NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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

MUNICIPALITY OF WAWA, ONTARIO

APM-REP-06144-0029

NOVEMBER 2013

For more information, please contact:
Nuclear Waste Management Organization
22 St. Clair Avenue East, Sixth Floor
Toronto, Ontario M4T 2S3 Canada
Tel 416.934.9814
Toll Free 1.866.249.6966
Email contactus@nwmo.ca
www.nwmo.ca

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT

PROCESSING AND INTERPRETATION OF GEOPHYSICAL DATA

Municipality of Wawa, Ontario

Prepared for

Geofirma Engineering Ltd.
and
Nuclear Waste Management Organization (NWMO)

by

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

NWMO Report Number:
APM-REP-06144-0029

Toronto, Canada **November, 2013**

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 the successful completion of an initial screening conducted during Step 2 of the site selection process.

The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. The findings of the overall preliminary assessment are reported in an integrated report (NWMO, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Municipality of Wawa and its periphery, referred to as the “Wawa area”, contain general areas that have the potential to meet NWMO’s geoscientific site evaluation factors.

This report presents the findings of a geophysical data interpretation assessment completed as part of the desktop geoscientific preliminary assessment of the Wawa area (Geofirma, 2013a). The purpose of this assessment was to perform a detailed interpretation of all available geophysical data (e.g., magnetic, gravity, electromagnetic and radiometric) for the Wawa area, Ontario. The aim is to identify additional information that can be extracted from the data, in particular regarding the coincidence of geophysical features with mapped lithology and structural features in the Wawa area.

The geophysical data covering the Wawa area show variability in dataset resolution. Low-resolution geophysical data (magnetic, gravity and radiometric) cover the entire Wawa area. In addition, a high-resolution magnetic survey covers the northeast margin of the area, and three magnetic/electromagnetic surveys provide higher resolution coverage over approximately 35% of the Wawa area. The higher resolution surveys focused on exploration in the greenstone belts, but extended into the edges of the neighbouring intrusive rocks.

The coincidence between the geophysical data and the mapped lithology was interpreted using all available geophysical data sets (e.g., magnetic, gravity, electromagnetic and radiometric), although magnetic data proved most reliable for this purpose. In general, the coincidence between the geophysical interpretation and the published geological maps is good, particularly regarding the contacts between the greenstone belts and the surrounding granitic intrusions. However, lithological variability within the granitic intrusions of interest could not be interpreted beyond what is presented in the geological maps due to the low resolution of the magnetic data, the subtle variations in magnetic response between lithologies and the interference from numerous dykes in the area.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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 preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations (NWMO, 2013).

This report presents the findings of a geophysical data processing and interpretation assessment completed as part of the desktop geoscientific preliminary assessment of the Wawa area (Geofirma, 2013a). The objective of the desktop geoscientific preliminary assessment is to determine whether the Wawa area contains general areas that have the potential to satisfy NWMO's site evaluation factors. The assessment focused on the Municipality of Wawa and its periphery, referred to as the "Wawa area".

1.1 Assessment Objective

This report documents the processing and interpretation of geophysical data for the Wawa area. Geophysical data forms an important component of assessing a region for its potential suitability to host a deep geological repository, and assisting in the identification of potentially suitable areas.

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

The primary role of geophysics is to extrapolate the surface analysis applied using geological maps, topography and satellite imagery into the subsurface. Drillholes, wells and other underground information may be available at individual points to supplement geological data acquired on surface. However, where these individual data points are limited (or non-existent), such as for the Wawa area, the critical advantage of airborne geophysical data is that it provides a basis for interpreting the subsurface physical properties across the area. This is particularly important in areas where bedrock exposure is limited by surface water bodies and/or overburden cover such as glacial sediments, such as in the Wawa area. A secondary role of geophysics is that it often elucidates certain characteristics of geological formations and structures that may not be easily discerned from surface mapping and analysis. Thirdly, it highlights tectonic and regional-scale features that may not be easily extracted from studies of a particular area on a more detailed scale.

1.2 Wawa Area

The Municipality of Wawa is located along the northeast shore of Lake Superior at Michipicoten Bay approximately 227 km north of Sault Ste. Marie, as shown in Figure 1. The Municipality of Wawa is approximately 420 km^2 in size and the Wawa area is 4,274 km^2. The settlement area of Wawa is situated at the south end of Wawa Lake, approximately 7 km northeast of the Lake Superior shoreline. The Municipality also includes the settlement areas of Michipicoten River Village, and Michipicoten Harbor, both on the shore of Lake Superior.

1.3 Qualifications of the Geophysical Interpretation Team

The team responsible for the geophysical review, processing and interpretation investigation component of the Phase 1 Geoscientific Desktop Preliminary Assessment of Potential Suitability for the Wawa area consisted of qualified experts from Paterson, Grant & Watson Limited (PGW). The personnel assigned to this assessment were as follows:

Dr. D. James Misener, Ph.D., P.Eng. – geophysical interpretation, report preparation

Dr. Misener 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 has directed implementation of geophysical data processing systems; initiated and managed major continental scale compilations of aeromagnetic/marine magnetic data in North America and worldwide including interpretation of aeromagnetic, radiometric, gravity and electromagnetic surveys in; Algeria, Brazil, Cameroon, Niger, Ivory Coast, Zimbabwe, Malawi, Kenya, China, Suriname, and Ireland.

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

Mr. Reford is a senior consulting geophysicist and Vice-President of PGW. Mr. Reford has 31 years of experience in project management, acquisition and interpretation of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data for clients throughout Canada and around the world. Projects include management of the geophysical component of Operation Treasure Hunt for the Ontario Ministry of Northern Development and Mines as well as a similar role for the Far North Geoscience Mapping Initiative (2006-2009). Mr. Reford has served as a consultant to the International Atomic Energy Agency (IAEA) in gamma-ray spectrometry and is co-author of two books on radioelement mapping.

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

Ms. Mueller-Markham is a senior consulting geophysicist for PGW. She has 18 years of experience in project management, acquisition, processing and modelling of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data throughout and gamma-ray spectrometer surveys for clients throughout Canada and around the world. In recent years, she has provided management and quality control for a number of OGS magnetic, gravity and electromagnetic surveys, and has reprocessed numerous industry surveys published by OGS.

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

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

Nikolay Paskalev, M.Sc. – GIS preparation

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

2 SUMMARY OF PHYSICAL GEOGRAPHY AND GEOLOGY

The Wawa area, shown in Figure 1, is underlain by a thin veneer of glacial soils and 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. 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.

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 (JDMA, 2013). Topography in the Wawa area is generally rugged and hilly with roughly 355 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 (JDMA, 2013). Bedrock terrain includes exposed bedrock and thin, discontinuous drift deposits generally less than one metre thick.

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). 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 (2013a) and the following is a summary of that information.

Figure 2 shows the general bedrock geology and main structural features of the Wawa area in 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 2) 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 2).

2.2.1 Western Batholith

The Western batholith is located in the northwestern corner of the Wawa area (Figure 2). 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, although based on lateral map extent they are anticipated to be several km thick. 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, p.27). 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, b and c) 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 centered 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 (2013a) 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., 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 synvolcanic 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. 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 2). 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 batholith covers 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, some of which are batholith in size. Thus, the Whitefish Lake batholith and Brulé Bay batholith, 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 2). 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 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 2). 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 approximately 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 2), with eleven named and numerous other unnamed faults included in the OGS bedrock geology database (Geofirma, 2013a). 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 2). 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, 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. 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.

2.3 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 a 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.

2.4 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. 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, this summary represents an initial preliminary interpretation for the Wawa area, which may be modified after site specific information has been collected.

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 synvolcanic 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 synvolcanic 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).

Time Period (billion years ago)	***Geological Event***
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).
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 synvolcanic 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.

2.5 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 3 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 3). 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 bedrock valleys. Materials encountered during drilling include thick sequences of clay, sand, and gravel.

2.6 Land Use

Land use within the 4,274 km2 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, 2013a). There are linear infrastructure corridors such as roads, railways, and electrical transmission lines, however these features do not adversely affect the geophysical interpretation.

3 GEOPHYSICAL DATA SOURCES AND QUALITY

For the Wawa area, geophysical data were obtained from available public-domain sources, particularly the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC). To supplement these data, geophysical surveys performed in the Wawa area by the mining industry were reviewed as assessment files, but it was determined that none were available that would improve the geophysical coverage.

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

3.1 Data Sources

Low-resolution geophysical data, particularly the magnetic, gravity and radiometric data obtained from the Geological Survey of Canada (GSC), cover the entire Wawa area. Three additional magnetic/electromagnetic surveys and one magnetic survey obtained from the Ontario Geological Survey (OGS) provided higher resolution coverage through much of the northern and central parts of the Wawa area (Figure 4). These surveys focused on exploration in the greenstone belts in the Wawa area, while also providing some coverage along the neighbouring margins of the batholiths and Wawa Gneiss domain. The geophysical data sets are discussed in detail in the following sections, and are summarized below in Table 2.

The assessment files archived at the OGS were reviewed for the Wawa area. There are numerous airborne geophysical surveys, and some ground geophysical follow-up, that focused on relatively small areas within the greenstone belts.

3.1.1 Magnetic Data

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

The resolution of the retrieved magnetic datasets varies greatly within the Wawa area. Surveys were flown over a period of 45 years, over which time the quality and precision of the equipment as well as the quality of the processing has improved. Variability in the quality of the survey coverage also influenced the ability of the magnetic data to identify geological structures of interest relevant to this assessment.

Low-resolution magnetic data from the GSC (individual surveys include Ontario 8, 17, the Lake Superior survey) provides complete coverage of the entire Wawa area (GSC, 2012). Magnetic data from these surveys form part of the GSC Regional Magnetic Compilation data. These surveys were flown at a terrain clearance of 305 m and flight line spacing of 805 m (1,900 m for the Lake Superior Survey), providing these surveys with a relatively low spatial resolution.

Additional, high-resolution surveys from the OGS (Wawa survey and Michipicoten survey) were flown at a lower terrain clearance (30-45 m) compared to the GSC surveys, and with tighter flight line spacing (200 m), providing these surveys with a relatively high spatial resolution (OGS, 2003a; 2003b). The Magpie River-Missinaibi Lake Survey consists of four separate survey blocks that were acquired by OGS from industry, provides the highest resolution with a line spacing of 75 m and terrain clearance between 40 to 60 m above ground surface (OGS, 2011a). The terrain clearance of this 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 located within the Wawa area was superseded by the higher resolution data from the Magpie – Missinaibi Lake survey. All the OGS surveys focused primarily on exploration in the greenstone belts, in the northern and central part of the Wawa area, providing 35% of the overall coverage. The survey line directions varied considerably, oriented roughly perpendicular to the local geologic strike.

3.1.2 Gravity Data

Gravity data provides complete coverage of the Wawa area (GSC, 2012) and consists of an irregular distribution of 40 station measurements with roughly a station every 10 to 15 km.

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

Despite the fact that data are of good quality, the sparseness of the measurement locations in the Wawa area can only be used to provide information about large scale geologic features. The resolution of the acquired gridded data is 2 km by 2 km.

3.1.3 Radiometric Data

The GSC radiometric data provides complete coverage of the Wawa area (GSC, 2012). The acquired data show the distribution of natural radioactive elements at surface: uranium (eU), thorium (eTh) and potassium (K), which can be interpreted to reflect the distribution of mineralogical and geochemical information in the area. The GSC radiometric data were flown at 5,000 m line spacing at a terrain clearance of 120 m above the surface. The retrieved radiometric data consisted of measurements of four variables:

- Potassium, K (%);
- Equivalent uranium, eU (ppm);
- Equivalent thorium, eTh (ppm); and
- Total Air Absorbed Dose Rate (nGy/h).

3.1.4 Electromagnetic Data

Two frequency domain electromagnetic (FDEM) surveys carried out by the OGS were retrieved from the Wawa Area survey (GDS1009; OGS, 2003b), and Michipicoten survey (GDS1010; OGS, 2003a) (Figure 4). The FDEM system used for the OGS Wawa survey was a Dighem III system to measure the inphase and quadrature components of three different frequencies (three coil pairs) towed below a helicopter with the sensor at a nominal terrain clearance of 30 m. The survey was flown at 200 m flight line spacing providing a relatively high spatial resolution.

The FDEM system used for the Michipicoten survey was an Aerodat HEM-802 system to measure the inphase and quadrature components of two different frequencies (two coil pairs) towed below a helicopter with the sensor at a nominal terrain clearance of 30 m. The survey was flown at 200 m flight line spacing providing a relatively high spatial resolution.

A time domain electromagnetic (TDEM) survey carried out for industry, and acquired by OGS, was retrieved from the Magpie River-Missinaibi Lake Survey (GDS1237; OGS, 2011a). The TDEM system used for this survey was a Geotech VTEM system to measure the off-time Z component response, windowed into 24 channels over a 6,860 µs or 7,203 µs period. The survey was flown in two campaigns using slightly different system configurations, towed below a helicopter. In the Wawa area and its buffer, the survey blocks to the west were flown in 2006 with a nominal terrain clearance of 40 m for the TDEM receiver. The survey blocks to the east were flown in 2007 with a nominal terrain clearance of 35 m for the TDEM receiver. The survey was flown at 75 m flight line spacing providing a very high spatial resolution.

The three EM surveys in the Wawa area overlay a small portion of the prospective geology of the Western batholith (granitic-granodioritic intrusion and gneisses), Wawa

Gneiss domain and Whitefish Lake and Brulé Bay batholiths (granitic-granodioritic intrusions) along their margin, as they focus on the greenstone belts. The TDEM system was designed to locate moderate to highly conductive ore deposits with a reduced sensitivity to conductive overburden, and can penetrate to depths of several hundred metres, depending on transmitter power and geology. The FDEM systems provide a greater capability for mapping conductive overburden and near-surface bedrock, at the expense of depth penetration to a few hundred metres at best.

3.2 Data Limitations

There is a fairly stark contrast between the high resolution of the magnetic surveys that cover the greenstone belts and the older regional low resolution coverage elsewhere in the Wawa area. Nevertheless, the magnetic data reflect quite coherent responses that elucidate the mapped geology, particularly in areas of limited bedrock exposure. There is differentiation and stratigraphy within the volcanic and metamorphic rocks in the northern and central parts of the Wawa area where the high resolution magnetic data is available. Similarly, the main structural regimes are clearly delineated by the magnetic data, regardless of resolution, but at different levels of detail.

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

- Coverage and quality of data – types available, density of the coverage, vintage and specifications of the instrumentation;
- Overburden – areal extent, thickness and physical properties; and
- Bedrock lithologies – physical properties and homogeneity.

The user of the geophysical information must bear in mind that each method relies on characterizing a certain physical property of the rocks. The degree to which these properties can be used to translate the geophysical responses to geological information depends mainly on the amount of contrast and variability in that property within a geological unit and between adjacent geological units. The usability of each data set also depends on its quality, especially resolution.

Table 2. Summary of the Characteristics for the Geophysical Data Sources in the Wawa Area.

Product	Source	Type	Line Spacing/ Sensor Height	Line Direction	Coverage	Date	Additional Comments
Lake Superior	GSC	Fixed wing magnetic	1900m/305m	0°	Covers southwest part of Wawa area	1987	Recorded digitally, levelled to a nationwide magnetic datum.
Ontario #8	GSC	Fixed wing magnetic	805m/305m	0°	Covers northwest part of Wawa area	1962	Recorded on analog charts, navigation and flightpath based on photomosaics, digitized from the GSC contour maps, levelled to a nationwide magnetic datum.
Ontario #17	GSC	Fixed wing magnetic	805m/305m	0°	Covers central and east parts of Wawa area	1963	Recorded on analog charts, navigation and flightpath based on photomosaics, digitized from the GSC contour maps, levelled to a nationwide magnetic datum.
GSC Gravity Coverage	GSC	Ground Gravity Measurements	10-15km/ surface	n/a	Entire Wawa area	1949-1987	Bouguer gravity field, first vertical derivative, horizontal gradient and the isostatic residual gravity field were extracted from the GSC gravity compilation. Station locations were extracted from the point data.
GSC Radiometric Coverage	GSC	Fixed wing radiometric data	5000m/120m	0°	Entire Wawa area (onshore)	1982	Grids of potassium, equivalent uranium, equivalent thorium, natural air absorbed dose rate, and ratios of eU/K, eTh/K and eU/eTh were extracted from the GSC's nationwide radiometric compilation.
Kapuskasing-Chapleau Survey (GDS1040)	GSC/OGS	Fixed wing magnetic	200m/100m	320°	small area in northeast corner of Wawa area	2001	The lower height, closer line spacing and vintage of this survey greatly improves standard GSC magnetic coverage. Survey covers very small area in northeastern corner of Wawa area, and is superseded by data from the Magpie River-Missinaibi Lake survey.
Wawa Survey (GDS1009)	OGS (OGS, 2003b)	Helicopter magnetic, FDEM (Dighem III 3-frequency)	200m/ Mag 45m FDEM 30m	varies (northeast to northwest)	Focused on the greenstone belts in the northern part of the area, and also covers some metasediments	1988	The lower height, closer line spacing and vintage of this survey greatly improves standard GSC magnetic coverage, and provides electromagnetic coverage. The data were reprocessed in 2003, which improved the quality.
Michipicoten Survey (GDS1010)	OGS (OGS, 2003a)	Helicopter magnetic, FDEM (HEM-802 2-frequency)	200m/ Mag 30m FDEM 30m	varies (northeast to northwest)	Focused on the Michipicoten Greenstone Belt in the central part of the area	1980	The lower height, closer line spacing and vintage of this survey greatly improves standard GSC magnetic coverage, and provides electromagnetic coverage. The data were reprocessed in 2003, which improved the quality.
Magpie River-Missinaibi Lake Survey (GDS1237)	OGS (OGS, 2011a)	Helicopter magnetic, TDEM (VTEM)	75m/ Mag 40-60m TDEM 35m	0°	Focused on the greenstone belts in the northeastern part of the area	2006/ 2008	The lower height, closer line spacing and vintage of this survey greatly improves standard GSC magnetic coverage, and provides electromagnetic coverage. Its closer line spacing and EM system focused on bedrock sources also provides superior data to Wawa survey (GDS1009). The data were reprocessed in 2011, which improved the quality.

4 GEOPHYSICAL DATA PROCESSING

All data were processed and imaged using the Oasis montaj software package (Geosoft, 2012). Three additional magnetic grids were prepared using the Encom PA software package (Pitney Bowes, 2012). The grids that resulted from the various processing steps were also loaded in ArcMAP 10 (ESRI, 2012) using a Geosoft plug-in.

4.1 Magnetic

The acquired magnetic data located within the Wawa area and surrounding buffer areas were processed using several common geophysical techniques in order to enhance the magnetic response to assist with interpretation (Milligan and Gunn, 1997). All surveys in the Wawa area where projected to the UTM16N/NAD83 coordinate system. Geophysical data from the surveys were upward or downward continued (if necessary) to a common flying height 45 m, and regridded to a common grid cell size of 40 m.

The GSC regional compilation was downward continued 260 m and an 8th-order 800 m low pass Butterworth filter was applied to reduce noise introduced by the downward continuation and coarse data. The Butterworth filter is a type of signal processing filter designed to have as flat a frequency response as possible in the pass band. The 800 m wavelength did not reduce the geological signal due to the line spacing of 805 m and the coarse sampling of the digitized data long the flightlines. The three OGS surveys were at/near a flying height of 45 m so that they were not downward (or upward) continued. The GSC regional grid was regridded to a grid cell size of 40 m.

The surveys were knitted together using Oasis montaj (Geosoft, 2012). The suture path between the grids was along the edge of the grid with the original higher resolution grid cell size so that the most detailed data was retained in the final product. The resultant grid was the residual magnetic intensity grid (i.e. total magnetic field after IGRF correction) and the basis for preparing the enhanced magnetic grids.

<u>Reduction to the Pole (RTP)</u>

The direction (inclination and declination) of the geomagnetic field varies over the Earth and influences the shape of the magnetic responses over geological sources. At the North Magnetic Pole the inducing magnetic field is vertical (i.e. inclination of 90° and declination of 0°), which results in the magnetic response being a symmetric positive magnetic peak over a source, in the absence of dip and magnetic remanence. Transforming the measured magnetic field to a pole reduced magnetic field simplifies the interpretation, particularly to determine the location and geometry of the sources (Baranov, 1957). For the Wawa area, the residual magnetic intensity grid was reduced to the pole using a magnetic inclination of 75.6° N and magnetic declination of 6.8° W (Figure 5).

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

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

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

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

First Vertical Derivative of the Pole Reduced Field (1VD)

The vertical derivative is commonly applied to the RTP magnetic field data in the Fourier domain to enhance shallower geologic sources in the data (Figure 6). This is particularly useful for locating contacts (e.g. the anomaly texture is revealed), and mapping structure (Telford et al., 1990). It is expressed as:

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

where *Z* is the vertical offset.

Second Vertical Derivative of the Pole Reduced Field (2VD)

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

$$2VD = {}^{d^2RTP}/_{dZ^2} \qquad \text{(eq. 4.3)}$$

One limitation of this filter is that the higher order derivatives tend to also enhance the high frequency noise in the data set. To reduce noise that resulted from aliasing during the minimum curvature gridding process, an 8th-order 200 m low-pass Butterworth filter was also applied.

Tilt Angle of the Pole Reduced Field

The tilt angle (Miller and Singh, 1994) has been applied to the RTP magnetic field data to preferentially enhance the weaker magnetic signals (Figure 8). This is particularly useful for mapping texture, structure, and edge contacts of weakly magnetic sources. It is expressed as:

$$TILT = \tan^{-1}\left\{\frac{\frac{dRTP}{dZ}}{\sqrt{\left([\frac{dRTP}{dX}]^2+[\frac{dRTP}{dY}]^2\right)}}\right\} \qquad \text{(eq. 4.4)}$$

where *X* and *Y* are the horizontal offsets in the east and north directions. The first vertical derivative is computed in the Fourier domain whereas the horizontal derivatives in *X* and *Y* are computed in the space domain.

Analytic Signal Amplitude

The amplitude of the analytic signal (AS) (Figure 9) is the square root of the sum of the squares of the derivatives in horizontal (*X* and *Y*), and vertical (*Z*) directions (i.e. the Fourier domain first vertical derivative and the space domain horizontal derivatives in the *X* and *Y* directions), computed from the total magnetic field (Nabighian, 1972):

$$AS = \sqrt{\left([\frac{dT}{dX}]^2 + [\frac{dT}{dY}]^2 + [\frac{dT}{dZ}]^2\right)} \qquad \text{(eq. 4.5)}$$

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

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

The SPI method locates the depths of edges in the gridded magnetic data (Thurston and Smith, 1997). It assumes a 2D sloping contact or 2D dipping thin sheet model. The SPI solutions extracted from the pole reduced magnetic field grid are stored in a database. The SPI values calculated are depths between the magnetic source and the instrument height. If the survey was flown at a constant terrain clearance, then the drape height could be subtracted from the SPI value to result in a depth below surface. For the GSC surveys and Magpie River-Missinaibi Lake surveys, only the average flying height was known. For the remaining surveys (Wawa, Michipicoten), the radar altimeter data were included in the survey database and were consequently used to more accurately determine the distance between the magnetic sensor and the computed depth to the magnetic source. The radar altimeter channel was gridded at the original grid cell size and sampled back to the SPI database. If the value of the depth to source is < 0, i.e. above ground, it is set to a value of zero. Thus, the SPI depth with respect to the ground surface is calculated as:

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

The SPI depths were calculated for each individual data set in the Wawa area (Figure 10). Low resolution grids are biased with deeper basement depths due to the lack of high frequency content. Thus, where a high resolution survey overlaps with a low resolution regional survey, the SPI depths from the low resolution grid were excluded. The final SPI depth grid was calculated with a grid cell size of 200 m.

Encom Magnetic Grids

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

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

Magnetic Peaks, Troughs and Edges

The semi-automated extraction of magnetic anomaly peaks, troughs and edges is useful for delineating structure, foliation, texture and contacts. Anomaly peaks typically trace the center of a source or the more magnetic horizons within a larger source. Anomaly troughs often complement the peaks, indicating a less magnetic horizon. They also may map a remanent (i.e. reversely) magnetized source, or magnetite depletions (e.g. along faults) which are a less magnetic source in a more magnetic host rock. Anomaly edges mark geological contacts or the boundaries of horizons within a geological unit. Offsets and orientation changes in the peaks, troughs and edges are useful for mapping faults and shears. Detection for peaks, troughs and edges was performed based on the CET (Centre for Exploration Targeting) Grid Analysis package in Oasis montaj (Geosoft, 2012).

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

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

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

The smallest filter wavelength used in this analysis for the Wawa area was four cells (equivalent to 160 m), over five scales. The filter sizes were therefore 160 m, 320 m, 640 m, 1280 m and 2560 m. All orientations were considered in the search for symmetry. A threshold value of 0.1 was applied, and a minimum line length of three cells (120 m) was set.

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

$$TDX = \tan^{-1}\left\{\frac{\sqrt{\left([\frac{dRTP}{dX}]^2+[\frac{dRTP}{dY}]^2\right)}}{\frac{dRTP}{dZ}}\right\} \qquad \text{(eq. 4.6)}$$

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

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

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

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

4.2 Gravity

The following four gravity grids and their gravity station locations (40 gravity measurements) were downloaded for the Wawa area the GSC gravity compilation (GSC, 2012) at 2000 m grid cell size:

- Bouguer gravity field (Figure **11**)
- First vertical derivative of the Bouguer gravity field (Figure 12)
- Total horizontal gradient of the Bouguer gravity field
- Isostatic residual gravity field.

All grids were reprojected to the Wawa area's coordinate system, UTM16N/NAD83. The first vertical derivative was computed by the GSC using the same methodology applied to the pole reduced magnetic field, as described in Section 4.1. The total horizontal gradient of the Bouguer gravity provided similar results as the first vertical derivative, and therefore was not presented in this report. The isostatic residual compensates for mass deficiencies at depth predicted from topography, preserving the shorter wavelength components of the field due to nearer surface sources. In the Wawa area, the isostatic residual field closely resembles the Bouguer gravity field due to the relatively gentle topography. The GSC applied standard gravity reduction methods to compute the free air and Bouguer gravity fields. A Bouguer correction density of 2.67 g/cm^3 was applied, the typical value for the Canadian Shield. As the data for the Wawa area were collected in 1987 and earlier, station elevations were likely determined using barometric altimeters (much less accurate than GPS) and terrain corrections were not applied.

4.3 Radiometric

The following seven radiometric grids (radioelement concentrations and ratios) were downloaded for the Wawa area, extracted from the GSC radiometric compilation (GSC, 2012) at 250 m grid cell size:

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

The determination of the radioelement concentrations, dose rate and ratios followed the methods and standards published by the International Atomic Energy Agency (IAEA, 2003), many of which were developed at the GSC. All grids were reprojected to the Wawa area's coordinate system, UTM16N/NAD83. The dose rate is a calibrated version of the measured "total count", and reflects the total radioactivity from natural and man-made sources. The radiometric data are presented in Figure 13 as a ternary RGB image of the three radioelements, with the intensity of potassium (%) displayed in red, equivalent thorium (ppm) in green and equivalent uranium (ppm) in blue. Areas of highest intensity of all three radioelements show light colours and trend towards white. Areas of lowest intensity of all three radioelements are dark colours and trend towards black.

4.4 Electromagnetic

The EM surveys flown by the Ontario Geological Survey were flown at 200 m and 75 m line spacing, which provides good resolution for mapping. Older surveys (pre-90's) were usually flown without GPS, which resulted in flightlines that wandered (sometimes crossing) and less accurate flightpath recovery using photomosaics.

The OGS surveys typically focus on the greenstone belts, extending into the edges of neighbouring granites and sometimes encompassing smaller plutons where the greenstones wrap around them. Helicopter surveys typically have a better signal/noise than fixed wing surveys due to closer proximity of the EM transmitter, EM receiver and magnetometer to the ground.

FDEM surveys typically include a grid of apparent resistivity (conductivity is simply the inverse). Newer surveys have an apparent resistivity for three frequencies reflecting shallower (highest frequency) to deeper (lowest frequency) responses – this helps in discriminating between overburden and bedrock responses. Coplanar coils are more responsive to mapping subhorizontal horizons, whereas coaxial coils are better suited to map subvertical conductors.

TDEM surveys typically include a grid of decay constant, which is used to discriminate bedrock conductors, and a grid of conductance or conductivity, which is oriented towards mapping conductive horizons. Newer systems measure three components: Z-component that best couples with subhorizontal conductors, X-component with subvertical conductors and sometimes Y-component with lateral (offline) conductors, or conductors not perpendicular to strike.

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

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

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

- Wawa (GDS1009) – Apparent resistivity grid (7200 Hz coplanar) and EM anomaly database.
- Michipicoten (GDS1010) – Apparent resistivity grid (3220 Hz coplanar) and EM anomaly database.
- Magpie River-Missinaibi Lake (GDS1237) – Decay constant grid (Z-component) and EM anomaly database (no grid of conductance or conductivity provided).

5 GEOPHYSICAL INTERPRETATION

5.1 Methodology

The coincidence of geophysical features with mapped lithology and structural features were identified and interpreted for the Wawa area using all available geophysical data sets. In particular, the pole reduced magnetic field and its first vertical derivative were the most reliable for mapping variations in geological contacts, identifying heterogeneity, and delineation and classification of structural lineaments (faults, dykes). The results from the structural lineament interpretations are presented in the lineament report for the Wawa area (Geofirma, 2013b). The first and second vertical derivatives were used to trace quasilinear magnetic anomaly peaks that outline the ductile features. These ductile features are interpreted as being associated with the internal fabric to the rock units and may include in places sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation. Enhanced grids of the magnetic field data were used to assist in the interpretation:

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

Gravity data were of insufficient resolution to be used for interpretation of geological units and boundaries. However, some general characterizations of the regional scale units were possible (Figure 11 and Figure 12). Similar comments apply to the radiometric data (Figure 13). The electromagnetic data were not used for interpreting lithologies as the magnetic data provided complete coverage of the Wawa area, and proved greatly superior from a mapping perspective in the Wawa area (Figure 14). However, certain geological features were evident in the electromagnetic data and are discussed below in the results.

The coincidence of the lithological units with the geophysical data was mainly recognized in the magnetic images from their anomaly amplitude, texture, width, and orientation characteristics. The automated peaks, troughs and edges generated from the magnetic data assisted in more accurate location of contacts. The magnetic anomaly characteristics and geophysical contacts were compared to the current mapped bedrock geology in order to identify similarities and/or changes in the lithological contact locations. In some cases, difference in the boundaries determined from the magnetic data and the mapped boundaries may reflect a subsurface response which may not match the mapped surface contacts (e.g. dipping unit) and/or a contact extended through locations with limited outcrop exposure (e.g. under overburden and drainage cover). Results of the coincidence between the geophysical interpretation and the mapped bedrock geology are presented in Figure 15. The geophysical data were primarily evaluated against the following published geological maps:

- Ontario Geological Survey, (OGS, 2011b), 1:250 000 scale bedrock geology of Ontario, Miscellaneous Release Data 126-Revision 1 (Figure 2 and Figure 15).

Additional information to support the geophysical interpretation was extracted, where appropriate, from the following bedrock geology maps:

- Johns, G.W., and S. McIlraith, 2002. Precambrian geology compilation map – Michipicoten sheet. Ontario Geological Survey, map 2669, scale 1:250:000.
- Santaguida, F. 2001. Precambrian geology compilation series – White River sheet; Ontario Geological Survey, Map 2666, scale 1:250,000.

5.2 Results

The following section presents a regional-scale description and interpretation of each geophysical data set in the Wawa area, followed by detailed interpretations of geophysical responses within the Western batholith (granitic-granodioritic intrusion and gneisses), Wawa Gneiss domain and Whitefish Lake and Brulé Bay batholiths (granitic-granodioritic intrusions). Using the published regional bedrock geology maps, and detailed geology maps where warranted and available, as a starting point, the detailed geophysical interpretation for the Wawa area is presented in Figure 15. The geological units referred to in this section match those of the published regional bedrock geology (OGS, 2011b), unless otherwise stated.

5.2.1 Magnetic

The magnetic data over the Wawa area exhibits a strong variability in its magnetic response associated with the intrusive rock units, particularly the Western, Brulé Bay and the Whitefish Lake batholiths, and the Wawa Gneiss domain, as well as the Mishibishu, Gamitagama, and Michipicoten greenstone belts. Although a portion of the Wawa area is covered by high-resolution magnetic data, the boundaries of the geological units are not always well-defined due to the low data quality over the large portions of the Wawa area, and an apparent lack of magnetic contrast between the rock units that have been mapped on the surface. In addition, the majority of the high-resolution magnetic coverage is over the greenstone belt units, leaving only lower resolution magnetic data covering large portions of the batholiths.

The areas mapped primarily as intrusive units of the Western, Brulé Bay and Whitefish Lake batholiths show the weakest magnetic response in the Wawa area (Figure 5). These rock units are primarily covered by lower resolution magnetic data, except for along the boundaries of the greenstone belts. The intrusive rock units primarily correspond to the mapped massive granodiorite to granite, and foliated and gneissic tonalite suites (shown on Figure 15). Areas mapped as gneissic tonalite suite dominate the Wawa Gneiss domain, form a large part of the Western batholith and also bound the northwest edge of the Whitefish Lake batholith. It is the least magnetic of the rocks outside the greenstone belts. Some magnetic foliation is apparent throughout this rock unit, but it is obscured by the numerous cross-cutting dykes and the low resolution data. The foliated tonalites are mapped over part of the Western batholith and are also located to the south along the north shore of Lake Superior. This unit is slightly more magnetic than the gneissic tonalite and tends to show more coherent magnetic foliation (Figure **15**, units B and C). The remaining portions of the intrusive rocks consists of massive granodiorite to granite, mapped over the central portion of the Whitefish Lake and Brulé Bay batholiths, the northern part of the Western batholith and a portion of the Wawa Gneiss domain to the southeast. These units are characterized by smooth, low magnetic responses, which are differentiated from the neighbouring gneissic tonalite units by the slightly higher background magnetic response and lack of foliation (Figure **15**, units A, H, I, and E).

In contrast to the intrusive rocks, areas primarily mapped as greenstone belt units show the strongest magnetic response in the Wawa area in the reduced to pole magnetic field (Figure 5). The greenstone belt units that impact the magnetic data primarily correspond to the mapped mafic to intermediate metavolcanics, felsic to intermediate metavolcanics, and mafic to ultramafic rocks. The mafic to intermediate metavolcanic rocks are characterized as subparallel curvilinear anomalies of high amplitude, forming the majority of the greenstone belts in the area. These anomalies are most evident in the first (Figure 6) and second vertical (Figure 7) derivative grids. The trend of these rock units tends to vary widely from one greenstone belt to another and within the belts as well, resulting from extensive ductile deformation of the greenstone belts. Particularly at the southern tip of the Michipicoten greenstone belt, these rocks may extend below Lake Superior, although the increased distance to the magnetic sensor due to the drop-off in depth tends to diminish the magnetic response making it difficult to differentiate geological contacts and lithologies. Locally, these units are layered with felsic to intermediate metavolcanic rocks characterized by subparallel curvilinear anomalies of lower amplitude where the contrast in magnetic susceptibility against the mafic to intermediate metavolcanics allow the rock types to be differentiated within the high-resolution magnetic data over the greenstone belts. These units are locally intermixed with iron formations recognized by strong curvilinear magnetic anomalies in which their orientations tend to parallel the magnetic layering of the metavolcanic rock units. This strong magnetic response is typical of iron formations located in the Archean greenstone belts of the Canadian Shield (Teskey et al., 1993). Metasedimentary rocks represent a minor component of the greenstone belts and are generally the least magnetic, as are the paragneisses and migmatites at the contact between the northeast margin of the Whitefish Lake batholith and the adjacent greenstone belt.

Magnetic responses across the entire Wawa area are dominated by linear magnetic highs that correspond to dykes on the bedrock geology map (Figure 6 and Figure 7). Dykes in the Wawa area are particularly dominated by the north-northwest-trending Matachewan swarm (West and Ernst, 1991). In the lower resolution magnetic data the dykes appear as broad linear anomalies (roughly 1 km wide) that extend over larger distances (tens of kilometers). Where these anomalies are traced into the higher resolution magnetic data they can typically be reinterpreted as multiple dykes, with anomaly widths of approximately a hundred metres. It is apparent that these dykes occur in much greater numbers in the eastern part of the Wawa area where, in the higher resolution magnetic data, spacing between adjacent dykes is on the order of a few hundred metres. In the western portion of the Wawa area, the spacing between dykes tends to be slightly wider, in some places on the order of a few kilometres. This is observed in both the low- and high-resolution magnetic data. The north-northeast to northeast-striking Biscotasing and Abitibi dykes are found at a few locations throughout the area. These dykes are younger than the other geological units in the area. In addition, several lineament trends have been interpreted using the magnetic data within the Wawa area. These lineaments are characterized as linear magnetic lows that transect, and perhaps produce offsets in the geophysical anomalies. Many of these lineaments in the magnetic data coincide well with the orientations of faults presented on the bedrock geology map. Detailed discussion of geophysical lineaments is included in the lineament report for the Wawa area (Geofirma, 2013b). A number of the lineaments interpreted from the magnetic data are also evident as lineaments in the topographic and satellite imagery data.

5.2.2 Gravity

The Bouguer gravity data and gravity station locations across the Wawa area are presented in Figure 11, and its first vertical derivative in Figure 12. The Wawa area has been surveyed by regional GSC ground gravity, with a total of 40 gravity stations spaced 10-15 km apart. The low-resolution of these data prevents detailed geological interpretation. Nevertheless, even with this marginal coverage, there is an observable correlation between the regional gravity lows and the geological units of the Western, Whitefish Lake and Brulé Bay batholiths. South of the Whitefish Lake batholith the gravity low anomaly extends into portions of the gneissic tonalite suite where the strong gravity low likely reflects the thickest portions of the Wawa Gneiss domain.

The greenstone belts tend to correlate with well-defined gravity highs that show a roughly northeast-southwest orientation. Similar to observations made from the magnetic data, the high gravity anomaly corroborates the extension of the greenstone units beneath Lake Superior.

5.2.3 Radiometric

Radiometric data in the Wawa area were of insufficient resolution to be used for interpretation of discrete geological contacts between different rock units (Figure 13). Nevertheless, some subtle patterns were identified over the entire Wawa area corresponding to radioelement concentrations within the different mapped units. Where the overburden material is locally derived, its radiometric response may serve as a proxy for the underlying bedrock geology.

The radiometric data over the Wawa Gneiss domain displays a moderate radioelement response that tends to be elevated in thorium. This distribution of thorium is predominantly associated with the gneissic tonalite units, which is similarly expressed in portions of the Western batholith. Within the Whitefish Lake batholith, the radioelement response is dominated by potassium, which predominantly corresponds to the massive granodiorite to granite unit. Along the western boundary of the Whitefish Lake batholith, the radioelement response becomes slightly elevated in uranium, corresponding to the boundary between the gneissic tonalite and the Michipicoten greenstone belt. The radioelement concentrations of the granodiorite to granite units within the Western batholith show higher levels of uranium and thorium, and the Brulé Bay batholith shows more uranium and potassium.

The greenstone belt units in the Wawa area display predominantly low responses in all three radioelements, which is typical of greenstone units. An exception is noted over the southern portion of the Michipicoten greenstone belt located between the Western batholith and the Whitefish Lake batholith, where the radioelement responses are high with a preference for uranium.

For the GSC radiometric compilation within the Wawa area, the radioelement responses are provided in Table 3.

Table 3. Radioelement Responses of the Wawa Area.

Radioelement	Minimum	Maximum	Mean
Potassium (%)	0.03	2.72	0.80
Uranium (ppm)	-0.89	2.56	0.54
Thorium (ppm)	-0.04	8.93	2.41
Natural air absorbed dose rate (nGy/h)	0.24	63.82	7.60

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

These levels are typical for mafic volcanics and mafic intrusions (IAEA, 2003) and towards the low end for intermediate to felsic volcanics, felsic (alkalic) intrusions and metamorphic rocks.

The low uranium levels suggest low radon risk. However, radon risk is also quite dependent on soil permeability and should be verified by soil gas measurements (IAEA, 2003). The highest uranium response in the area is located within the gneissic tonalite suite in the extreme northwest corner of the area.

5.2.4 Electromagnetic

The electromagnetic surveys (Figure 14) encompass most of the three greenstone belts in the Wawa area, with minor coverage of the intrusive units along the boundaries. The gridded data delivered with the surveys published by OGS were imaged together with the EM anomaly databases, to highlight the conductive responses. They show a mixture of sources, including cultural (e.g. power lines), surficial (e.g. clays and lake-bottom sediments) and bedrock (e.g. conductive horizons, sulphide minerals). The interpretation focused on delineating bedrock sources into conductors that traverse a few to several flightlines (i.e. 200 m to 1000 m or more). For the most part, the bedrock conductors tend to form linear anomalies which are aligned subparallel with the magnetic horizons that reflect the orientation of the dominant structural trend within the greenstone belts. A few conductors seem to be aligned with incised topography (drainage features), which could reflect electrically conductive clays and transported sediments. Some conductors that extend into the batholiths and metasediments may be associated with faults/fractures.

Overall, the EM coverage over the intrusive batholiths in the Wawa area is rather limited. In general, the EM has reduced application for bedrock mapping in the Wawa area, as most of the units are resistive. Many of the conductivity anomalies are predominantly associated with the presence of conductive minerals in drainage-related sediments and overburden deposits.

5.3 Geophysical Interpretation of the Prospective Geology in the Wawa Area

The following section provides more detailed interpretations with a focus on the prospective geology of the Western batholith (granitic-granodioritic intrusion and gneisses), Wawa Gneiss domain and Whitefish Lake and Brulé Bay batholiths (granitic-granodioritic intrusions) of the Wawa area. The interpretations include a description of the geophysical characteristics of each unit, as well as a refinement of geologic contacts, where possible, and the identification of internal heterogeneities within the structures, if present. These interpreted features are presented alongside the current bedrock geology mapping on Figure 15, noting that the interpretations are preliminary and require future geologic validation. The refined contacts and identified features are labeled A to L on Figure 15, and discussed further in the sections below.

5.3.1 Western Batholith

The Western batholith consists of granodiorite to granite, gneissic tonalite suite and foliated tonalite based on geological mapping by the OGS in the northwestern part of the Wawa area (Figure 15). The Western batholith is bounded by the Michipicoten greenstone belt to the east and north, the Mishibishu greenstone belt to the west and Lake Superior to the south. Interpretation of the magnetic data over the Western batholith is rather limited by the lower resolution (805 m line spacing) of the GSC magnetic surveys, with the exception of the high-resolution magnetic data along the intrusion boundary zone adjacent to the greenstone belt units. Despite the use of the low-resolution magnetic data over the majority of the Western batholith, some general internal contacts have been interpreted between the various intrusive units with a moderate to low level of certainty. In general, the interpreted contacts show modest agreement with the distribution of mapped bedrock lithologies, in particular along the boundary between the intrusive units and the greenstone belt. The batholith boundary is expressed as a well-defined contact zone that is characterized by a transition into the higher magnetic response of the greenstone units. Evidence of the boundary is partially exposed within the coverage of the high-resolution magnetic data.

In general, the magnetic results within the Western batholith show a predominantly low background response with increased variability associated with localized high magnitude anomalies. This variability may correspond to the distribution of mapped bedrock lithologies in the batholith, although interpretation of their lithological contacts is difficult. Some mafic to intermediate metavolcanics and mafic-ultramafic rocks are mapped towards the south end of the Western batholith, and the magnetic variability within the batholith could also reflect the presence of these rocks on a larger extent (Figure 15, unit D). The granodiorite to granite units (Figure 15, unit A) predominantly show a lower magnetic response within the batholith, and tend to increase gradually towards the contact zones adjacent to the greenstone belts and the gneissic tonalites. This geological contact against the gneissic tonalites appears as a broadly defined high magnetic zone, and may reflect an increased presence of magnetic mineral content associated with alteration along the contact (Figure 15, unit B). The southern portion of the Western batholith is largely underlain by the foliated tonalite suite (Figure 15, unit C) that exhibits an indistinct gradient contact with the gneissic tonalite (Figure 15, unit B) to the north. This unit is slightly more magnetic than the gneissic tonalite and tends to show more coherent magnetic foliation.

The contact between the greenstones and the granodiorite to granite units along the northwest edge of the Western batholith has been interpreted further south than indicated by the geological mapping, due to the higher amplitude and east-west orientation of the magnetic responses in the area (Figure 15, unit A). Furthermore, within the west end of the Western batholith, a broad magnetic high lies on-strike with the mafic to intermediate metavolcanics further to the west, with a similar signature. This may reflect a thinning of the batholith overlying a buried extension of the greenstones and/or intermixing of the greenstones and intrusive rocks.

East of the Trembley fault, the granodiorite to granite persists eastwards until it contacts the Michipicoten greenstone belt. As noted for unit A further to the west, the eastern portion of unit A also shows magnetic evidence of metavolcanic/metasedimentary contamination, where curvilinear anomalies lying subparallel to the magnetic horizons in the greenstones are evident.

Over the Western batholith, the pronounced gravity low centered north and west of the Old Woman River fault and west of the Mildred Lake fault correlates with the mapped and interpreted granodiorite-granite tonalite complex. The sparse data coverage also reflects the “pinch-out” of the gneissic tonalite suite towards the western edge of the map.

Over the Western batholith, the granodiorite-granite shows elevated responses in all three radioelements, with particularly higher uranium and thorium. The gneissic tonalite within the Western batholith shows moderate radioelement responses with a preference for thorium (Figure 15, unit B).

5.3.2 Wawa Gneiss Domain

The magnetic responses over the Wawa Gneiss domain are quite subdued, with a slightly lower background compared to the neighbouring Brulé Bay and Whitefish Lake batholiths. The north-northwest-striking dykes stand out and their strong responses interfere with the interpretation of the subtle responses of the host rocks. Some east-northeast-striking foliation is evident, mainly in the central and eastern portions of the domain. The density of dykes west of the Agawa Canyon fault is greatly reduced compared to the remainder of the domain.

We have subdivided the Wawa Gneiss domain and inferred the location of contacts between the granodiorite-granite (Figure 15, unit E) and the gneissic tonalite (Figure 15, unit F) based on the magnetic data. The northern border of gneissic tonalite with the Michipicoten greenstone belt, as well as the slivers of mafic to intermediate volcanics east of the Agawa Canyon fault, both exhibit a sharp magnetic gradient contact. Overall, the magnetic interpretation shows little change from the bedrock mapping, except for the greenstone contacts in places and some changes to the extent of the granodiorite-granite (Figure 15, unit E), where the latter shows slightly elevated magnetic responses in comparison to the adjacent gneissic tonalite (Figure 15, unit F). This is corroborated by the magnitude of the Matachewan dykes' magnetic response appearing more subdued within unit H, indicating a moderately overall higher magnetic response for the granodiorite-granite.

The migmatite unit (Figure 15, unit G) immediately south of the Whitefish Lake batholith possesses a somewhat weaker regional background magnetic response than the surrounding intrusive units, and an east-northeast foliation in places, allowing interpretation of this unit despite the subtle contrasts in response with adjacent units. It is cut by several dykes, confirming that it pre-dates the Matachewan dyke swarm. There is a change in dyke orientation in the vicinity of the migmatite, from north-northwest in the south to more northwesterly in the north, indicating that it is located along an axis of regional deformation. In contrast, the migmatite in the southeast corner of the Wawa area truncates several Matachewan dykes, especially to the east, although most are apparent on either side of the northeast-striking belt.

The mapped distribution of the gneissic tonalite of the Wawa Gneiss domain correlates with regional gravity lows which cannot be distinguished from those over the Whitefish Lake and Brulé Bay batholiths, partly due to the very sparse coverage. The granite-granodiorite to the southeast does correlate with a weak regional gravity high, in contrast to the Whitefish Lake and Brulé Bay batholiths, suggesting the former is a relatively thin intrusion.

The gneissic tonalite within the Wawa Gneiss domain shows moderate and variable radioelement responses with a preference for thorium. The correlation between mapped geology and radioelements responses in the southeast part of the Wawa area is not particularly good.

5.3.3 Whitefish Lake and Brulé Bay Batholiths

The Whitefish Lake and Brulé Bay batholiths cover the central portion of the Wawa area, southeast of the Michipicoten greenstone belt, and are mapped primarily as granodiorite to granite rock. In most cases within the Whitefish Lake and Brulé Bay batholiths the magnetic results show a predominantly low background response with increased variability associated with localized high magnitude linear anomalies interpreted as dykes. The low-resolution magnetic coverage is of marginal use for improving the determination of intrusive contacts relative to the published geological mapping. In cases where geological contacts could not be identified in the magnetic data, the regional scale contacts from the bedrock geology map were used.

Geological contacts of the intrusive units are almost nonexistent in the magnetic data, with the exception of the contact between the gneissic tonalite suite with the Michipicoten greenstone belt. This contact is characterized as magnetic high response corresponding to the appearance of magnetic layering reflecting ductile features along the margin of the metavolcanic rocks, in contrast with the much more subdued responses of the gneissic tonalite and granite-granodiorite to the south (Figure 15, units H and L). This contact is typically well-defined in the magnetic data and correlates well with the bedrock geology map. Some exceptions are observed, where the transition from the higher amplitude and more active magnetic field of the greenstones is evident that may shift the contact on the order of hundreds of metres, sometimes accompanied by a change in orientation of the stratigraphy/foliation between units. This interpretation is obscured in places by the intense dyke activity. For example, contacts observed in the magnetic data between gneissic tonalite and granite-granodiorite are marked by disruptions of the dyke magnetic signatures. The density of dykes to the west (Brulé Bay batholith) is greatly reduced compared to the remainder of the complex.

The gravity data exhibit a regional-scale gravity low that generally corresponds to the location of the Whitefish Lake batholith, and to a lesser extent the Brulé Bay batholith. For the most part the gravity lows coincide with the granodiorite-granite mapped east of the Agawa Canyon fault. Along the southern boundary of the Whitefish Lake batholith the gravity response shows a gradual increase associated with the location of the migmatite and granodiorite-granite intrusion near Kinniwabi and Shakashi Lakes. This slightly higher gravity response may reflect thinning of the batholith or an increase in rock density associated with the adjacent migmatite unit. The gravity low response generally extends, becoming more prominent, further south into portions of the gneissic tonalite suite.

Within the Whitefish Lake batholith, the radioelement response is dominated by potassium associated with the granodiorite-granite unit. Along the western boundary of the batholith the radioelement response becomes slightly elevated in uranium, which may correspond to the boundary between the batholith and the nearby Michipicoten greenstone belt.

6 SUMMARY OF RESULTS

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

The geophysical data covering the Wawa area show variability in data set resolution. Low-resolution geophysical data, particularly the magnetic, gravity and radiometric data obtained from the Geological Survey of Canada, cover the entire Wawa area. Three additional magnetic/electromagnetic surveys and one magnetic survey obtained from the Ontario Geological Survey provided higher resolution coverage over approximately 35% of the Wawa area in its north and central parts. These surveys focused primarily on mineral exploration in the greenstone belts, with a slight overlap into the neighbouring intrusions and metasediments.

The coincidence between the geophysical data and the mapped lithology and structural faults were interpreted using all available geophysical data sets (e.g., magnetic, electromagnetic, gravity and radiometric). In particular, the pole reduced magnetic field (RTP) and its first vertical derivative (1VD) were the most reliable for mapping variations in geological contacts, and identifying heterogeneity. In general, the coincidence between the geophysical interpretations and the published geological maps is in good agreement, but in some locations the geophysical data provided new interpretations. Some of the contacts are tentative between the less magnetic units, particularly where the interpretation relied on low resolution data.

The majority of the strongest magnetic responses in the Wawa area are found in the greenstone belts, where they are associated with the location of mafic metavolcanics, mafic intrusions and iron formation. Outside the greenstones, the magnetic responses are more subtle and coupled with the low resolution coverage, makes determination of contacts difficult. Some foliation and remnants of metavolcanics are evident. Where the major batholiths (Western, Whitefish Lake, Brulé Bay) and the Wawa Gneiss domain are in contact with the greenstone belts, the distinction is much clearer.

The north-northwest to northwest-striking Matachewan dyke swarm and the northeast-striking Biscotasing and Abitibi dyke swarms cut virtually all of the geological units throughout the Wawa area. There is a much greater density of Matachewan dykes, especially in the eastern part of the area.

Resolution of the gravity data were insufficient to be used for interpretation of geological units and boundaries. However, some general characterizations of the regional scale geological units were possible. The Bouguer gravity field shows regional-scale gravity lows associated with the batholiths and gneisses, with the strongest negative responses likely reflecting thickening of these rocks. The greenstone belts are characterized by an axis of high gravity responses through the centre of the area on a roughly northeast-southwest strike.

Radiometric responses due to the presence of potassium, uranium and thorium related minerals are typical of the Canadian Shield, relatively elevated over the granite-granodiorite batholiths, moderate over the gneisses and lower over the greenstone belts. The regional nature of the radiometric data and presence of some lakes makes differentiation difficult.

Electromagnetic surveys show a mixture of sources, including cultural (*e.g.* power lines), surficial (*e.g.* clays and lake-bottom sediments) and bedrock (*e.g.* conductive horizons, sulphide minerals). The coverage and bedrock responses are concentrated mainly in the greenstones, where conductive horizons parallel the magnetic horizons and correlate with ductile deformation. Coverage that extends into the batholiths and metasediments shows some bedrock conductors that may be associated with faults/fractures.

Respectfully Submitted,

PATERSON, GRANT & WATSON LIMITED

D. James Misener, Ph.D., P.Eng.
President

Stephen W. Reford, B.A.Sc., P.Eng.
Vice-President

7 REFERENCES

Archibald, F.T., 2008. Technical Report, Diamond Drilling Project for Peter J. Calbert Claim 3018179 – Chabanel.

Arias, Z.G. and H. Helmstaedt, 1989. Structural evolution of central and east-central Michipicoten (Wawa) greenstone belt, Superior Province; in Geoscience Research Grant Program Summary of Research 1988-1989, Ontario Geological Survey, Miscellaneous Paper 143, 210-226.

Ayer, J.A., R.V. Conceição, J.W.F. Ketchum, R.P. Sage, L. Semenyna and D.A. Wyman, 2003. The timing and petrogenesis of diamondiferous lamprophyres in the Michipicoten and Abitibi greenstone belts, In: Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, 10-1 to 10-9.

Ayres, L.D., 1969. Geology of Townships 31 and 30, Ranges 20 and 19, Ontario Geological Survey Geological Report 69, 126 p.

Baranov, V., 1957. A new method for interpretation of aeromagnetic maps: pseudo-gravimetric anomalies. Geophysics, 22, 359-383.

Bates, M.P. and H.C. Halls, 1991. Broad-scale Proterozoic deformation of the central Superior Province revealed by paleomagnetism of the 2.45 Ga Matachewan dyke swarm, Canadian Journal of Earth Sciences, 28, 1780-1796.

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

Breaks, F.W. and J.R. Bartlett, 1991. Geology of the Eyapamikama Lake Area; Ontario Geological Survey, Open File Report 5792, 132 p.

Breaks, F.W. and W.D. Bond, 1993. The English River Subprovince-An Archean Gneiss Belt: Geology, Geochemistry and associated mineralization; Ontario Geological Survey, Open File Report 5846, Vol.1, 1-483, 884 p.

Brown, A., R.A. Everitt, CD. Martin and C.C. Davison 1995. Past and Future Fracturing In AECL Research Areas in the Superior Province of the Canadian Precambrian Shield, with Emphasis on The Lac Du Bonnet Batholith, Atomic Energy of Canada Ltd. Report, AECL-11214, COG-94-528, 138 p.

Bursnall, J.T., A.D. Leclair, D.E. Moser and J.A. Percival, 1994. Structural correlation within the Kapuskasing uplift, Canadian Journal of Earth Science., 31, 1081-1095.

Card, K.D. 1979. Regional geological synthesis, central Superior Province; In: Current Research, Part A, Geological Survey of Canada, Paper 79-1A, 87-90.

Card, K.D. 1982. Progress report on regional geological synthesis, central Superior Province; In: Current Research, Part A, Geological Survey of Canada, Paper 82-1A, 23-28.

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

Card, K.D. and A. Ciesielski, 1986. Subdivisions of the Superior Province of the Canadian Shield; Geoscience Canada, 13, 5-13.

Card, K.D. and K.H. Poulsen, 1998. Geology and mineral deposits of the Superior Province of the Canadian Shield; Chapter 2 in Geology of the Precambrian Superior and Grenville Provinces and Precambrian Fossils in North America, (co-ord.) S. Lucas; Geological Survey of Canada, Geology of Canada, n.7, 13-194.

Cooper, G.R.J., and Cowan, D.R. 2006. Enhancing potential field data using filters based on the local phase, Computers and Geosciences, 32, 1585-1591.

Corfu, F. and R.P Sage, 1992. U-Pb age constraints for deposition of clastic metasedimentary rocks and late-tectonic plutonism, Michipicoten Belt, Superior Province; Canadian Journal of Earth Sciences, 29, 1640-1651.

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

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

Ernst, R.E. and K.L. Buchan, 1993. Paleomagnetism of the Abitibi dyke swarm, southern Superior Province, and implications for the Logan Loop; Canadian Journal of Earth Sciences, 30, 1886-1897.

ESRI, 2012. ArcMAP mapping and GIS system, v. 10.0 SP4, ESRI Inc.

Evans, D.A.D. and H.C. Halls, 2010. Restoring Proterozoic deformation within the Superior craton; Precambrian Research,183, 474-489.

Fairhead, J.D. and Williams, S.E. 2006. Evaluating normalized magnetic derivatives for structural mapping, Society of Exploration Geophysicists Expanded Abstracts, 26, 845-849.

Geofirma (Geofirma Engineering Ltd.), 2011. Initial Screening for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel, Municipality of Wawa, Ontario, Final report prepared for Nuclear Waste Management Organization, October.

Geofirma (Geofirma Engineering Ltd.), 2013a. Phase 1 Geoscientific Desktop Preliminary Assessment of Potential Suitability for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel, Municipality of Wawa, Ontario. Prepared for Nuclear Waste Management Organization (NWMO). NWMO Report Number: APM-REP-06144-0027.

Geofirma (Geofirma Engineering Ltd.), 2013b. Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation, Municipality of Wawa, Ontario. Prepared for Nuclear Waste Management Organization (NWMO). NWMO Report Number: APM-REP-06144-0030.

Geosoft, 2012. Oasis montaj geophysical processing system, v 7.5, Geosoft Inc.

GSC (Geological Survey of Canada), 2012. Geoscience Data Repository for Geophysical and Geochemical Data, gdr.nrcan.gc.ca. (data accessed 2012)

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

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

Halls, H.C. and J. Mound, 1998. The McEwan Lake fault: gravity evidence for new structural element of the Kapuskasing zone, Canadian Journal of Earth Sciences, 35, 696-701.

Halls, H.C., H.C. Palmer, M.P. Bates and W.C. Phinney, 1994. Constraints on the nature of the Kapuskasing structural zone from the study of Proterozoic dyke swarms, Canadian Journal of Earth Science, 31, 1182-1196.

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

Holden, E. J., Dentith, M. and Kovesi, P. 2008. Towards the automated analysis of regional aeromagnetic data to identify regions prospective for gold deposits, Computers & Geosciences, 34, 1505-1513.

IAEA (International Atomic Energy Agency), 2003. Guidelines for radioelement mapping using gamma ray spectrometry data, IAEA-TECDOC-1363.

JDMA (J.D. Mollard and Associates Ltd.), 2013. Phase 1 Geoscientific Desktop Preliminary Assessment, Terrain and Remote Sensing Study, Municipality of Wawa, Ontario. Prepared for Geofirma Engineering Ltd. and Nuclear Waste Management Organization (NWMO). NWMO Report Number: APM-REP-06144-0028

Jackson, S.L. and Sutcliffe, R.H. 1990. Central Superior Province geology: evidence for an allochthonous, ensimatic, southern Abitibi greenstone belt, Canadian Journal of Earth Sciences, 27, 582-589.

Johns, G.W., and S. McIlraith, 2002. Precambrian geology compilation map – Michipicoten sheet. Ontario Geological Survey, map 2669, scale 1:250:000.

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

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

Ketchum, J.W.F., J.A. Ayer, O. van Breemen, N.J. Pearson and J.K. Becker, 2008. Pericontinental crustal growth of the southwestern Abitibi Subprovince, Canada – U-Pb, Hf, and Nd isotope evidence; Econ. Geology, 103, 1151-1184.

Langford, F.F. and J.A. Morin. 1976. The development of the Superior province of northwestern Ontario by merging island arcs: American Journal of Science, 276, 1023-1034.

Manson, M.L. and H.C. Halls, 1994. Post-Keweenawan compressional faults in the eastern Lake Superior region and their tectonic significance, Canadian Journal of Earth Sciences, 31, 640-651.

Manson, M.L. and H.C. Halls, 1997. Proterozoic reactivation of the southern Superior Province and its role in the evolution of the Midcontinent Rift., Canadian Journal of Earth Sciences, 34, 562-575.

Massey, N.W.D. 1985. Geology of Mishewawa Lake Area, Algoma District; Ontario Geological Survey Open File Report 5532, 128 p.

McCrank, G.F.D., J.D. Misiura and P.A. Brown, 1981, Plutonic Rocks in Ontario, Geological Survey of Canada, Paper 80-23.

McGill, G.E, and C.H. Shrady, 1986. Evidence for a Complex Archean Deformational History; Southwestern Michipicoten Greenstone Belt, Ontario, Journal of Geophysical Research, 91, n. B13, E281-E289.

Miller, H.G. and Singh, V., 1994. Potential field tilt - a new concept for location of potential field sources, Journal of Applied Geophysics, 32, 213-217.

Milligan, P.R. and Gunn, P.J. 1997. Enhancement and presentation of airborne geophysical data, AGSO Journal of Australian Geology & Geophysics, 17, n. 2, 63-75.

MOE (Ontario Ministry of the Environment), 2012. Water Well Information System (WWIS) – Well Record Data (accessed October, 2012).

Morris, T.F., 2001a. Quaternary geology, Franz-Manitowik Lake – Kinniwabi Lake area. Ontario Geological Survey, map 2573, scale 1:50,000.

Morris, T.F., 2001b. Quaternary geology, Hawk Junction – Michipicoten River area. Ontario Geological Survey, map 2574, scale 1:50,000.

Moser, D.E., 1994. The geology and structure of the mid crustal Wawa gneiss domain: a key to understanding tectonic variation with depth and time in the late Archean Abitibi-Wawa orogen, Canadian Journal of Earth Sciences, 31, 1064-1080.

NWMO, 2010. Moving forward together: Process for selecting a site for Canada's deep geological repository for used nuclear fuel, May 2010.

Nabighian, M.N. 1972. The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: Its properties and use for automated anomaly interpretation. Geophysics, 37, 507-517.

NWMO, 2013. Preliminary Assessment for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel - Municipality of Wawa, Ontario - Findings from Phase One Studies. NWMO Report Number: APM-REP-06144-0025.

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

OGS (Ontario Geological Survey) 2002. Kapuskasing-Chapleau Aeromagnetic Survey, magnetic data; Ontario Geological Survey, Geophysical Data Set 1040 - Revised.

OGS (Ontario Geological Survey), 2003a. Ontario airborne geophysical surveys, magnetic and electromagnetic data, Michipicoten area, Geophysical Data Set 1010 - Revised.

OGS (Ontario Geological Survey), 2003b. Ontario airborne geophysical surveys, magnetic and electromagnetic data, Wawa area, Geophysical Data Set 1009 - Revised.

OGS (Ontario Geological Survey), 2005. Ontario Drill Hole Database-December 2005 Release. Ontario Geological Survey, Data Set 13-Revision.

OGS (Ontario Geological Survey), 2011a. Ontario airborne geophysical surveys, magnetic and electromagnetic data, grid, profile and vector data, Magpie River–Missinaibi Lake area - Purchased Data, Geophysical Data Set 1237.

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

Percival, J.A., 1990, Archean tectonic setting of granulite terranes in the Superior Province, Canada: a view from the bottom, 171-193, In: Granulites and Crustal Evolution (D. Vielzeuf & P. Vidal, eds.), Kluwer, Dordrecht, The Netherlands.

Percival, J.A., and Easton, R.M., 2007, Geology of the Canadian Shield in Ontario – An Update: Geological Survey of Canada Open File Report 5511, 67 p.

Percival, J.A., and G.F. West, 1994. The Kapuskasing uplift: A geological and geophysical synthesis, Canadian Journal of Earth Sciences, 31, 1256-1286.

Percival, J.A. and T. Skulski, 2000. Tectonothermal evolution of the northern Minto block, Superior Province, Québec, Canada, The Canadian Mineralogist, 38, 345-378

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

Phinney, W.C. and H.C. Halls, 2001. Petrogenesis of the Early Proterozoic Matachewan dyke swarm, Canada and implications for magma emplacement and subsequent deformation, Canadian Journal of Earth Sciences, 11, 1541-1563.

Pilkington, M. and Keating, P.B., 2009. The utility of potential field enhancements for remote predictive mapping, Canadian Journal of Remote Sensing, 35, S1-S11.

Pitney Bowes, 2012. Encom PA (Profile Analyst) geophysical processing system, v 12.0, Pitney Bowes Software.

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

Powell, W.G., Hodgson, C.J., Hanes, J.A., Carmichael, D.M., McBride, S. and Farrar, E. 1995. 40Ar/39Ar geochronological evidence for multiple postmetamorphic hydrothermal events focused along faults in the southern Abitibi greenstone belt, Canadian Journal of Earth Sciences, 32, 768-786.

Reid, R.G., R.P. Bowen, B.A. Reilly, J. Logothetis and K.B. Heather, 1991. Geology, structure and economic geology of the Mishibishu Lake area; Ontario Geological Survey, Open File Report 5774, 503 p.

Reid, R.G., R.P. Bowen, K.B. Heather, J. Logothetis and B.A. Reilly, 1992a. Precambrian geology, Mishibishu Lake area, Pukaskwa River sheet; Ontario Geological Survey, Preliminary Map P.3150, scale 1:15,840.

Reid, R.G., R.P. Bowen, K.B. Heather, J. Logothetis and B.A. Reilly, 1992b. Precambrian geology, Mishibishu Lake area, Macassa Creek sheet; Ontario Geological Survey, Preliminary Map P.3151, scale 1:15,840.

Reid, R.G., R.P. Bowen, K.B. Heather, J. Logothetis and B.A. Reilly, Reid, 1992c. Precambrian geology, Mishibishu Lake area, Mishibishu Lake sheet; Ontario Geological Survey, Preliminary Map P.3152, scale 1:15,840.

Reilly, B.A. 1991. Geology of the Iron Lake Area; Ontario Geological Survey, Open File Report 5783, 28 p.

Renault, J. R., 1962. Geologic Report on the Lithology of the Canyon-Eton Area and the Nature of the Agawa Lineament, A.C and H.B. Railway Report, Sault Algoma No. 1 Project (A.C.R.), Ontario Department of Mines, Sault Ste. Marie Office, MNDM AFRI # 41N09SW001, July 15.

Sage, R.P., 1979. Wawa Area, District of Algoma, In: Summary of Field Work, 1979, by the Ontario Geological Survey, Edited by V.G. Milne, O.L. White, R.B. Barlow and C.R. Kustra, Ontario Geological Survey Miscellaneous Paper 90, 49-53.

Sage, R.P., 1994. Geology of the Michipicoten Greenstone Belt, Ontario Geological Survey, Open File Report 5888, 592 p.

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

Sears, S.M., 1994. Report of a Work Program on the Trembley Siding Property, Wawa Area, Ontario, Mining Lands Branch Report, MNDM AFRI # 41N15NW0011, January.

Shi, Z. and Butt, G. 2004. New enhancement filters for geological mapping, Extended Abstracts, Australian Society of Exploration Geophysicists, 5 p.

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

Stott, G.M., J.A. Ayer, A.C. Wilson and G.P.B. Grabowski, 2002. Are the Neoarchean diamond-bearing breccias in the Wawa area related to late-orogenic alkalic and “sanukitoid” intrusions?; In: Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, 9-1 to 9-10.

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

Telford, W. M., L.P. Geldart, and R.E. Sheriff, 1990. Applied Geophysics Second Edition. Cambridge University Press, 1990-10-26, 792 p.

Teskey, D. J., P. J. Hood, L. W. Morley, R. A. Gibb, P. Sawatzky, M. Bower, and E. E. Ready, 1993, The aeromagnetic survey program of the Geological Survey of Canada; contribution to regional geological mapping and mineral exploration: Canadian Journal of Earth Sciences, 30, 243-260.

Thurston, J.B. and Smith, R.S., 1997. Automatic conversion of magnetic data to depth, dip, and susceptibility contrast using the SPI™ method, Geophysics, 62, 807-813.

Thurston, P.C, G.M. Siragusa, and R.P. Sage, 1977. Geology of the Chapleau Area: Districts of Algoma, Sudbury, and Cochrane, Ontario Division of Mines, Geoscience Report 157, Toronto, Ontario, 349 p.

Turek, A., R. Keller and W.R. Van Schmus, 1990. U-Pb Ages of volcanism and plutonism in the Mishibishu Greenstone Belt near Wawa, Ontario, Canadian Journal of Earth Sciences, 31, 1064-1080.

Turek, A., R.P. Sage and W.R. Van Schmus 1992. Advances in the U-Pb zircon geochronology of the Michipicoten greenstone belt, Superior Province, Ontario, Canadian Journal of Earth Sciences, 29, 1154-1165.

Turek, A., P. E. Smith and W.R. Van Schmus, 1982. Rb-Sr and U-Pb ages of volcanics and granite emplacement in the Michipicoten belt, Wawa, Ontario; Canadian Journal of Earth Sciences, 19, 1608-1626.

Turek, A., P.E. Smith and W.R. Van Schmus,1984. U-Pb zircon ages and the evolution of the Michipicoten plutonic-volcanic terrane of the Superior Province, Ontario, Canadian Journal of Earth Sciences, 21, 457-464.

Vaillancourt, C., A.C. Wilson, and G.R. Dessureau, 2003. Synthesis of Archean geology and diamond-bearing rocks in the Michipicoten greenstone belt: geology of Menzies Township; In: Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, 9-1 to 9-11.

Vaillancourt, C., J.A. Ayer, S.M. Zubowski and S.L. Kamo. 2004. Project Unit 03-002. Synthesis and Timing of Archean Geology and Diamond-bearing Rocks in the Michipicoten Greenstone Belt: Menzies and Musquash Townships; in Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, 6-1 to 6-9.

Vaillancourt, C., J.A. Ayer and M.A. Hamilton, 2005a. Synthesis of Archean geology and diamond-bearing rocks in the Michipicoten greenstone belt: Results from microdiamond extraction and geochronological analysis; in Summary of Field Work and Other Activities 2005, Ontario Geological Survey, Open File Report 6172, 8-1 to 8-13

Vaillancourt, C., G.R. Dessureau and S.M. Zubowski, 2005b. Precambrian geology of Menzies Township; Ontario Geological Survey, Preliminary Map P.3366, scale 1:20,000.

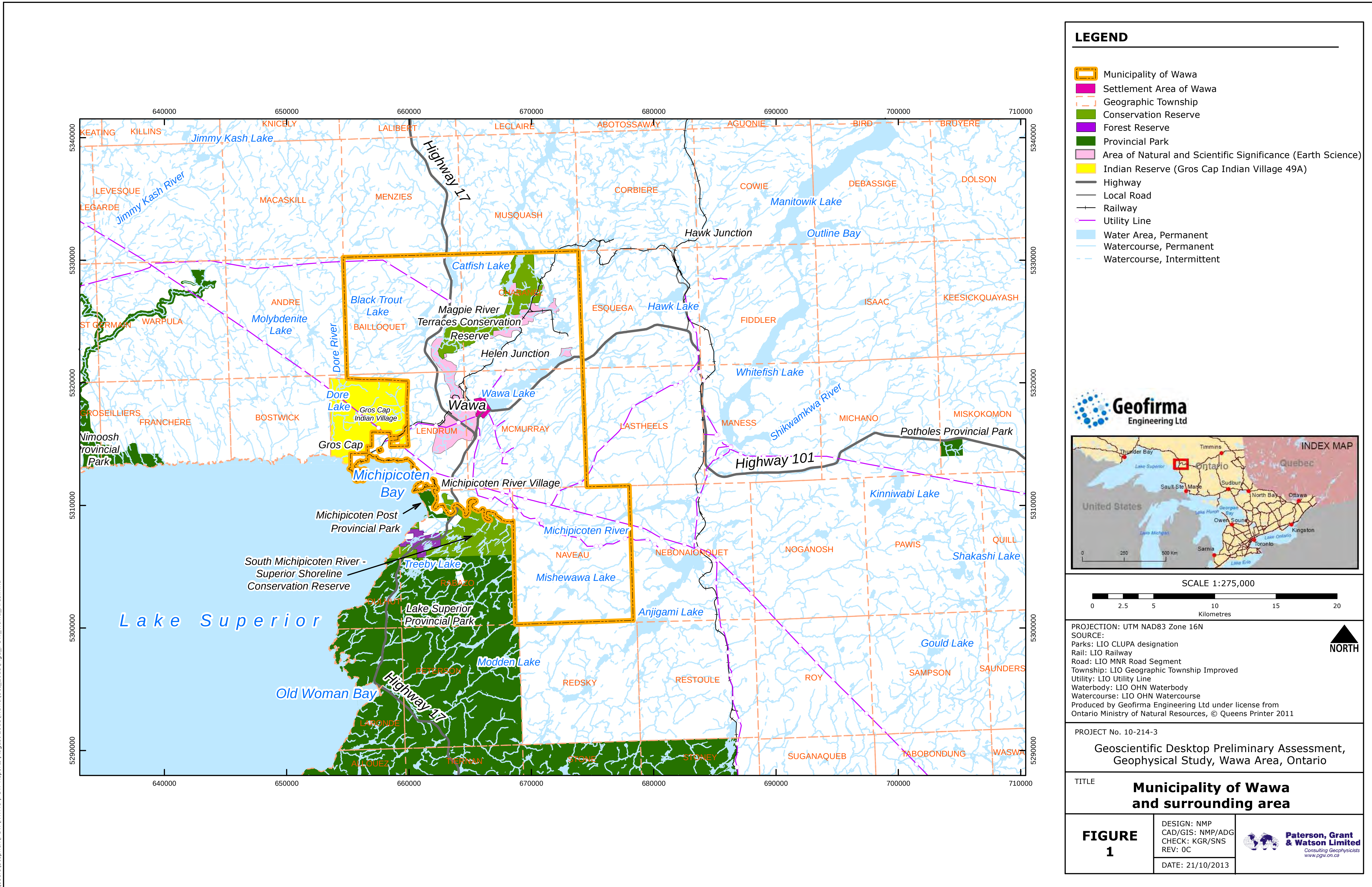
West, G.F. and R.E. Ernst, 1991. Evidence from aeromagnetics on the configuration of Matachewan dykes and the tectonic evolution of the Kapuskasing Structural Zone, Ontario, Canada, Canadian Journal of Earth Sciences, 28, 1797-1811.

Williams, H.R., Stott, G.M., Heather, K.B., Muir T.L. and Sage, R.P., 1991. Wawa Subprovince, In: Geology of Ontario, Special Volume 4, Part 1, 485-546.

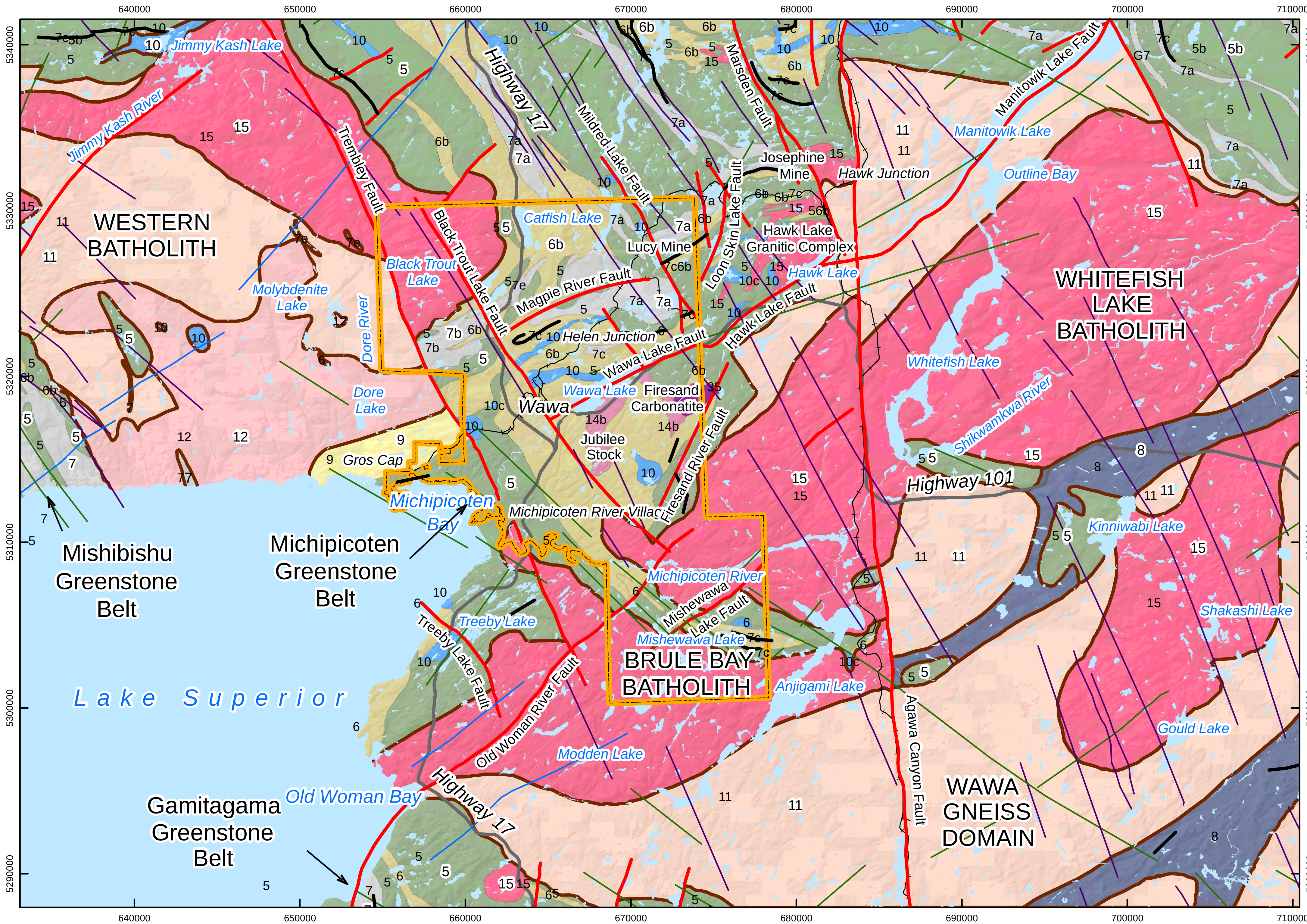
Wyman, D.A., J.A. Ayer, R.V. Conceição and R.P. Sage, 2006. Mantle processes in an Archean orogeny: Evidence from 2.67 Ga diamond-bearing lamprophyres and xenoliths, Lithos, 89, 300-328.

Wyman, D.A., C. O'Neill and J.A. Ayer, 2008. Evidence for modern-style subduction to 3.1 Ga: A plateau-adakite-gold (diamond) association; in Condie, K.C. and Pease, V., eds., When Did Plate Tectonics Begin on Planet Earth?; Geological Society of America Special Paper 440, 129-148.

FIGURES



LEGEND
Municipality of Wawa
Settlement Area of Wawa
Geographic Township
Conservation Reserve
Forest Reserve
Provincial Park
Area of Natural and Scientific Significance (Earth Science)
Indian Reserve (Gros Cap Indian Village 49A)
Highway
Local Road
Railway
Utility Line
Water Area, Permanent
Watercourse, Permanent
Watercourse, Intermittent
Geofirma Engineering Ltd
INDEX MAP
Thunder Bay
Timmins
Ontario
Quebec
Sault Ste Marie
Sudbury
North Bay
Ottawa
United States
Owen Sound
Kingston
Toronto
Sarnia
SCALE 1:275,000
0 2.5 5 10 15 20
Kilometres
PROJECTION: UTM NAD83 Zone 16N
SOURCE:
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
Produced by Geofirma Engineering Ltd under license from
Ontario Ministry of Natural Resources, © Queens Printer 2011
NORTH
PROJECT No. 10-214-3
Geoscientific Desktop Preliminary Assessment,
Geophysical Study, Wawa Area, Ontario
TITLE
Municipality of Wawa
and surrounding area
FIGURE
1
DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR/SNS
REV: 0C
DATE: 21/10/2013
Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca
640000 650000 660000 670000 680000 690000 700000 710000
5340000 5330000 5320000 5310000 5300000 5290000
Lake Superior
Highway 17
Highway 101
Wawa
Hawk Junction
Helen Junction
Gros Cap
Gros Cap Indian Village
Michipicoten Bay
Michipicoten River Village
Michipicoten Post Provincial Park
South Michipicoten River - Superior Shoreline Conservation Reserve
Magpie River Terraces Conservation Reserve
Lake Superior Provincial Park
Potholes Provincial Park
Nimoosh Provincial Park
Old Woman Bay
Jimmy Kash Lake
Jimmy Kash River
Molybdenite Lake
Dore River
Dore Lake
Black Trout Lake
Catfish Lake
Hawk Lake
Wawa Lake
Manitowik Lake
Outline Bay
Whitefish Lake
Shikwamkwa River
Kinniwabi Lake
Michipicoten River
Mishewawa Lake
Anjigami Lake
Treeby Lake
Modden Lake
Gould Lake
Shakashi Lake
KEATING
KILLINS
KNICELY
LALIBERT
LECLAIRE
ABOTOSSAWAY
AGUONIE
BIRD
BRUYERE
LEVESQUE
LEGARDE
MACASKILL
MENZIES
MUSQUASH
CORBIERE
COWIE
DEBASSIGE
DOLSON
ANDRE
WARPULA
ST GERMAIN
BAILLOQUET
CHABANEL
ESQUEGA
FIDDLER
ISAAC
KEESICKQUAYASH
GROSEILLIERS
FRANCHERE
BOSTWICK
LENDRUM
MCMURRAY
LASTHEELS
MANESS
MICHANO
MISKOKOMON
NAVEAU
NEBONAIONQUET
NOGANOSH
PAWIS
QUILL
RABAZO
DULUTH
PETERSON
REDSKY
RESTOULE
ROY
SAMPSON
SAUNDERS
LARONDE
ALLOUEZ
TIERNAN
STONE
STONEY
SUGANAQUEB
TABOBONDUNG
WASWA
C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig1_PGW_Wawa_Area.mxd



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, ironformation, 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

Geofirma Engineering Ltd

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
Produced by Geofirma Engineering Ltd under license from
Ontario Ministry of Natural Resources, ©Queens Printer 2011

NORTH

PROJECT No. 10-214-3
Geoscientific Desktop Preliminary Assessment, Geophysical Study, Wawa Area, Ontario

TITLE
Bedrock Geology of the Wawa Area

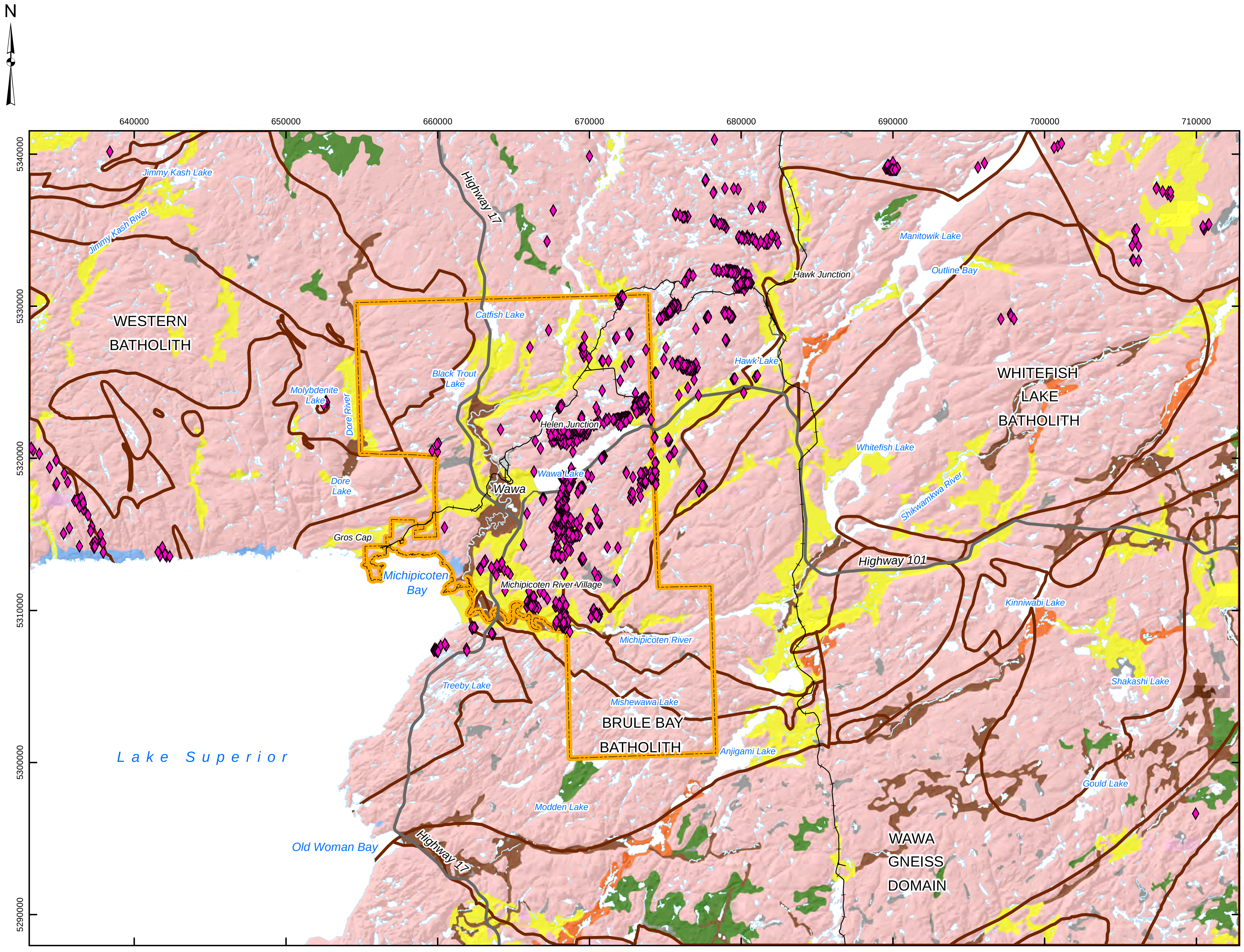
FIGURE 2

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

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig2_PGW_Wawa_Bedrock_Geology.mxd



C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig3_PGW_Wawa_Surficial_Geology.mxd

LEGEND

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

Surficial Geology (NOEGTS Landform)

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

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE: MNR, obtained 2010-2012
NOEGTS: OGS MRD-160 (scale 1:100,000)
Geology: MRD126-REV1-Bedrock Geology of Ontario, 2011
Diamond Drill Holes: OGS MRD 126-Bedrock Geology, 2007
Produced by Geofirma Engineering Ltd under license from Ontario Ministry of Natural Resources, ©Queens Printer 2011

PROJECT No. 10-214-3

Geoscientific Desktop Preliminary Assessment, Geophysical Study, Wawa Area, Ontario

TITLE

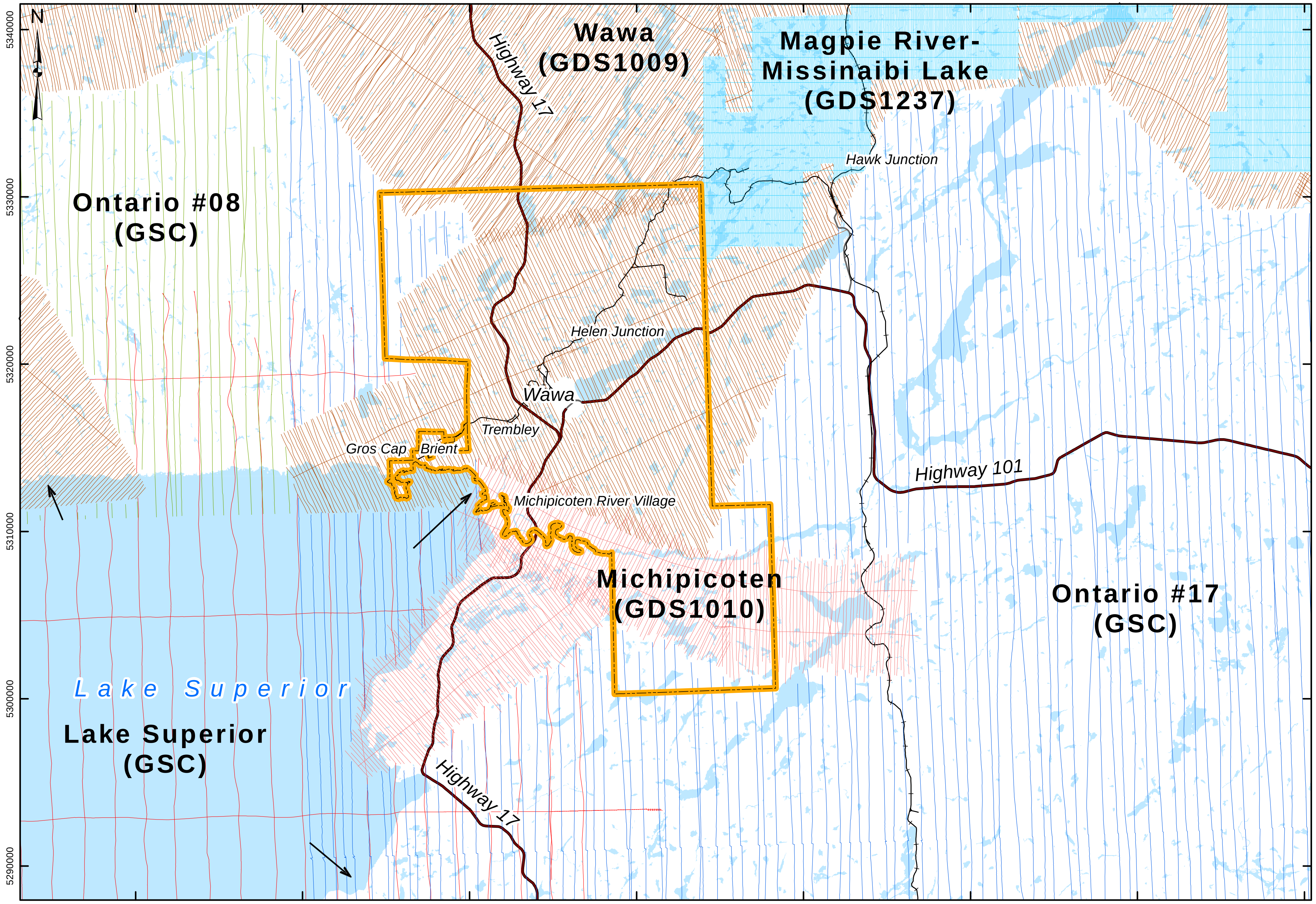
Surficial Geology of the Wawa Area

FIGURE 3

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

DATE: 08/11/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Water Area, Permanent
- Flightpath OGS Magpie River–Missinaibi Lake
- Flightpath OGS Wawa
- Flightpath OGS Michipicoten
- Flightpath GSC Ontario #08
- Flightpath GSC Ontario #17
- Flightpath GSC Lake Superior

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N

SOURCE: MNR, 2012
FLIGHTPATH: OGS GDS1009, GDS1010, GDS1040, GDS1237
GSC nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT,
GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE **Airborne Geophysical Coverage of the Wawa Area**

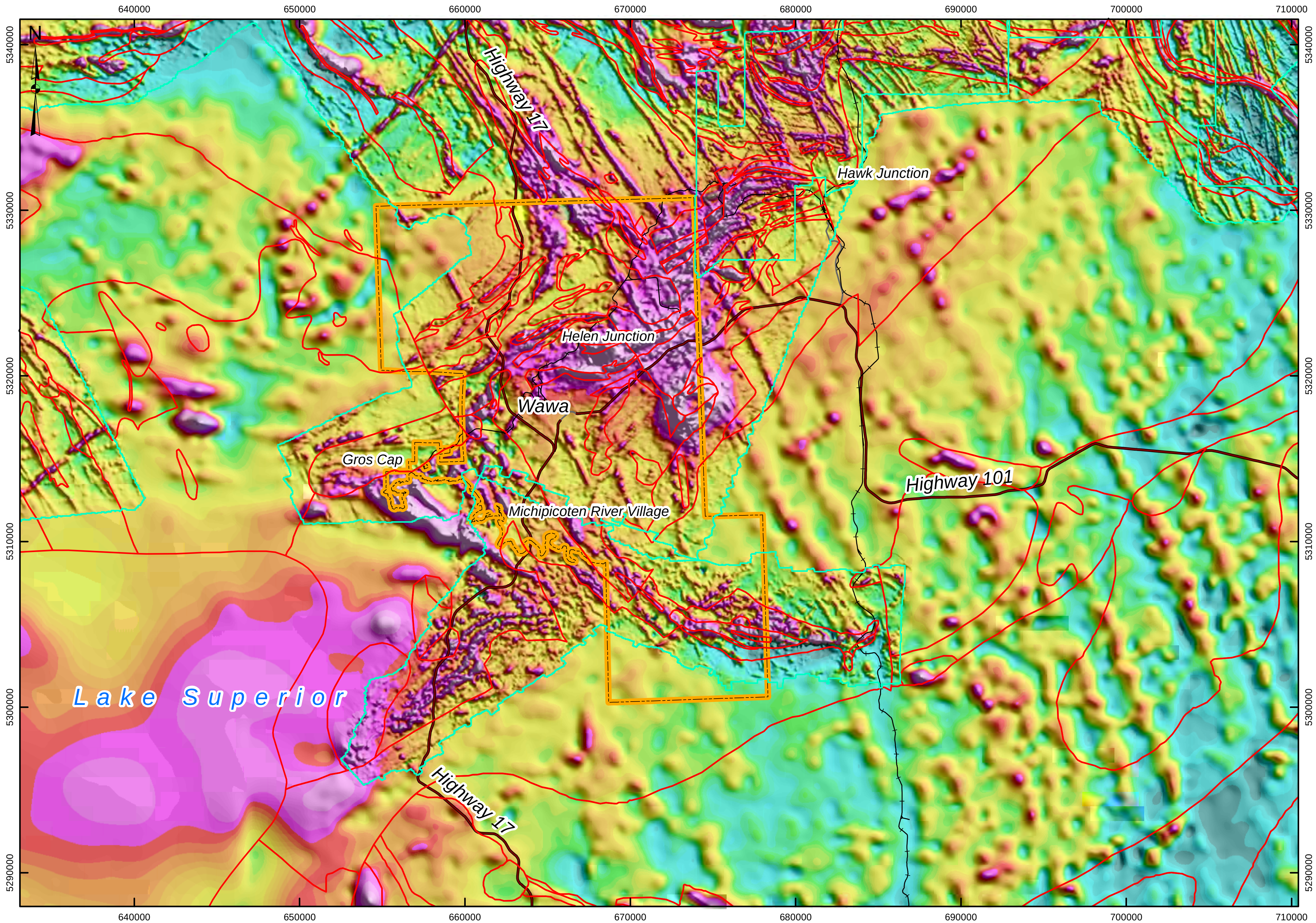
FIGURE 4

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig4_PGW_Wawa_Flightpath.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts
- Geophysical Survey Outlines

RTP (nT): 19501, 610, 470, 350, 240, 180, 140, 110, 80, 60, 40, 20, 0, -10, -30, -40, -50, -60, -80, -90, -100, -110, -130, -140, -160, -180, -210, -250, -5415

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20

Kilometres

PROJECTION: UTM NAD83 Zone 16N

SOURCE: MNR, 2012

Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011

High-resolution magnetics: OGS GDS1009, GDS1010, GDS1040, GDS1237

Regional magnetics: GSC nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

Residual magnetic field reduced to pole

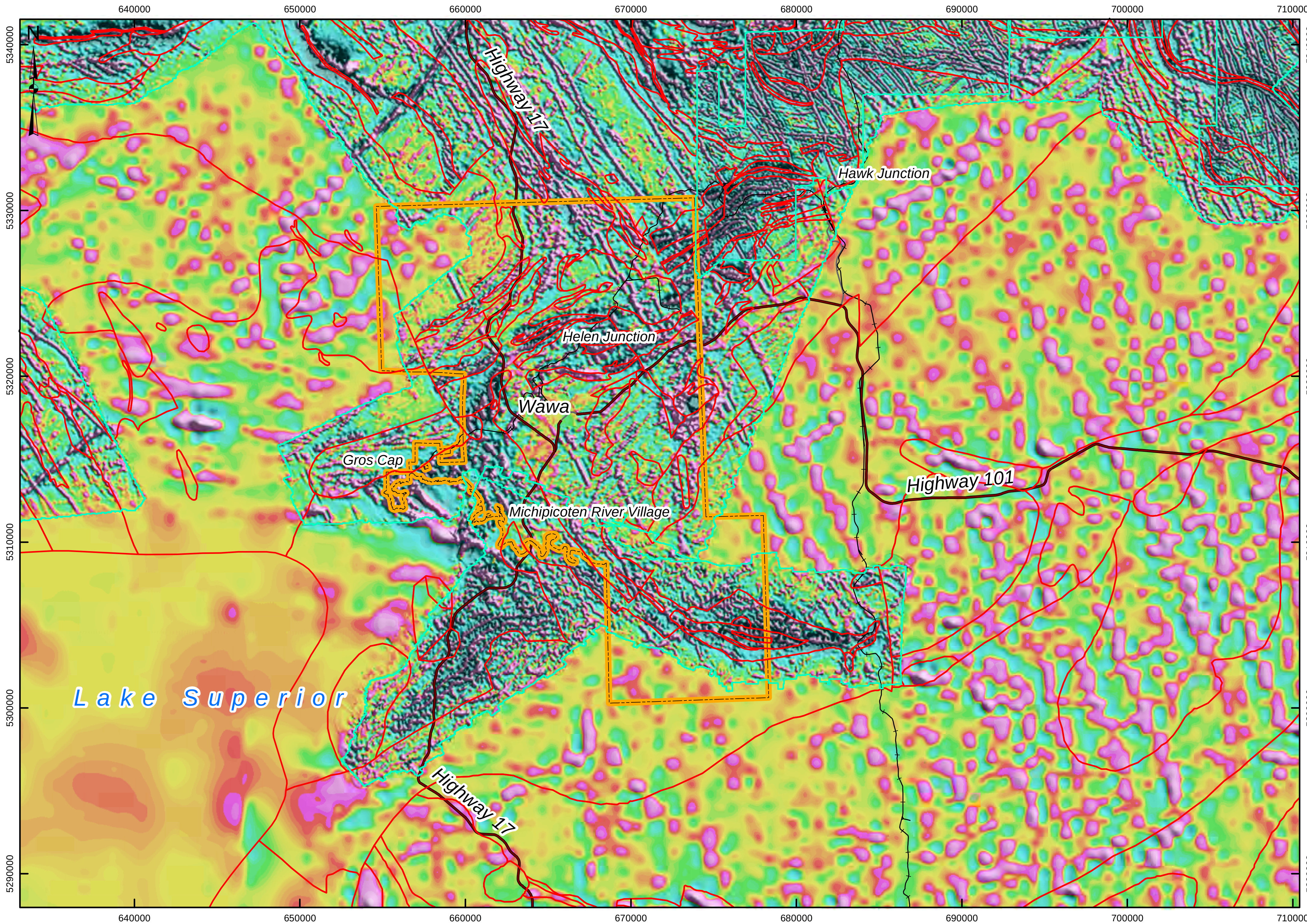
FIGURE 5

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig5_PGW_Wawa_Mag_RTP.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts
- Geophysical Survey Outlines

1VD of RTP (nT/m)

184.365, 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, -61.698

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE: MNR, 2012
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
High-resolution magnetics: OGS GDS1009, GDS1010, GDS1040, GDS1237
Regional magnetics: GSC nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

First vertical derivative of the pole reduced magnetic field

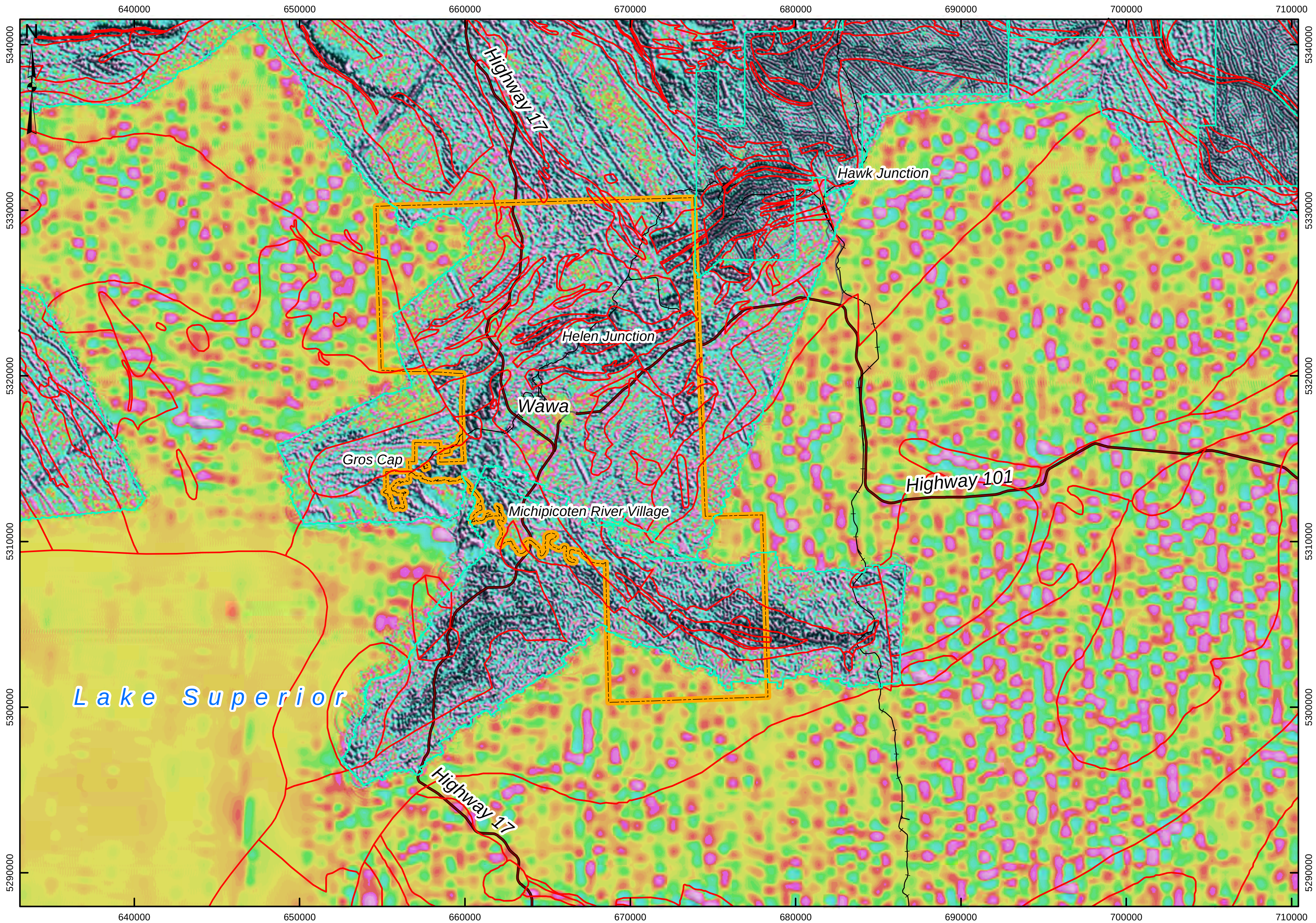
FIGURE 6

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Fig6_PGW_Wawa_Mag_RTP_1VD.mxd



LEGEND

Municipality of Wawa
Highway
Local Road
Railway
Bedrock Geology Contacts
Geophysical Survey Outlines

4.04609
0.01412
0.00528
0.00244
0.00132
0.00082
0.00052
0.00034
0.00020
0.00012
0.00006
0.00002
0.00000
-0.00002
-0.00004
-0.00010
-0.00016
-0.00024
-0.00034
-0.00050
-0.00070
-0.00100
-0.00152
-0.00246
-0.00420
-0.00758
-0.01612
-2.08857

2VD of RTP
(nT/m2)

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE: MNR, 2012
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
High-resolution magnetics: OGS GDS1009, GDS1010, GDS1040, GDS1237
Regional magnetics: GSC nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT,
GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

Second vertical derivative of the pole reduced magnetic field

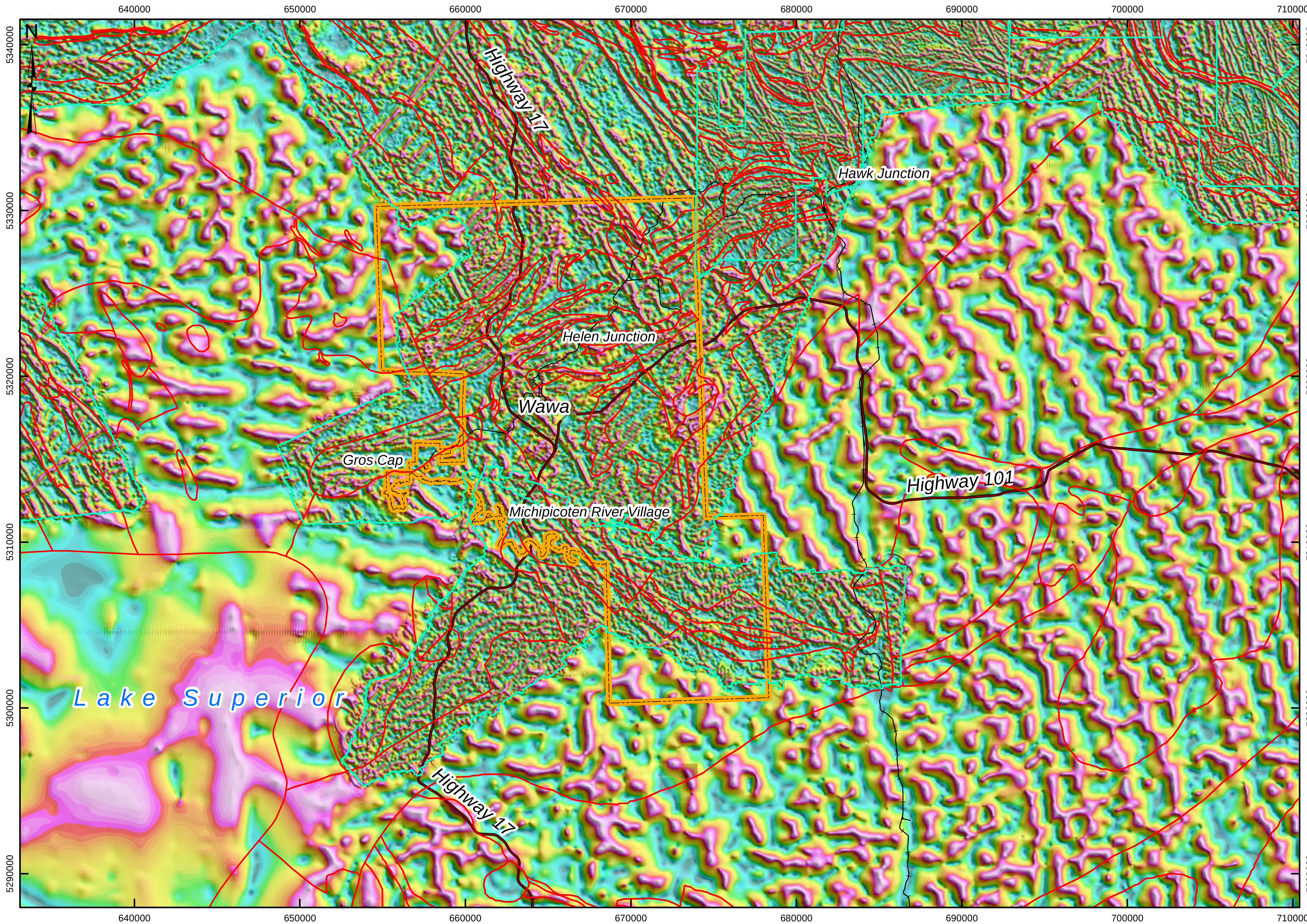
FIGURE 7

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig7_PGW_Wawa_Mag_RTP_2VD.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts
- Geophysical Survey Outlines

Tilt Angle (radians)

1.57
1.25
1.09
0.96
0.84
0.71
0.59
0.48
0.36
0.25
0.13
0.02
-0.08
-0.18
-0.28
-0.38
-0.47
-0.56
-0.64
-0.72
-0.80
-0.88
-0.95
-1.02
-1.09
-1.16
-1.23
-1.30
-1.39
-1.57

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE: MNR, 2012
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
High-resolution magnetics: OGS GDS1009, GDS1010, GDS1040, GDS1237
Regional magnetics: GSC nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

Tilt angle of the pole reduced magnetic field

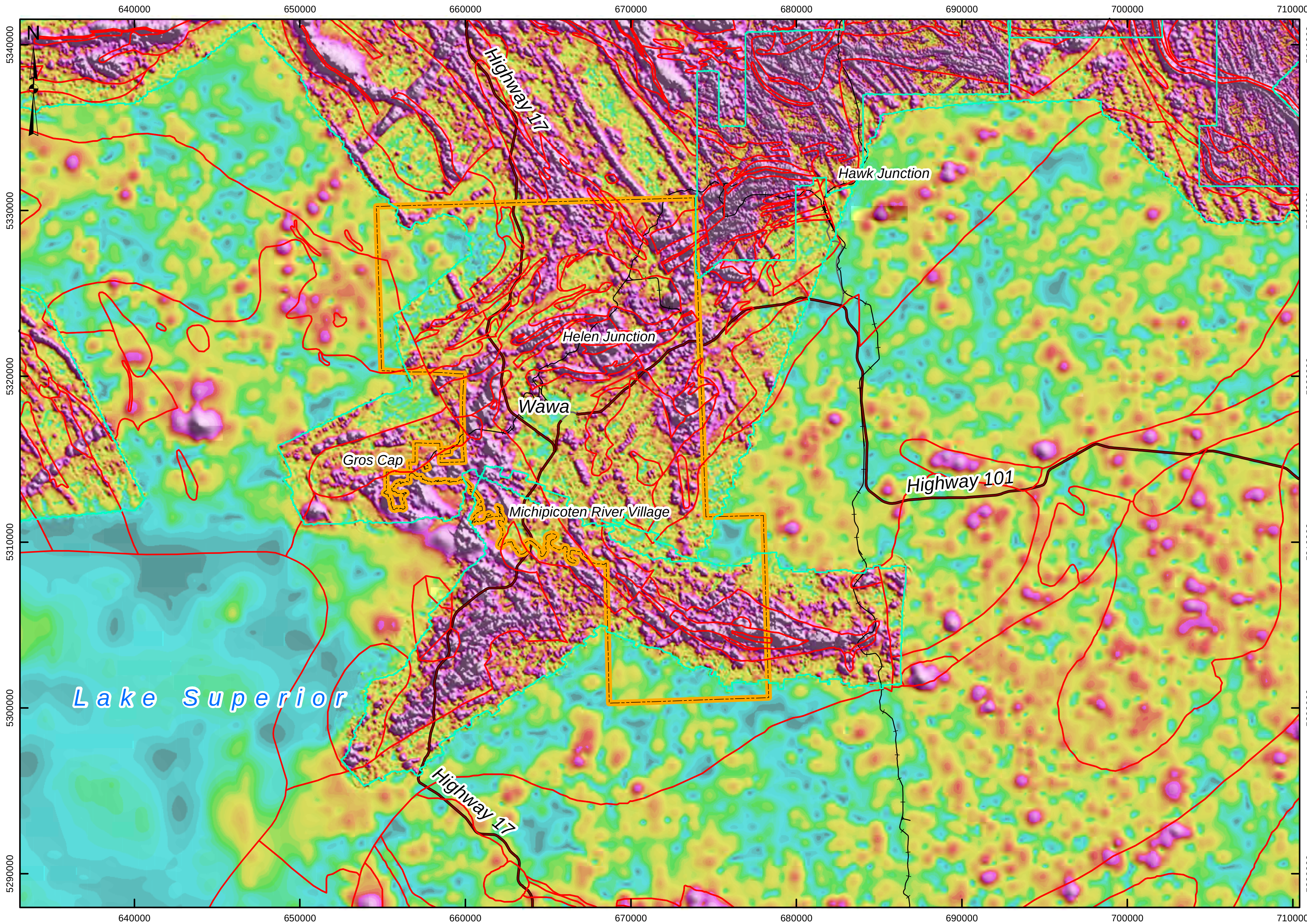
FIGURE 8

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig8_PGW_Wawa_Mag_RTP_Tilt.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts
- Geophysical Survey Outlines

225.89
2.34
1.38
0.98
0.74
0.59
0.49
0.42
0.36
0.32
0.28
0.26
0.23
0.21
0.19
0.17
0.16
0.14
0.13
0.12
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.00

Analytic Signal
(nT/m)

Geofirma
Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N

SOURCE: MNR, 2012
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
High-resolution magnetics: OGS GDS1009, GDS1010, GDS1040, GDS1237
Regional magnetics: GSC nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

Analytic signal amplitude of the total magnetic field

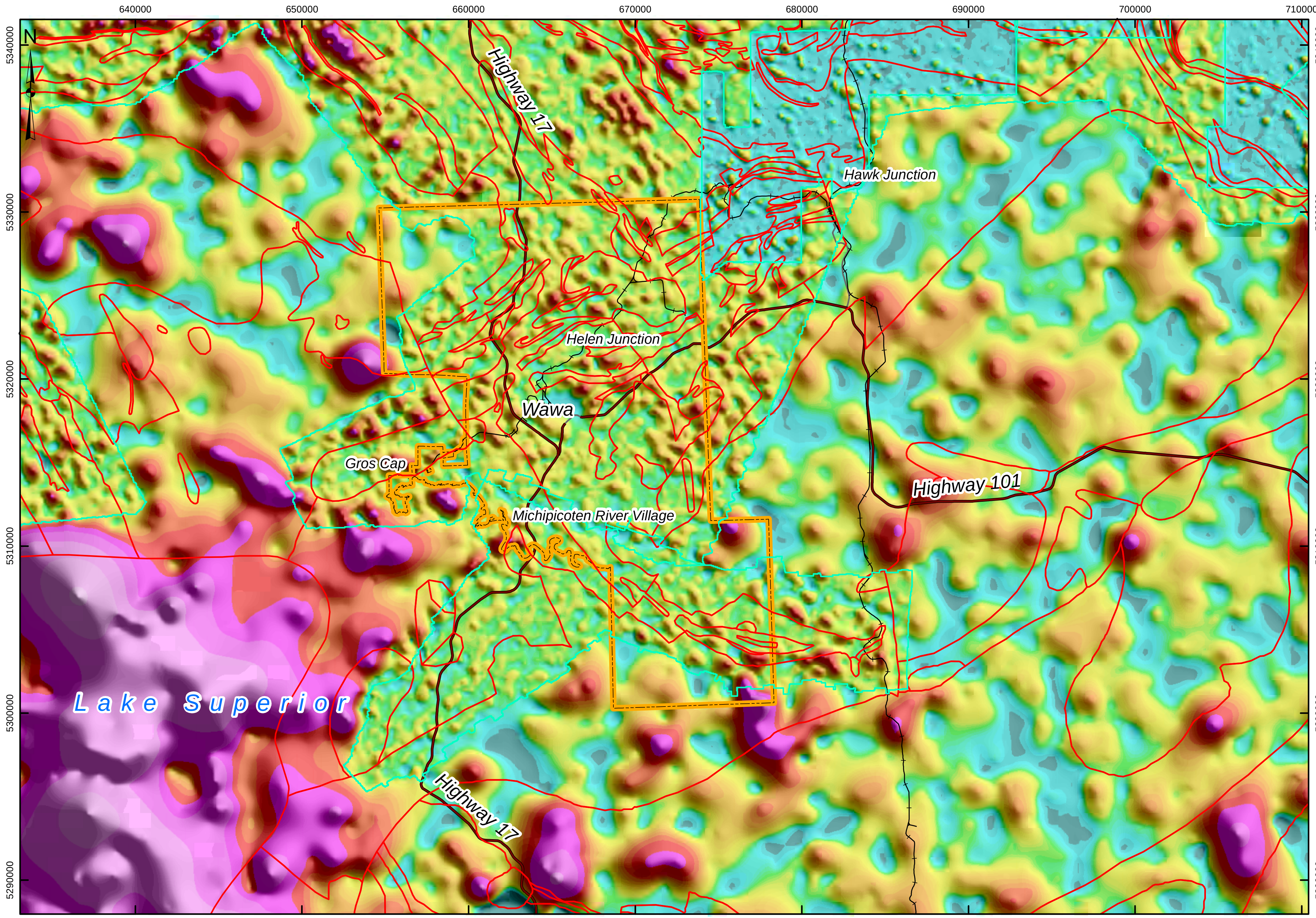
FIGURE 9

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig9_PGW_Wawa_Mag_ASIG.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts
- Geophysical Survey Outlines

40141
4530
2675
1515
815
485
330
245
200
165
140
125
110
100
90
80
75
65
60
55
50
45
40
35
30
20
10
0
-197

Depth
(m below surface)

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N
SOURCE: MNR, 2012
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
High-resolution magnetics: OGS GDS1009, GDS1010, GDS1040, GDS1237
Regional magnetics: GSC nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

Depth to magnetic sources from source parameter imaging

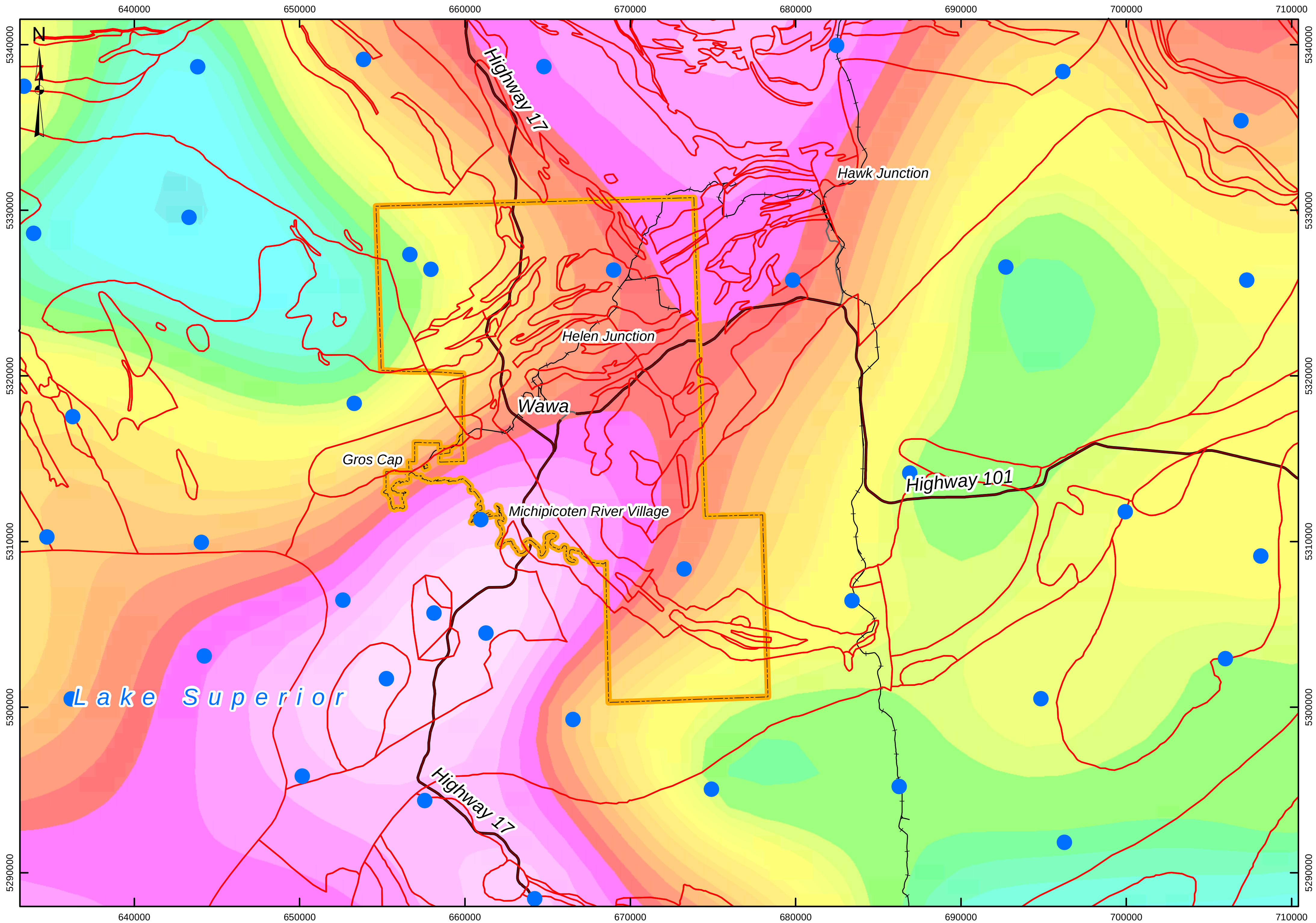
FIGURE 10

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig10_PGW_Wawa_Mag_SPIDepth.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts
- Gravity Stations

-12, -27, -31, -34, -37, -40, -42, -45, -47, -49, -51, -52, -54, -55, -56, -57, -58, -59, -60, -62, -63, -64, -65, -66, -68, -69, -71, -76

Bouguer Gravity
(mGal)

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N

SOURCE: MNR, 2012
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
Gravity: Geological Survey of Canada nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

Bouguer gravity field with station locations

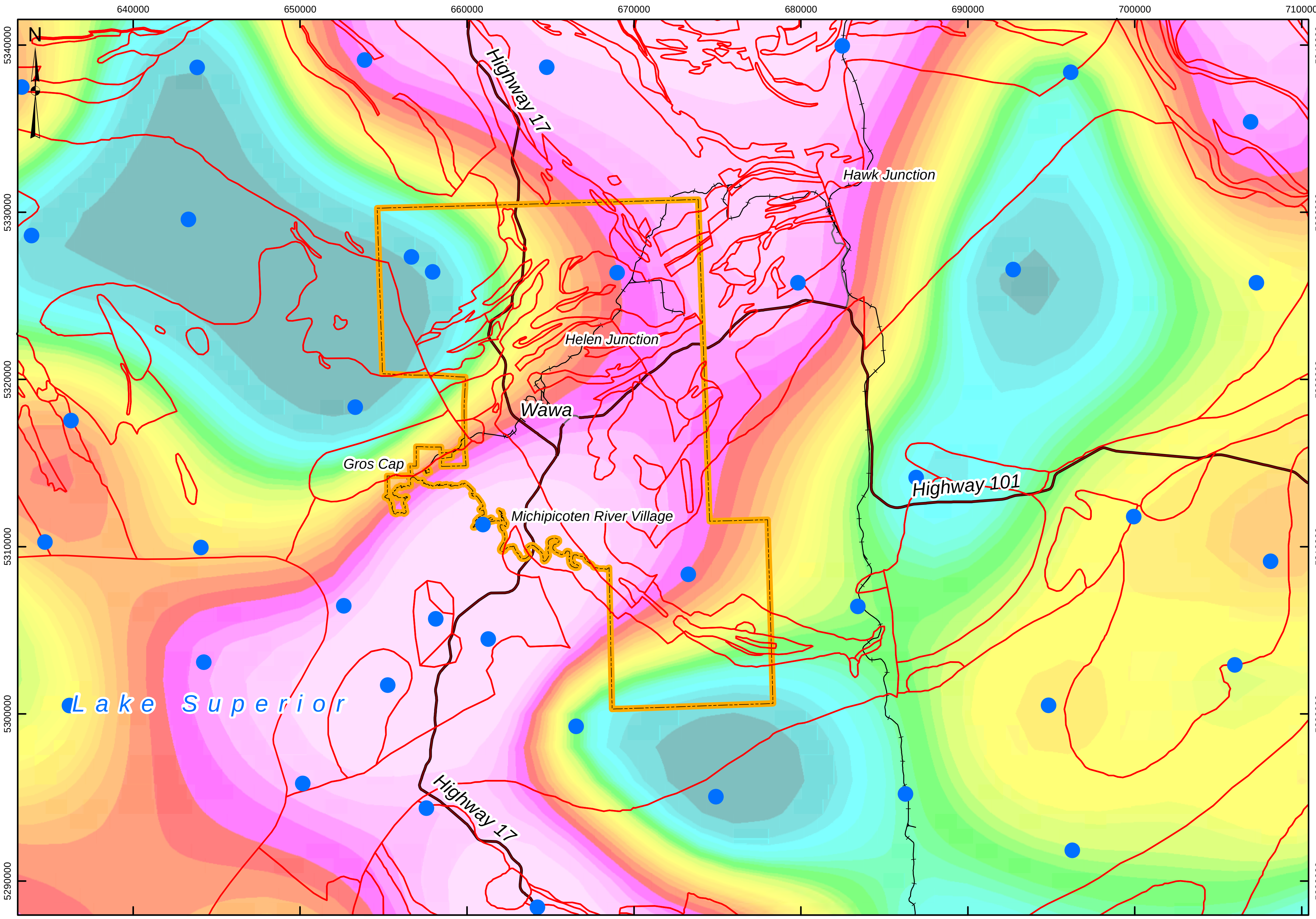
FIGURE 11

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig11_PGW_Wawa_Grav_Boug.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts
- Gravity Stations

0.00320
0.00140
0.00110
0.00090
0.00075
0.00055
0.00040
0.00025
0.00015
0.00005
0.00000
-0.00005
-0.00015
-0.00020
-0.00025
-0.00030
-0.00035
-0.00040
-0.00050
-0.00055
-0.00060
-0.00070
-0.00075
-0.00080
-0.00085
-0.00095
-0.00105
-0.00115
-0.00140
-0.00288

1VD of Bouguer Gravity
(mGal/m)

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N

SOURCE: MNR, 2012
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
Gravity: Geological Survey of Canada nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE **First vertical derivative of the Bouguer gravity field with station locations**

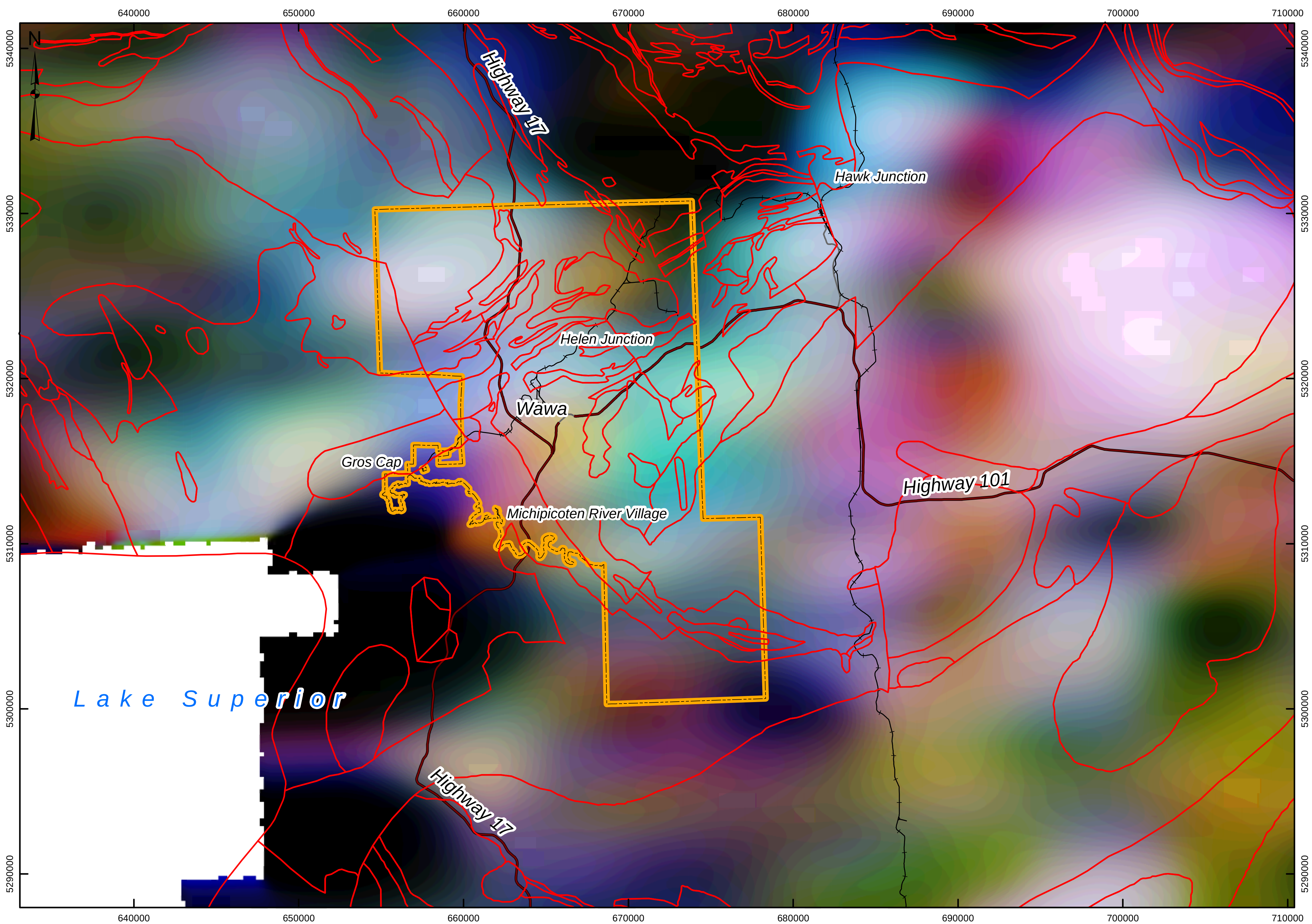
FIGURE 12

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

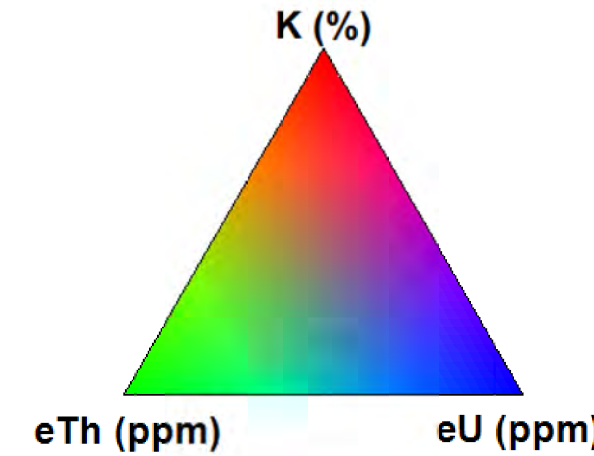
Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig12_PGW_Wawa_Grav_Boug_1VD.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts



Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

PROJECTION: UTM NAD83 Zone 16N

SOURCE: MNR, 2012
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
Radiometrics: Geological Survey of Canada nationwide compilation

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

Radiometric ternary image (RGB = K-eTh-eU)

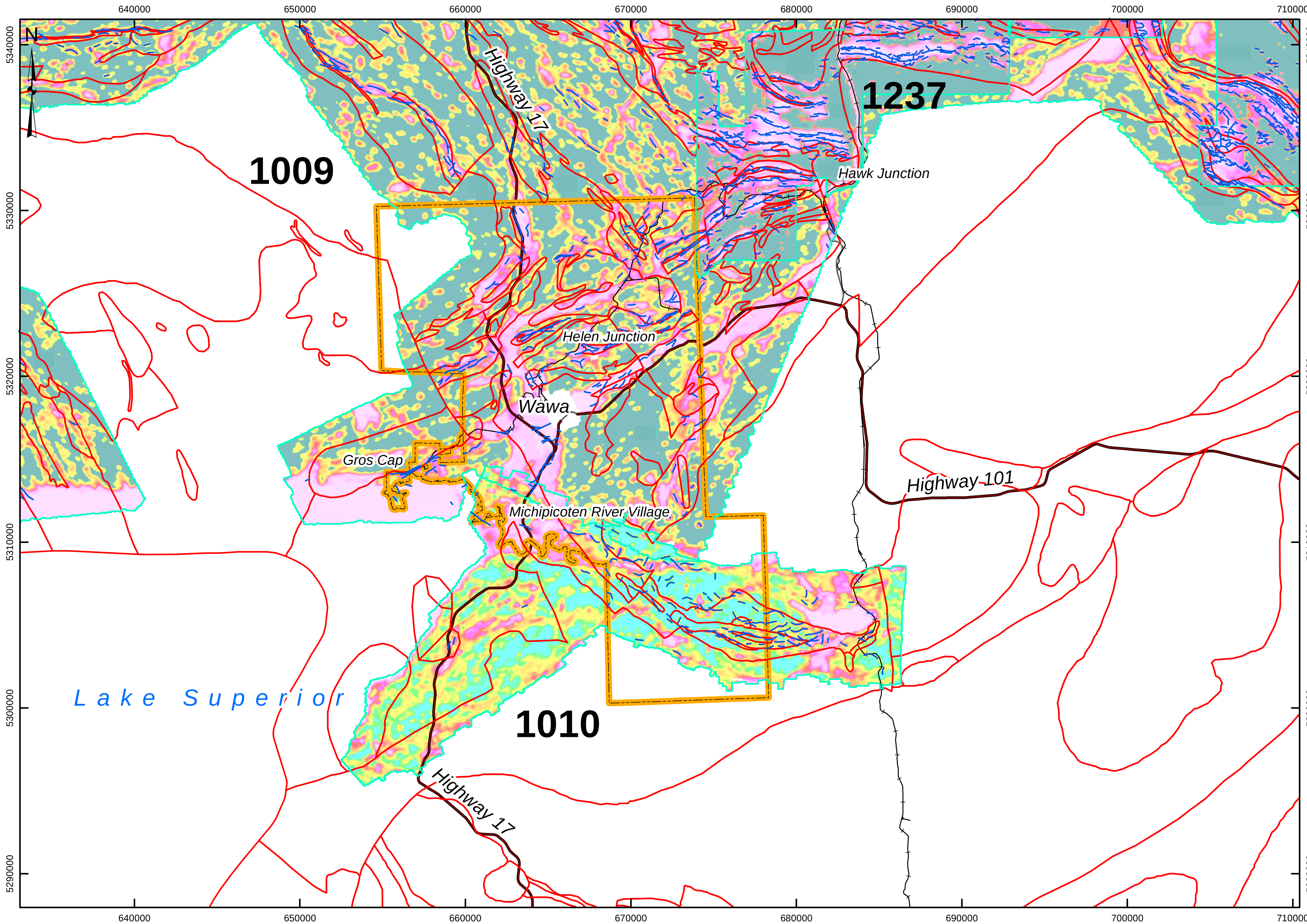
FIGURE 13

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig13_PGW_Wawa_Rad_Ternary.mxd



LEGEND

- Municipality of Wawa
- Highway
- Local Road
- Railway
- Bedrock Geology Contacts
- EM Survey Outlines
- EM Conductors

1009 - Conductivity (S/m)

1010 - Conductivity (S/m)

1237 - Decay Constant (us)

Geofirma Engineering Ltd

SCALE 1:275,000

0 2.5 5 10 15 20

Kilometres

PROJECTION: UTM NAD83 Zone 16N

SOURCE: MNR, 2012

Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011

Electromagnetics: OGS GDS1009, GDS1010, GDS1237

PROJECT No. 10-214-3

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, WAWA AREA, ONTARIO

TITLE

EM conductors over decay constant (GDS1237) and apparent conductivity (GDS1009 and GDS1010)

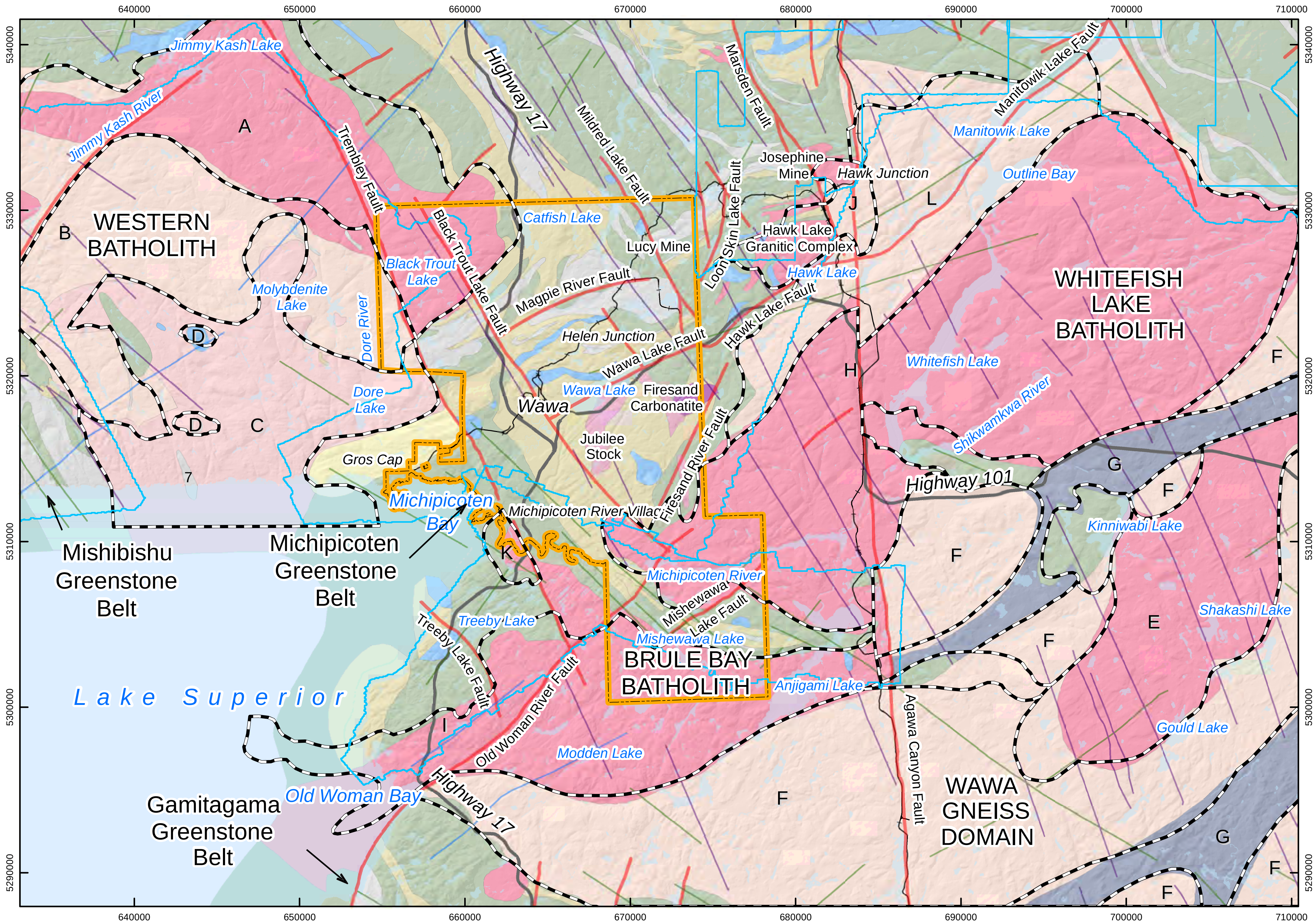
FIGURE 14

DESIGN: SWR
CAD/GIS: SWR
CHECK: ELM/SNS
REV: 0A

DATE: 21/10/2013

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig14_PGW_Wawa_EM_Cond_Decay.mxd



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, ironformation, 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
- Geophysical Survey Outlines
- A Geologic Units Interpreted From gGeophysics

SCALE 1:275,000

0 2.5 5 10 15 20
Kilometres

NORTH

PROJECTION: UTM NAD83 Zone 16N
SOURCE:
Geology: MRD126-REV1 Bedrock Geology of Ontario, 2011
Basemap; Railway, Road, Geographic Township, Waterbody, Watercourse, LIO
Produced by Geofirma Engineering Ltd under license from
Ontario Ministry of Natural Resources, ©Queens Printer 2011

PROJECT No. 10-214-3
Geoscientific Desktop Preliminary Assessment, Geophysical Study, Wawa Area, Ontario

TITLE
Geophysical Interpretation Showing Distribution of Bedrock Units for the Wawa Area

FIGURE 15

DESIGN: NMP
CAD/GIS: SWR
CHECK: DJM
REV: 0C
DATE: 21/10/2013

Geofirma Engineering Ltd

Paterson, Grant & Watson Limited
Consulting Geophysicists
www.pgw.on.ca

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Wawa\Oct_2013\Fig15_PGW_Wawa_Bedrock_Geology_Interpretation.mxd