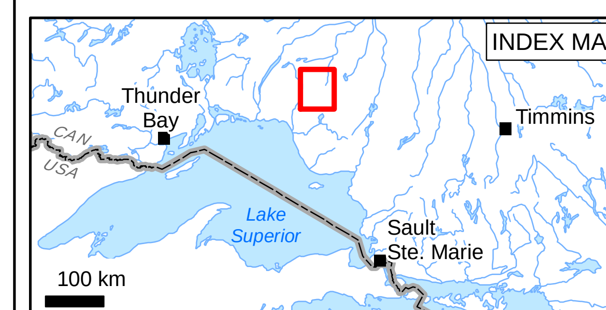
LEGEND

- Manitouwadge Municipal Boundary
- Settlement
- Waterbody
- Mapped Fault
- Iron Formation
- Batholith/Pluton boundary
- Quetico - Wawa subprovince boundary
- Mapped Dyke

Dyke (RA_2)	Fault (RA_2)
1	1
2	2
3	3

Bedrock Geology

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



REFERENCE

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

10 km

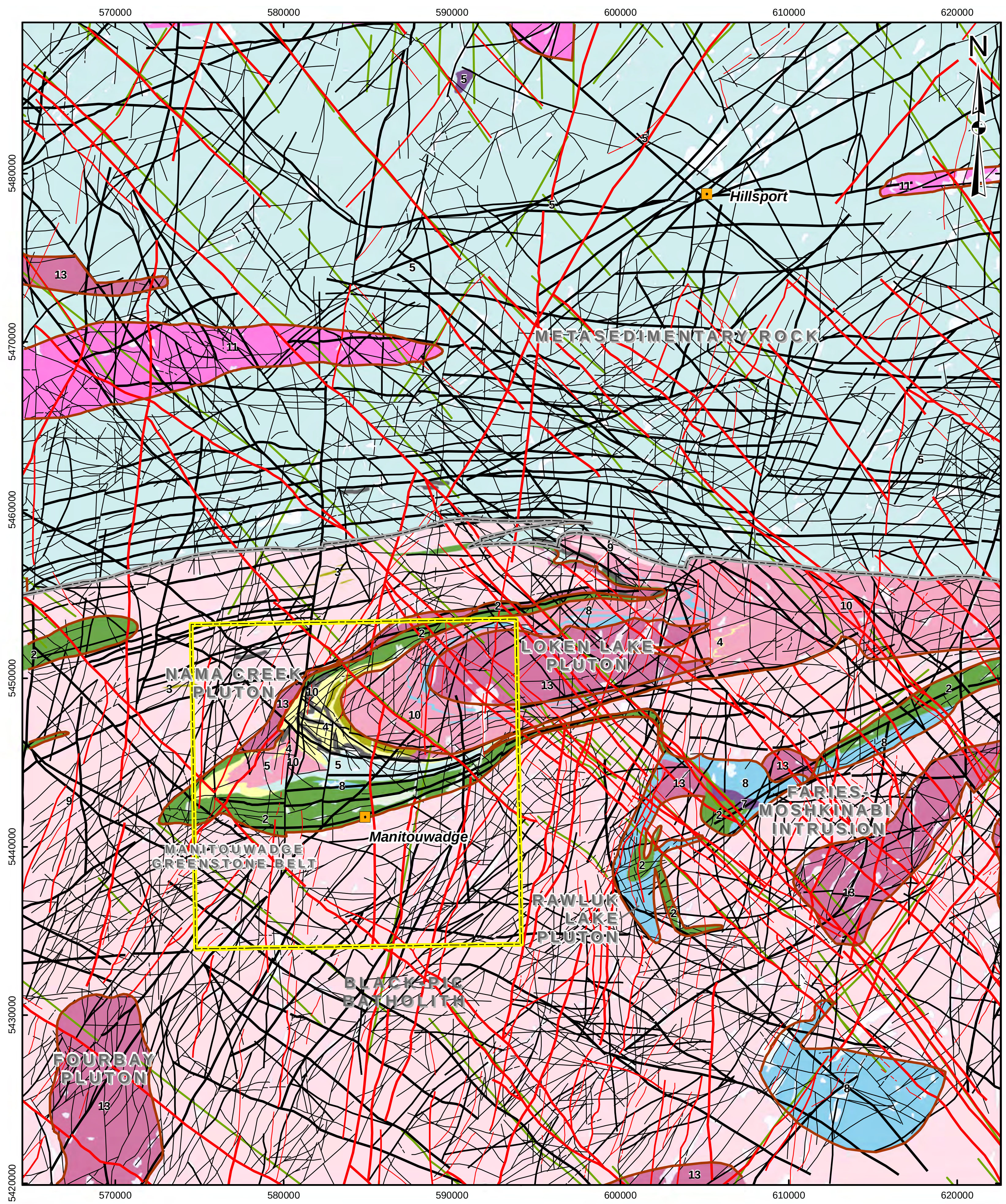
srk consulting

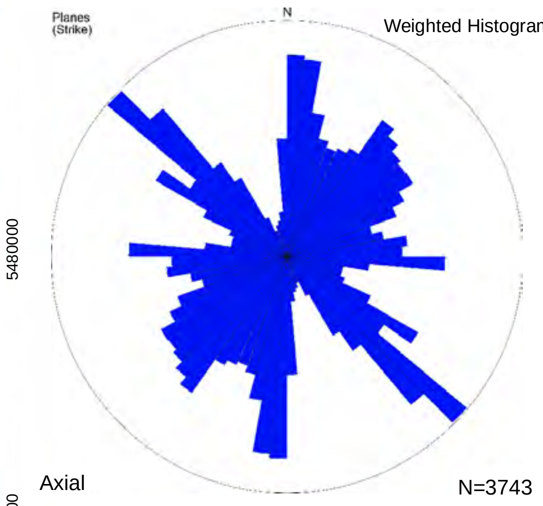
PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Lineament Classification by Reproducibility Assessment (RA_2) overlying bedrock geology of the Manitouwadge Area

DESIGN	PRM	11 May 2012	Figure 12	REVISION 3
GIS	JA	15 Jan 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

Name: SRK_NWMO_MAN_Fig12_RA2.mxd





Length-weighted rose diagram of interpreted lineaments in the Manitouwadge area

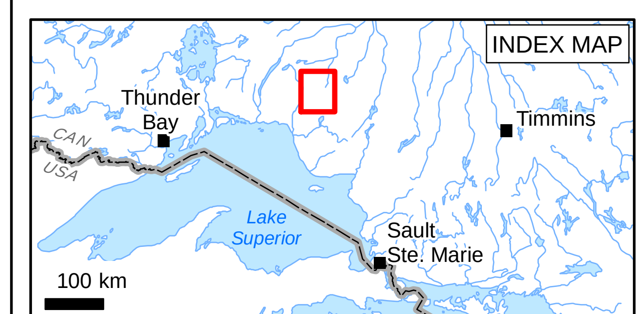
LEGEND

- Manitouwadge Municipal Boundary
- Settlement
- Waterbody
- Mapped Fault
- Iron Formation
- Batholith/Pluton boundary
- Quetico - Wawa subprovince boundary
- Mapped Dyke

Dyke (Length)	Fault (Length)
<1km	<1km
1-5	1-5
5-10	5-10
>10km	>10km

Bedrock Geology

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



REFERENCE

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

10 km

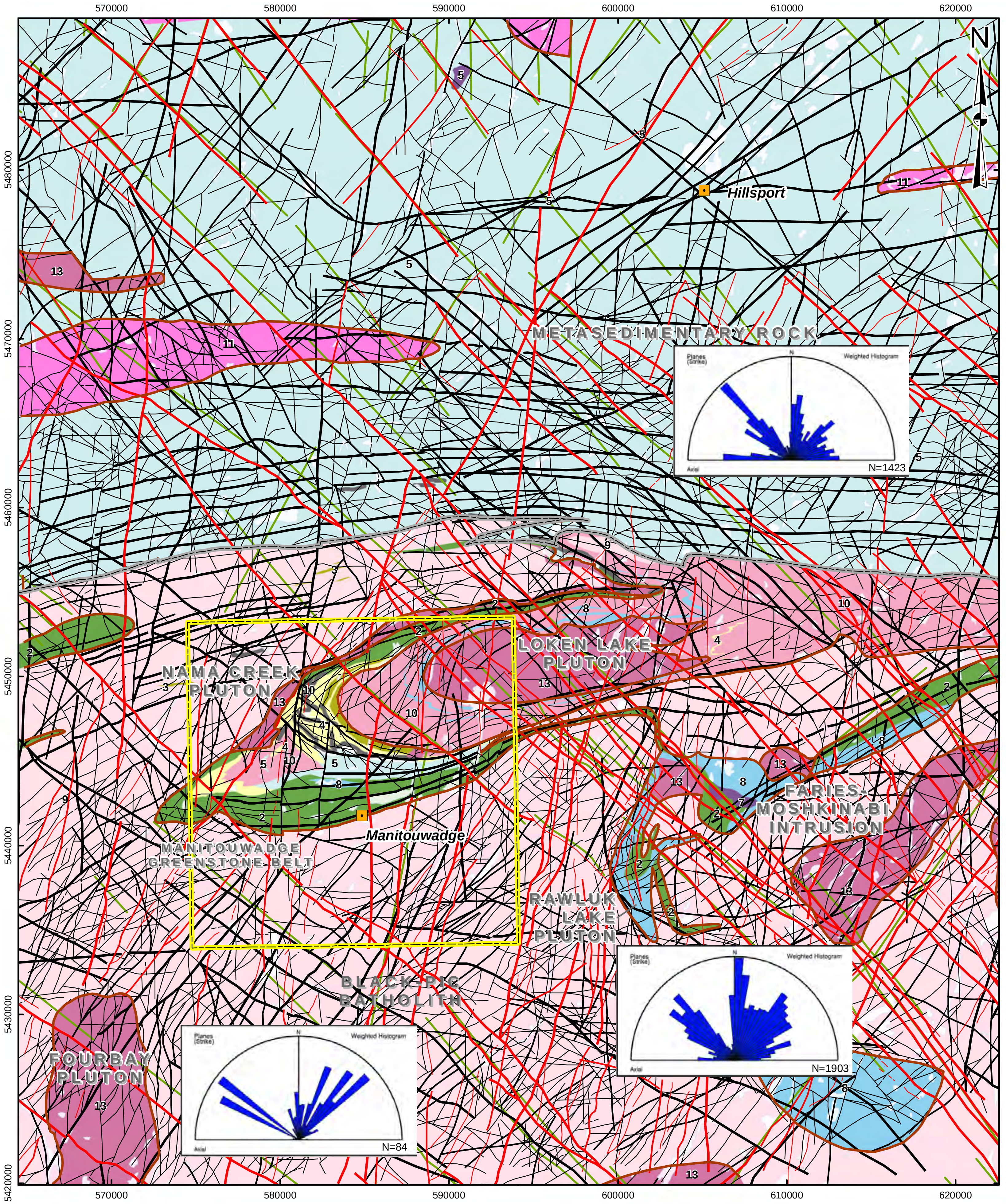
srk consulting

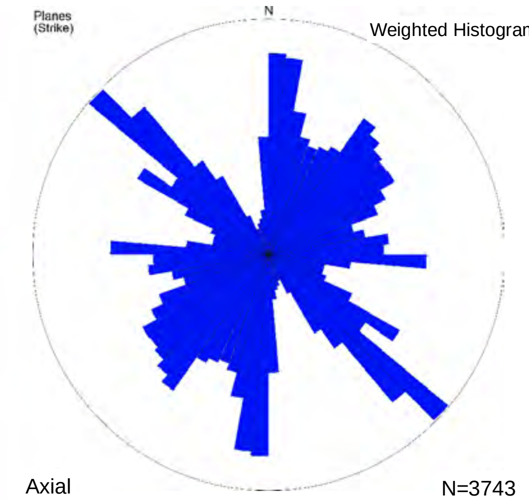
PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Lineament Classification by Length overlying bedrock geology of the Manitouwadge Area

DESIGN	11 May 2012	Figure 13	REVISION 4
GIS	15 Jan 2014		UTM ZONE 16
CHECK	20 Mar 2014		NAD 1983
REVIEW	20 Mar 2014		1:275,000

Name: SRK_NWMO_MAN_Fig13_Length.mxd





Length-weighted rose diagram of interpreted lineaments in the Manitouwadge area

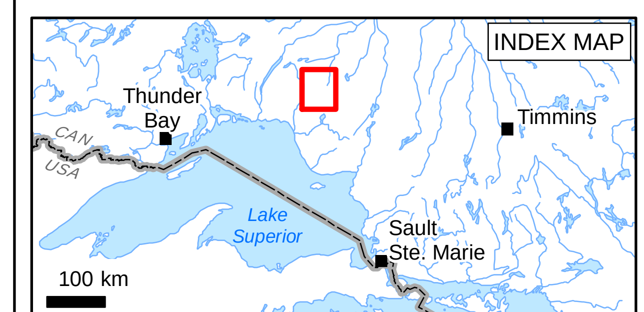
LEGEND

- Manitouwadge Municipal Boundary
- Settlement
- Waterbody
- Mapped Fault
- Iron Formation
- Batholith/Pluton boundary
- Quetico - Wawa subprovince boundary
- Mapped Dyke

Dyke (Length)	Fault (Length)
<1km	<1km
1-5	1-5
5-10	5-10
>10km	>10km

Bedrock Geology

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



REFERENCE

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

10 km

srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Manitouwadge Area, Ontario

TITLE
Lineament Distribution Relative to Lithological Units overlying bedrock geology for the Manitouwadge Area

DESIGN	PRM	11 May 2012	Figure 14	REVISION 4
GIS	JA	15 Jan 2014		UTM ZONE 16
CHECK	CN	20 Mar 2014		NAD 1983
REVIEW	CN	20 Mar 2014		1:275,000

Name: SRK_NWMO_MAN_Fig14_OrientationRoses.mxd