NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation

MUNICIPALITY OF WAWA, ONTARIO

APM-REP-06144-0030

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Phase 1 Geoscientific Desktop Preliminary Assessment

Lineament Interpretation
Municipality of Wawa, Ontario

Revision: 0 (Final)

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EXECUTIVE SUMMARY

In December, 2011 the Municipality of Wawa, Ontario expressed interest in continuing to learn more about the Nuclear Waste Management Organization nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the Wawa 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, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Municipality of Wawa and its perimery, referred to as the "Wawa area", contains general areas that have the potential to meet NWMO's gesocientific site evaluation factors.

This report presents the findings of a lineament investigation assessment completed as part of the desktop geoscientific preliminary assessment of the Wawa area (Geofirma, 2013). The lineament assessment focused on identifying surficial and geophysical lineaments and their attributes using publicly-available digital data sets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the Wawa area. The assessment of interpreted lineaments in the context of identifying general areas that have the potential to meet NWMO's geoscientific site evaluation factors is provided in the desktop preliminary geoscientific assessment report (Geofirma, 2013).

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, publicly-available data sets (aeromagnetic, CDED, SPOT and Landsat);
- 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, reproducibility and coincidence.

The distribution of lineaments in the Wawa area potentially reflects the bedrock structure, and the resolution of the data sets used. Surface lineament density, as demonstrated in this assessment, is not influenced by overburden cover due to the limited overburden cover and the exposed rugged bedrock terrain across the Wawa area. Lineament density, however, is influenced by the resolution of the data sets as demonstrated by the comparison of aeromagnetic lineaments interpreted from low resolution surveys with surficial (CDED and Landsat/SPOT) datasets. The results of the assessment suggest that highest lineament densities are in the Brulé Bay batholith and the lowest lineament densities are in the Wawa Gneiss domain. The lineament densities in the Western batholith and Whitefish Lake batholith are between those of Brulé Bay batholith and the Wawa Gneiss domain.

It may be possible, with further detailed investigation, to assign the formation of the identified lineaments to distinct deformation events. However, it is difficult at the desktop stage to provide any further constraint on the timing of lineament development beyond denoting all identified lineaments as composite D_3-D_7 structures that were formed during a protracted period of time post-dating 2.671 billion years ago.

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1 INTRODUCTION

In December, 2011 the Municipality of Wawa, Ontario expressed interest in continuing to learn more about the Nuclear Waste Management Organization nine-step site selection process (NWMO 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the Wawa area for safely hosting a deep geological repository (Step 3).

The overall preliminary assessment of potential suitability is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations (NWMO, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Wawa 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 assessment completed as part of the desktop geoscientific preliminary assessment of the Wawa area (Geofirma, 2013). The lineament assessment focussed on identifying surficial and geophysical lineaments and their attributes using publicly-available digital data sets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the Wawa area. The assessment of interpreted lineaments in the context of identifying general areas that have the potential to meet NWMO's geoscientific site evaluation factors is provided in the desktop preliminary geoscientific assessment report (Geofirma, 2013). The lineament assessment focused on the Municipality of Wawa and its periphery, referred to as the "Wawa area".

1.1 Scope of Work

The scope of work for this assessment includes the completion of a lineament interpretation of remotely-sensed data sets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the Wawa area (approximately 4,274 km^2 including Lake Superior), in northern Ontario (Figure 1). The lineament investigation interprets the location and orientation of possible individual fractures or fracture zones and helps to evaluate their relative timing relationships 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 mapped from multiple, publicly-available data sets that include satellite imagery (Système Pour l'Observation de la Terre - SPOT and Landsat), digital elevation models (DEM, Canadian Digital Elevation Data; CDED), and aeromagnetic geophysical survey data;
- Lineament interpretations from each source data type were made by two documented specialist observers for each data set;
- Lineaments were analyzed based on an evaluation of the quality and limitations of the available data sets, age relationships, reproducibility tests, particularly the coincidence of lineaments extracted by different observers, coincidence of lineaments extracted from different data sets, and/or documentation in literature; and
- Classification was done to indicate the significance of lineaments based on orientation, length, reproducibility and coincidence.

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

- ***Ductile lineaments:*** 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:*** For this preliminary desktop interpretation, any 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 Wawa area.

The desktop interpretation of remotely-sensed datasets necessarily includes a component of uncertainty as a result of data quality, scale of Wawa area, expert judgement, and to a certain extent, the quality of the pre-existing knowledge of the bedrock geology of the Wawa area. Therefore the ductile, brittle or dyke categorization of each identified feature, as described herein, is preliminary, and would need to be confirmed during future stages of the site evaluation process.

1.2 Qualifications of the Interpretation Team

The project team employed in the lineament interpretation component of the Phase 1 geoscientific desktop preliminary assessment of potential suitability consisted of qualified experts from Geofirma Engineering Ltd, Ottawa, J.D. Mollard and Associates (2010) Limited, Regina (JDMA), Patterson, Grant & Watson, Toronto (PGW) and Stott Geoconsulting Ltd., Sudbury. Geofirma coordinated the lineament assessment and completed interpretation of surficial lineaments from satellite and CDED data sets. PGW and Stott Geoconsulting conducted the lineament interpretation on the geophysical data, and JDMA provided interpretation of surficial lineaments.

The following is a brief description of the qualifications and roles of key project team members.

Kenneth Raven, M.Sc., P.Eng. P.Geo. is President of Geofirma Engineering Ltd. He has over 30 years' experience in lineament mapping and structural geological interpretation in Canadian Shield settings, included mapping and interpretation of air photo and airborne geophysical data sets at numerous mine sites, and Atomic Energy of Canada Ltd. research areas investigated as part of the Canadian Nuclear Fuel Waste Management Program. He also completed similar lineament studies at the Chalk River Laboratories in the mid-1990s as part of a siting study for a cavern storage facility for low level radioactive waste. Mr. Raven reviewed Geofirma identification of surficial lineaments and provided overall review of the lineament assessment including final lineament merging and interpretation.

Dr. Pouran Behnia, Ph.D. of Geofirma Engineering Ltd. is a geologist with more than 14 years of professional and academic GIS experience in remote predictive mapping using multispectral (Landsat, SPOT, ASTER, GeoEye) and hyperspectral data, integrating geo-exploration data for mineral prospect analysis; and landslide susceptibility mapping using knowledge and data driven methods. She has technical expertise with GIS applications, data integration procedures, data management and visualization. Dr. Behnia recently completed a 3-year post-doctoral placement with the Remote Sensing Division of the Geological Survey of Canada and has completed remote predictive mapping of Canada's North using satellite, DEM and geophysical data sets Dr. Behnia completed identification of surficial lineaments from DEM and satellite imagery data sets.

Sean Sterling, M.Sc., P.Eng., P.Geo. is a senior geoscientist with Geofirma Engineering Ltd. He. has 18 years of specialized experience and expertise in characterization and investigation of fractured bedrock sites including use of Ontario GIS geomapping datasets. He recently provided senior geoscience direction to NMWO on geoscientific characterization of the Bruce nuclear site for hosting a deep geologic repository for low and intermediate level radioactive wastes. Mr. Sterling supervised merging of individual geophysical, DEM and satellite lineament data sets and the final lineament interpretation, as well as development of merging rules and calculation of lineament statistics.

Dru Heagle, Ph.D., P.Geo. is a senior geoscientist with Geofirma Engineering Ltd. He has 16 years of geoscience experience in regional geological/hydrogeological characterization, site characterization and environmental monitoring of the Bruce nuclear site for NWMO, and integrated use of geological, hydrogeological and hydrogeochemical data sets. He has worked as a Research Assistant and Scientist at the Universities of Waterloo and Calgary. Dr. Heagle completed review of this Lineament Interpretation Report.

Lynden Penner, M.Sc., P.Eng., P.Geo. is President of JDMA. He has undertaken the advancement of lineament research through the application of aerial and satellite imagery, DEMs, and GIS technology for a variety of projects including oil and gas exploration, potash mine development, groundwater exploration and contamination, CO_2 sequestration studies, and assessing gas leakage from oil and gas wells beginning in 1986 and continuing to present. Given his expertise in mapping and understanding lineaments, Mr. Penner advised JDMA project team members on lineament mapping approaches and reviewed JDMA mapping of surficial lineaments from remotely sensed imagery.

Dr. Jason Cosford, Ph.D., P.Geo. has contributed to a wide range of terrain analysis studies conducted by JDMA, including routing studies (road, rail, pipeline, and transmission line), groundwater exploration, granular resource mapping, and environmental sensitivity analyses. Dr. Cosford provided JDMA interpretation of the surficial lineaments from DEM and satellite imagery data sets.

Dr. James Misener, Ph.D., P.Eng. is President of PGW and a senior geophysicist with 37 years of experience in all aspects of geophysics and geophysics software applications. Dr. Misener founded Geosoft Inc. and led its development of world-leading geosciences software applications until he succeeded Dr. Paterson as President of PGW. He completed mapping of geophysical lineaments.

Dr. Greg Stott, Ph.D. of Stott Geoconsulting Ltd. has mapped and written extensively on structural/tectonic evolution of the Quetico, Wabigoon, Uchi and Wawa Subprovinces of the Superior Province of the Canadian Shield, including interpretation of airborne geophysical surveys. He has over 30 years' experience in structural geological mapping of the Superior Province of the Canadian Shield with the Geological Survey of Canada and with the Ontario Geological Survey. Dr. Stott completed mapping of geophysical lineaments including ductile lineaments, and also provided text on the structural and geological history of the Wawa area.

1.3 Report Organization

Section 2 describes the geological setting of the Wawa area, which includes subsections on physical geography, bedrock geology, geological and structural history, Quaternary geology, and land use. Section 3 provides information on the source data and explains the methodology used to identify and assess lineaments. Section 4 presents the findings of the lineament interpretation with a description of lineaments by each data set and a description and classification of integrated lineaments. Section 5 offers a discussion of the findings, specifically the lineament density, reproducibility and coincidence, lineament length, fault and lineament relationships, and relative age relationships. Section 6 is a summary of the report. References and signature page are provided in Sections 7 and 8. Report figures are provided at the end of the report.

The primary source for all of the background information presented herein is the main report written by Geofirma (2013). This report also draws upon information from the supporting reports on terrain analysis (JDMA, 2013) and geophysics (PGW, 2013).

2 SUMMARY OF PHYSICAL GEOGRAPHY AND GEOLOGY

The Wawa area is underlain by a thin veneer of glacial soils and the approximately 3.0 to 2.6 billion year old bedrock of the Superior Province of the Canadian Shield – a stable craton that forms the core of the North American continent (Figure 2). The Canadian Shield is an assemblage of Archean-age plates and accreted juvenile arc terranes and sedimentary basins of Proterozoic age that were progressively amalgamated over geologic time scales. Figure 2 shows that there have only been two earthquakes, both of Nuttli magnitude less than 3, recorded within the region surrounding the Wawa area since seismic data collection started in 1985 (NRCan, 2012). No events were located in the Wawa area itself.

The Superior Province has been divided into various regionally extensive east-northeast-trending subprovinces based on lithology, age, genesis and metamorphism (e.g., Langford and Morin, 1976; Card and Ciesielski, 1986; Card, 1990). The Wawa area is located in the southeastern portion of the Wawa Subprovince; a belt of rocks about 900 km long and 150 km wide, extending from central Minnesota in the United States to the Kapuskasing area in northeastern Ontario. The Wawa Subprovince is bounded on the north by the metasedimentary rocks of the Quetico Subprovince, and to the south by Proterozoic aged (approximately 1.9 to 1.1 billion-year old) rocks of both the Southern Province and rocks associated with the Mid-continent Rift system. About 50 km to the east, the Wawa Subprovince is truncated by the Kapuskasing structural zone that separates the Wawa Subprovince from the Abitibi Subprovince (and is sometimes referred to as the Abitibi-Wawa belt).

More recently, the regional subdivisions have been revised and distinct tectonic areas are now discussed in terms of lithotectonic terranes and domains (Percival and Easton, 2007; Stott et al., 2010). Terranes are defined as tectonically bounded regions with characteristics distinct from adjacent regions prior to their accretion into the Superior Province, whereas domains refer to lithologically distinct portions within a terrane (Stott et al., 2010). The Wawa area is located in the Wawa-Abitibi Terrane. Although most of the literature reviewed for this assessment retains the older terminology, for the purpose of this report, both terms subprovince and terrane have been retained, choosing one over the other when it is believed to be more appropriate.

2.1 Physical Geography

A detailed discussion of the physical geography of the Wawa area is provided in a separate terrain analysis report (JDMA, 2013) and the following is a summary of that information.

The Wawa area exhibits topographic and drainage features that are characteristic of the Canadian Shield physiographic region in the vicinity of the Great Lakes, elevated topography that ranges from dome-like highlands in the north and eastern parts of the area, that drain though deep bedrock valleys to Lake Superior (Figure 5). Topography in the Wawa area is generally rugged and hilly with roughly 424 m of relief variation, ranging from a minimum elevation of about 183.2 mASL (metres above sea level) at Lake Superior to a maximum elevation of about 607 mASL or more within the bordering highlands across the Wawa area. Topographic highs generally correspond to bedrock outcrops while topographic lows are generally areas of thicker overburden in bedrock valleys. Bedrock terrain covers roughly 75% of the Wawa area (Figure 4). Bedrock terrain includes exposed bedrock and thin, discontinuous drift deposits generally less than one metre thick.

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The Wawa area contains a large number of lakes of various sizes (Figure 1), four of which are larger than 10 km^2 (Lake Superior, Manitowik Lake, Whitefish Lake and Anjigami Lake) and two of which are larger than 20 km^2. Excluding Lake Superior, all of the other lakes cover only about 7% of the Wawa area (JDMA, 2013). The large lakes are sufficiently large to conceal lineaments up to about ten kilometres in length, and nests of lakes have additional potential to conceal or reveal lineaments, especially when the lakes are located in areas where lineaments are obscured by overburden deposits (see also Section 2.4). There is considerable relief between the lakes in most areas.

2.2 Bedrock Geology

The bedrock geology of the Wawa area is described in detail in Geofirma (2013) and the following is a summary of that information.

Figure 3 shows the general bedrock geology and main structural features of the southeastern part of the Wawa Subprovince, where the Wawa area is located. The bedrock geology is composed predominantly of irregularly distributed Archean greenstone belts (Michipicoten, Gamitagama, and Mishibishu) surrounded by granitic bodies of various compositions and sizes, with smaller mafic intrusive rocks locally present. The Michipicoten greenstone belt makes a regional reference point, and the surrounding granitoid terranes are named differently on its southern and northern flanks.

To the south, between the Michipicoten greenstone belt and the Kapuskasing structural zone, the granitoid terrane is referred to as the Wawa Gneiss domain (Thurston et al., 1977; Moser, 1994). The granitoid terrane to the west of the Michipicoten greenstone belt is generally referred to as the Western batholith (Card and Poulsen, 1998). The Western batholith and Wawa Gneiss domain, along with the Whitefish Lake and Brulé Bay batholiths (Figure 3) were identified as geological formations with geoscientific characteristics that are potentially suitable for hosting a deep geological repository within the Wawa area (Geofirma, 2011). Mafic (diabase) dykes, largely of Proterozoic age, occur in “swarms” across the entire region, including in the Wawa area (Figure 3).

2.2.1 <u>Western Batholith</u>

The Western batholith is located in the northwestern corner of the Wawa area (Figure 3). The composition of the Western batholith is based largely on OGS mapping (Reilly 1991, Reid et al., 1991, and Vaillancourt et al., 2005b) covering different sections of the batholith and adjacent greenstone belts. The Western batholith (part of the Pukaskwa batholith of Reid et al., 1991) has been subdivided into areas dominated by three compositionally distinguishable plutonic suites: gneissic tonalite; foliated tonalite, granodiorite and quartz diorite; and massive granite, granodiorite, quartz diorite to local diorite. All the suites are approximately 20 to 30 km long and 10 to 15 km wide. There is no information available on the thickness of these units. Turek et al. (1984) dated the gneissic tonalite suite at approximately 2.698 billion years old.

Reilly (1991) reported that the north to northwestern margin of the Western batholith shows a transition of rafted inclusions, mafic intrusions and migmatitic textures along the granite-greenstone contacts. In addition, there is evidence of an aureole of contact strain and metamorphism imposed by the batholith on the adjacent greenstone belt rocks up to 1 km wide (Reilly, 1991). The complexity of transition along the boundary suggests that the contact is marked not only by shearing, but sheet-like intrusions of granitic magma into the adjacent amphibolitic basalt with local rafted inclusions of amphibolite and felsic dykes injected from the adjacent phase of the batholith.

On the eastern side of the Western batholith, Vaillancourt et al. (2005b) have subdivided it into two phases in western Menzies Township: a metamorphosed, coarse to medium-grained tonalite to diorite phase, and a younger massive granodiorite intrusion. Unlike the older tonalite phase with a semi-conformable contact with the adjacent greenstone strata, the latter pluton scalloped more deeply, crosscutting the adjacent volcanic stratigraphy and appears to have intruded as a separate plug. In the compilation map of Santaguida (2001), these two bodies lie within a singular massive, arcuate granodiorite intrusion separating the foliated to locally gneissic tonalite-granodiorite in the core of the Western batholith from the main Wawa greenstone belt to the north. The relationship between the metamorphosed tonalite intrusion, occupying southwestern Menzies Township, and the western half of the Western batholith is unclear.

Mapping by Reid et al. (1992a, 1992b and 1992c) suggests a more uniform composition and fabric in the western half of the batholith. Most of the western half of the Western batholith was mapped as part of a multi-year OGS mapping project centred on the Mishibishu Lake greenstone belt (Reid et al., 1991). Their focus was on the greenstone belt and the batholith received less intensive coverage but with sufficient detail to permit some generalizations. From their data, most of the batholith is composed of massive to foliated biotite and hornblende-biotite tonalite to granodiorite with only local gneisses.

The results of the review of available geoscientific information completed by Geofirma (2013) indicate that previous mapping of much of the Western batholith by Reid et al. (1992a, b, c) could be re-visited owing to the rather generalized style of mapping granitic batholiths 20 years ago. However, sufficient information from previous maps suggests that the Western batholith is probably characterized by a broad zone of migmatitic interlayers and inclusions of mostly amphibolitic, supracrustal rocks enveloped as sheet-like inclusions within tonalite gneiss along the greenstone belt margins. The batholith also appears to contain less inclusion-rich foliated tonalite to diorite intrusions (e.g., in Menzies Township) and a large younger granodiorite pluton, which particularly dominates the western third of the batholith.

2.2.2 Wawa Gneiss Domain

The Wawa Gneiss domain was mapped and described by Moser (1994 and references therein) in a region just east of the Wawa area. It is a 10 to 15 km thick array of tonalitic and granodioritic orthogneiss and plutons surrounding extensive bodies of amphibolite- to granulite grade mafic gneiss and paragneiss (Jackson and Sutcliffe, 1990; Percival, 1990; Moser, 1994). The gneiss domain is dominantly composed of tonalite to granodiorite gneiss and foliated tonalite but, within the Wawa area, it has not been adequately mapped to provide much insight. East of the Wawa area the gneisses are northwest-trending and curvi-planar (Bursnall et al., 1994). West of the eastern limit of the Wawa area the foliation trend in the gneisses is west to southwest (Moser 1994, p.1067). East of the greenstone belt and Hawk Lake, the gneiss domain is composed of a mix of quartz diorite to tonalite with one U-Pb zircon age of approximately 2.746 billion years, comparable to the age of the second cycle (Wawa assemblage) in the greenstone belt (Turek et al., 1982). Evidence of similar comparable ages, within adjacent granitoid terrains, to volcanic assemblages reflects the widespread presence of syn-volcanic magma chambers preserved within external batholiths of relatively older metamorphosed tonalite to quartz diorite.

What can be inferred from a reconnaissance mapping by Card (1979, 1982) is the presence of large, younger, and more massive to foliated granodiorite batholithic bodies, like the Whitefish Lake batholith, that intruded the tonalite gneiss in the Wawa Gneiss domain (Figure 3). These late tectonic intrusions are similar to the very large late tectonic granitic batholiths in the Ignace area and across the Berens River region to northwest of Pickle Lake in northwestern Ontario. They are most likely tabular or pancake-shaped owing to their large horizontal width relative to known depths of the crust.

2.2.3 Whitefish Lake / Brulé Bay Batholith

The Whitefish Lake batholith (Williams et al., 1991) is a massive granodiorite to granite intrusion within the Wawa Gneiss domain, making up much of the central eastern portion of the Wawa area (Figure 3). This intrusion has been dated at approximately 2.694 billion years old (Turek et al., 1984). South of the extension of the Michipicoten greenstone belt which bisects the batholith, the batholith has previously been referred to as the Brulé Bay batholith (McCrank et al., 1981). The Whitefish Lake-Brulé Bay batholiths cover an approximate elongated area with northeast and southwest axes of approximately 62 km by 15 km, respectively. No specific information was found on the thickness of these two granitic bodies, though as part of the regional granitoid terrane, they would likely exceed several km in thickness (Percival, 1990).

There has been very little mapping related to the Whitefish Lake-Brulé Bay batholiths and surrounding Wawa Gneiss domain. Williams et al. (1991; p. 510 therein) note that reconnaissance mapping by Card (1979, 1982) attempted to subdivide the granitoid complexes into older tonalitic bodies and younger granodiorite to granite intrusions. Thus, the Whitefish Lake batholith and Brulé Bay batholiths, as outlined by Johns and McIlraith (2002), are derived from the east-central sheet, Bedrock Geology of Ontario Map 2543 (OGS, 1991), which in turn bases the batholiths on Card (1979, 1982) who conducted regional reconnaissance roadside outcrop visits. Hence, the general subdivisions of the granitoid regions in the Wawa Gneiss domain and enclosed batholiths are largely based on reconnaissance mapping.

2.2.4 Greenstone Belts

There are three greenstone belts within the Wawa area: the Michipicoten, Gamitagama and Mishibishu greenstone belts (Figure 3). These greenstone belts are supracrustal assemblages formed by mafic to felsic volcanic cycles between approximately 2.9 and 2.7 billion years ago. The economic and regional geology, as well as structural setting of the Michipicoten, Mishibishu and Gamitagama greenstone belts are summarized by Williams et al. (1991). The Michipicoten greenstone belt is a structurally and stratigraphically complex assemblage of volcanic, sedimentary and intrusive rocks, metamorphosed to greenschist facies and localized amphibolite facies (Williams et al., 1991; Sage, 1994).

The only significant developments subsequent to the Williams et al. (1991) summary are additional age determinations (e.g., Turek et al., 1992; Vaillancourt et al., 2005a); geological mapping by Vaillancourt et al. (2005b) in the Menzies Township area; papers summarizing research on the Kapuskasing structural zone (e.g. Moser, 1994; Percival and West, 1994; and Halls et al., 1994); and papers describing a comparatively unique Archean suite of diamondiferous lamprophyres and related diatreme breccias in the Menzies and Musquash Townships (e.g., Wyman et al., 2006 and references therein). This additional information provides constraints on the interpreted orogenic evolution of the

Wawa region, modelled in a shallowly dipping plate subduction setting. The Michipicoten greenstone belt is the largest of the greenstone belts in the Wawa area and is further described below.

The Michipicoten greenstone belt has been subdivided into three cycles (tectonic assemblages) of bimodal mafic to felsic volcanism erupted episodically at approximately 2.888 billion years ago (Hawk assemblage), approximately 2.736 to 2.750 billion years ago (Wawa assemblage), and approximately 2.7 billion years ago (Catfish assemblage) (Turek et al., 1982: 1984; Vaillancourt et al., 2004; Ayer et al., 2003). Preservation of the oldest cycle is limited to a small area in the vicinity of Hawk Lake on the eastern margin of the Wawa belt along with a subvolcanic intrusion. The other two cycles are interleaved and folded across the width of the belt. An imprecisely dated episode of emplacement of diamondiferous lamprophyric dykes and related diatreme breccias occurred approximately 2.674 billion years ago (Stott et al., 2002; Ayer et al., 2003). Clastic sedimentation followed as evidenced from the presence of diamonds and other gems deposited in polymictic conglomerate. The main period of regional shortening and batholithic uplift overlapped with sedimentation and also affected the late diatreme breccias. The late tectonic, approximately 2.673 billion year old, syenitic Dickenson Lake stock (Turek et al., 1990) intrudes the greenstone belt rocks and is approximately coeval at 2.677 billion years ago with the diamondiferous breccias and lamprophyre dykes (Stott et al., 2002).

2.2.5 Mafic Dykes

Mapping of the swarms of mafic diabase dykes in the Wawa area was compiled by Santaguida (2001) and Johns and McIlraith (2002). There are two main sets of diabase dykes that intrude all rock types in the Wawa area (Figure 3.4). The first set consists of the dominant northwest-trending and subvertically-dipping Matachewan swarm of dykes (Bates and Halls, 1991; West and Ernst, 1991; Phinney and Halls, 2001). The Matachewan dykes, reaching up to 40 m in width, were emplaced between approximately 2.473 and 2.446 billion years ago in the area between Lake Superior and James Bay (Phinney and Halls, 2001). The approximately 1.141 billion years old Abitibi (Ernst and Buchan, 1993) and approximately 2.167 billion years old Biscotasing (Hamilton et al., 2002) dyke swarms comprise subvertical, northeast-trending structures. A potential origin of the northeast-trending diabase dykes in relation to uplift of the Kapuskasing structural zone has been posed by Halls and Davis (2004). Others of this northeast-trending set are related to the approximately 2.126 to 2.101 billion year old Marathon swarm (Halls et al., 2008). Both northwest and northeast-trending sets of dykes are compositionally indistinguishable.

Sage (1994) and Vaillancourt et al. (2003) also reported a younger set of dykes identical to the older ones, which occupy the same system of fractures, with northwest and northeast trends, and are of presumed Proterozoic age. At least some of the northeast-trending dykes are of Keweenawan age, approximately 1.142 billion years old (Vaillancourt et al., 2003; Massey, 1985), coincident with the development of the Mid-continent Rift and opening of a small, linear ocean basin that underlies Lake Superior.

2.2.6 Faults

Faults are a common feature of the bedrock in the Wawa area (Figure 3), with eleven named and numerous other unnamed faults included in the OGS bedrock geology database. In general, there are three main orientations of mapped faults, trending northwest, north and northeast (McGill and Shrady, 1986; Sage, 1994; Manson and Halls, 1997). The relative ages of regional faulting across the Wawa area suggest that the oldest faults (which are largely unmapped) tend to trend east, overprinted by northwest and northeast-trending faults, followed by late north-trending faults.

Northwest-trending faults include the Trembley, Black Trout Lake, Mildred Lake, Marsden and Treeby faults. The largest of these are the Trembley, Mildred Lake and Marsden faults, which range from 12 to 55 km in length in the Wawa area. These northwest-trending faults are aligned with the Matachewan swarm diabase dykes which were emplaced approximately 2.45 billion years ago (Phinney and Halls, 2001), and were likely tectonically active in the late Archean and early Proterozoic eras (Sage, 1994). Although little is known about the complete tectonic history of these northwest-trending faults, it is suggested that some (e.g., Mildred Lake fault) may be deep structures that represent the locus of conduits for emplacement of diamondiferous pyroclastic tuff breccias (Archibald, 2008). Observations along a portion of the Trembley fault suggest that it caused major displacement, either sinistral or vertical motion, of greenstone belt rocks in the southwestern part of the Michipicoten greenstone belt (Sears, 1994). In general, sinistral offset is suggested for all northwest-trending faults during uplift of the Kapuskasing structural zone.

North-trending structures include the Agawa Canyon fault and similarly oriented McEwan Lake fault (Halls and Mound, 1998), and the much shorter Loon Skin Lake fault. The Agawa Canyon fault, sometimes referred to as the McVeigh Creek fault, extends across the Wawa area approximately 10 km to the east of the Municipality of Wawa (Figure 3). This fault can be traced many kilometres south of the Michipicoten greenstone belt, and its northerly orientation is uncommon in the area. The fault is considered to be post-Keweenawan in age (i.e. younger than approximately 1.1 billion years), and associated with the Mid-continent Rift (Manson and Halls, 1997). It is generally considered to have a normal, east-side-down movement history (e.g., Renault, 1962). The McEwan Lake fault is an approximately 30 km long, north-trending structure located approximately 30 km east of the Agawa Canyon fault and south of Hwy 101 in the eastern part of the Wawa area. This fault, which is not mapped by the Ontario Geological Survey and therefore is not shown in Figure 3, is reported to be related to the Kapuskasing structural zone and is assumed to be of a similar age as the Agawa Canyon fault.

Northeast-trending faults include the Wawa Lake, Hawk Lake, Manitowik Lake, Old Woman River, Mishewawa and Firesand River faults (Figure 3). The largest of these northeast-trending structures, the combined Wawa Lake, Hawk Lake and Manitowik Lake fault, crosses the entire Wawa area and is commonly genetically associated with major dextral offset along the Kapuskasing structural zone (Sage, 1994). This large fault has also been interpreted as a reactivated structure with an Archean origin (Turek et al., 1992; Sage, 1994). The Firesand River carbonatite was emplaced approximately 1.084 billion years ago (Sage, 1979) in the junction of the Wawa Lake and Hawk Lake faults. The presence of this type of intrusive rock in the Wawa Lake-Hawk Lake fault would imply a deep root for this fault, probably reaching lower crust or upper mantle depth (Sage, 1994).

The Kapuskasing structural zone is interpreted by Percival and West (1994) as a tilted block which was uplifted during the Paleoproterozoic era, approximately 1.9 billion years ago (Sage, 1994; Manson and Halls, 1997). The uplift resulted in exposure of the upper 30 km of the crust, with increasing deeper structural levels below the Michipicoten greenstone belt being exposed to the east. In this interpretation, the Michipicoten greenstone belt has been subjected to less than 10 km of erosion, while the Wawa Gneiss domain has been subjected to between 10 and 20 km of erosion. In general, dextral offset is suggested for all northeast-trending faults during uplift of the Kapuskasing structural zone.

2.2.7 Metamorphism

In general, there is limited local preservation of pre-Neoarchean metamorphism within the Canadian Shield (e.g., Breaks and Bartlett, 1991; and Percival and Skulski, 2000). The Superior Province largely preserves low pressure – low to high temperature Neoarchean metamorphism, from approximately 2.710 to 2.640 billion years ago, but there is a widespread tectonothermal overprint of Archean crust by Paleoproterozoic deformation and typically amphibolite facies metamorphism across the Churchill Province through northernmost Ontario under the northern Hudson Bay lowland, western Manitoba, northern Saskatchewan and Nunavut (e.g., Skulski et al., 2002; Berman et al., 2005).

In the Archean Superior Province, the relative timing and grade of regional metamorphism corresponds to the type of lithologic composition of the subprovinces (Easton, 2000; Percival et al., 2006). Granite-greenstone subprovinces contain the oldest, Neoarchean metamorphism of lower greenschist to amphibolite facies in volcano-sedimentary assemblages and synvolcanic to syntectonic plutons. Both metasediment- and associated migmatite-dominated subprovinces, such as the English River and Quetico, and dominantly plutonic and orthogneissic subprovinces, such as the Winnipeg River, display younger, syntectonic middle amphibolite to granulite facies metamorphism (Breaks and Bond, 1993; Corfu et al., 1995).

Sub-greenschist 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). Most late orogenic shear zones in the Superior Province and Trans-Hudson Orogen experienced lower to middle greenschist retrograde metamorphism. Post-metamorphic events along faults in the Abitibi greenstone belt show a drawn-out record through 40Ar/39Ar dating to approximately 2.500 billion years ago, the significance of which remains unclear (Powell et al., 1995). The distribution of contrasting grades of metamorphism is a consequence of relative uplift, block rotation and erosion from Neoarchean orogenesis and subsequent local Proterozoic orogenic events and broader epeirogeny during Proterozoic and Phanerozoic eons. In northwestern Ontario, the concurrent post-Archean effects are limited to poorly documented reactivation along faulted Archean terrane boundaries (e.g., Kamineni et al., 1990 and references therein).

In northeastern Ontario, the Kapuskasing structural zone, located east of the Wawa area, is an approximately 1.9 billion year old thrust structure that uplifts a westward-tilted Archean crust and juxtaposes greenschist facies rocks exhumed from <10km depth on its west side near Wawa against granulite facies rocks on its east side that have been exhumed from approximately 30 km depth (Percival and West, 1994). Approximately 1.0 billion years ago, far-field reactivation of faults by compression from the Grenville Orogeny produced a sub-greenschist metamorphic overprint along pre-existing faults in the vicinity of Lake Nipigon and near Lake Superior (Manson and Halls, 1994).

The greenstone belt rocks of the Wawa area have been metamorphosed to the greenschist grade of regional metamorphism, with an aureole of contact metamorphism of amphibolite grade at the margins of large internal and external plutons (Ayres, 1969; Easton, 2000). Relative to smaller greenstone belts (e.g., Hemlo) the grade of metamorphism in the Michipicoten greenstone belt is low. Within the Wawa Gneiss domain, the grade of metamorphism increases eastward toward the Kapuskasing structural zone, reflecting exposure of progressively deeper structural levels (Easton, 2000). Like all other rocks in the Wawa area, the diabase dykes have been affected by greenschist grade regional metamorphism. They usually display well-developed chilled margins, related to emplacement, and aureoles of contact metamorphism.

Overall, most of the Canadian Shield, outside of unmetamorphosed, late tectonic plutons, contains a complex episodic history of metamorphism largely of Neoarchean age with broad tectonothermal overprints of Paleoproterozoic age around the Superior Province and culminating at the end of the Grenville Orogeny approximately 950 million years ago.

2.3 Geological and Structural History

Direct information on the geological and structural history of the Wawa area is limited. The geological and structural history summarized below integrates the results from studies undertaken elsewhere throughout and proximal to the regional area shown in Figure 3. It is understood that there are potential problems in regional correlation of specific structural events within a D_x numbering system and in the application of such a system to the local geological history. Nonetheless, the summary below represents an initial preliminary interpretation for the Wawa area, which may be modified after site-specific information has been collected.

Accordingly, the geological and structural history of the Wawa area can be summarized as a tectonic succession of seven deformation events (D_1 to D_7), that occurred between approximately 2.9 and 1.0 billion years ago, and comprised three major episodes of volcanism and sedimentation, as recorded in the Michipicoten greenstone belt (Turek et al., 1984; Sage, 1994). These episodes were coeval with the emplacement of syn-volcanic plutons and batholiths that later became exposed during regional orogenic deformation and associated tectonic uplift. Syn-orogenic activity also included emplacement of diatreme breccias and alkali plutons within or marginal to the greenstone belts (e.g., Stott et al., 2002). Major folding, refolding and thrusting of the strata were followed by, or concurrent with, the aforementioned uplift of the external batholiths.

Paleoproterozoic diabase dykes recorded subsequent displacement along sinistral northeast-trending faults across the Kapuskasing structural zone (West and Ernst, 1991; Halls et al., 1994). Uplift of the Kapuskasing structural zone has been constrained to have occurred approximately 1.9 billion years ago (Percival and West, 1994). Most episodes of late movement along faults probably terminated by Keweenawan time, approximately 1.100 billion years ago, during the development of the Mid-continent Rift along Lake Superior, since northeast-trending dykes of this age (Abitibi swarm) crosscut all major north and northwest-trending faults without displacement (West and Ernst, 1991). A set of faults that are probably related to late compression during the Grenville Orogeny occurs south of the Michipicoten greenstone belt near Cape Gargantua.

Table 1 provides a simplified summary of the geological history of the Wawa area.

Table 1 Summary of the Geological and Structural History of the Wawa Area

Time Period (billion years ago)	*Geological Event*
ca. 2.89 to 2.88	First cycle of volcanism and coeval emplacement of the Hawk Lake granitic complex along the eastern margin of Michipicoten greenstone belt (Sage, 1994).
ca. 2.75 to 2.72	Formation of most of the greenstone belts of the Wawa Subprovince (Ketchum et al., 2008). Second cycle of volcanism and syn-volcanic plutonism in the Michipicoten greenstone belt (Turek et al., 1992), including Jubilee stock (approximately 2.745 to 2.742 billion years ago) and Jostle Lake tonalite (2.721 billion years ago) emplacement in the Western batholith southwest of the Michipicoten greenstone belt.
ca. 2.701 to 2.694	Onset of the collision of the Wawa-Abitibi terrane against the Superior Superterrane. Third cycle of volcanism and sedimentation in Michipicoten greenstone belt, including deposition of Catfish assemblage between approximately 2.701 and 2.698 billion years ago and deposition in basin in-fill of 'Doré conglomerates' as early as approximately 2.698 billion years ago. Emplacement of external granitoids surrounding greenstone belts, including the Western batholith at approximately 2.698 billion years ago and the Whitefish Lake batholith at approximately 2.694 billion years ago.
ca. 2.682	D_1 nappe-style and D_2 folding and thrusting deformation events. D_2 was characterized by southward-vergent (northward dipping) refolding and thrust imbrication of a major D_1 nappe fold (Corfu and Sage 1992).
ca. 2.679 to 2.674	Crystallization of mafic to ultramafic, heterolithic, diamondiferous diatreme breccias and shoshonitic lamprophyre dykes that intrude Michipicoten greenstone belt (Vaillancourt et al., 2005a; Stott et al., 2002). Lamprophyre dyke emplacement reflects an episode of crustal extension, possibly during late-stage termination of relatively flat subduction of oceanic plateau crust and slab breakoff (Wyman et al., 2006; 2008).
ca. 2.677	Termination of the penetrative effects of Archean orogenesis in the Wawa area (end of regional D_2). Emplacement of the Dickenson Lake stock in the Michipicoten greenstone belt approximately 2.677 billion years ago.
ca. 2.671 to 2.662	Emplacement of a suite of felsic intrusive stocks, including Maskinonge Lake and Troupe Lake stocks (approximately 2.671 billion years ago) and Lund Lake stock (approximately 2.662 billion years ago) along the northern part of the Michipicoten greenstone belt. These intrusions postdate the penetrative regional D_1 and D_2 deformation events and thereby constrain the dominant record of belt-scale recumbent D_1 nappe folding and D_2 thrust imbrication and refolding (Arias and Helmstaedt, 1989) to between approximately 2.682 and 2.671 billion years ago. East-trending D_3 dextral shear zones are concurrent with or postdate this suite of alkalic to calc-alkalic plutons. Subsequent late tectonic crustal cooling and residual collisional stresses created a generation of D_4 brittle-ductile to brittle faults and brittle fractures of undetermined late orogenic age. The cooling and exhumation of late tectonic plutons produced brittle fractures within the plutons, collectively treated as D_5 features. There is a probable overlap in timing between regional D_4 and D_5 structures. Emplacement of one of the youngest (approximately 2.662 billion years ago) granitic felsic plutons in the Wawa area (Turek et al., 1984).
ca. 2.45	Intrusion of the Matachewan diabase dyke swarm which radiates northwestward from a plume centre near present day Sudbury, Ontario.
ca. 2.17	Intrusion of the northeast-trending Biscotasing quartz tholeiite dyke swarm.
ca. 2.11	Intrusion of the northeast-trending Marathon/Kapuskasing dyke swarm from a plume centre south of Lake Superior (Halls et al., 2008).

Time Period (billion years ago)	***Geological Event***
ca. 1.92 to 1.9	Brittle (D_6) reactivation of regional-scale faults during the Trans-Hudson Orogeny. Approximately 1.9 billion years ago uplift of the Kapuskasing structural zone was contemporaneous with dextral movements on northeast-trending faults, and sinistral movements on north- to northwest-trending faults, and a twenty three-degree rotation of the western Superior Province relative to the eastern Superior Province (Halls et al., 1994; Percival and West, 1994; Evans and Halls, 2010).
ca. 1.141	Intrusion of the northeast-trending Abitibi dyke swarm extending from the Mid-continent Rift along Lake Superior (e.g., Ernst and Buchan, 1993).
ca. 1.1	Keweenawan Mid-continent Rift gabbro and tholeiitic basalt were emplaced south and southwest of Wawa, with local felsic intrusions derived by melting of Archean crust, including emplacement of Firesand River carbonatite approximately 1.048 billion years ago.
ca. 1.0 to 0.95	Late (D_7) north-trending or northwest-trending crustal shortening and reverse fault movement during the Grenville Orogeny (Manson and Halls, 1994).

The following sequence of structural deformation (D) events characterizes the Wawa area:

- D_0 primary bedding in sediments and volcanics within the volcanic belts.
- D_1 tectonic deformation produced a regional recumbent nappe-style of folding (F_1) of lithostratigraphic units in the Michipicoten greenstone belt.
- D_2 refolding of the recumbent D_1 nappe structure was followed by thrust faulting with faults and bedding dipping shallowly to steeply towards the northeast. The D_1 and D_2 events are constrained from field relationships to have occurred between approximately 2.682 and 2.671 billion years ago.
- D_3 applies to the east-trending and north-northwest trending dextral shear zones and faults and to the northeast-trending sinistral shear zones and faults during late stage Archean orogenesis in the Wawa area.
- D_4 applies to later brittle faults and fractures trending north-northwest and northeast (if present) and to the north-trending brittle faults including the Agawa Canyon fault. These brittle structures mark a period of crustal cooling under residual stress and affect rocks of the volcanic belts as well as syn-volcanic and syn-orogenic plutons.
- D_5 collectively includes conjugate late brittle faults and fractures trending north-northwest, north-northeast, north, and east, preserved in late tectonic plutons of the Wawa area. These are late cooling structures most typically as local, relatively short fractures. Some faults and fractures may have been reactivated during later D_6 Proterozoic events.
- D_6 events are collectively characterized by the development of Proterozoic faults and reactivation of Archean faults. These include faults developed during the Proterozoic uplift of the Kapuskasing structural zone (approximately 1.9 billion years ago) with regional crustal rotation about a vertical axis. This rotation produced, within and bordering the Kapuskasing structural zone, northwest-trending sinistral faults and northeast-trending dextral faults, which are opposite in displacement sense to the general Archean faults of similar orientations. Also included in these D_6 events are possible reactivations of north-trending faults by the Keweenawan event (approximately 1.100 billion years ago) during the Mid-continent Rift along and underlying the upper Great Lakes region. These structures are generally undefined and probably reactivations only. These Proterozoic events could overprint Early Proterozoic dyke swarms such as the approximately 2.45 billion year old north-northwest trending Matachewan

swarm.

- D_7 involved the activation of reverse faults perpendicular to the extensional axis of the Mid-continent Rift; these faults crosscut Keweenawan bedded units and mark approximately 1.0 billion-year-old north-trending or northwest-trending crustal compression during the Grenville Orogeny (Manson and Halls, 1994).

Little information is available for the geological history of Wawa area for the period following the Grenville Orogeny and the Mid-continent Rift after approximately 1.0 billion years ago. During the Paleozoic Era, much of the Superior Province was inundated by shallow seas and Paleozoic strata dating from the Ordovician to Devonian are preserved within the Hudson Bay and Michigan basins. The presence of a small outlier of Paleozoic strata known as the Temiskaming outlier in the New Liskeard area indicates that Paleozoic cover was formerly much more extensive and much of the present surface of the Canadian Shield lies close to an exhumed paleoplain interpreted to be of Ordovician age (Brown et al., 1995).

While there is a restricted area of Mesozoic strata within the Moose River Basin and there is evidence of Mesozoic-age emplacement of kimberlitic pipes and dykes elsewhere in northern Ontario, no post-Precambrian to pre-Quaternary rocks are known to be present within the Wawa area. The contact between bedrock and the overlying unconsolidated Quaternary sediments represents an unconformity exceeding one billion years.

2.4 Quaternary Geology

Information on Quaternary geology in the Wawa area is described in detail in the terrain report (JDMA, 2013) and is summarized here.

Most of the Wawa area has exposed bedrock, and Quaternary deposits are predominantly located in bedrock controlled valleys. Figure 4 illustrates the extent and type of Quaternary deposits in the Wawa area and the location of the water wells and diamond drillholes from which information on overburden thickness was obtained. The Quaternary geology of the Wawa area is fully described in Morris (2001a, 2001b), upon which most of this section is based.

All Quaternary deposits within the Wawa area were deposited during the Late Wisconsin by the Labrador sector of the Laurentide Ice Sheet. Bedrock striae indicate that there were two prominent ice flow directions. The oldest and most pervasive ice flow was south to southwest (159° to 240°). A later, weaker ice flow was to the southwest and west (220° to 290°). The younger set of striae was formed during the latter stages of glaciation as the ice sheet began to thin and bedrock topography began to influence the direction of ice flow.

During ice retreat, ice-contact stratified drift was deposited as recessional moraine, eskers and dead ice topography, leaving a thin (less than 1 m thick) till veneer that drapes the bedrock surface. This till veneer, when present, is the uppermost deposit across most of the Wawa area (labelled “Bedrock and Bedrock-Drift Complex” on Figure 4). Glaciofluvial outwash was deposited primarily within bedrock-controlled valleys directly from the ice margin or from wasting ice detached from the ice sheet. Also during retreat, the ice sheet was fronted by glacial meltwaters associated with the Lake Superior basin or by glacial meltwater impounded by the ice sheet and topographically higher ground. Glaciolacustrine materials were deposited in these waters, filling the deeper bedrock valleys.

According to the water well records (MOE, 2012) and the diamond drillhole database (OGS, 2005) overburden thicknesses generally range from 0 to 15 m, although thicknesses of up to 130 m exist in the bedrock valleys. Materials encountered during drilling include thick sequences of clay, sand, and gravel.

The impact that the variable distribution of Quaternary sediments has on the results of the lineament interpretation is discussed in Section 5.

2.5 Land Use

Land use within the 4,274 km^2 Wawa area outside of the settlement areas, is predominately parkland, conservation reserve, Indian reserve and unoccupied Crown land consisting of forest, wetland, lakes and exposed bedrock (Geofirma, 2013). There are linear infrastructure corridors such as roads, railways, and electrical transmission lines, however these features do not adversely affect the interpretation of bedrock lineaments.

3 METHODOLOGY

3.1 Source Data Descriptions

The lineament interpretation was conducted using available surficial (CDED digital elevation models, SPOT and Landsat satellite imagery), and geophysical (aeromagnetic) datasets for the Wawa area. Available data were assessed for quality, processed as necessary to improve quality and reviewed before use in the lineament interpretation.

CDED (Figure 5), SPOT-5 and Landsat-7 (Figure 6) datasets were used to identify surficial lineaments expressed in the topography, drainage, and vegetation. The resolution of the Landsat, SPOT and CDED data sets was consistent across the Wawa area and provided sufficient detail to allow for the identification of surficial lineaments as short as a few hundred metres in length. The higher resolution of the Landsat/SPOT imagery allowed for finer structures to be identified that were not resolved by the CDED data; but, the CDED data often revealed subtle trends masked by the surficial cover captured in the Landsat/SPOT imagery. The geophysical dataset for the Wawa area included low-resolution coverage across the entire Wawa area as well as smaller regions of increased resolution within the area (Figure 7), principally in the central and northern portions over the greenstone belts. In all cases, the best resolution data available was used for the lineament interpretation. Table 2 provides a summary of the source datasets used for the lineament interpretation.

3.1.1 Surficial Data

3.1.1.1 Digital Elevation Models (DEMs)

Canadian Digital Elevation Data (GeoBase, 2011), 1:50,000 scale, 0.75 arc second (20 m resolution) elevation models served as important data sources for analyzing and interpreting lineaments in the Wawa area. Figure 5 shows the CDED dataset enhanced with a hill shade format with a sun angle of 45 degrees from horizon and an orientation (azimuth) of 45 degrees. The digital elevation model (DEM) used for this assessment was constructed by Natural Resources Canada (NRCan) using provincial data created through the Water Resources Information Program (WRIP) of the Ontario Ministry of Natural Resources (MNR). The data represented 1:20,000 scale source data acquired through the Ontario Base Mapping (OBM) program, which was a major photogrammetric program conducted across Ontario between 1978 and 1995. Four main OBM data sets were used: OBM contours, OBM spot heights, WRIP stream network, and lake elevations derived using the OBM spot heights and OBM 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 dataset was sufficient to undertake the lineament interpretation.

The files were transferred from geographic coordinates to UTM projection using bilinear resampling, which assigns a value to each output cell based on a weighted average of the four nearest cells in the input raster. Compared with cubic convolution, bilinear resampling can sometimes produce a noticeably smoother surface, whereas cubic convolution can produce a sharper image. However, the differences between the two methods are generally trivial and the selection of bilinear resampling was arbitrary. The projected files were then assembled into a mosaic by JDMA (Figure 5). Table 3 lists the tiles used in the final mosaic.

Table 2 Summary of Source Data Information for the Lineament Interpretation, Wawa Area

Dataset	*Product*	*Source*	*Resolution*	*Coverage*	*Acquired*	*Additional Comments*
DEM	Canadian Digital Elevation Data (CDED);1:50,000 scale	Geobase	20 m	Entire Wawa area	1978-1995	Hill-shaded used for mapping
Satellite Imagery	Spot4/5; Orthoimage, multispectral/ panchromatic	Geobase	10 m (panchromatic) 20 m (multispectral)	Entire Wawa area	2005 -2007	Good Coverage
	Landsat-7; Orthoimage, multispectral/ panchromatic	USGS	15 m (panchromatic) 30 m (multispectral)	Entire Wawa area	2000	Good Coverage
Geophysics	Lake Superior	Geological Survey of Canada	1900 m line spacing 305 m sensor height	southwest part of Wawa area	1987	Lowest resolution dataset
	Geological Survey of Canada Regional Magnetic Compilation (Ontario 8 and 17)	Geological Survey of Canada	805 m line spacing 305 m sensor height	Entire Wawa area	1962, 1963	Low resolution dataset
	Wawa Survey (GDS1009)	Ontario Geological Survey	200 m line spacing 45 m sensor height	Covers greenstone belts in northern half of Wawa area northeast corner of Wawa area	1988	Limited usefulness due to greenstone belt coverage
	Michipicoten Survey (GDS1010)	Ontario Geological Survey	200 m line spacing 30 m sensor height	Covers Michipicoten greenstone belt in central part of Wawa area	1980	Limited usefulness due to minimal coverage in Wawa area
	Kapuskasing-Chapleau Survey (GDS1040)	Ontario Geological Survey/ Geological Survey of Canada	200 m line spacing, 100 m sensor height	Covers small greenstone belt in northeast corner of study areaWawa area	2001	Limited usefulness due to minimal coverage in Wawa area
	Magpie River-Missinaibi Lake Survey (GDS1237)	Ontario Geological Survey	75 m line spacing 40-60 m sensor height	Covers small greenstone belt in north-central part of Wawa area	2006 - 2008	Limited usefulness due to minimal coverage in Wawa area

Table 3 Summary of 1:50,000 Scale CDED Tiles Used for Lineament Interpretation of the Wawa Area

NTS Tiles	*East/West Coverage*	*Ground Resolution (arcsec.)*
41N/09-11, 14-16	Both	0.75
41O/13	Both	0.75
42B/04	Both	0.75
42C/01-03	Both	0.75

For better identification of linear features, hill-shaded images were created in Arc-GIS in four main illuminating azimuths of 45º, 90º, 180º, and 315º (measured clockwise from the north) with the solar incidence angle of 45º from horizon. It was determined that the resolution of the DEM dataset was sufficient to undertake the lineament interpretation with those data. Hill-shaded angles of 045º and 315º were used for the majority of the lineament interpretation. Both hill-shade and slope rasters were useful for mapping lineaments.

3.1.1.2 Satellite Imagery

SPOT imagery, together with Landsat-7 images was used as the satellite data sources for lineament interpretations in the Wawa area. Table 4 presents the main specifications of SPOT and Landsat imagery.

Table 4 Summary of SPOT and Landsat Imagery Scenes Used for Lineament Interpretation of the Wawa Area

Scene-ID	*Image Centre (Lat/Long)*	*Satellite, Sensor*	*Date of Image*
S4_08410_4760_20070510	48°00', -84°10'	SPOT-4, HRVIR	May 10, 2007
S5_08419_4731_20070503	47°31', -84°19'	SPOT-5, HRG	May 03, 2006
S5_08450_4760_20060901	48°00', -84°50'	SPOT-5, HRG	September 01, 2006
S5_08501_4731_20060901	47°31', -85°01'	SPOT-5, HRG	September 01, 2006
S5_08522_4828_20060609	48°28', -85°22'	SPOT-5, HRG	June 09, 2006
S5_08531_4760_20050621	48°00', -85°31'	SPOT-5, HRG	June 21, 2005
S5_08438_4828_20070503	48°28', -84°38'	SPOT-5, HRG	May 03, 2007
L71022027_02720001019	47°27', -84°45'	LANDSAT-7, ETM^+	October 19, 2000

SPOT multispectral (20 m resolution) and panchromatic (10 m resolution) orthoimagery were used for identifying surficial lineaments and exposed bedrock within the Wawa area. SPOT multispectral data consist of several bands, each recording reflected radiation within a particular spectral range, and each having a radiometry of 8-bits (or a value ranging from 0 to 255). Seven SPOT images (scenes) provided complete coverage for the Wawa area (Table 4). The scenes include one from the SPOT-4 satellite (May 2007) and six from the SPOT-5 satellite (one acquired in 2005, 4 acquired in 2006 and one acquired in 2007). SPOT 5 images were acquired using the High Resolution Geometric (HRG) sensor. Each image covers a ground area of 60 km by 60 km.

For quality control, NRCan provides images that have a maximum of 5% snow and ice cover, 5% cloud cover and a maximum viewing angle of 15º. 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, projected using Universal Transverse Mercator (UTM) projection referenced to the North American Datum 1983 (NAD83).

It was determined that the resolution of the SPOT dataset was sufficient to undertake the lineament interpretation. The scenes were processed to create a single panchromatic mosaic (JDMA, 2013). An automated contrast matching technique was applied to the images which minimizes sharp variances in pixel intensity, giving the single image a cohesive appearance. The images were extended beyond the defined boundaries of the Wawa area to allow for the mapping of continuous lineaments extending beyond the Wawa area.

A Landsat Enhanced Thematic Mapper Plus (ETM+) image of path 22 and row 27 acquired on October 19, 2000 (Table 2) was used in concert with the SPOT imagery. The Landsat ETM+ is a sensor carried onboard the Landsat-7 satellite, managed by NASA and has acquired images of the Earth nearly continuously since July 1999, with a 16-day repeat cycle. Landsat ETM+ image data consist of eight spectral bands, with a spatial resolution of 30 m for bands 1 to 5 and band 7. The resolution of panchromatic band is 15 m (Table 2) and the spectral resolution of all bands is 8-bits. The approximate scene size is 170 km north-south by 183 km east-west. Landsat data in spite of having lower spatial resolution compared to SPOT data, because of having higher spectral resolution proved to be very useful for bedrock and structural mapping. The Landsat orthorectified image was downloaded from USGS Global Visualization Viewer (http://glovis.usgs.gov) in GeoTIFF format.

In order to generate Landsat color composite images, the original images were processed using PCI Geomatica image processing software. Figure 6 is an example of a false colour composite of the Landsat imagery that was created by assigning a primary colour (red, green and blue) to three of the spectral bands (band-7, -4 and -2, respectively). Different materials reflect and absorb solar radiation differently at different wavelengths and therefore have varying intensities within each of the Landsat bands. When combined into a single image, the above colour assignment results in a pixel colour that tends to approach a “natural” representation. Image processing and different colour assignments can be used to enhance the presence of different material categories, such as vegetation type, water, soil or man-made features.

To support lineament interpretation, contrast enhancement was applied on the Landsat images to obtain better discrimination between various lithological and structural features. To do this, areas covered with water and ice were first masked on images. Threshold values on Landsat band-1 and band-4 were used to remove ice and water from the images, respectively. The radiometric ranges obtained for the water- and ice-free images were then used to enhance the original images by applying a linear contrast stretching.

3.1.2 Geophysical Data

The geophysical dataset incorporates aeromagnetic, gravity and radiometric data available across the entire Wawa area, and some limited electromagnetic data. However, only aeromagnetic data was extensively used for the lineament interpretation. The coarse resolution of the gravity and radiometric data were insufficient to interpret lineaments. Table 5 provides a summary of the acquisition parameters for each aeromagnetic dataset used. The magnetic data located within the Wawa area were processed using several common geophysical techniques in order to enhance the magnetic response to assist with the interpretation of geophysical lineaments. The enhanced magnetic grids used in the lineament interpretation include the first and second vertical derivatives, and the tilt angle filter grids. These enhanced grids were processed and imaged using the Geosoft Oasis montaj software package. Acquisition parameters, processing methods and enhanced grids associated with the geophysical datasets used in the lineament interpretation are discussed in detail in PGW (2013). Three additional magnetic grids using a combination of gradient and amplitude equalization filters were prepared using the Encom (Pitney Bowes) Profile Analyst software package in order to highlight the edges of magnetic sources. The combination of all of the enhanced magnetic grids provide much improved resolution of subtle magnetic fabrics and boundaries in areas that appear featureless in the total magnetic field. Figure 7 shows a compilation of the first vertical derivative of total magnetic field (reduced to pole) of each of these aeromagnetic datasets.

As shown in Figure 7, the quality of geophysical data varied significantly across the Wawa area, as a function of the flight line spacing, the flying height and the age of the survey. The integrity of the higher quality data was maintained throughout and the poorest resolution data was only used where higher resolution data was unavailable. It was determined that overall the quality of the data was sufficient to perform the lineament interpretation at the scale of the Wawa area.

Table 5 Summary of Geophysical Survey Acquisition Parameters for Lineament Interpretation of the Wawa Area

Survey	*Flight Line Spacing (m)*	*Grid Cell Size (m)*	*Sensor Height (m)*
Lake Superior	1900	500	305
GSC Regional Compilation	805	200	305
Wawa	200	40	45
Michipicoten	200	40	30
Kapuskasing- Chapleau	200	40	100
Magpie River – Missinaibi Lake	75	20	40

The majority of the Wawa area is covered by low-resolution aeromagnetic data published by the Geological Survey of Canada (GSC) and downloaded from their Geoscience Data Repository for Geophysical and Geochemical Data (GSC, 2012). This data was acquired at a flight line spacing of 805 m and a sensor height at 305 m. An additional low-resolution survey was acquired at a flight line spacing of 1900 m and a sensor height at 305 m over Lake Superior.

Three higher resolution magnetic surveys, published by the Ontario Geological Survey (OGS), were available for use in the lineament interpretation. These include the Wawa survey that covers the greenstone belts in the northern half of the Wawa area with a flight line spacing of 200 m and a sensor height of 45 m (OGS, 2003b), the Michipicoten survey that covers the Michipicoten greenstone belt in the central part of the Wawa area with a flight line spacing of 200 m and a sensor height of 30 m (OGS, 2003a), and the Magpie River-Missinaibi Lake dataset consisting of four separate survey blocks that covers much a greenstone belt in the north-central part of the Wawa area with a flight line spacing of 75 m and sensor height of 40 to 60 m above ground survey (OGS, 2011). Variability of terrain clearance of this last data set depends on the survey parameters used during acquisition of each survey block. The Kapuskasing-Chapleau survey covers a small northeast corner of the Wawa area with a fight line spacing of 200 m and a sensor height of 100 m (OGS, 2002; GSC, 2012). Data from this survey location within the Wawa area was superseded by the higher resolution data from the Magpie – Missinaibi Lake survey. All of these OGS surveys focused on the greenstone belts, and provide only marginal coverage of intrusive rocks in the Wawa area.

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 publicly available surficial (DEM, Landsat/SPOT) and geophysical (aeromagnetic) datasets described above.

The interpretation guidelines for brittle and dyke lineaments used in the subsequent analysis involved three steps:

1. Identification of lineaments by two interpreters for each dataset (DEM, Landsat/SPOT, MAG) and assignment of certainty level (1, 2 or 3);
2. Integration of lineament interpretations by data set (Figures 8, 9 and 10) and first determination of reproducibility (RA_1); and
3. Integration of lineament interpretations for all three datasets (Figures 12 and 13) and determination of coincidence (RA_2).

In addition, ductile geophysical lineaments (Figure 11) were manually picked using the aeromagnetic geophysical survey data by a single documented specialist observer.

Each identified lineament feature was classified in an attribute table in ArcGIS. The description of the attribute fields used is included in Table 6. Fields 1 to 9 are populated during the first step. Fields 10 and 11 are populated during the second step. Fields 12 to 19 are populated in the third and final step.

Table 6 Summary of Attribute Table Fields Populated for the Lineament Interpretation

#	*Attribute*	*Brief Description*
1	Rev_ID	Reviewer initials
2	Feat_ID	Feature identifier
3	Data_typ	Dataset used (DEM, Landsat/SPOT, Geophys)
4	Feat_typ	Type of feature used to identify each lineament
5	Name	Name of feature (if known)
6	Certain	Certainty value (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

#	***Attribute***	***Brief Description***
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	Vector average direction of all line segments forming the lineament (1 – 180°)
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	Geophys	Feature identified in geophysical dataset (Yes or No)
15	DEM	Feature identified in DEM dataset (Yes or No)
16	Landsat/SPOT	Feature identified in Landsat/SPOT dataset (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	Notes	Comment field for additional relevant information on a feature

*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 judgement 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.

A detailed description of the three workflow steps, as well as the way each associated attribute field is populated for each interpreted brittle or dyke lineament is provided below.

3.2.1 Step 1: Lineament Identification and Certainty Level

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 datasets. This action resulted in the production of two interpretations for each of the DEM, Landsat/SPOT, and aeromagnetic datasets and a total of six individual GIS layer-based interpretations. Each interpreter assigned a certainty/uncertainty descriptor (attribute field 'Certain' = 1-low, 2-medium or 3-high) to each feature in their interpretation based on their judgment concerning the clarity of the lineament within the dataset. 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 datasets ultimately came down to expert judgment and experience of the interpreter.

The geophysical data set also allowed the interpreter to assess the feature type of the lineaments. The brittle geophysical lineaments were interpreted as linear fractures exhibit magnetic signals that are lower than the surrounding bedrock. Where clear offsets can be determined, the brittle fractures can be further characterized as faults, and attributed accordingly. In Wawa, the presence of dyke lineaments were characterized as linear traces in which the magnetic signal of the identified feature was higher than the surrounding bedrock. The ductile lineaments were traced as curvi-linear features using the geophysical data representing the internal fabric of the rock units.

It is understood that some of the lineament attributes (e.g. width and relative age) will be further refined as more detailed information becomes available in subsequent stages of characterization.

3.2.2 Step 2: Reproducibility Assessment 1 (RA_1)

The two individual GIS lineament maps from each dataset were then integrated to provide a single interpretation for the DEM (Figure 8), Landsat/SPOT (Figure 9) and aeromagnetic (Figure10) data that included the results of the first stage reproducibility assessment (RA_1). Reproducibility is judged based on the coincidence, or lack thereof, of interpreted lineaments within an assigned buffer zone. For example, if a lineament was identified by both interpreters within an overlapping buffer zone, then it was deemed coincident.

An initial buffer zone width (Buffer_RA_1) of 200 m was selected to evaluate coincidence. For many of the lineaments, coincidence could be demonstrated with a smaller buffer width, and in these cases a buffer width of either 100 m or 50 m, depending on the maximum offset, was entered in the attribute field. Where coincident interpreted lineaments were identified, the one line that appeared to best represent the surficial or geophysical expression of the feature (based on the judgment of the integrator) was retained and assigned attributes. In some instances, where deemed appropriate, either an existing line was edited or a new line was drawn as part of the merging process to best capture the expression of the lineament. This single feature was then assigned a reproducibility value of two (RA_1 = 2), recording the identification of the feature by two interpreters. Where a lineament was identified by only one of the interpreters, it received a buffer zone width of zero (Buffer_RA1 = 0) and a reproducibility value of one (RA_1 = 1) in the attribute table.

3.2.3 Step 3: Reproducibility Assessment (RA_2)

In step 3, the three dataset-specific interpretations were integrated into a single map following a similar reproducibility assessment (RA_2) procedure. In this second assessment, reproducibility is based on the coincidence, or lack thereof, of interpreted lineaments between different individual data sets within an assigned buffer zone (Buffer_RA_2). Coincident lineaments were assigned a Buffer_RA_2 value of 200 m, 100 m, or 50 m, depending on the maximum distance between individual lineaments. Where coincident lineaments were identified, one of the existing lines was selected or edited to represent that feature; and in some cases, where appropriate, a new line was drawn that best captured the merger of individual lineaments, in a process similar to the integration of RA_1 lineaments.

The merged lineaments were then assigned a reproducibility (coincidence) value (RA_2) of two or three, depending on whether the feature was identified in any two or all three of the assessed data sets. That is, for coincident lineaments, a single integrated feature, attributed accordingly, is carried forward into the final mapped interpretation. If a lineament was identified in only one data set, and thus not a coincident lineament, it received a reproducibility value of one (RA_2 = 1) in the attribute table. The data sets within which each feature have been identified is indicated in the appropriate attribute table field (Geophys, DEM, Landsat/SPOT).

4 FINDINGS

4.1 Description of Lineaments by Data Set

4.1.1 Surficial Datasets (CDED and Landsat/SPOT)

Interpreted lineaments from the CDED and Landsat/SPOT datasets are shown on Figures 8 and 9, respectively. The following paragraphs provide an overview of results from these surface-based interpretations.

A total of 927 lineaments comprise the dataset of merged lineaments identified by the two interpreters from the CDED digital elevation data (Figure 8). These lineaments range in length from 590 m to 111 km, with an arithmetic mean length of 6.5 km and a median length of 4.7 km. The most notable features of the CDED lineament orientations when plotted on a rose diagram weighted by length (Figure 8 inset) are the dominant northeast and north-northwest trends, and a subordinate east trend. The northeast-trending CDED lineaments show a wider range of orientation variability compared to the north-northwest-trending set of lineaments. The east-trending CDED lineament set is less clearly defined including some west-northwest trends. Certainty values of 3, 2 and 1 were assigned to 224 (24%), 444 (48%) and 259 (28%) of the CDED lineaments, respectively. The RA_1 reproducibility assessment shows reproducibility between the two pickers for 381 of the CDED lineaments (41%, RA_1 = 2) and a lack of reproducibility for 546 of the CDED lineaments (59%, RA_1 = 1). The lack of reproducibility is likely due to the fact that the two pickers selected slightly different numbers of CDED lineaments (715 vs 586) and the indistinct nature of some of features in the available datasets.

The Landsat/SPOT lineament dataset compiled from the merger of lineaments identified by the two interpreters yielded a total of 1,114 lineaments (Figure 9). The length of the Landsat/SPOT lineaments ranges from 260 m to 97.4 km, with an arithmetic mean length of 5.4 km and a median length of 4.1 km. When the azimuths of the lineaments are plotted on a rose diagram weighted by length (Figure 9 inset), there are similar orientation trends but slightly different strengths compared to those evident in the CDED dataset. The most prominent orientation is northeast and this trend is more sharply defined in the satellite imagery than the CDED dataset. Secondary lineament trends from the satellite imagery include an east trend and a minor north-northwest trend. Nineteen percent (19%) of the Landsat/SPOT lineaments, a total of 213, were assigned a certainty value of 3. Certainty values of 2 and 1 were assigned to 574 (52%) and 327 (29%) of the satellite lineaments, respectively. The reproducibility assessment shows reproducibility for 513 (46%) of the satellite lineaments (RA_1 = 2), and a lack of reproducibility for 601 (54%) of the satellite lineaments (RA_1 = 1). The lack of reproducibility is likely due to the fact that the two pickers selected slightly different numbers of satellite lineaments (900 vs 762), the indistinct nature of some of features in the available datasets, and the reliance on different satellite images (Landsat vs SPOT) by the two pickers.

Orientation data for the CDED lineaments appear to be more scattered than those for the Landsat/SPOT lineaments, with only broadly comparable dominant orientations of northeast, east and north-northwest. Both interpretations are largely unaffected by the limited Quaternary cover in the Wawa area. Generally, lineaments identified in CDED and Landsat/SPOT datasets are comparable, with 19% more lineaments identified in the satellite imagery than the CDED dataset. This increased occurrence reflects the increased resolution of the satellite imagery over the CDED dataset.

4.1.2 Geophysical Data

The airborne geophysical data interpretation was able to distinguish between features that could be interpreted as brittle or dyke lineaments (Figure 10) and ductile lineaments (Figure 11). Aeromagnetic features interpreted to reflect ductile lineaments are useful in identifying the stratigraphy and structure within the greenstone belts and to a lesser extent, internal fabrics in the gneissic and foliated intrusive rocks of the Wawa area. The degree of deformation within the greenstone belts and the “wrapping” of the greenstone stratigraphy around the younger intrusive formations is apparent in PGW (2013) and to a lesser degree in Figure 11. Figure 11 also highlights the greater degree of fabric development in the foliated and gneissic tonalite suites of the Western batholith relative to the Whitefish Lake-Brulé Bay batholith and the Wawa Gneiss domain. The ductile lineaments are shown to provide context to our understanding of the tectonic history of the Wawa area, but were not included in the statistical analysis undertaken with the dataset. Therefore the following discussion relates only to those lineaments interpreted as brittle fracture or dyke lineaments.

A total of 789 lineaments comprise the data set of merged lineaments identified by the two interpreters from the geophysics data (Figure 10). Of the 789 lineaments, 441 are interpreted as fractures, while 348 are interpreted as dykes (Figure 10). The length of the geophysical fracture lineaments ranged from 950 m up to 65.6 km, with an arithmetic mean length of 12.7 km and a median length of 10.4 km. Azimuth data, weighted by length (Figure 10 inset), for the geophysical lineaments interpreted as fractures exhibit a wide range of orientations with trends apparent in the north-northwest, northeast, east and north directions.

The 348 lineaments identified as dykes, which includes smaller mapped segments of the same dyke, belong primarily to the north-northwest trending suite of Matachewan dykes (Figure 10 inset). A second minor set of northeast-oreinted dykes is related to either of the Abitibi or Biscotasing swarms. The length of the geophysical dyke lineaments ranged from 200 m up to 38.6 km, with an arithmetic mean length of 4.8 km and a median length of 3.0 km. There is an apparent spatial variation in the distribution of these dykes with an increased occurrence of the north-northwest trending Matachewan dykes in the eastern half of the Wawa area (i.e., within the Wawa Gneiss domain and Whitefish Lake batholith). The Brulé Bay batholith, the Western batholith, and the western part of the Wawa Gneiss domain appear to have lower occurrences of dykes than the eastern half of the Wawa area.

Two hundred and eighty one (64%) of the geophysical fractures were assigned the highest level of certainty (Certainty = 3), while 129 (29%) and 31 (7%) of the fractures were given certainty values of 2 and 1, respectively. A total of 276 (79%) of the dykes identified from geophysical data were assigned a certainty value of 3, while 59 (17%) of the dykes were given certainty values of 2 and 13 (4%) were given values of 1. The reproducibility assessment identified coincidence for 26 fractures (6%) (RA_1 = 2) and a lack of coincidence for 415 of the interpreted faults (94%) (RA_1 = 1). The reproducibility assessment identified reproducibility for 113 of the interpreted dykes (32%) (RA_1 = 2) and a lack of reproducibility for 235 of the interpreted dykes (68%) (RA_1 = 1). The low reproducibility results for both geophysical fractures and dykes reflects the indistinct nature of some of features in the available datasets, and the higher level of interpretation necessary to select geophysical lineaments with low-resolution aeromagnetic data compared to surficial datasets.

4.2 Description and Classification of Integrated Lineament Coincidence (RA_2)

The integrated lineament data set produced by determining the coincidence of all lineaments interpreted from the CDED, Landsat/SPOT imagery, and geophysics data is presented on Figures 12 and 13. Figure 12 displays the lineament classification based on the coincidence values determined by Reproducibility Assessment (RA_2) and including a normalized lineament length rose diagram of the entire dataset as an inset. Figure 13 displays the lineament classification based on length of interpreted lineaments, and includes the same length-weighted frequency rose diagram as an inset. The merged lineaments were classified by length using four length bins: >10 km, 5-10 km, 1-5 km and <1 km. These length bins were defined based on an analysis of the lineament length frequency distributions for the Wawa area.

The final merged lineament data set contains a total of 2,079 lineaments comprising 1,731 fractures and 348 dykes that range in length from 200 m to 111 km. The arithmetic mean length of these lineaments is 7.1 km and the median length is 4.7 km. Lineaments in the >10 km and 5-10 km length bins represent 21% and 26% of the final merged lineaments, respectively, while lineaments in the 1-5 km and <1 km length bins represent 49% and 4% of the final merged lineaments, respectively. Orientation data for the final merged lineament data set (inset of Figures 12 and 13) exhibit a fairly uniform distribution of three prominent trends. The normalized lineament length rose diagram for all final merged lineaments shows the presence of three main lineament orientations of comparable prominence – northeast, north-northwest and east. The north-northwest trending lineament set includes fractures and Matachewan dykes. The northeast- and east-trending lineament sets are comprised mainly of fractures.

Results from RA_2 for the final merged lineament data set (Figure 12) shows that RA_2 scores of 2 or 3 are only available for the 1,967 identified fractures. As interpreted dykes are only identified from aeromagnetic data and often do not appear to exhibit a distinct surficial expression that is recognized in either the satellite imagery or the CDED data, almost of the interpreted dykes have RA_2 scores of 1. The results of RA_2 shows that 68 lineaments (4%) were identified and coincident on all three data sets (RA_2 = 3), and 492 lineaments (28%) were coincident with a lineament from one other data set (RA_2 = 2). A total of 1,519 lineaments (73% of 2,079 lineaments) lacked a coincident lineament from the other data sets (RA_2 = 1). There is much greater coincidence between surficial fracture lineaments (interpreted from CDED and satellite imagery) than between the geophysical fracture lineaments and either of the surficial data sets. Approximately 25% of the final merged geophysical fracture lineaments (111 out of 441) were coincident with a mapped surficial lineament.

The low RA_2 scores for the geophysical fracture and dyke lineaments and the low RA_1 scores for the geophysical fracture and dyke lineaments are likely reflective of the inherent difficulty in interpreting low-resolution aeromagnetic data, as exists for much of the Wawa area.

4.3 Description of Lineaments of Potentially Suitable Geologic Units in the Wawa Area

As described in Section 2.2, the bedrock geology of the Wawa area is dominated by large granodiorite and gneissic bodies that intrude older metavolcanic rocks associated with greenstone belts. These intrusive rocks, which are considered potentially suitable formations, include the Western batholith, the Whitefish Lake and Brulé Bay batholiths and the Wawa Gneiss domain. The following discussion describes the dominant interpreted lineament orientations and characteristics for each of these bedrock formations. Lineament data are presented separately for the Whitefish Lake batholith and the Brulé Bay batholith. The boundary between these two batholiths is delineated by the southwestward extension of Michipicoten greenstone belt to the west of the Agawa Canyon fault (e.g., Figure 12).

There were 442 lineaments identified over an area of approximately 631 km^2 of the Western batholith. These lineaments consist of 396 fractures and 46 dykes. Azimuth data weighted by length for all of the lineaments from the Western batholith exhibit dominant northeast, north-northwest and east trends (Figure 14). A minor northwest lineament trend is also evident. Interpreted fracture lineaments in the Western batholith identified all major OGS mapped faults, including the Trembley and Black Trout Lake faults, as shown on Figure 3. Both Matachewan and Abitibi/Biscotasing dykes cross the Western batholith and were identified in the lineament interpretation.

The Whitefish Lake batholith spans approximately 548 km^2 of the Wawa area. A total of 369 lineaments consisting of 315 fractures and 54 dykes, were interpreted over the Whitefish Lake batholith. The rose diagram, weighted by length, for lineaments from the Whitefish Lake batholith shows three strong trends; east-northeast, east and north-northwest (Figure 14). Interpreted fracture lineaments in the Brulé Bay batholith identified all major OGS mapped faults, including the Agawa Canyon fault, as shown on Figure 3. Matachewan dykes transect most of the Whitefish Lake batholith and represent a significant part of the north-northwest trending lineament set.

There were 200 lineaments consisting of 188 fractures and 12 dykes, identified over an area of approximately 254 km^2 of the Brulé Bay batholith. Orientation data for the Brulé Bay batholith on a rose diagram weighted by length indicate three strong trends to the north, east and northeast (Figure 14). Interpreted fracture lineaments in the Brulé Bay batholith include all major OGS mapped faults, including the Old Woman River fault, the Trembley fault, the Treeby Lake fault and the Mishewawa Lake fault, as shown on Figure 3. A small number of dykes cut across the Brulé Bay batholith and were identified in the lineament interpretation.

The Wawa Gneiss domain covers most of the southeastern and eastern portions of the Wawa area (approximately 1205 km^2), where 761 lineaments were identified. These lineaments consist of 639 fractures and 122 dykes. The rose diagram weighted by length for lineament azimuths from this gneissic suite shows three dominant trends: northeast to east-northeast, north-northwest and east (Figure 14). Interpreted fracture lineaments in the Wawa Gneiss domain identified all major OGS mapped faults, including the Manitowik Lake fault and the Agawa Canyon fault, as shown on Figure 3. Both Matachewan and Abitibi/Biscotasing dykes cross the Wawa Gneiss domain with more frequent occurrence east of the Agawa Canyon fault and were identified in the lineament interpretation.

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

Lineament density across the Wawa area (see Figures 12 and 13) appears uniformly relatively high, likely in part as a result of the very limited extent of overburden cover and the rugged bedrock terrain throughout the Wawa area. Of the 2,079 lineaments mapped from CDED, Landsat/SPOT and geophysical data, more than two-thirds are derived from surficial data sources (CDED and Landsat/SPOT). Overall increased aeromagnetic lineament density, particularly for dykes, might be anticipated in the event that higher resolution airborne geophysical data was available for the Wawa area. However, given the lack of both overburden cover and the uniformly low resolution aeromagnetic data currently available over all of intrusive formations of potential suitability (i.e., Western, Whitefish Lake and Brulé Bay batholiths, and the Wawa Gneiss domain), the interpreted lineaments provide a common and rational basis for identification of differences in lineament density between potentially suitable formations.

Review of Figures 8, 9, 10, 12 and 13 shows that overall lineament density as defined by the presence of final merged fractures and dykes is generally relatively high in the four main potentially suitable geologic units.

The dyke lineament densities are highest in the Whitefish Lake batholith and Wawa Gneiss domain, and lowest in the Brulé Bay batholith followed by the Western batholith. This spatial pattern of higher dyke lineament density in the eastern parts of the Wawa area is likely in part related to proximity to the Kapuskasing structural zone located 30 to 40 km east of the Wawa area.

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 and coincidence values are discussed in detail in Sections 4.1 and 4.2.

The findings from the reproducibility assessment RA_1 indicate that approximately 43.5% of surficial lineaments (46% for Landsat/SPOT; 41% for CDED) were identified by both interpreters (Figures 8 and 9). Importantly, longer lineaments with higher certainty values were identified more often by both interpreters. However, the reproducibility assessment of the geophysical lineaments shows that only 136 (17%) of the total number of fracture and dyke lineaments (789) were identified by both interpreters (Figure 10). As with the surficial lineaments, longer geophysical lineaments with higher certainty values were also recognized more often by both interpreters (RA_1=2).

Coincidence between features identified in the various datasets was evaluated in the second Reproducibility Assessment (RA_2). As would be expected, the surficial lineaments interpreted from CDED and Landsat/SPOT show the highest coincidence at about 37% (510 out of 1,372 merged surficial fracture lineaments were coincident between CDED and satellite) which corresponds to 29% of total fracture lineaments that were coincident between CDED and satellite (510 out of 1,731). This 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. In contrast, about 25% (111 out of 441) of the interpreted geophysical fractures were coincident with surficial fractures, corresponding to 6% (111 out of 1731) of the total lineament dataset (fractures) that shows coincidence. This low coincidence between surficial and geophysical lineaments is not unexpected, and may be the result of various factors, such as: deep structures that are identified in geophysics may not have a surface expression; surficial features may not extend to great depth; structural features may not possess a magnetic susceptibility contrast with the host rock; surface expressions of lineaments may be masked by the presence of overburden; and/or the geometry of the feature (e.g. dipping versus vertical). All these may be further constrained by the resolution of the datasets. Regardless of the degree of coincidence, the observed overlap in dominant lineament orientation between all datasets (north-northwest, northeast and east - see insets on Figures 8, 9 and 10) suggests that all datasets 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.

5.3 Lineament Length

There is no information available on the depth extent into the bedrock of the lineaments interpreted for the Wawa area. In the absence of available information, the interpreted length may be used as a proxy for the depth extent of the identified structures. A preliminary assumption may be made that the longer interpreted lineaments in the Wawa area may extend to greater depths than the shorter interpreted lineaments, and that longer lineaments may be hydrogeologically and geomechanically more important at potential repository depths than shorter lineaments.

As described in Section 4.2, lineaments in the >10 km and 5-10 km length bins represent 21% and 26% of the final merged lineaments, respectively, while lineaments in the 1-5 km and <1 km length bins represent 49% and 4% of the final merged lineaments, respectively. Longer interpreted lineaments generally have higher certainty, reproducibility and coincidence 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 identified are related to bedrock structures.

Figure 12 shows the interpreted lineaments classified by lineament length. Four lineament length bins (0-1 km, 1-5 km, 5-10 km, > 10 km) were used for this analysis and a length weighted frequency rose diagram indicates the dominant lineament orientations (inset of Figure 12). Three prominent lineament orientation sets (north-northwest, northeast, and east), can be clearly recognized in the length-weighted dataset.

5.4 Fault and Lineament Relationships

As discussed above in Section 5.1, there are 2,079 interpreted lineaments in the Wawa area. The main known and named faults in the Wawa area, and their approximate orientations, as shown in Figure 3, include the following:

- Manitowik Lake fault, Hawk Lake fault, Wawa Lake fault, Magpie River fault, Firesand River fault, Mishewawa Lake fault and Old Woman River fault – northeast-trending;
- Trembley fault, Black Trout Lake fault, Mildred Lake fault, Marsden fault and Treeby Lake fault – north-northwest trending; and
- Agawa Canyon fault – north-trending.

As discussed in part in Section 4.3, all of the named faults listed above are associated with specific interpreted lineaments and, with the exception of the late Agawa Canyon and McEwan Lake faults, the trend of these faults correspond with the major lineament trends of northeast and north-northwest. The north-trending Agawa Canyon and McEwan Lake faults are late, large-scale structures that do not have extensive parallel features observed in the lineament interpretation of the Wawa area. The east-trending set of lineaments evident from satellite and geophysical datasets does not correspond with known and labeled faulting in the Wawa area. Based on prevalence of east-trending ductile lineaments (see Figure 11), the east-trending lineament set may be reflective of ductile deformation as well as brittle deformation events.

Whether there is a relationship between the regional stress field and known mapped faults and observed lineament orientations is difficult to determine.

The principal horizontal neotectonic stress orientation in central North America is generally oriented approximately east-northeasterly (63º ± 28º; Zoback, 1992), although anomalous stress orientations have also been reported in the mid-continent that include a 90º 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, 2000), 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 interpreted 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-northeasterly neotectonic stress regime. The combined set of lineaments from all sources includes trends to the north-northwest, northeast and east. These features were formed by Precambrian paleostress regimes and constitute zones of weakness that are more amenable to reactivation under certain stress conditions than the surrounding rock mass. On this basis, should the identified lineaments be reactivated under the current stress regime, the north-northwest oriented lineaments will likely reactivate as reverse or strike slip faults, the east oriented lineaments will likely reactivate as strike slip faults, and the northeast oriented lineaments will likely re-activate in tension or as strike-slip faults.

5.5 Relative Age Relationships

The structural history of the Wawa area, outlined in Section 2.3, provides a framework that assists in constraining the relative age relationships of the interpreted bedrock lineaments. In brief summary, seven main regionally distinguishable deformation episodes (D_1 to D_7) are inferred to have overprinted the bedrock geological units of the Wawa area. D_1 to D_2 developed a gneissic foliation and isoclinal folds/nappe structure between approximately 2.682 and 2.671 billion years ago in the older gneissic rocks. D_3 events developed east- and north-northwest-trending dextral shear zones and faults and northeast-trending sinistral shear zones and faults during late stage Archean orogenesis. D_4 produced later brittle faults and fractures trending northwest and northeast and north-trending brittle faults including the Agawa Canyon fault. D_5 collectively included the activation of conjugate late brittle faults and fractures trending north-northwest, northeast, north and east. D_3 to D_5 events occurred between approximately 2.671 and 2.662 billion years ago. D_6 collectively included Proterozoic faults and reactivated Archean faults associated with uplift of the Kapuskasing structural zone, located approximately 50 km east of the Wawa area, that occurred between approximately 1.9 and 1.1 billion years ago. D_7 included reverse fault movements perpendicular to the extensional axis of the Mid-continent Rift that marked an episode of approximately 1.0 billion year old north- and north-northwest-directed crustal compression.

Paleoproterozoic diabase dykes are abundant across the Wawa area, dominated by the northwest -trending Matachewan swarm emplaced between ca.approximately 2.473 and 2.446 billion years ago, and the subordinate northeast- trending dykes of the approximately 2.17 billion year old Biscotasing suite and the approximately 2.11 billion year old Marathon/Kapuskasing suite.

The relative ages of faulting across the Wawa area suggest that the oldest faults tend to trend east, overprinted by north-northwest and northeast-trending faults, followed by late north-trending faults. In the Wawa area, the most prominent faults are related to the Proterozoic northeast-trending dextral displacement across the Kapuskasing structural zone and associated north-northwest trending sinistral faults. These sinistral faults are well illustrated by the OGS compilation maps that show displacement of the greenstone belt into separate panels. The aeromagnetic data confirms this pattern. The most prominent dextral fault in the area is the Wawa-Hawk-Manitowik fault (or Manitowik fault) just west of the Whitefish Lake batholith. This fault is a major component in the westernmost dextral movement of the Kapuskasing structural zone.

Most episodes of late movement along faults in the Wawa area probably terminated by Keweenawan time, approximately 1.100 billion years ago, during the emplacement of the Mid-continent Rift along Lake Superior, since northeast-trending dykes of this age (Abitibi swarm) crosscut all major north and northwest-trending faults without displacement (West and Ernst, 1991). Local evidence of a set of faults occurs south of the Michipicoten greenstone belt near Cape Gargantua that is probably related to late compression during the Grenville Orogeny.

Given the issues of variable resolution and irregularly distributed overburden cover, it is difficult at the desktop stage of the preliminary assessment of potential suitability to assign temporal relationships with any degree of confidence to the identified lineaments. The only distinction that can be made is between older ductile and younger brittle features, albeit with the caveat that many of the 'ductile' lineaments may have developed under brittle conditions and have simply re-activated the pre-existing ductile fabric. Therefore, a tentative preliminary interpretation of the lineament dataset is that the identified ductile (i.e. stratigraphic and foliation-related) lineaments originated largely as pre-approximately 2.671 billion year old features while the brittle lineaments (including dyke lineaments) may be considered to be composite D_3-D_7 structures that were formed during a protracted period of time (since approximately 2.671 billion years ago).

6 SUMMARY

This report documents the source data, workflow and results from a lineament interpretation of publicly-available digital data sets for the Wawa area in northern Ontario. The lineament analysis provides an interpretation of the location and orientation of possible individual fractures or fracture zones 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 Wawa area potentially reflects the bedrock structure and the resolution of the data sets used. Surface lineament density, as demonstrated in this assessment, is not influenced by overburden cover due to the limited overburden cover and the exposed rugged bedrock terrain across the Wawa area. Lineament density is influenced by the resolution of the data sets as demonstrated by the comparison of aeromagnetic lineaments interpreted from low resolution surveys with surficial (CDED and Landsat/SPOT) datasets. The results of the final merged lineament mapping suggests highest lineament densities are in the Brulé Bay batholith and the lowest lineament densities lineaments are in the Wawa Gneiss domain. The lineament densities in the Western batholith and Whitefish Lake batholith are between those of Brulé Bay batholith and the Wawa Gneiss domain.

In terms of reproducibility, longer interpreted lineaments generally have higher certainty, reproducibility and coincidence values. Comparison between the various datasets (RA_2), indicates that the highest level of coincidence is between surficial lineaments interpreted from CDED and Landsat/SPOT. This 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. The low coincidence between surficial and geophysical lineaments may be the result of various factors: deep structures identified in geophysics may not have a surface expression; surficial features may not extend to great depth; structural features may not possess a magnetic susceptibility contrast with the host rock; surface expressions of lineaments may be masked by the presence of overburden; the geometry of the feature (e.g. dipping versus vertical); and the differing quality of the datasets used to map lineaments.

The orientations observed for the combined set of lineaments from all sources (except stratigraphic horizon and foliation-related features) include strong trends to the north-northwest, northeast and east with a minor north-trend. It may be possible, with further detailed investigation, to assign the formation of the identified lineaments to distinct deformation events. However, it is difficult at the desktop stage to provide any further constraint on the timing of lineament development beyond denoting all identified lineaments as composite D_3-D_7 structures that were formed during a protracted period of time post-dating approximately 2.671 billion years ago.

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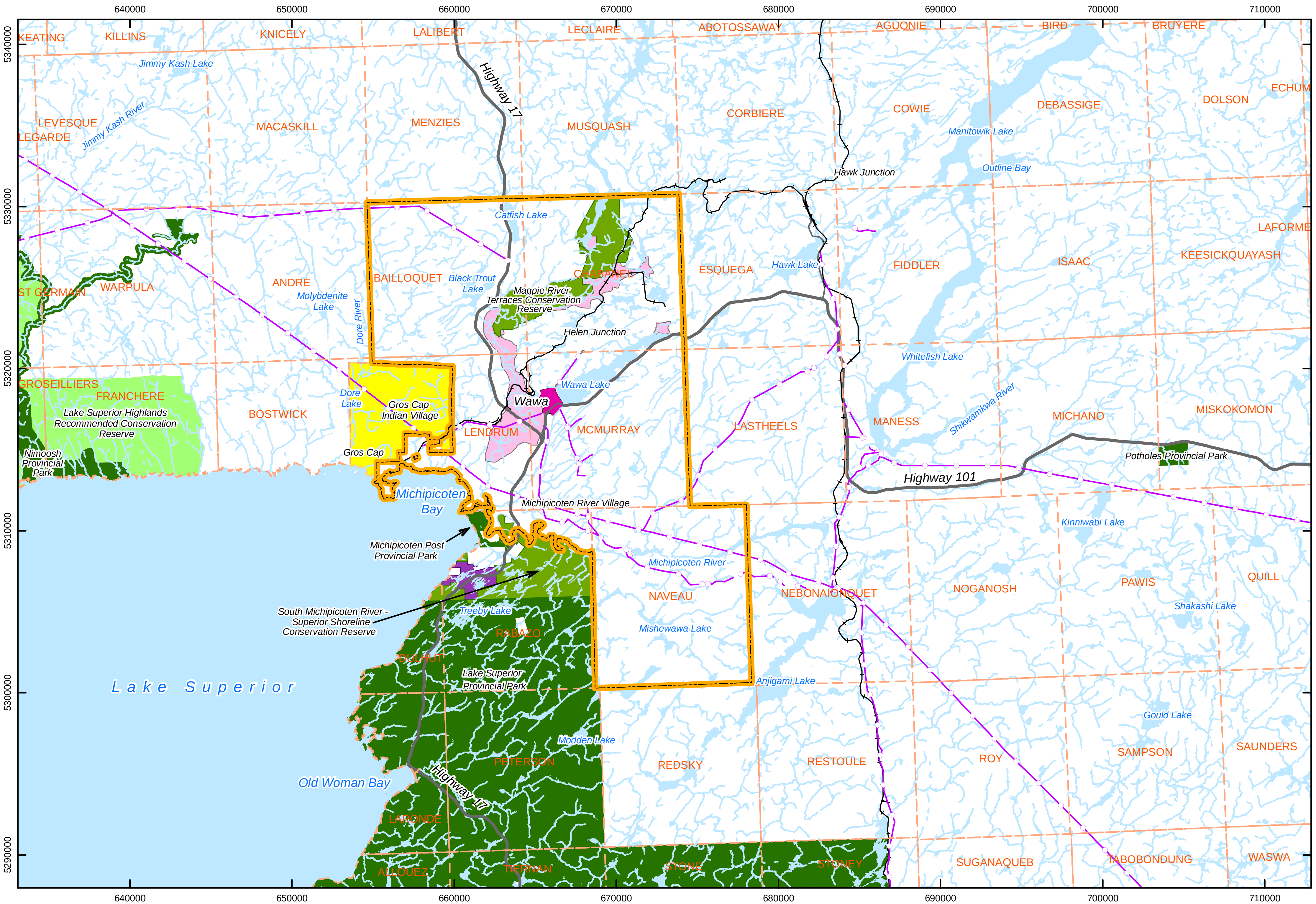
8 REPORT SIGNATURE PAGE

Respectfully submitted,

Geofirma Engineering Ltd.

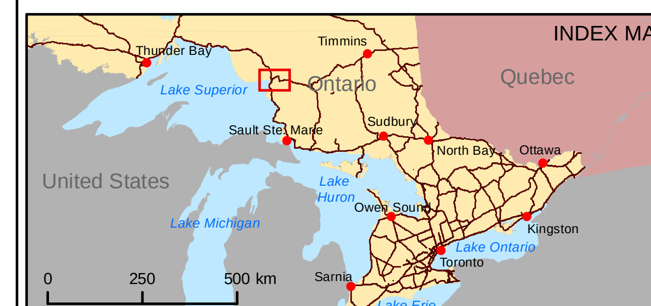
Sean Sterling, P.Eng., P.Geo.
Senior Geoscientist

Kenneth Raven, P. Eng., P.Geo.
Principal



LEGEND

- Municipality of Wawa
- Settlement Area of Wawa
- Geographic Township
- Conservation Reserve
- Recommended Conservation Reserve
- Forest Reserve
- Provincial Park
- Area of Natural and Scientific Interest (Earth Science)
- Indian Reserve (Gros Cap Indian Village 49A)
- Highway
- Local Road
- Railway
- Utility Line
- Water Area, Permanent
- Watercourse, Permanent
- Watercourse, Intermittent



SCALE 1:275,000

0 2.5 5 10 15 20

Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
ANSI: LIO ANSI, Earth Science; Candidate ANSI, Earth Science
Parks: LIO CLUPA designation
Rail: LIO Railway
Road: LIO MNR Road Segment
Township: LIO Geographic Township Improved
Utility: LIO Utility Line
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
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NORTH

PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

Municipality of Wawa and Surrounding Area

FIGURE 1

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 13/11/2013

Geofirma Engineering Ltd

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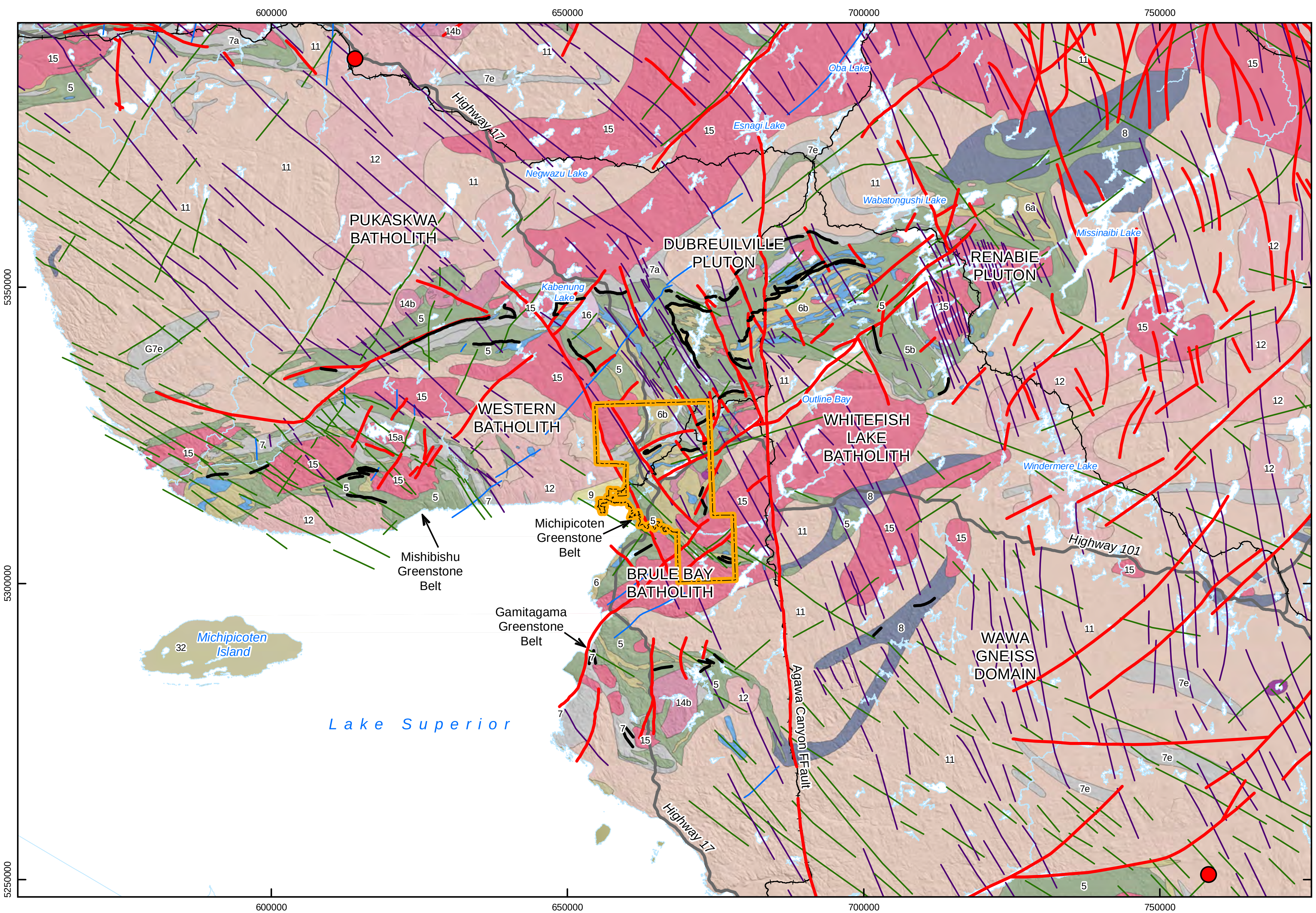

LEGEND

- Municipality of Wawa
- Highway
- Railway
- Water Area, Permanent
- Iron Formation
- Mapped Geological Fault

Mapped Dyke

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

Seismic Events (Magnitude)

- 2.0 - 3.0

**no events greater than 3 magnitude within mapping area

Bedrock Geology

- 36 Jacobsville Gp.; Oronto Gp
- 35 Carbonatite-alkalic intrusive suite (1.0 to 1.2 Ga)
- 32 Osler Gp., Maminse Point Fm., Michipicoten Island Fm.
  - 32b Rhyolite, quartz feldspar porphyry; associated conglomerate and arkose
- 16 Hornblendite - nepheline syenite suite
- 15 Massive granodiorite to granite
  - 15a Potassium feldspar megacrystic units
- 14-Diorite-monzodiorite-granodiorite suite
  - 14a Diorite, monzonite, quartz monzonite
  - 14b Granodiorite, granite
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
  - 10c Ultramafic rocks
- 9 Coarse clastic metasedimentary rocks
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
  - 7a Paragneisses and migmatites
  - 7b Conglomerate and arenite
  - 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
  - 6a Dacitic and Andesitic flows, tuffs and breccias
  - 6b Rhyolitic, rhyodacitic flows,tuffs and breccias
- 5 Mafic to intermediate metavolcanic rocks
  - 5b Basaltic and andesitic flows, tuffs and breccias

INDEX MAP

SCALE 1:750,000

0 5 10 20 30 40

Kilometres

NORTH

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
Seismic: Earthquakes Canada, (1985-2012)
Road: Selected Roads from LIO MNR Road Segment
Township: LIO Geographic Township Improved
Underlaying DEM: CDED Digital Elevation Model, Geobase, 2011
Waterbody: Selected Waterbodies from LIO OHN Waterbody
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PROJECT No. 10-214-3
NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE Regional Tectonic Setting of the Wawa Area

FIGURE 2

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 11/7/2013

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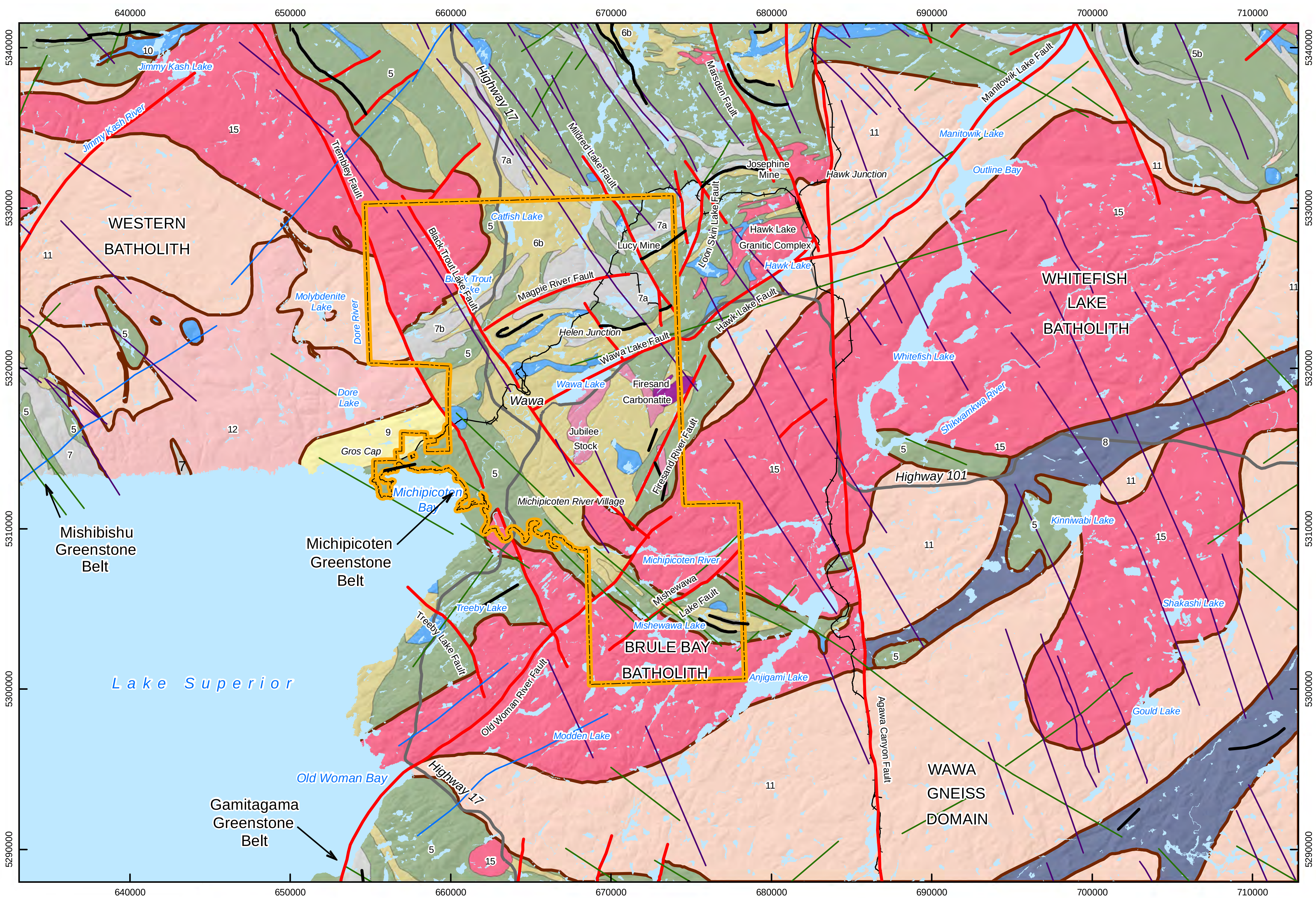

LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent
- Outline of Geologic Unit
- Iron Formation
- Mapped Geological Fault

Mapped Dyke

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

Bedrock Geology

- 35 Carbonatite-alkalic intrusive suite (1.0 to 1.2 Ga)
- 15 Massive granodiorite to granite
- 14-Diorite-monzodiorite-granodiorite suite
  - 14b Granodiorite, granite
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
  - 10c Ultramafic rocks
- 9 Coarse clastic metasedimentary rocks
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
  - 7a Paragneisses and migmatites
  - 7b Conglomerate and arenite
  - 7c Marble, chert, iron formation, minor metavolcanic rocks
  - 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
  - 6b Rhyolitc, rhyodacitic flows,tuffs and breccias
- 5 Mafic to intermediate metavolcanic rocks
  - 5b Basaltic and andesitic flows, tuffs and breccias

INDEX MAP

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
Basemap; Railway, Road, Geographic Township, Waterbody, Watercourse, LIO
Underlaying DEM: CDED Digital Elevation Model, Geobase, 2011
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NORTH

PROJECT No. 10-214-3
NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE
Bedrock Geology
of the Wawa Area

FIGURE
3

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 07/11/2013

Geofirma Engineering Ltd

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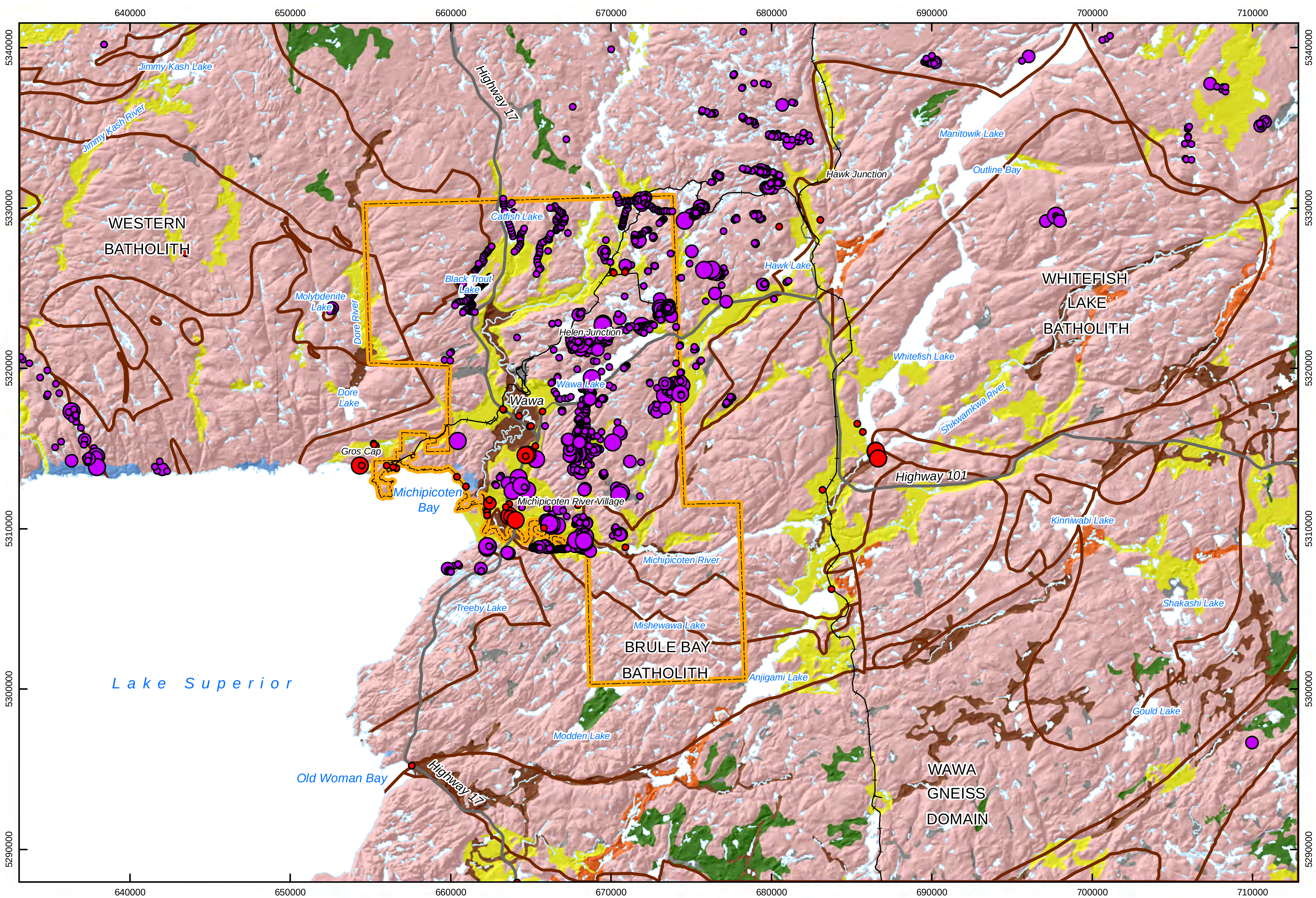


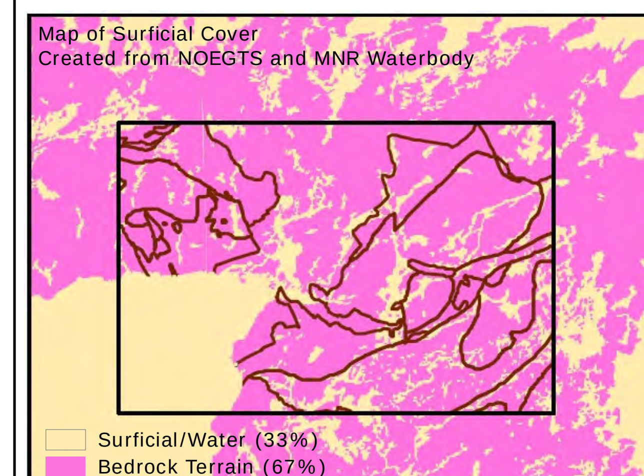
LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent
- Outline of Geologic Unit

Water Well (MOE) Depth to Bedrock (m)	Drill Hole (OGS) Depth to Bedrock (m)
0.0 - 5.0	0.0 - 5.0
5.1 - 15.0	5.1 - 15.0
> 15.1	> 15.1

Surficial Geology (NOEGTS Landform)

- Organic
- Modern alluvial
- Glaciolacustrine
- Glaciofluvial outwash
- Glaciofluvial esker
- Ground moraine
- Bedrock



SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

NORTH

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
NOEGTS: OGS MRD-160 (scale 1:100,000)
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Drill Hole: OGS Drill Hole Database (Data Set 13)
MOE Wells: Ministry of Environment, 2012
Rail: LIO Railway
Road: LIO MNR Road Segment
Township: LIO Geographic Township Improved
Underlaying DEM: CDED Digital Elevation Model, Geobase, 2011
Waterbody: LIO OHN Waterbody
Produced by Geofirma Engineering Ltd under license from
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PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

Surficial Geology of the Wawa Area

FIGURE 4

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 11/7/2013

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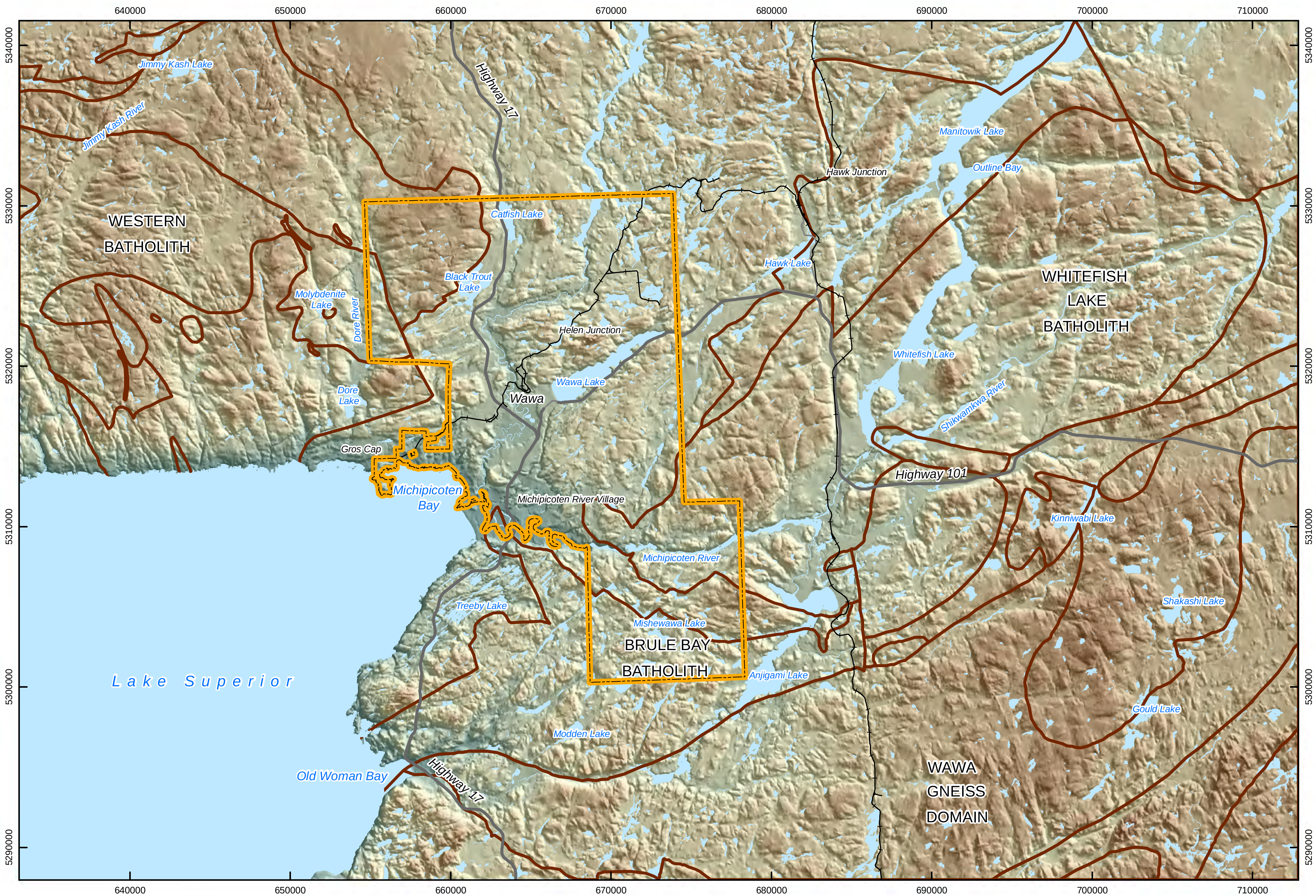

LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent
- Outline of Geologic Unit

Elevation (mASL)

610

367

185

SCALE 1:275,000

0 2.5 5 10 15 20

Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Topography: CDED Digital Elevation Model, Geobase, 2011
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Rail: LIO Railway
Road: MNR Road Segment
Township: LIO Geographic Township Improved
Underlaying DEM: CDED Digital Elevation Model, Geobase, 2011
Waterbody: LIO OHN Waterbody
Produced by Geofirma Engineering Ltd under license from
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NORTH

PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

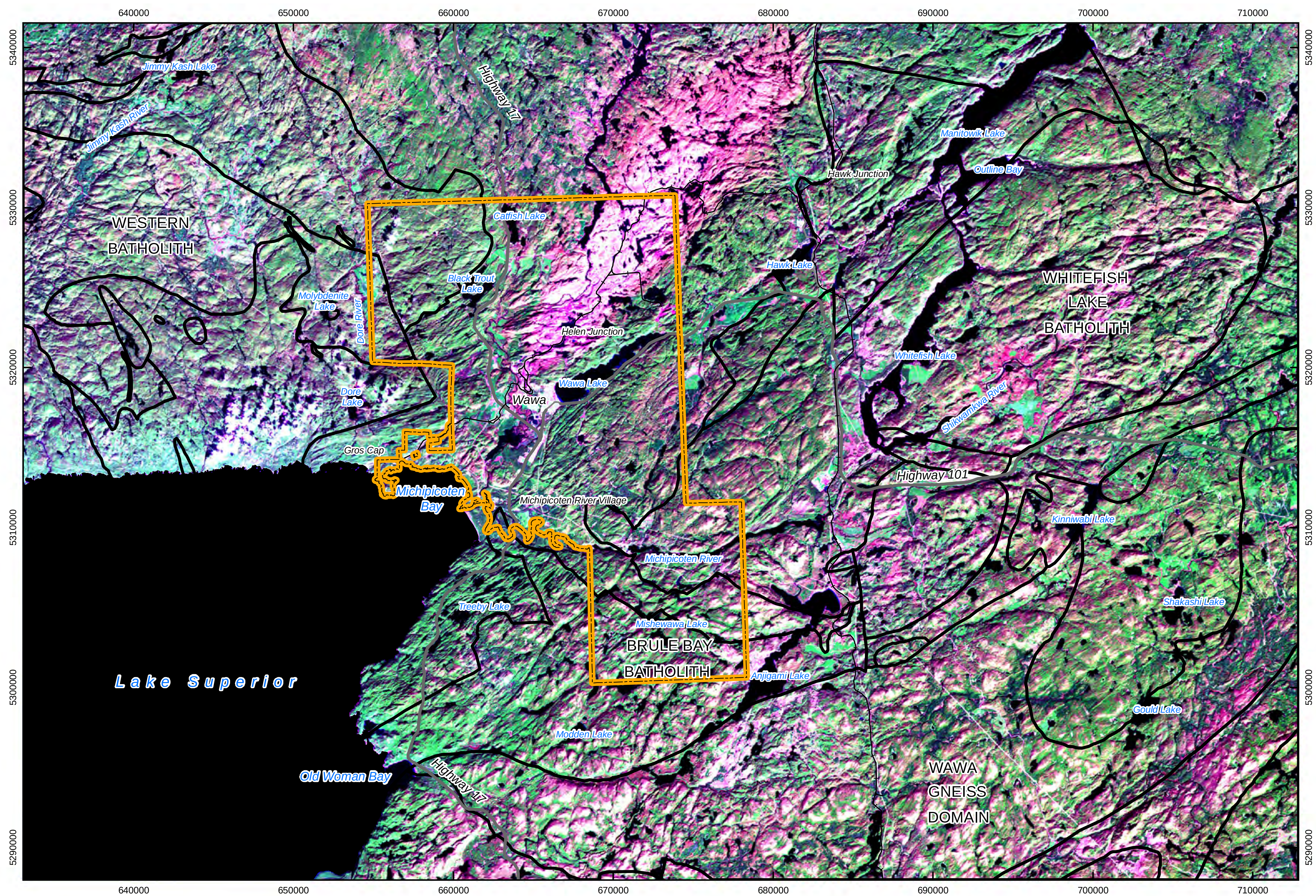
CDED Digital Elevation Model of the Wawa Area

FIGURE 5

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNA
REV: 0

DATE: 11/11/2013

Geofirma Engineering Ltd

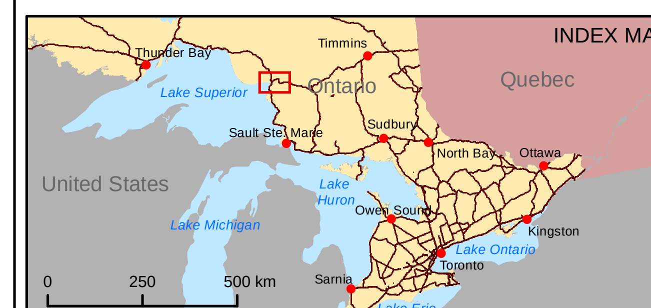


LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Outline of Geologic Unit

Landsat

- Red: Band 7
- Green: Band 4
- Blue: Band 2



SCALE 1:275,000

0 2.5 5 10 15 20 Kilometres

NORTH

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Imagery: Landsat 7, USGS (30m resolution)
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Rail: LIO Railway
Road: LIO MNR Road Segment
Township: LIO Geographic Township Improved
Produced by Geofirma Engineering Ltd under license from Ontario Ministry of Natural Resources, ©Queens Printer 2011

PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

Landsat Satellite Data of the Wawa Area

FIGURE 6

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 11/7/2013

Geofirma Engineering Ltd

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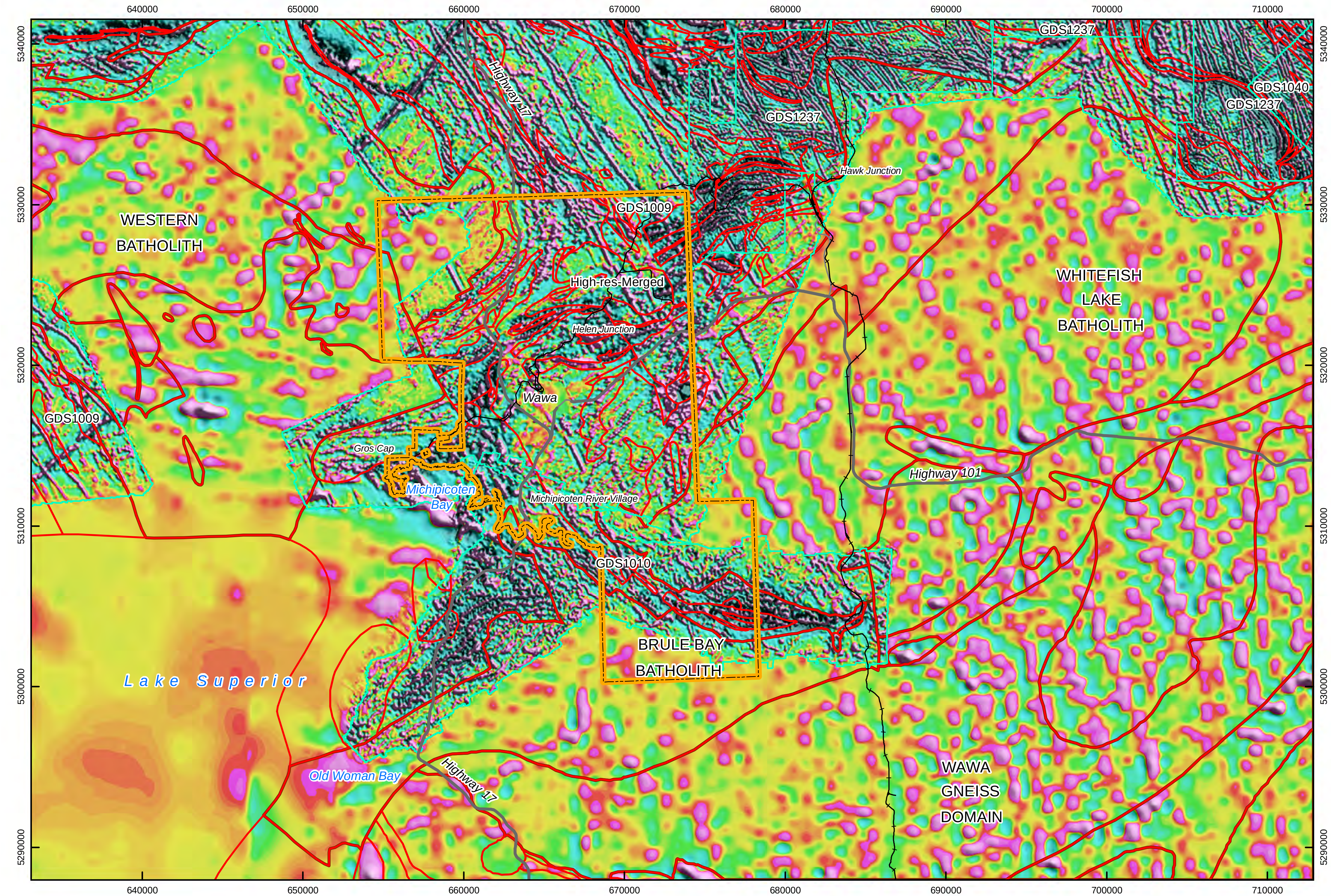


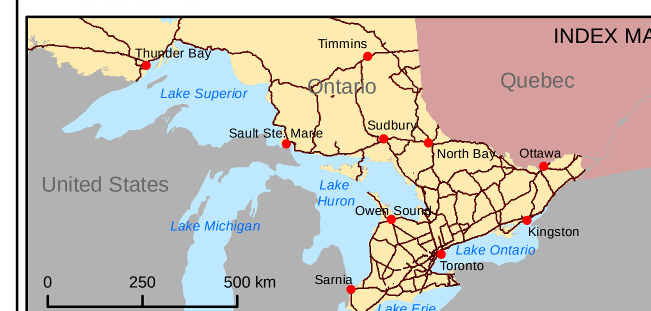
LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Outline of Geologic Unit
- Higher Resolution Geophysical Surveys

MAG

1.155, 0.525, 0.300, 0.190, 0.130, 0.085, 0.060, 0.040, 0.020, 0.005, 0.000, -0.010, -0.015, -0.025, -0.035, -0.050, -0.065, -0.080, -0.100, -0.120, -0.150, -0.180, -0.220, -0.275, -0.355, -0.475, -0.675, -1.115

1VD of RTP
(nT/m)



SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

NORTH

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Aeromagnetic Reduced Magnetic Field: PGW (2012)
Geophysical Surveys Outline: PGW (2012)
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Rail: LIO Railway
Road: Selected Roads from LIO MNR Road Segment
Township: LIO Geographic Township Improved
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PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

First Vertical Derivative of the Pole-Reduced Magnetic Field of the Wawa Area

FIGURE 7

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 11/7/2013

Geofirma Engineering Ltd

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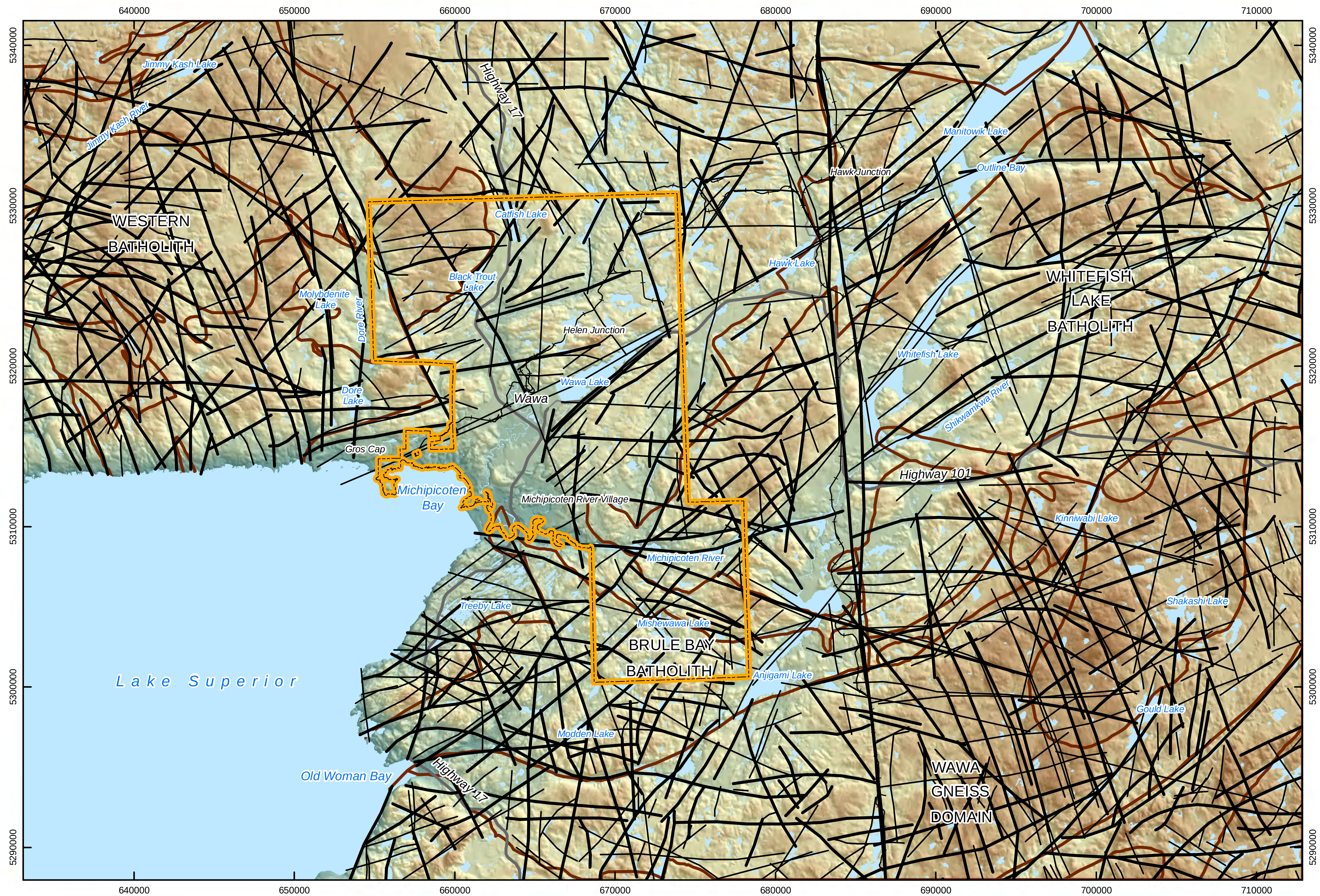


LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent
- Outline of Geologic Unit

CDED Lineament Reproducibility (RA_1)

- Fracture (RA_1 = 1)
- Fracture (RA_1 = 2)

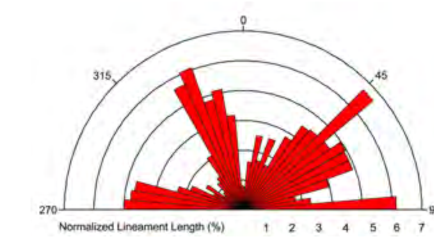
Elevation (mASL)

610

367

185

Wawa CDED Data -
Normalized Lineament Length in 5 Degree Azimuth Bins



Total CDED Lineaments = 927

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Topography: CDED Digital Elevation Model, Geobase, 2011
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Fractures: Geofirma Engineering, JDMA
Rail: LIO Railway
Road: LIO MNR Road Segment
Township: LIO Geographic Township Improved
Waterbody: LIO OHN Waterbody
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NORTH

PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

CDED Reproducibility
Assessment (RA_1)

FIGURE
8

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 11/13/2013

Geofirma Engineering Ltd

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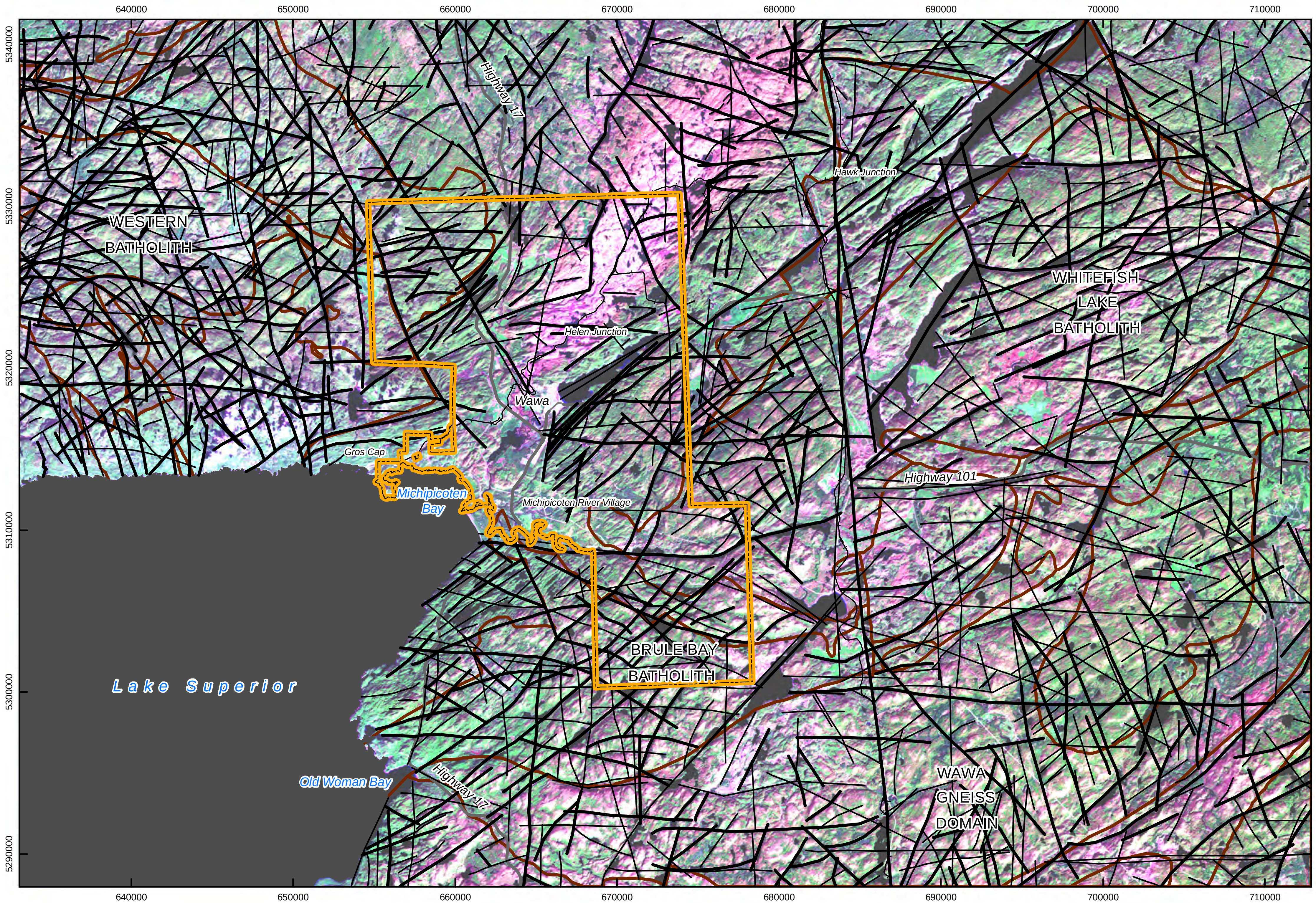


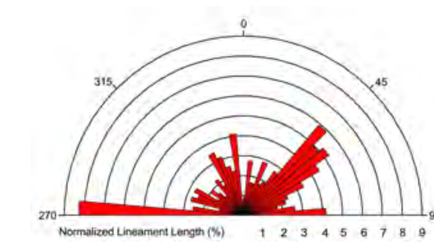
LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Outline of Geologic Unit

Landsat/SPOT Lineament Reproducibility (RA_1)

- Fracture (RA_1 = 1)
- Fracture (RA_1 = 2)

Wawa Landsat/SPOT Data -
Normalized Lineament Length in 5 degree Azimuth Bins



Total Landsat/SPOT Lineaments = 1,114

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Imagery: Landsat 7, USGS (30m resolution)
Fractures: Geofirma Engineering, JDMA
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Rail: LIO Railway
Road: LIO MNR Road Segment
Township: LIO Geographic Township Improved
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NORTH

PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

Landsat/SPOT Reproducibility Assessment (RA_1)

FIGURE 9

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 8/14/2013

Geofirma Engineering Ltd

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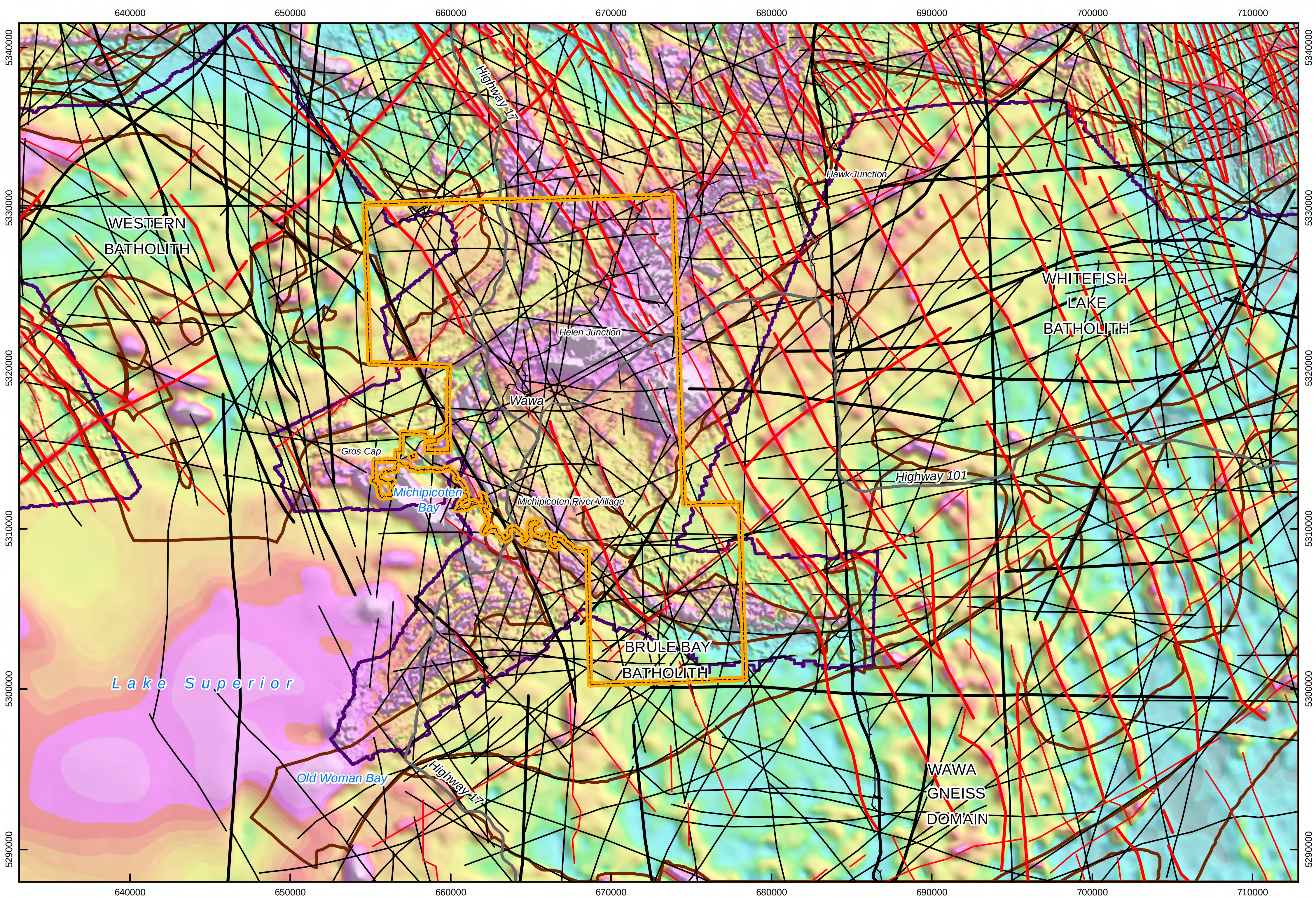


LEGEND

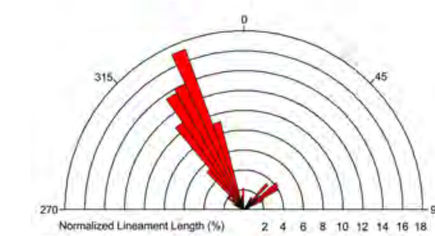
- Municipality of Wawa
- Highway
- Local Road
- Railway
- Outline of Geologic Unit
- Higher Resolution Geophysical Surveys

Aeromagnetic Lineament Reproducibility (RA_1)

- Fracture (RA_1 = 1)
- Fracture (RA_1 = 2)
- Dyke (RA_1 = 1)
- Dyke (RA_1 = 2)

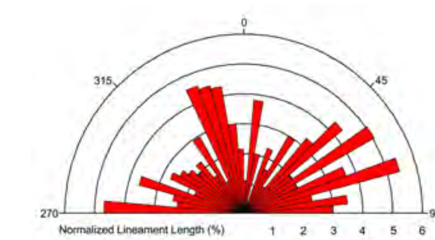
Magnetic - See Figure 7 for magnetic legend

Wawa Geophysical Dykes -
Normalized Lineament Length in 5 Degree Azimuth Bins



Total Geophysical Dykes = 348

Wawa Geophysical Fractures -
Normalized Lineament Length in 5 Degree Azimuth Bins



Total Geophysical Fractures = 441

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

NORTH

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Aeromagnetic Reduced Magnetic Field: PGW (2012)
Geophysical Surveys Outline: PGW (2012)
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Dykes and Faults: PGW, Greg Stott
Rail: LIO Railway
Road: Selected Roads from LIO MNR Road Segment
Township: LIO Geographic Township Improved
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PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE **Aeromagnetic Reproducibility Assessment (RA_1)**

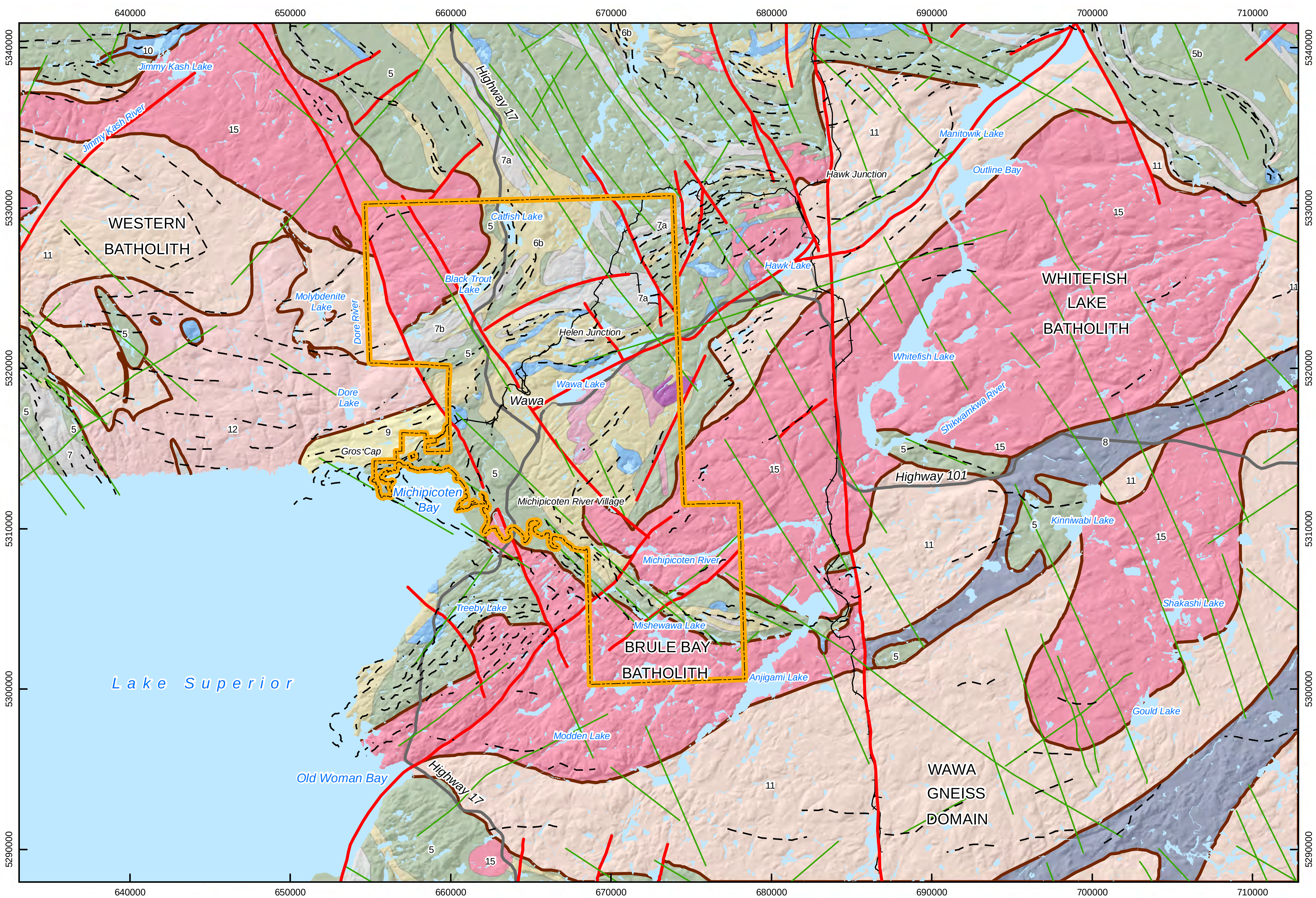
FIGURE 10

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 11/7/2013

Geofirma Engineering Ltd

G:\Data\Project\Wawa\Maps\10-214-3_Wawa\Wawa_2012_Report_Maps\Map_LineamentReport\10-214-3_Wawa_Figure10_Aeromagnetic_Reproducibility_Assessment_R0.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent
- Outline of Geologic Unit
- Mapped Geological Fault
- Mapped Dyke
- Ductile Lineament

Bedrock Geology

- 35 Carbonatite-alkalic intrusive suite (1.0 to 1.2 Ga)
- 15 Massive granodiorite to granite
- 14-Diorite-monzodiorite-granodiorite suite
- 14b Granodiorite, granite
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
- 10c Ultramafic rocks
- 9 Coarse clastic metasedimentary rocks
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
- 7a Paragneisses and migmatites
- 7b Conglomerate and arenite
- 7c Marble, chert, iron formation, minor metavolcanic rocks
- 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
- 6b Rhyolitc, rhyodacitic flows,tuffs and breccias
- 5 Mafic to intermediate metavolcanic rocks
- 5b Basaltic and andesitic flows, tuffs and breccias

SCALE 1:275,000

0 2.5 5 10 15 20

Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Rail: LIO Railway
Road: LIO MNR Road Segment
Township: LIO Geographic Township Improved
Underlaying DEM: CDED Digital Elevation Model, Geobase, 2011
Waterbody: LIO OHN Waterbody
Produced by Geofirma Engineering Ltd under license from Ontario Ministry of Natural Resources, ©Queens Printer 2011

NORTH

PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

Ductile Lineaments of the Wawa Area

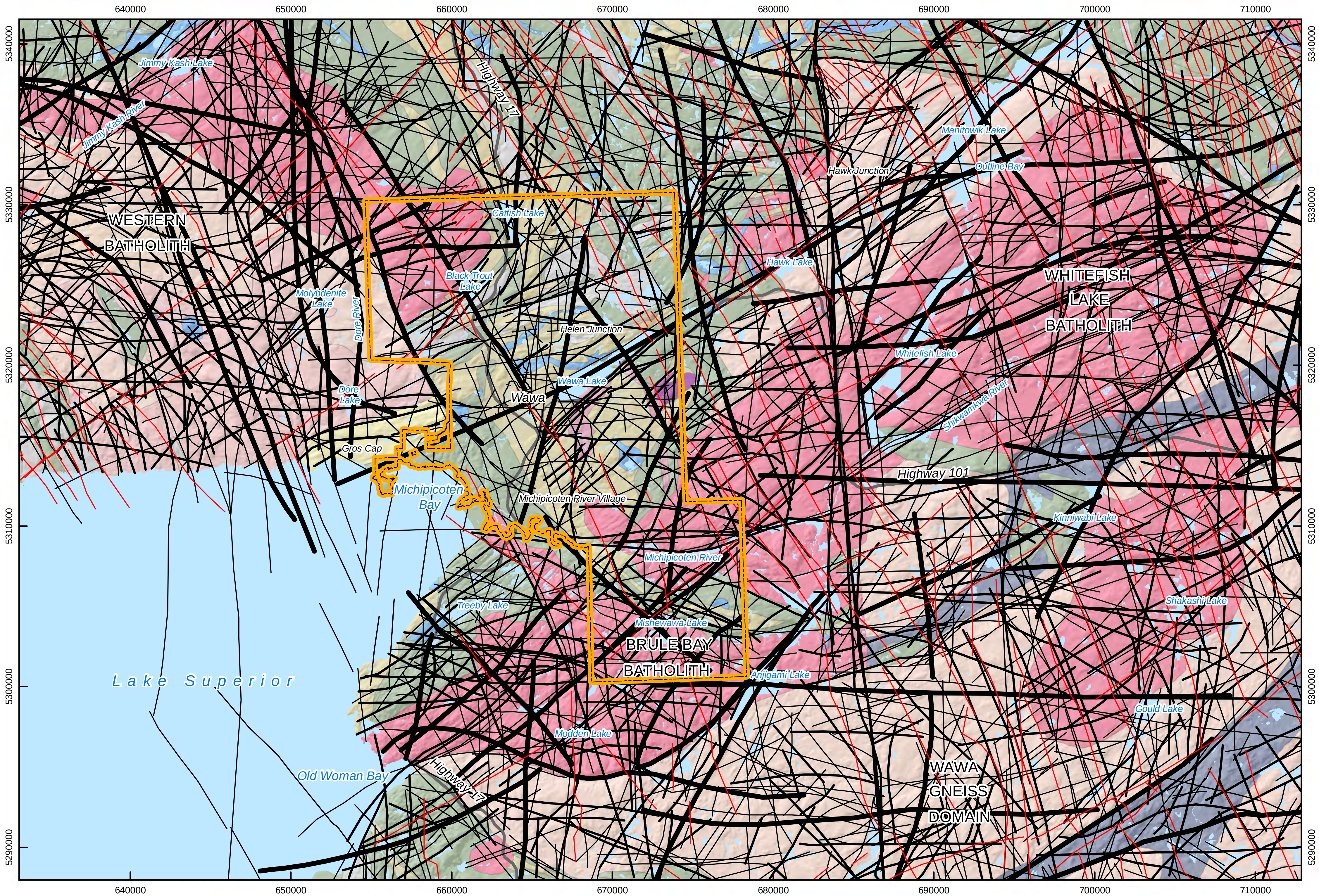
FIGURE 11

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 07/11/2013

Geofirma Engineering Ltd

G:\Data\Project\Wawa\Maps\10-214-3_Wawa\Wawa_2012_Report_Maps\Map_LineamentReport\10-214-3_Wawa_Figure11_Ductile_Features_of_the_Wawa_Area_R0.mxd



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LEGEND

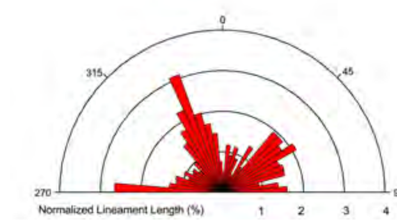
- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent

Lineament Reproducibility (RA_2)

- Fracture (RA_2 = 1)
- Fracture (RA_2 = 2)
- Fracture (RA_2 = 3)
- Dyke (RA_2 = 1) *no dyke with RA_2 > 1

Bedrock Geology - see Figure 3 for geology legend

Wawa All Data -
Normalized Lineament Length in 5 Degree Azimuth Bins



Total Lineaments = 2,079

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Dykes, Faults and Fractures: Geofirma Engineering, JDMA, PGW, Greg Stott
Rail: LIO Railway
Road: LIO MNR Road Segment
Township: LIO Geographic Township Improved
Underlaying DEM: CDED Digital Elevation Model, Geobase, 2011
Waterbody: LIO OHN Waterbody
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NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

Lineament Classification by Reproducibility Assessment (RA_2) of the Wawa Area

FIGURE 12

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0

DATE: 07/11/2013

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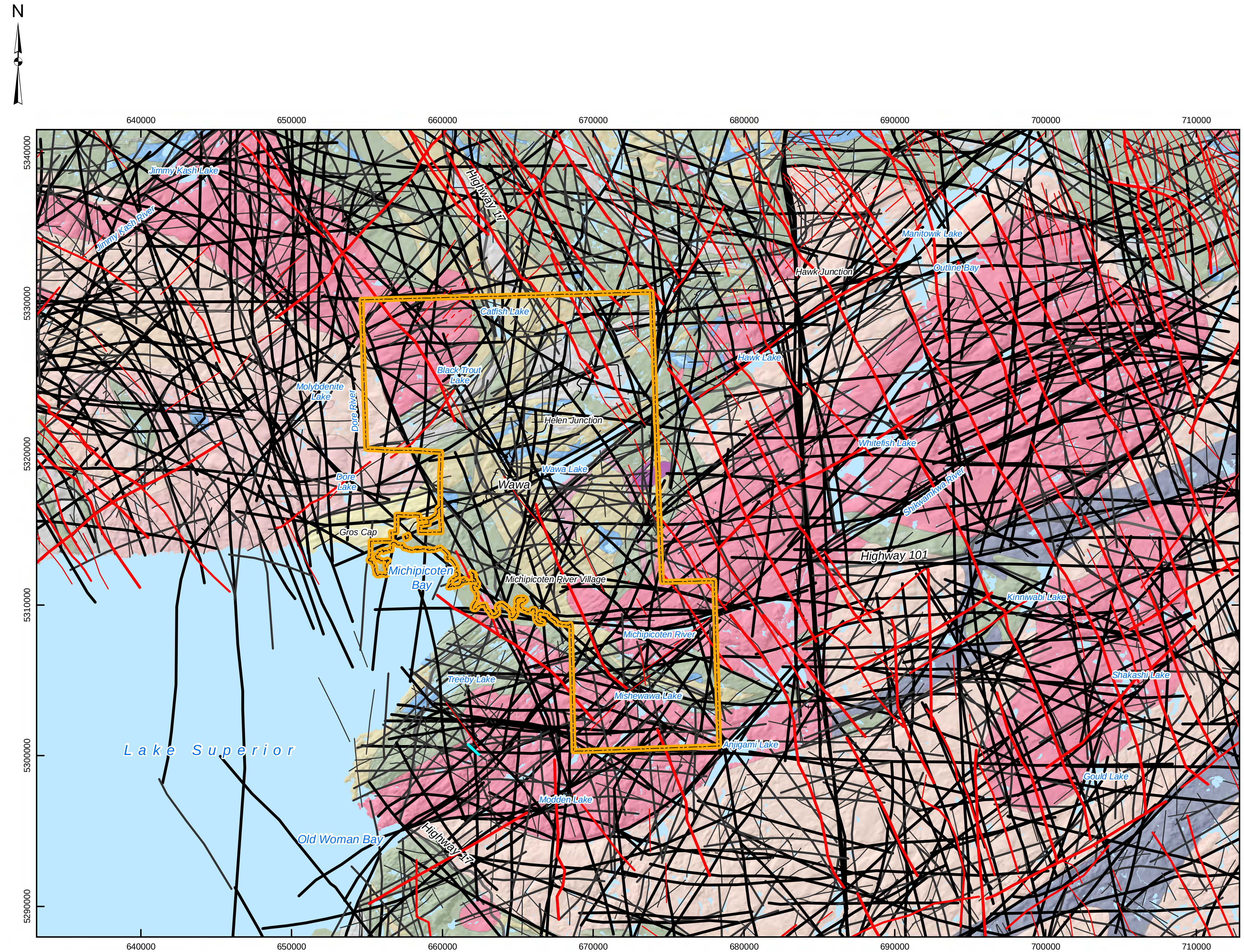


LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent

Fracture (length)

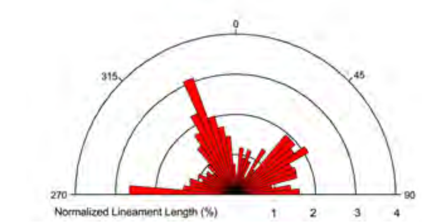
- 0 - 1 km
- 1 - 5 km
- 5 - 10 km
- 10+ km

Dyke (length)

- 0 - 1 km
- 1 - 5 km
- 5 - 10 km
- 10+ km

Bedrock Geology - see Figure 3 for geology legend

Wawa All Data -
Normalized Lineament Length in 5 Degree Azimuth Bins



Total Lineaments = 2,079

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Dykes, Faults and Fractures: Geofirma Engineering, JDMA, PGW, Greg Stott
Rail: LIO Railway
Road: LIO MNR Road Segment
Township: LIO Geographic Township Improved
Underlaying DEM: CDED Digital Elevation Model, Geobase, 2011
Waterbody: LIO OHN Waterbody
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NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

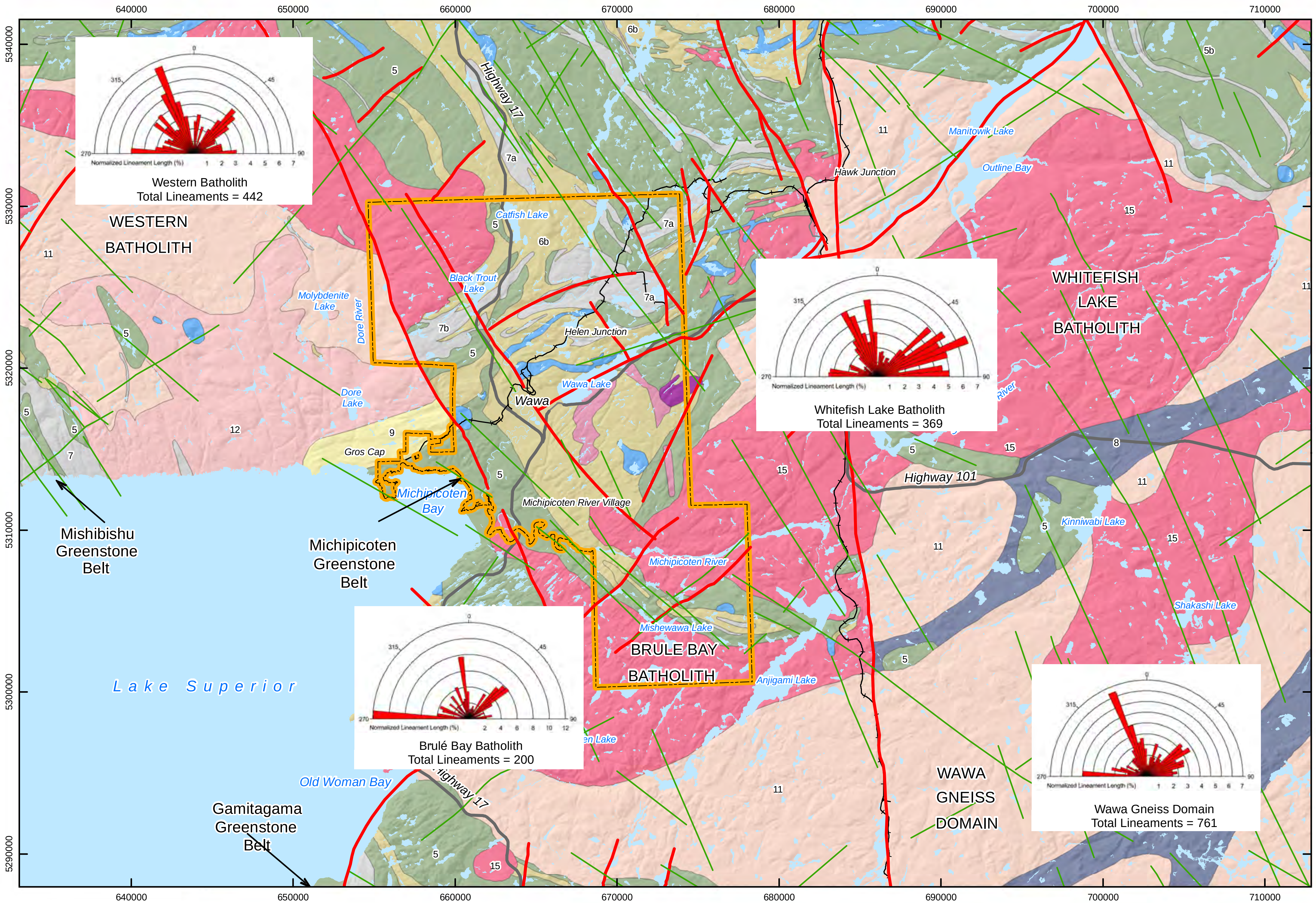
TITLE
Lineament Classification by Length of the Wawa Area

FIGURE 13

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0
DATE: 07/11/2013

Geofirma Engineering Ltd

G:\Data\Project\Wawa\Maps\10-214-3_Wawa\Wawa_2012_Report_Maps\Map_LineamentReport\10-214-3_Wawa_Figure13_Lineament_Classification_by_Length_R0.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent
- Mapped Geological Fault
- Mapped Dyke

Bedrock Geology

- 36 Jacobsville Gp.; Oronto Gp
- 35 Carbonatite-alkalic intrusive suite (1.0 to 1.2 Ga)
- 32 Osler Gp., Maminse Point Fm., Michipicoten Island Fm.
  - 32b Rhyolite, quartz feldspar porphyry; associated conglomerate and arkose
- 16 Hornblendite - nepheline syenite suite
- 15 Massive granodiorite to granite
  - 15a Potassium feldspar megacrystic units
- 14-Diorite-monzodiorite-granodiorite suite
  - 14a Diorite, monzonite, quartz monzonite
  - 14b Granodiorite, granite
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
  - 10c Ultramafic rocks
- 9 Coarse clastic metasedimentary rocks
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
  - 7a Paragneisses and migmatites
  - 7b Conglomerate and arenite
  - 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
  - 6a Dacitic and Andesitic flows, tuffs and breccias
  - 6b Rhyolitic, rhyodacitic flows,tuffs and breccias
- 5 Mafic to intermediate metavolcanic rocks
  - 5b Basaltic and andesitic flows, tuffs and breccias

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Dykes, Faults and Fractures: Geofirma Engineering, JDMA
Rail: LIO Railway
Road: Selected Roads from LIO MNR Road Segment
Township: LIO Geographic Township Improved
Waterbody: LIO OHN Waterbody
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PROJECT No. 10-214-3

NWMO Wawa Desktop Feasibility Study
Lineament Interpretation Report

TITLE

Lineament Orientations of Potentially Suitable Geologic Units in the Wawa Area

FIGURE 14

DESIGN: NMP
CAD/GIS: VMS/NMP
CHECK: KGR/SNS
REV: 0

DATE: 11/7/2013

Geofirma Engineering Ltd

G:\Data\Project\Wawa\Wawa_2012_Report_Maps\Map_LineamentReport\10-214-3_Wawa_Figure14_Lineament_Orientations_of_Batholiths_and_Plutons_R0.mxd