NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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

MUNICIPALITY OF CENTRAL HURON, ONTARIO

APM-REP-06144-0129

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PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT

PROCESSING AND INTERPRETATION OF GEOPHYSICAL DATA

Municipality of Central Huron

Final Report (R0)

Prepared for

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

by

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EXECUTIVE SUMMARY

In July 2014, the Municipality of Central Huron (herein "the Municipality") expressed interest in continuing to learn more about the Nuclear Waste Management Organization (NWMO) nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the Municipality 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 of the Municipality are reported in the integrated report (NWMO, 2015). The objective of the Geoscientific Desktop Preliminary Assessment is to determine whether the Municipality contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

The purpose of the geophysical interpretation was to provide additional information of the geological features associated with both the Paleozoic sedimentary units and the underlying crystalline rocks of the Precambrian basement within the Municipality and its immediate periphery referred to as the Central Huron area. Available geophysical data were assessed to determine potential lithological variations within the Precambrian basement, and identify broad lithological domains. An attempt was made using gravity data in the Central Huron area to identify features within the Precambrian basement, as well as potential features such as pinnacle reef structures and the presence of thick salt occurrence within the overlying Paleozoic sedimentary sequence.

The geophysical data covering the Municipality vary from low to high data set resolution. Lower resolution magnetic, gravity and radiometric data were obtained from the Geological Survey of Canada (GSC) for the entire Central Huron area. These were supplemented by moderate resolution magnetic and high-resolution gravity multi-client data sets acquired from industry sources. No electromagnetic data were available for the Municipality or Central Huron area.

In this study, available magnetic data were used to assess the lithological variations within the Precambrian basement, since the overlying sediments are magnetically transparent. The magnetics identified two broad lithological domains indicating variability in rock type or metamorphic grade. Magnetics and gravity data also identified ductile features in the Precambrian basement that are interpreted as being associated with the internal fabric of the crystalline basement and likely include tectonic foliation or gneissosity. The Bouguer gravity data were assessed in order to focus on identifying features within the overlying Paleozoic sedimentary sequence such as lateral variations in rock density associated with lateral changes in depositional environments, such as pinnacle reefs and salt units. This assessment suggests that there is some correspondence of the Bouguer gravity data with pinnacle reefs, but no discernable correspondence of gravity data with salt unit occurrence in the Central Huron area. Radiometric results show a strong correlation with the distribution of the mapped Quaternary deposits, as well as impacts from varying amounts of vegetation cover, soil moisture, and surface water. Radon risks throughout the Central Huron area are considered to be low.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

In July 2014, the Municipality of Central Huron 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 Municipality for safely hosting a deep geological repository (Step 3). The overall preliminary assessments are multidisciplinary studies 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, 2015).

This report summarizes the processing and interpretation of airborne magnetic and ground gravity geophysical data as part of the Geoscientific Desktop Preliminary Assessment for the Central Huron area (Geofirma Engineering Ltd., 2015a). The objective of the Geoscientific Desktop Preliminary Assessment is to determine whether the Municipality of Central Huron contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors. The assessment focused on the Municipality and its immediate periphery, referred to as the Central Huron area (Figure 1).

1.1 Objective

The geophysical data provide supporting information useful for assessing the Central Huron area to assist in the identification of potentially suitable general areas. The purpose of this study was to perform a review of available geophysical data for the Central Huron area, followed by a detailed interpretation of all available geophysical data (e.g., magnetic, gravity and radiometric) to identify additional information that could be extracted from the data.

The role of the geophysical interpretation within the Central Huron area is to provide additional information on the geological features associated with the Paleozoic sedimentary units and the underlying crystalline rocks of the Precambrian basement. In particular, the available data are assessed to determine the lithological variations within the Precambrian basement, and to identify broad lithological domains. Interpretations derived from the magnetic data are then compared to results from available literature on basement lithology of the Grenville Province in southern Ontario, as well as on the Precambrian basement rocks exposed further to the northeast of the Central Huron area. Available gravity data in the Central Huron area are utilized to identify features within the Precambrian basement, as well as potential features such as pinnacle reef structures and the presence of thick salt occurrence within the overlying Paleozoic sedimentary sequence. Where possible, the gravity data are compared to known features located in the Paleozoic formations, such as pinnacle reefs and variations in the thickness of salt units, both of which are known to occur within the Central Huron area.

1.2 Assessment Area

The preliminary assessment focused on the area within the boundaries of the Municipality of Central Huron. Areas beyond the municipal boundaries were not considered. For the purpose of the assessment, geoscientific information was collected and interpreted for the Municipality and surrounding areas, referred to in this report as the Central Huron area (Figure 1).

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 Preliminary Assessment of Potential Suitability for the Municipality of Central Huron consisted of qualified experts from Paterson, Grant & Watson Limited (PGW). The personnel assigned to this study were as follows:

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

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. Dr. Misener acted as the Project Manager and chief Interpretation Geophysicist and co-ordinated the preparation of the Geophysical Report.

Stephen Reford, B.A.Sc., P.Eng. – alternate project manager

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. Mr. Reford acted as assistant Project Manager.

Edna Mueller-Markham, M.Sc., P.Geo. – 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, digital terrain data 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 Ontario Geological Survey (OGS) magnetic, gravity and electromagnetic surveys, and has reprocessed numerous industry surveys published by OGS. Ms. Mueller-Markham acted as a chief data processor and prepared all geophysical maps.

Winnie Pun, M.Sc. – data processing

Ms. Pun has completed 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. Ms. Pun assisted Ms. Mueller-Markham in data processing and presentation.

Nikolay Paskalev, M.Sc. – GIS preparation

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

2 SUMMARY OF PHYSICAL GEOGRAPHY AND GEOLOGY

2.1 Physical Geography

A detailed discussion of the physical geography of the Central Huron area including physiography, topography, surface water/wetlands and built-up areas is provided in a separate Terrain and Remote Sensing Study Report (JDMA, 2015) and the following is a summary of that information.

The Central Huron area is found within a set of landforms and landform complexes that resulted from the advance and retreat of the glaciers during the Late Wisconsinan glaciation. These landforms provide a map of the glacial and postglacial events that were largely responsible for producing the detailed topography of the area. The physiography of the Central Huron area is classified into a set of six physiographic units based on the presence of distinct landforms such as valleys, drumlin fields, escarpments and till plains (JDMA, 2015). Five of these physiographic units extend into the Municipality. The dominant physiographic units within the Municipality in terms of extent are the Horseshoe moraines (64.1% of Municipality), the Stratford till plain (20.6% of Municipality) and the Huron slope (14.1% of Municipality). The Huron fringe and Teeswater drumlin field are very minor physiographic units in the Municipality representing 1.2% and 0.01% respectively of the Municipality. These physiographic units are in part reflected in the surficial geology of the area (Section 2.3).

The large-scale topography in the Central Huron area is controlled by bedrock topography, whereas the detailed topography is almost entirely controlled by surficial landforms. The elevation gradient in the Central Huron area from east to west (Lake Huron) is from 366 to 176 m, with this elevation drop occurring over an approximate 35 km lateral distance. The elevation minimum is defined by the surface of Lake Huron, with a chart datum of 176 m. The highest points in the Central Huron area with elevations of 366 m, are located along the Mitchell Moraine at the east edge of the Central Huron area. Steep slopes are rare in the Central Huron area and associated with drumlins, river valleys, spillway margins, kames and till ridges, and raised shore bluffs.

Apart from Lake Huron, the Central Huron area contains no large lakes. The largest lake in the area with an extent of 1.3 km^2 is associated with the Hullett Marsh Complex, located in the southeast part of the Municipality (Figure 1). Water bodies and wetlands cover 0.8% and 5.6% of the land within the Central Huron area, respectively.

Built-up areas are found in the villages and towns of the Municipality. The largest of these built-up areas are associated with settlements of Clinton, Holmesville, Londesborough and Kinburn (Figure 1).

2.2 Bedrock Geology

The bedrock geology of southern Ontario and the Central Huron area is described in detail in Geofirma Engineering Ltd. (2015a) and the following is a summary of that information.

2.2.1 Geological Setting

The bedrock geology of southern Ontario consists of a thick Paleozoic sequence of sedimentary rocks ranging in age from Cambrian to Mississippian deposited between approximately 540 and 323 million years ago (Johnson et al., 1992). This sedimentary sequence rests unconformably on the Precambrian crystalline basement rocks of the Grenville Province, which is the southeastern-most subdivision of the Canadian Shield. The Grenville Province comprises 2,690 to 990 million year old metamorphic rocks deformed during orogenic events 1,210 million to 970 million years ago (Percival and Easton, 2007;

White et al., 2000). The Grenville Province is considered to have been relatively tectonically stable for the past 970 million years (Williams et al., 1992).

Southern Ontario is underlain by two paleo-depositional centres referred to as the Michigan Basin and the Appalachian Basin. The Appalachian Basin is an elongate foreland basin that parallels the Appalachian orogen and comprises primarily siliciclastic sediments. The Michigan Basin is a broadly circular carbonate-dominated, evaporite-bearing intracratonic basin. These basins are separated by the northeast-trending Algonquin and Findlay arches. These arches, along with the east-southeast-trending Chatham Sag structural depression, define a regional basement high beneath southern Ontario that extends further southwestward into the northeastern United States.

The Paleozoic succession underlying the Central Huron area was deposited within the Michigan Basin. The Paleozoic rocks have a maximum thickness of about 4,800 m at the centre of the Michigan basin; at the northeast corner of the Central Huron area the thickness is about 900 m (OGSRL, 2014). The Paleozoic strata dip gently (3.5 to 12 m/km) to the west or southwest throughout the Ontario portion of the Michigan Basin (Armstrong and Carter, 2010).

Figure 2 shows the bedrock geological map for southern Ontario, and Figure 3 shows a vertically exaggerated representative regional cross-section constructed approximately east-west about 60 km north of the Central Huron area. The location of the cross-section is shown on Figure 2. The geological cross-section (Figure 3) shows the west-southwesterly dip of the Paleozoic sedimentary formations from the Niagara Escarpment in the east to below Lake Huron in the west. The large vertical exaggeration of 50 times used in Figure 3 results in apparent moderate formation dips when, in reality, the sedimentary formations along the cross section and within the Central Huron area are flat lying with dips of 1º or less. These moderate west-southwesterly dips result in outcrop or subcrop exposure of increasingly older sedimentary formations from west to east across southern Ontario, as shown on Figure 2.

2.2.2 Geological and Tectonic History

The structural and tectonic history of southern Ontario includes both Precambrian and Phanerozoic events. These events are described below and summarized in Table 1.

As mentioned above, the Paleozoic sedimentary sequence of southern Ontario lies unconformably on the Precambrian crystalline basement of the Grenville Province of the Canadian Shield. The Grenville Province is a complex orogenic belt that truncates several older geologic provinces. Basement rocks in southern Ontario have been affected by approximately 1,210 to 970 million year old orogenic events, referred to generally as the Grenville Orogeny. The Grenville Orogeny is generally interpreted to have involved northwest-directed thrusting and imbrication of the entire crust, presumably as a result of collision with another continental landmass originally located somewhere to the southeast. Older tectonic events including the approximately 2,700 million year old Kenoran Orogeny and the approximately 2,000-1,700 million year old Trans-Hudson/Penokean Orogeny, built the proto-North American craton upon which Grenville deformation was imprinted (Easton, 1992). Post-Grenville extension associated with rifting prior to the initial opening of the Iapetus Ocean began approximately 970 million years ago (Thomas, 2006).

The deposition of the sedimentary rocks within the Michigan and Appalachian basins was largely dependent on two tectonic influences (Johnston et al., 1992). These were the orogenic activity at the eastern margin of North America, which provided clastic input to both the Appalachian and Michigan basins, and the resultant tectonic forces that controlled the positioning of the basins and arches separating the basins. The Algonquin Arch acted as a major structural control on depositional patterns, rising and falling with respect to the Michigan and Appalachian basins in response to epirogenic movements and horizontal tectonic forces during the course of several distinct Paleozoic orogenic episodes (Howell and van der Pluijm, 1999).

Table 1. Timetable of major tectonic events in Southern Ontario

Million Years Before Present	***Tectonic Activity***	***Reference***
1,210 – 1,180	Regional metamorphism in Central Metasedimentary Belt Boundary Zone (proto-Grenville)	Easton (1992), Lumbers et al. (1990), Hanmer and McEachern (1992)
1,109 – 1,087	Magmatism and formation of Midcontinent Rift	Van Schmus (1992)
1,030 – 970	Main phase of Grenville Orogeny	Carr et al. (2000), White et al. (2000)
970 – 530	Rifting and opening of the Iapetus Ocean	Thomas (2006)
530 – 320	Subsidence of Michigan Basin and Uplift of Frontenac and Algonquin Arches (episodic)	Howell and van der Pluijm (1999), Sanford et al. (1985), Kesler and Carrigan (2002)
470 – 440	Taconic Orogeny • E-W to NW-SE compression, uplift in foreland (Frontenac and Algonquin Arches)	Quinlan and Beaumont (1984), Sloss (1982), McWilliams et al. (2007)
410 – 320	Caledonian/Acadian Orogeny • E-W to NW-SE compression, uplift (Frontenac and Algonquin Arches)	Gross et al. (1992), Marshak and Tabor (1989), Sutter et al. (1985), Kesler and Carrigan (2002)
300 – 250	Alleghenian Orogeny • E-W to NW-SE compression	Gross et al. (1992), Engelder and Geiser (1980)
200 – 50	• Opening of the Atlantic Ocean • St. Lawrence rift system created • Reactivation of Ottawa-Bonnechère Graben • NE-SW extension • Uplift	Kumarapeli (1976, 1985)
Pre-50 – Present	• NE-SW compression (from ridge push) • Post-glacial uplift	Barnett (1992)

Coincident with sediment deposition, the bedrock of southern Ontario was subject to a complex history of Paleozoic tectonism that included the Taconic (Ordovician), Caledonian/Acadian (Devonian) and Alleghenian (Carboniferous) orogenies (Howell and van der Pluijm, 1999). Subsequent events include the Mesozoic initiation of far field stresses associated with the opening of the Atlantic Ocean (Jurassic), compression from global-scale plate reorganization and ridge push (late Cretaceous-Eocene), and finally post-glacial uplift (Quaternary).

2.2.3 Precambrian Geology

The geology of the Precambrian crystalline basement of the Grenville Province in southern Ontario has been well characterized by surface mapping north of the Paleozoic/Precambrian basement boundary, regional geophysical data (aeromagnetics and gravity), regional seismic reflection surveys and geochemical, geochronological and petrographic analyses of rock samples recovered from boreholes (O'Hara and Hinze, 1980; Green et al., 1988; Carr et al., 2000; Carter and Easton, 1990; Easton and Carter, 1995; Carter et al., 1996).

The Precambrian basement in southern Ontario has been grouped into two lithologic belts – the Central Gneiss Belt, located between the Grenville Front Tectonic Zone and the Central Metasedimentary Belt Boundary Zone, and the Central Metasedimentary Belt located southeast of the Central Metasedimentary Belt Boundary Zone. The Grenville Front Tectonic Zone and the Central Metasedimentary Belt Boundary Zone are major subparallel shear zones several kilometres or more in width that are generally assumed to be related to the approximately 1 billion year old Grenville Orogeny (Easton, 1992). These shear zones are characterized by strongly deformed rocks with northeast-trending, moderately to shallowly southeast-dipping tectonic layering and southeast plunging mineral lineations (Easton and Carter, 1995). Similar subparallel zones of intense deformation on a smaller scale form boundaries between lithotectonic terranes within both the Central Gneiss Belt and Central Metasedimentary Belt (Easton and Carter, 1995).

Major tectonic zones in southern Ontario are defined by extrapolation of the exposed basement structural boundaries beneath the Paleozoic cover. This process is aided by field mapping, borehole stratigraphic correlation, interpretation of seismic, aeromagnetic and gravity surveys (e.g., Boyce and Morris, 2002; Wallach et al., 1998), and by geochemical, geochronological and petrographic analyses of samples recovered from drill cuttings and core (Carter and Easton, 1990; Carter et al., 1996).

Based on aeromagnetic data and borehole samples, the Precambrian basement below the sedimentary rock cover has been subdivided into several lithotectonic domains and boundary zones similar in scale and form to those found where the Precambrian bedrock of the Grenville Province is exposed (Carter and Easton, 1990). Much of southern Ontario, including the Central Huron area, is underlain by Precambrian crystalline basement of the Central Gneiss Belt and consists mainly of quartzofeldspathic gneissic rocks that have generally been metamorphosed to upper amphibolite facies, and locally to granulite facies. Most of these gneisses are believed to be plutonic in origin, with subordinate amounts of metasedimentary gneiss.

The Huron Domain is a lithotectonic domain within the Central Gneiss Belt, and underlies the Central Huron area. The Huron Domain acted as a single crustal block during the Paleozoic. It is defined by Carter and Easton (1990), Easton and Carter (1995) and Carter et al. (1996) based on lithologic data from boreholes and published aeromagnetic maps. Geofirma Engineering Ltd. (2015a) provides additional information and mapping outlining the Huron Domain and tectonic boundary zones.

2.2.4 Paleozoic Stratigraphy

Table 2 illustrates the Paleozoic bedrock stratigraphy for the Central Huron area as presented by Geofirma Engineering Ltd. (2015a). The Paleozoic stratigraphic nomenclature has evolved over time and a recent compilation by Armstrong and Carter (2010) provides the current standard for usage. Two key stratigraphic designations have recently been revised. Firstly, strata traditionally referred to as Middle Ordovician, i.e., Black River and Trenton groups (from Armstrong and Carter, 2006), are now

Table 2 Stratigraphy of the Central Huron area (after Armstrong and Carter, 2010)

Standard Reference		Central Huron Area		
Devonian	Middle		Dundee Fm	
Devonian	Middle	Detroit R. Gp	Lucas Fm	
Devonian	Middle	Detroit R. Gp	Amherstburg Fm	
Devonian	Lower		Bois Blanc Fm	
Silurian[b]	Upper		Bass Islands Fm	
Silurian[b]	Upper	Salina Gp		G Unit F Unit E Unit D Unit C Unit B Unit A2 Unit A1 Unit A0 Unit[c]
Silurian[b]	Upper		Guelph Fm	
Silurian[b]	Lower		Amabel-Lockport Fm.	*Goat Island Mem* *Gasport Mem* *Lions Head Mem*
Silurian[b]	Lower	Clinton Gp	Fossil Hill Fm	
Silurian[b]	Lower	Cataract Gp	Cabot Head Fm	
Silurian[b]	Lower	Cataract Gp	Manitoulin Fm	
Ordovician[a]	Upper		Queenston Fm	
Ordovician[a]	Upper		Georgian Bay Fm	
Ordovician[a]	Upper		Blue Mountain Fm	
Ordovician[a]	Upper	Trenton Gp	*Collingwood Mem*	
Ordovician[a]	Upper	Trenton Gp	Cobourg Fm[1]	
Ordovician[a]	Upper	Trenton Gp	Sherman Fall Fm[2]	
Ordovician[a]	Upper	Trenton Gp	Kirkfield Fm[3]	
Ordovician[a]	Upper	Black River Gp	Coboconk Fm[3]	
Ordovician[a]	Upper	Black River Gp	Gull River Fm	
Ordovician[a]	Upper	Black River Gp	Shadow Lake Fm	
Cambrian		Cambrian		
Precambrian		Precambrian		

Notes:
Gp - Group
Fm - Formation
Mem - Member
a - Strata traditionally referred to as Middle Ordovician (i.e,, Black River and Trenton groups; Armstrong and Carter, 2006) are now considered part of the Upper Ordovician.
b - The formal term Middle Silurian (e.g., Armstrong and Carter, 2006) has been abandoned so all strata have been re-assigned to either the Lower or Upper Silurian.
c - A-0 Unit (Salina Formation) is recognized based on site characterization activities at the Bruce nuclear site (Intera, 2011)
The Rochester Fm and Reynales Fm are Southwestern Ontario - Lake Erie equivalents of the Lion's Head Mem (Amabel Gp) and Fossil Hill Fm

Surface Nomenclature Equivalent (approx.):
1 - Lindsay Fm; 2 - Verulam Fm; 3 - Bobcaygeon Fm

~~~ Unconformity ~~~
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considered part of the Upper Ordovician. Secondly, the formal term Middle Silurian (from Armstrong and Carter, 2006) has been abandoned so all strata have been re-assigned to either the Lower or Upper Silurian.

In addition, the stratigraphic nomenclature in Table 2 and Figure 3 adopts the subsurface nomenclature of Armstrong and Carter (2010), while geological mapping as shown in Figures 2 and 4 uses an outcrop nomenclature. This distinction primarily applies to the Trenton and Black River groups, where the Bobcaygeon Formation (outcrop) is equivalent to the Coboconk and Kirkfield formations (subsurface), and the Verulam and Lindsay formations (outcrop) are approximately equivalent to the Sherman Fall and Cobourg formations (subsurface), respectively.

The Paleozoic stratigraphy in the Central Huron area includes shale, carbonate and evaporite units formed predominantly from marine sediments that were deposited when this portion of eastern North America was located at tropical latitudes and intermittently covered by shallow seas (Johnson et al., 1992; Armstrong and Carter, 2010).

2.2.4.1 Cambrian

The Cambrian bedrock geology in southern Ontario is dominated by white to grey quartzose sandstone with regional lithological variations that include fine to medium crystalline dolostone, sandy dolostone, and argillaceous dolostone to fine to coarse quartzose sandstone (Hamblin, 1999). Cambrian sedimentary rocks unconformably overlie the Precambrian basement. These sedimentary rocks are generally characterized as a succession of clastic and carbonate rocks resulting from transgressive Cambrian seas that flooded across the broad platform of the Algonquin Arch and into the subsiding Michigan and Appalachian basins (Hamblin, 1999). The Cambrian units are largely absent over the Algonquin Arch as the result of a pre-Ordovician regional-scale unconformity (Bailey Geological Services Ltd. and Cochrane, 1984a). The Cambrian unit is interpreted to pinch out eastwards about 5 to 10 km east of Lake Huron (Bailey Geological Services Ltd. and Cochrane, 1984a), and thus is expected to be absent beneath the eastern and central parts of the Central Huron area. There are no surface exposures of the Cambrian unit in southern Ontario

2.2.4.2 Upper Ordovician

Unconformably overlying the Cambrian unit is a thick sequence of Upper Ordovician sedimentary units with a distinctly bimodal composition consisting of a carbonate-rich lower unit and a shale-rich upper unit. The lower unit was deposited during a major marine transgression (Coniglio et al., 1990) prior to the westward inundation of the carbonate platform by the upper shale-dominated sediments (Hamblin, 1999). The Upper Ordovician carbonates subcrop in the northeastern part of southern Ontario around Lake Ontario and Lake Simcoe, and the Upper Ordovician shales subcrop east of the Niagara Escarpment between Owen Sound and Niagara Falls (Figure 2).

The lower carbonate unit of the Upper Ordovician succession is a thick sequence of predominantly limestone formations (carbonate and argillaceous carbonate sedimentary rocks), which include, from bottom to top: the Shadow Lake, Gull River and Coboconk formations of the Black River Group; and the Kirkfield, Sherman Fall, and Cobourg (including the Collingwood Member) formations of the Trenton Group (Table 2). These rocks range in character from coarse-grained bioclastic carbonates to carbonate mudstone with interbedded calcareous and non-calcareous shales. The Shadow Lake Formation, at the base of the Black River Group, is characterized by poorly sorted, red and green sandy shales, argillaceous and arkosic sandstones, minor sandy argillaceous dolostones and rare basal arkosic conglomerate. The lower part of the overlying Gull River Formation consists mainly of light grey to dark brown limestones and the upper part of the formation is very fine grained with thin shale beds and partings. The Coboconk Formation, at the top of the Black River Group, is composed of light grey-tan to brown-grey, medium to very thick bedded, fine to medium grained bioclastic limestones (Armstrong and Carter, 2010).

The Kirkfield Formation, at the base of the Trenton Group, is characterized by fossiliferous limestones with shaley partings and locally significant thin shale interbeds. The overlying Sherman Fall Formation ranges in lithology from dark grey argillaceous limestones interbedded with calcareous shales, found lower in the formation, to grey to tan bioclastic, fossiliferous limestones that characterize the upper portions of the formation. The overlying Cobourg Formation is described regionally as a grey, fine-grained limestone to argillaceous limestone with coarse-grained fossiliferous beds and a nodular texture. The Cobourg Formation is also subdivided to include an upper Collingwood Member that consists of dark grey to black, calcareous shales with increased organic content and distinctive fossiliferous limestone interbeds (Hamblin, 2003; Armstrong and Carter, 2010).

The upper unit of the Upper Ordovician succession is characterized by a thick sequence of predominantly shale sedimentary rocks, which comprise from base to top: the Blue Mountain, Georgian Bay and Queenston formations. The Blue Mountain Formation is characterized by uniform soft and laminated grey non-calcareous shale with minor siltstone and minor impure carbonate (Johnson et al., 1992; Hamblin, 1999). In the lower part of the Blue Mountain Formation there is downward gradation from grey to greenish-grey shales to a very dark grey to black shale (Armstrong and Carter, 2010). This lower part of the Blue Mountain Formation was historically named the Rouge River Member (Russell and Telford, 1983). The overlying Georgian Bay Formation is composed of blue-grey shale with intermittent centimetre-scale siltstone and limestone interbeds. The Queenston Formation is characterized by maroon, with lesser green, shale and siltstone with varying amounts of carbonate. The top of the Queenston Formation is marked by a regional erosional unconformity (Table 2; Armstrong and Carter, 2010).

2.2.4.3 Lower Silurian

The Lower Silurian units, including the Cataract and Clinton groups and the Amabel-Lockport and Guelph formations, unconformably overlie the Upper Ordovician shales (Table 2). A major marine transgression at the top of the Clinton Group marks the transition to deposition of the extensive carbonate-dominated Amabel and Guelph formations. These Lower Silurian units form the cap-rock of the Niagara Escarpment in outcrop. The Lower to Upper Silurian boundary occurs within the Guelph Formation (Table 2; Brunton and Dodge, 2008).

The Cataract Group unconformably overlies the Upper Ordovician Queenston Formation and includes a lower unit of grey argillaceous dolostone and minor grey-green shale, and an upper clastic unit which consists of grey to green to maroon noncalcareous shales with minor sandstone and carbonate interbeds. The Clinton Group is composed of thin- to medium-bedded, very fine- to coarse-grained fossiliferous dolostone.

The Amabel-Lockport Formation includes a lower unit of light grey to grey-brown, finely crystalline, thin- to medium-bedded, sparingly fossiliferous dolostone with minor chert nodules. It also includes an upper unit of blue-grey, fine- to coarse-grained, thick bedded to massive dolostone, which locally contains minor dolomitic limestone.

The Guelph Formation lithology varies from reefal to inter-reefal dolostones and dolo-mudstones (Armstrong and Goodman, 1990). Reefal facies represent pinnacle, patch and barrier reefs and their distribution defines the key aspects of the paleogeography during deposition. The widespread inter-reefal dolostones are typically sucrosic, dark brown to black dolo-mudstones with pebble-size fragments lithologically similar to the underlying Goat Island unit (Armstrong and Carter, 2006). Within the Central Huron area, the Guelph Formation is characterized by facies deposited between the basinward pinnacle reef belt found along the eastern shore of Lake Huron, the patch reefs found in the eastern parts of the Central Huron area, and the basin margin reef complex typically located east of the Central Huron area (Johnson et al., 1992).

2.2.4.4 Upper Silurian

The Upper Silurian units include the evaporite and evaporite-related sedimentary rocks of the Salina Group, and overlying dolostones and minor evaporites of the Bass Islands Formation (Table 2). The Upper Silurian units subcrop in a northwest trending belt that extends from south of Niagara Falls to west of Owen Sound (Figure 2). The Salina Group is characterized by repeated, cyclical deposition of carbonate, evaporite and argillaceous sedimentary rocks, comprising Units A through G. Parts of the Silurian salt beds (i.e., A-2, B, D, E and F Unit salts) are present in the Central Huron area, thinning and pinching out eastward from Lake Huron (Sanford, 1993; 1977). Underground excavation mining of salt at the Goderich Mine is from the Salina A2 Unit salt at a depth of about 550 m (Hewitt, 1962). In areas where salt has been removed by dissolution, collapse structures are present within the overlying uppermost Silurian and Devonian strata.

A change to less-restricted depositional conditions was responsible for deposition of the Bass Islands Formation, which is a microcrystalline, commonly bituminous, dolostone containing evaporite mineral clasts. The contact with the overlying Devonian carbonates marks a major unconformity characterized by subaerial exposure (Uyeno et al., 1982).

2.2.4.5 Lower and Middle Devonian

The Lower and Middle Devonian units unconformably overlie the Upper Silurian Bass Islands Formation and are dominated by carbonate sedimentary rocks of the Bois Blanc Formation, the Detroit River Group consisting of the Amherstburg and Lucas formations, and the Dundee Formation (Table 2). The Bois Blanc Formation consists of cherty, fossiliferous limestones and argillaceous dolostones that unconformably overlie Silurian strata. The Amherstburg Formation is a bituminous bioclastic fossiliferous limestone and dolostone. The Lucas Formation is a fine-crystalline, fossiliferous dolostone and limestone and subcrops in the northeast and north-central parts of the Central Huron area, mostly outside of the Municipality. The Dundee Formation, which is the dominant subcropping bedrock formation within the Municipality of Central Huron (Figure 4), comprises sparsely fossiliferous limestones and minor dolostones that unconformably overly the Detroit River Group.

2.2.5 Faulting of the Paleozoic Strata

Figure 2 shows basement-seated faults that displace the Paleozoic strata in southern Ontario. These faults were compiled from several sources by the Ontario Geological Survey (Armstrong and Carter, 2010) and given relative ages based on the youngest geological unit that is offset: i) Shadow Lake/Precambrian, ii) Trenton Group and iii) Rochester Formation (Silurian-aged). These faults are interpreted based on vertical displacements of key unit-top surfaces in the Paleozoic strata, based on earlier compilation and assessment work completed by Brigham (1971) and Bailey Geological Services

Ltd. and Cochrane (1984a; 1984b). Vertical displacement of unit top surfaces was identified based primarily on hand contouring and interpretation of formation top data in the Petroleum Wells Subsurface Database (OGSRL, 2014). Where these data are numerous, such as in the southwestern corner of southern Ontario, the faults are identified with a high degree of confidence, and are often named (e.g., Dawn Fault and Electric Fault). In areas where oil and gas exploration wells are widely spaced, faults are identified with a low degree of confidence. As shown in Figure 4, there are no OGS mapped faults within the Central Huron area.

2.3 Quaternary Geology

Information on Quaternary geology in the Central Huron area is described in detail in the Terrain and Remote Sensing Study Report (JDMA, 2015) and a summary of that information is provided here.

Quaternary glaciations have played a major role in shaping and creating the landscape of southern Ontario (Barnett, 1992). Glacial landforms and associated sediments within the Central Huron area were formed and deposited by the Huron and Georgian Bay lobes of the Laurentide Ice Sheet during the Late Wisconsinan 23,000 to 10,000 years ago. Exposures of older deposits are rare as they are mostly buried beneath the Late Wisconsinan sediments and can only be seen in such places as riverbank exposures, lake bluffs or man-made exposures in quarries and pits (Barnett, 1992). The surficial deposits of the Central Huron area have been mapped at the scale of 1:50,000 by Cooper and Fitzgerald (1977), Cooper et al., (1977) and Cowan et al. (1986).

Overburden thickness in the Central Huron area ranges from zero up to about 91 m with an average thickness of 28 m (Gao et al., 2006). Within the Municipality the overburden thickness ranges from zero to 80 m with an average of 31 m. The thickest overburden in the area is associated with areas of high relief and elevation, and with till moraines and kame moraines, particularly the Wyoming Moraine and the northeast extension of the Wawanosh Moraine (Figure 5). The thinnest drift occurs along the Maitland and South Maitland rivers, where bedrock is exposed locally in the channels. Overburden thickness generally increases from east to west across the Municipality.

Figure 5 shows the surficial Quaternary geology of the Central Huron area. Table 3 provides a summary in percentages of the areal extent of the different surficial deposits mapped within the Central Huron area and within the Municipality.

Table 3. Extent of of surficial deposits based on primary genesis of deposit

Area	*Primary genesis (expressed as % area)*						
	Fluvial	*Glacial Morainal*	*Glacio-fluvial*	*Glacio-lacustrine*	*Lacustrine*	*Organic*	*Bedrock*
Municipality of Central Huron	2.0	45.8	34.2	17.8	0.0	0.1	0.1
Central Huron area	2.4	53.4	26.3	17.0	0.1	0.7	0.1

Glacial morainal deposits occur extensively throughout the Central Huron area, covering 53.4% of the area and consisting of, in decreasing order of abundance, the Rannoch Till, the St. Joseph Till and the Elma Till. Glaciofluvial deposits consisting primarily of sand or sand and gravel are exposed over 26.3% of the Central Huron area. These glaciofluvial deposits are associated with kames, eskers and outwash plains. Glaciolacustrine deposits are exposed over 17.0% of the Central Huron area, with about 79% of these deposits mapped as fine-grained sediments consisting of silts and clays and the remaining 21% as sand or sand and gravel. Other surficial deposits including fluvial, lacustrine, organic and bedrock are all relatively minor occurrences in the Central Huron area.

The eastern part of the Municipality is characterized by thin drift, low relief, high elevation and low permeability surficial deposits principally comprised of Rannoch Till of the Stratford till plain. The central part of the Municipality is dominated by a very hummocky and irregular area of topography underlain largely by glaciofluvial deposits associated with the Wawanosh Moraine. Ice-contact deposits of sand and gravel are abundant in this area. The ice-contact deposits in the Wawanosh Moraine overlie Elma Till and locally underlie Rannoch Till. The Wyoming Moraine represents a north-south trending band of hummocky topography about 5 to 6 km wide located in the western part of the Municipality. A network of meltwater channels extends between the Wawanosh and Wyoming moraines and in the valleys of the Maitland and Bayfield rivers (Figure 5). The westernmost part of the Municipality along Lake Huron is characterized by a bevelled till plain with shallow deposits of permeable sand overlying several metres of silt and clay.

2.4 Land Use

Land use within the Central Huron area consists mostly of agricultural lands, wetlands, forested areas, and developed/built-up areas with residential, commercial and industrial land uses. Wetlands and forested areas represent 5.6 % and 15.6 % respectively of the Central Huron area.

3 GEOPHYSICAL DATA SOURCES AND QUALITY

Geophysical data were obtained from available public-domain sources, including the Geological Survey of Canada (GSC), and two proprietary sources. To provide a regional context to the assessment, geophysical data were collected for the Municipality of Central Huron and its surrounding region. The interpretation of the data focused on the Central Huron area only.

The types of geophysical data obtained included aeromagnetic, gravity, and radiometric. The flight path of the aeromagnetic surveys is shown in Figure 6. The gravity station locations are shown in Figure 7.

The quality of the available data was assessed to determine which data sets were suitable for inclusion in this study. The geophysical surveys covering the Central Huron area show variability in data set resolution, which is a function of the flight line or station spacing, the sensor height (airborne surveys), 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 interpretation. The integrity of the higher quality data was maintained throughout.

3.1 Data Sources

The geophysical data obtained from the Geological Survey of Canada (GSC) provide coverage of magnetic and gravity data for the entire Central Huron area. Higher resolution aeromagnetic data from a proprietary survey was obtained and incorporated into this assessment for the Strathroy area, covering the western half of the Central Huron area (Figure 6). In addition to the regional GSC gravity data, higher resolution ground gravity data was obtained covering 100 percent of the Central Huron area (Figure 7). Radiometric data from the GSC covers only the land portion of the Central Huron area. Ontario Geological Survey (OGS) geophysical data does not exist within the Central Huron area. The characteristics of each of the geophysical data sets are summarized in Table 4, and discussed in detail below.

3.1.1 Magnetic Data

Magnetic data over the Central Huron area were collected as part of various surveys illustrated in Figure 6 and by using different survey parameters outlined in Table 4. Magnetic data shows the distribution of magnetic and nonmagnetic geological bodies within the subsurface, particularly useful for delineating spatial geometry of bodies of rock, and the presence of structural features.

The resolution of the retrieved magnetic data sets varies greatly within the Central Huron area. Surveys were flown over a period of 23 years, during which the quality and precision of the equipment as well as the quality of the processing improved. Low-resolution magnetic data from the GSC provides coverage for the entire Central Huron area, comprising two individual survey data sources (Table 4; GSC, 2014). The Waterloo survey covers the largest portion of the onshore assessment area, flown at a terrain clearance of 305 m and flight line spacing of 926 m. The Lake Huron survey provides the lowest spatial resolution in the assessment area, and covers the water body portion, and in parts on lap onto the onshore portion of the assessment area. The Lake Huron survey was flown at a terrain clearance of 303 m and flight line spacing of 1,900 m.

Table 4. Summary of the characteristics for the geophysical data sources in the Central Huron area

Product	***Source***	***Type***	***Line Spacing/ Sensor Height***	***Line Direction***	***Location***	***Date***	***Additional Comments***
Waterloo	GSC	Fixed wing magnetic	926m/305m	90°	Eastern portion of Central Huron area	1986	Large overlap with newer survey to the south.
Lake Huron	GSC	Fixed wing magnetic	1,900 m/303 m	90°	Western half of Central Huron area	1986	Low resolution survey over Lake Huron
Strathroy	Randsburg International Gold Corp., Spector (1999)	Fixed wing magnetic	700 m x 700 m grid/450m above sea level	0° x 90°	Western half of Central Huron area	1999	Higher resolution than GSC surveys. Terrain clearance varies from 130m to 275m.
GSC Gravity Coverage	GSC	Ground gravity measurements	6 km (onshore), 1.6 km x 18 km (offshore)/ surface		Entire Central Huron area	1945-2007	Station spacing variable.
PGW Gravity Coverage	PGW	Ground gravity measurements	0.4 km x 2 km/ surface		Entire land portion of Central Huron area	1950s	Much higher resolution than GSC coverage. Station spacing variable.
Southern Ontario Radon Survey – Block 2	GSC	Fixed wing radiometric	1,000 m/150 m	90°	Entire Central Huron area	2009	Low resolution survey, east-west flight lines

GSC – Geological Survey of Canada (2014)
PGW – Paterson, Grant & Watson Limited

In addition to the low-resolution magnetic data collected by the GSC, the Strathroy survey covering the western half of the Central Huron area was acquired through a data license agreement with Randsburg International Gold Corporation. This survey is medium-resolution and was flown on a 700 m x 700 m grid pattern at a survey elevation of 450 m above sea level (Spector, 1999). Because the survey was flown at a constant elevation, the terrain clearance varied from approximately 130 m to 275 m above ground surface.

3.1.2 Gravity Data

Gravity data within the Central Huron area were acquired from two sources, comprising relatively sparse coverage from the GSC gravity database (GSC, 2014), and a dense network of gravity stations from a proprietary data set compiled from numerous ground surveys conducted in Southwest Ontario for oil and gas exploration. The acquired GSC gravity data consists of an irregular distribution of station measurements providing coverage of the entire Central Huron area (Figure 7). On land, the data consists of 27 station measurements comprising roughly a station every 3 to 6 km.

The proprietary data set includes a dense network of gravity stations (roughly 45 times the density of the GSC coverage) providing 100 % coverage of the on land portion of the Central Huron area (Figure 7). The gravity measurements were acquired mainly along local roads, with an average station separation of approximately 400 m. In addition to providing sufficient coverage to the Central Huron area, the data set extends for several kilometers into the surrounding region.

3.1.3 Radiometric Data

Radiometric data collected by a GSC survey (GSC, 2014) provides complete coverage of the onshore portion of the Central Huron area. The Southern Ontario Radon Survey – Block 2 survey was flown in 2009 with a flight line spacing of 1,000 m, a nominal terrain clearance of 150 m. The line direction for Southern Ontario Radon Survey – Block 2 survey was east-west.

3.1.4 Formation Top and Overburden Data

To support the interpretation of gravity data in the Central Huron area, an updated database of the depth to several key formation tops was used to construct depth contour maps. Geofirma Engineering Ltd. (2015b) provides details on the approach and methodology used to update borehole data from the Oil, Gas and Salt Resources Library (OGSRL, 2014) through the re-interpretation of key formation tops using borehole geophysical data.

In total, 335 boreholes were obtained from the OGSRL database for the Central Huron area and its surrounding region, providing information on depth to formation tops. Gamma ray and neutron logs available from 111 of these boreholes were used to re-interpret the depth to eight key formation tops. Within the Central Huron area there are a total of 48 boreholes, 20 of which also have borehole geophysical data available for the re-interpretation of key formation tops.

The top of bedrock surface was contoured using data from the MNDM’s Miscellaneous Release Data 207 Bedrock Topography and Overburden Thickness Mapping, Southern Ontario (Gao et al., 2006). The source for the ground surface data set used to construct depth contour maps was the topographic model created from Shuttle Radar Topographic Mission (SRTM) data provided by the National Aeronautical and Space Administration (NASA, 2006).

3.2 Data Limitations

The magnetic surveys that cover the Central Huron area, with the exception of the Strathroy proprietary aeromagnetic survey, consist of older regional low resolution coverage. Nevertheless, the magnetic data reflect quite coherent responses that identify subsurface geology. A cursory review of the magnetic data for the area indicates that the sedimentary section within the Central Huron area is magnetically transparent (O´Hara and Hinze, 1980). There is an extensive array of basement responses that shows variable lithologies, and ductile structures. The magnetic data is critical for mapping the basement and linking with the other data sets to determine which structures control and/or penetrate the overlying sedimentary section.

The two data types considered, magnetic and gravity, contribute to the interpretation of bedrock geology. The usefulness of the radiometric data is limited for interpreting the bedrock geology; however, this data set provides sufficient information to assess the coincidence with the distribution of mapped overburden deposits in the Central Huron area. The limitation in applying these data types to the Central Huron 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; and
- Overburden – areal extent, thickness and physical properties

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

The main limitation associated with the borehole data used to construct depth contour maps is the sparse spatial distribution of the boreholes in the Central Huron area and surrounding region. It is common, outside of well clusters associated with hydrocarbon pools, for any two boreholes within Central Huron area to be 5 km apart on average, and no well control exists beneath Lake Huron. Furthermore, very few boreholes extend through the entire sequence of Paleozoic bedrock; therefore vertical control is limited on some of the deeper bedrock formations (Geofirma Engineering Ltd., 2015b).

4 GEOPHYSICAL DATA PROCESSING AND WORKFLOW

All data were processed and gridded using the Geosoft Oasis montaj software package (Geosoft, 2012). Several magnetic data grids were prepared using the Encom PA software package (Pitney Bowes, 2012). Gravity data and formation tops were incorporated into ModelVision Pro 11 (Pitney Bowes, 2011) to support the interpretation of gravity data in the Central Huron area. The grids that resulted from the various processing steps were loaded in ArcMAP 10 (ESRI, 2012).

4.1 Magnetic

All magnetic surveys in the Central Huron area were projected to the UTM17N/NAD83 coordinate system. Total magnetic intensity grid data from the surveys were upward or downward continued (if necessary) to a common flying height of 305 m, and re-gridded to a common grid cell size of 100 m. The GSC surveys were all flown at or close to 305 m mean terrain clearance. The Strathroy survey was flown at a constant barometric altitude of 450 m above sea level. This ranges approximately between 130 and 275 m above the terrain. Using Oasis montaj (Geosoft, 2012) this magnetic grid was upward continued to a mean terrain clearance of 305 m.

Microlevelling was required for all magnetic surveys, with the exception of the Strathroy survey in the Central Huron area in order to remove the apparent flight line noise from the total magnetic intensity grid data. This procedure removes the residual flight line noise that remains after conventional control line levelling, and is increasingly important as the resolution of aeromagnetic surveys has improved and the requirement of interpreting subtle geophysical anomalies has increased. The separation of noise from signal in the profile data is done by determining the wavelength and amplitude of the noise and applying filters to remove it. The wavelength and amplitude used in microlevelling is summarized in Table 5.

Table 5. Parameters used for microlevelling process applied to magnetic survey data

Survey	***Amplitude Limit***	***Naudy Filter Wavelength***
Waterloo	5 nT	2,000 m
Lake Huron	10 nT	5,000 m
Strathroy	No microlevelling required	

The surveys were merged together using Oasis montaj (Geosoft, 2012), where the suture path between the grids was chosen 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 merging of data sets, in particular along the boundary with the Strathroy survey, produced a linear artifact in the data along the data set boundary. The resultant grid was the residual magnetic intensity grid (i.e. total magnetic field after IGRF (International Geomagnetic Reference Field) correction) and the basis for preparing the enhanced magnetic grids.

Several data processing steps were completed on the residual magnetic intensity grid data including:

- Reduction to the Pole (RTP)
- First Vertical Derivative of the Pole Reduced Field (1VD)
- Second Vertical Derivative of the Pole Reduced Field (2VD)
- Tilt Angle of the Pole Reduced Field
- Analytic Signal Amplitude

- Total Horizontal Gradient of the Pole Reduced Field

Each of these processing steps is further discussed below.

Reduction to the Pole (RTP)

The direction (inclination and declination) of the geomagnetic field varies over the Earth and influences the shape of the magnetic responses over geological sources. At the North Magnetic Pole the inducing magnetic field is vertical (i.e. inclination of 90° and declination of 0°), which results in the magnetic response being a symmetric positive magnetic peak over a source, in the absence of dip and magnetic remanence. Transforming the measured magnetic field to a pole reduced magnetic field simplifies the interpretation, particularly to determine the location and geometry of the sources (Baranov, 1957). For the Municipality of Central Huron, the residual magnetic intensity grid was reduced to the pole using a magnetic inclination of 72° N and magnetic declination of 9° W (Figure 8) based upon an IGRF (International Geomagnetic Reference Field) model, dated June 1, 1999. This date is the middle of the year 1999, the year of the Strathroy survey was flown, which is the highest resolution survey in the Central Huron area.

The RTP filter, L, is applied to the residual magnetic field after it is transformed to the Fourier wavenumber domain, and is defined as follows:

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

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

where:

θ = wavenumber
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 9). This is particularly useful for lithologic mapping (e.g. the anomaly texture is revealed), locating contacts and mapping structure (Telford et al., 1990). It is expressed in the space domain as:

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

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 in the Fourier domain to further enhance shallower geologic sources in the data (Figure 10). This is particularly useful for lithologic mapping (e.g. the anomaly texture is revealed), locating contacts and mapping structure close to surface (Telford et al., 1990). It is expressed in the space domain as:

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

where Z is the vertical offset.

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. The Butterworth filter is a type of signal processing filter designed to have as flat a frequency response as possible in the pass band.

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 11). This is particularly useful for mapping texture, structure, and edge contacts of weakly magnetic sources. It is expressed as:

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

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

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

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.

Total Horizontal Gradient of the Pole Reduced Field

The total horizontal gradient is the square root of the sum of the squares of the derivatives in the horizontal (X and Y) directions (i.e. the space domain horizontal derivatives in X and Y), computed from the pole reduced magnetic field

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

The total horizontal gradient is useful in locating the vertical edges (contacts) of magnetic source bodies.

4.2 Gravity

The GSC gravity data were gridded with a 2 km grid cell size and the proprietary gravity data were gridded with a 100 m grid cell size, both using a minimum curvature gridding algorithm. The GSC Bouguer gravity data were re-gridded to a 100 m grid cell size prior to being merged with the proprietary gravity data. The suture path between the grids is located along the adjoining grid boundaries, with the original higher resolution grid cell size so that the most detailed data was retained in the final product. The high-resolution proprietary Bouguer gravity data was not tied to the national gravity network. Thus, when it was merged with the GSC gravity data, a shift was applied to the GSC data by determining the average difference in the Bouguer gravity values in the area of overlap between the GSC and proprietary data. The merging of the two data sets resulted in an artifact along the boundary of the two data sets, which is also coincident with the boundary of Lake Huron.

Both the GSC data and the proprietary data have been reduced using standard gravity methods to compute the Bouguer gravity fields (Telford et al., 1990), using a density of 2.67 g/cm^3 which is the average density of crustal bedrock typically used for the Canadian Shield. Although the data was reduced using this value, the bulk rock density of the Precambrian basement derived from borehole measurements at the Bruce nuclear site near Kincardine was measured as 2.54 g/cm^3 (Intera Engineering Ltd., 2011). Despite this value being slightly lower in density, it may simply reflect a bedrock unit of lesser density or alteration and weathering of the Precambrian bedrock surface.

As the data for the Central Huron area were collected as far back as 1945, the older survey's station elevations were likely determined using barometric altimeters (much less accurate than GPS) and terrain corrections were not applied.

Gravity Model Development

In order to facilitate the interpretation of gravity data in the Central Huron area, the key formation tops and overburden data were used to define key formation packages to be incorporated into a gravity model to determine the expected gravity effect (Figure 16). Elevations of the key formation tops were gridded using Oasis Montaj minimum curvature gridding algorithm with a grid cell size of 500 meters (Geosoft, 2012), with the exception of the Cobourg and Precambrian surfaces. The Cobourg and Precambrian surfaces were computed with a grid cell size of 1,000 m. This larger cell size for these surfaces is based on a fewer number of boreholes which intersects these two surfaces. Surfaces were generated using a minimum curvature gridding tolerance of 0.001 and percent-pass tolerance of 99.99 % with a blanking distance between 20 and 40 km. In some cases the depths of adjacent gridded surfaces overlapped resulting in a negative thickness. In such cases, the overlap area was examined and the surface with valid data was used in both surfaces, resulting in a thickness of zero for that part of the model.

The key formation top grids were used to define the thickness of seven key formation packages over the extent of the Central Huron area. The thickness of each formation package was determined by the difference in elevation between the overlying and underlying gridded surfaces.

To determine the weighted bulk density to be assigned to each formation package, the volume of each formation within the package was calculated and a weighted average of the density for each formation was determined (Table 6). The gravity effect of each model layer has been computed from its thickness, depth and density using ModelVision Pro 11 (Pitney Bowes, 2011). The thickness distribution coupled with the volume weighted bulk density of the key formation packages provide key input to determine the modeled gravity effect, which is used to remove the influence of the formation package responses from the observed Bouguer gravity (e.g., Hammer, 1963). Because of the sparse distribution of well data and the limited information on the key formation packages extending into Lake Huron, the modeled gravity effect was not calculated under Lake Huron (Figure 17). The resulting stripped Bouguer gravity is only determined for the land portion of the Central Huron area.

Table 6. The upper and lower boundary formation tops that define the individual formation packages, and their weighted densities (density values adapted from Intera Engineering Ltd., 2011).

	Upper Bound	*Lower Bound*	*Weighted Density (g/cm^3)*
1	Surface	Top of Bedrock	2.00
2	Top of Bedrock	Bass Island	2.70
3	Bass Island	Salina G Unit	2.76
4	Salina G Unit	Cabot Head	2.66
5	Cabot Head	Queenston	2.62
6	Queenston	Cobourg-Collingwood	2.64
7	Cobourg-Collingwood	Precambrian	2.67
	Precambrian	---	2.54

4.3 Radiometric

The following seven radiometric grids (radioelement concentrations and ratios) were downloaded for the Municipality of Central Huron and are gridded with a 250 m 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 grids were previously merged by the GSC. The determination of the radioelement concentrations, dose rate and ratios followed the methods and standards published by the International Atomic Energy Agency (IAEA, 2010), many of which were developed at the GSC. All grids were re-projected to the Central Huron area local coordinate system, UTM17N/NAD83. The dose rate is a calibrated version of the measured total count, and reflects the total radioactivity from natural and man-made sources (Figure 18).

5 GEOPHYSICAL INTERPRETATION

5.1 Methodology

The geophysical data within the Central Huron area were assessed in order to understand the responses from the various geological features associated with the Paleozoic sedimentary units and the underlying crystalline rocks of the Precambrian basement. The available magnetic data, and to a lesser extent gravity data, were used to assess the lithological variations within the Precambrian basement, and to identify broad lithological domains. This assessment relied most heavily on the pole reduced magnetic field and its first and second vertical derivatives for mapping the domain boundaries and providing discussion on any basement heterogeneity. The first and second vertical derivatives were used to outline similar magnetic anomaly patterns reflecting potential variability in the basement rock ductile features. These ductile features are interpreted as being associated with the internal fabric of the crystalline basement and likely include tectonic foliation or gneissosity. Interpretations derived from the magnetic data were then compared to results from available literature on basement lithology of the Grenville Province in southern Ontario (e.g. O’Hara and Hinze, 1980; Turek and Robinson, 1982; Carter and Easton, 1990; Easton and Carter, 1995; Carr et al, 2000; Boyce and Morris, 2002), as well as on the Precambrian basement rocks exposed to the northeast of the Central Huron area (Easton, 1992).

The use of both the observed and the modeled Bouguer gravity data in the Central Huron area focused on identifying features within the Precambrian basement as well as the overlying Paleozoic sedimentary sequence. The observed gravity data were stripped using the modeled Bouguer gravity to determine the influence of the Paleozoic sedimentary sequence and the overburden deposits on the overall gravity response. Because of the sparse distribution of well data and the limited information on the key formation packages extending into Lake Huron, the modeled gravity effect was not calculated under Lake Huron and the resulting stripped Bouguer gravity is only determined for the land portion of the Central Huron area. Where possible, the observed and stripped gravity data were used to identify coincidence with known features located in the Paleozoic formations, such as pinnacle reefs and variations in the thickness of salt units, both of which are known to occur within the Central Huron area. In an effort to confirm the usefulness of this gravity data to identify these features, the gravity data were compared to the location of known pinnacle reefs (OGS, 2011) and to the known extent of salt units (Sanford, 1977).

In the Central Huron area, where bedrock is mostly covered by overburden, the radiometric data have been used in an attempt to confirm the distribution of the mapped Quaternary deposits, and also provide some discussion on the radon risk within the Central Huron area.

The following sections present the results and interpretations of each geophysical data set in the Central Huron area.

5.2 Magnetic Results

The magnetic data over the Central Huron area exhibit mainly broad magnetic responses, which are presumably associated with geological features of the Precambrian basement rocks underlying the Paleozoic sedimentary units. In general, it is understood that magnetic anomalies that are caused by sedimentary units are much weaker than those generated from igneous and metamorphic rock. In the case of the Central Huron area, it is assumed that the majority of the observable magnetic response is generated from the Precambrian basement rocks, and the overlying sedimentary units are considered magnetically transparent. This is consistent with the interpretation of magnetic data over Lake Huron by O’Hara and Hinze (1980).

Based on the distribution of magnetic responses in the reduced to pole magnetic field data (Figure 8), and their character in the first and second vertical derivatives, tilt angle and analytic signal maps (Figures 9 to 12), two lithological domains (A and B) have been interpreted in the Precambrian basement of the Central Huron area (Figure 13). The interpretation of these lithological domains is based on variability in the intensity and curvilinear pattern development in the magnetic data, most particularly observed in the first and second vertical derivative grids. Magnetic data covering a portion of Lake Huron north of the Central Huron area shows the most pronounced magnetic high within the region, which has a strong northeast trend (PGW, 2014). This complex anomaly has previously been interpreted as having a strong magnetic intensity which parallels the Grenville Front Tectonic Zone, which is the boundary between the Grenville and Superior provinces of the Canadian Shield (O'Hara and Hinze, 1980; Boyce and Morris, 2002). A north-south trending linear feature apparent in the data is an artifact produced during merging data sets along the boundary with the Strathroy survey. This feature has no geological significance.

The Precambrian crystalline basement beneath the Central Huron area has been defined as the Huron Domain of the Grenville Province based on borehole data that intersect the basement rocks (Carter and Easton, 1990). Lithologically, the Huron domain is described as predominantly containing variable amounts of granitic, monzonitic and tonalitic rocks that are strongly gneissic, which in general corresponds to a lower magnetic intensity (Figure 8). The interpretation of magnetic data as part of this assessment further divides the Huron Domain in the Central Huron area based on subtle variability in the character and pattern of the magnetic data sets.

In the western and central portions of the Central Huron area, and underlying most of the Municipality, Domain A is identified consisting of several curvilinear magnetic features that trend west to west–northwest. These anomalies have moderate magnetic intensity on the pole reduced magnetic field map (Figure 8), and are best represented as high magnitude features on the first vertical derivative and tilt angle maps (Figures 9 and 11). The eastern most boundary of Domain A is largely defined by a change in the magnetic character to a more north-northeast oriented pattern. Where similar rock units are exposed north of the Central Huron area, several mapped domains similarly show northwest-trending fold structures (Easton 1992), and are observable in the regional magnetic data for southern Ontario (Gupta, 1991).

In the eastern portion of the Central Huron area the magnetic response shows a predominant northeastern trend (Figure 8). This magnetic character is outlined as Domain B (Figure 13), and underlies only the easternmost portion of the Municipality. Due to the weaker magnetic response, the vertical derivatives and the tilt angle maps were used to emphasize the subtle magnetic response. The resulting magnetic features appear as distinct wavy curvilinear to elliptical magnetic anomalies which are interpreted to reflect large areas of complex ductile shearing and folding that is preserved in the Precambrian basement rocks. These anomalies where also identified by Boyce and Morris (2002) in this region of southern Ontario. Easton and Carter (1995) suggest these elliptical magnetic features may represent metamorphosed plutons, where the trend variability corresponds to gneissosity, foliation, folds and shear zones preserved within the Precambrian basement rock near the northeast-trending Grenville Front Tectonic Zone.

In addition to the magnetic response from the Precambrian basement source rocks, magnetic response may also be derived from the presence of salt deposits within the sedimentary sequence in the Central Huron area. Results from other studies have shown the potential for deposits of pure halite, gypsum, or anhydrite to result in low magnitude responses (Gunn, 1997). In addition, a few salt deposits have resulted in magnetic high responses that have been attributed to banding of diamagnetic magnetite within these units (Smith and Whitehead, 1989). However, the magnetic data in the Central Huron area do not provide any supporting evidence that the Salina salt units, based on subsurface mapping by Sanford (1977), result in a response in the magnetic data. Instead, as described above, the interpreted magnetic responses tend to be attributed to patterns that reflect the Precambrian basement, and show no spatial association to the mapped salt deposits.

5.3 Gravity Results

5.3.1 Observed Bouguer Gravity

The observed Bouguer gravity data over the Central Huron area exhibits mainly broad responses that can be attributed to spatial variability in rock density as well as changes in formation thickness in the Paleozoic sedimentary sequence and the deeper Precambrian basement rocks. Variability in the observed Bouguer gravity response in the Central Huron area is shown in Figure 14, and its first vertical derivative is shown in Figure 15.

The Bouguer gravity data (Figure 14) display a significant gravity gradient, increasing to the west. The highest gravity response is observed along the western edge of the Central Huron area, which has been suggested to reflect a potential thickening of the Precambrian basement rocks associated with the Grenville Front Tectonic Zone striking north-northeast (Easton, 1992).

In the case of the broad gravity responses, it is assumed they are primarily associated with variations in rock density due to changes in lithology and geometry of the Precambrian basement rocks. Similar assumptions have been made elsewhere in southern Ontario, where the gravity responses are attributed to the Precambrian basement (O'Hara and Hinze, 1980). The first vertical derivative of the Bouguer gravity (Figure 15) shows clear high magnitude features that display similar trends and texture as the magnetic data. As an example, a north-northeast trending gravity feature in the eastern part of the Central Huron area is very roughly coincident with the interpreted boundary between the magnetic Domains A and B. Similarly, these features are interpreted to correspond mainly to patterns within the Precambrian basement rocks. Some of the higher magnitude features in this data are likely to reflect changes in rock density and lithology of the basement. Although lateral variations in rock density within Paleozoic sedimentary sequence may also produce localized Bouguer gravity responses associated with lateral changes in depositional environments, such as pinnacle reefs and salt units.

Known pinnacle reefs (e.g. Tipperary pools) and salt deposits were compared to the observed Bouguer gravity (Figure 14) and its first vertical derivative data (Figure 15) to identify coincidence. The first vertical derivative emphasized the weaker localized gravity responses in order to attempt to identify features in the Paleozoic sequence. Here, small positive anomalies within the gravity data in the Central Huron area correlate well with most of the occurrences of known pinnacle reefs within the Paleozoic sedimentary sequence (Figures 14 and 15). Despite these anomalies being visible in the gravity data, it is sometimes difficult to distinguish these features from anomalies generated from the crystalline basement rocks. The pinnacle reefs of the Tipperary and Tipperary South pools are the largest occurrences within the Municipality and are shown as small positive Bouguer gravity anomalies (1.0 to 1.5 mGal). The Tipperary pool tends to be more visible in the Bouguer gravity data (Figure 14), and is also shown as a more distinct anomaly in the vertical derivative grid (Figure 15). Similarly, the Tuckersmith 30-III SHR Pool also coincides with a positive Bouguer gravity anomaly of 0.5 mGal, located approximately 1 km south of the Municipality. Similar positive gravity anomalies are observed within the Municipality, some of which could be pinnacle reefs. Previous studies in southern Ontario have used gravity data in an effort to locate pinnacle reefs (Pohly, 1966).

Known salt units in the Central Huron area range have an average cumulative thickness of about 76 m (OGSRL, 2014). The extent of these known salt units was compared to the observed gravity (Figure 14). Although a broad positive (high) response occurs within the area of known salt deposits, the response is more likely due to the deeper anomaly associated with the Grenville Front Tectonic Zone to the west of the Central Huron area.

The Bouguer gravity data within the Central Huron area also appears to be sensitive to variability in thickness and overall lower densities of the overburden deposits. These deposits tend to produce gravity anomalies that are lesser in magnitude and wavelength, and are largely overprinted by the broader high magnitude responses from the Precambrian basement rocks. Through modeling much of this surficial artifact can be removed using overburden thickness information derived from the available water well database (e.g. Gao et al., 2006).

5.3.2 Bouguer Gravity Effect from Modeling

The cumulative results of the modeled Bouguer gravity response from each of the Paleozoic key formation packages and the overburden deposits show a range of approximately 2.7 mGal across the Central Huron area (Figure 16). The modeled Bouguer gravity results display a higher gravity effect in the central portion of the Central Huron area, with a lower magnitude response towards Lake Huron. The majority of the variability observed in the modelled gravity effect results from the model's sensitivity to the higher quality data set for the overburden deposit thickness, in particular, to its strong density contrast with the underlying Paleozoic bedrock. As expected, areas of thick overburden such as along the Wyoming Moraine (Figure 14 in JDMA, 2015) tend to correlate well with large-scale, low-amplitude responses shown in the modeled gravity effects (Figure 16).

The stripped Bouguer gravity data show a range of approximately 13 mGal, which is derived by subtracting the modeled gravity effect from the observed Bouguer gravity results (Figure 17). In general, the distribution of the stripped Bouguer gravity data is similar to the observed Bouguer gravity data (Figure 14) within the Central Huron area. The more broad-scale features still display the same general appearance, which provides further support for the source being mainly from the basement rocks. It appears as though the removal of the modeled gravity effect primarily accounted for the influence of overburden units on the gravity data.

In addition, when compared to the observed Bouguer gravity data, the process of removing modeled gravity effect (e.g. stripped Bouguer gravity) does not appear to significantly enhance the locations of the known pinnacle reef structures or salt units within the Central Huron area. Similar to the observed Bouguer gravity, it is assumed that although a small amount of this resulting response may be attributed to the Paleozoic layers, the majority of the signal is thought to be derived from the lithological variability within the Precambrian basement rocks. The exception to this general observation may be the pinnacle reefs associated with the Tipperary and Tuckersmith 30-III SHR pools, which show an increased correlation with local increases in stripped Bouguer gravity anomalies (Figure 17).

5.4 Radiometric Results

The radiometric data in the Central Huron area (Figure 18) show a strong correlation with the distribution of the mapped Quaternary deposits, as well as impacts from varying amounts of vegetation cover, soil moisture, and surface water. The distributions of mapped morainal deposits (Figure 5) are associated with a strong radiometric dose rate response, and are elevated in concentrations of both equivalent thorium and potassium. The portions of the Central Huron area that have a lower dose rate tend to correlate with mapped glaciofluvial and glaciolacustrine deposits (Figure 5).

For the GSC radiometric compilation within the region of Central Huron area, the radioelement responses are summarized in Table 7.

Table 7. Radioelement response statistics

Radioelement	***Minimum****	***Maximum***	***Mean***
Potassium (%)	-0.47	2.12	1.36
Equivalent uranium (ppm)	-0.94	1.91	0.77
Equivalent thorium (ppm)	-1.56	7.85	4.69
Natural air absorbed dose rate (nGy/h)	-8.22	53.33	33.86

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

The low uranium levels suggest low radon risk (Ford et al, 2001). However, radon risk is also quite dependent on soil permeability and should be verified by soil gas measurements (IAEA, 2010).

6 SUMMARY OF RESULTS

The purpose of the geophysical interpretation was to provide additional information of the geological features associated with both the Paleozoic sedimentary units and the underlying crystalline rocks of the Precambrian basement within the Municipality and its immediate periphery, referred to as the Central Huron area. Available geophysical data were assessed to determine potential lithological variations within the Precambrian basement, and identify broad lithological domains. An attempt was made using gravity data in the Central Huron area to identify features within the Precambrian basement, as well as potential features such as pinnacle reef and the presence of thick salt occurrence within the overlying Paleozoic sedimentary sequence.

The geophysical data covering the Municipality vary from low to high resolution data sets. Lower resolution magnetic, gravity and radiometric data were obtained from the Geological Survey of Canada (GSC) for the entire Central Huron area. These were supplemented by moderate resolution magnetic and high-resolution gravity multi-client data sets acquired from industry sources. No electromagnetic data were available for the Central Huron area.

In this study, available magnetic data were used to assess the lithological variations within the Precambrian basement, since the overlying sediments are assumed to be magnetically transparent. The magnetic data predominantly highlights ductile features interpreted as internal fabric of the Precambrian crystalline basement, and likely include tectonic foliation or gneissosity. Based on the changes in magnetic character, two lithological domains have been interpreted from the magnetics in the basement rocks underlying the Municipality of Central Huron (Figure 13). Domain A underlies the western most part of the Municipality, and consists of magnetic features that trend west to northwest. In the easternmost portion of the Municipality of Central Huron, Domain B corresponds to magnetic responses trending in a northeasterly direction, although at a weaker magnitude.

The gravity data exhibit anomaly features that display trends and texture similar to the magnetic data, and reflect deformation patterns and possible changes in the rock density and lithology of the basement rocks. In the eastern part of the Central Huron area the gravity data shows evidence of a north-northeast trending gravity feature that is coincident with the interpreted boundary between the magnetic Domains A and B. Locally, the gravity data correlates well with most of the occurrences of known pinnacle reefs within the Paleozoic sedimentary sequence. The pinnacle reefs of the Tipperary and Tipperary South pools are both shown as small positive Bouguer gravity anomalies (approximately 1.0 to 1.5 mGal). The Tipperary pool tends to be more visible in the Bouguer gravity data (Figure 14), and is also shown as a more distinct anomaly in the vertical derivative grid (Figure 15). Similarly, the Tuckersmith 30-III SHR Pool also coincides with a positive gravity anomaly just south of the Municipality. Although there is a broad high gravity response within the area of known salt deposits, this anomaly is not believed to correspond to the salt deposits. This anomaly is more likely due to the deeper anomaly associated with the Grenville Front Tectonic Zone to the west of the Central Huron area. It appears as though the removal of the modeled gravity effect primarily accounted for the influence of overburden units on the gravity data.

Radiometric results show a strong correlation with the distribution of the mapped Quaternary deposits, as well as impacts from varying amounts of vegetation cover, soil moisture, and surface water. The most elevated responses in potassium and thorium are evident over the morainal deposits. Radon risks throughout the Central Huron area are considered to be low.

Respectfully Submitted,

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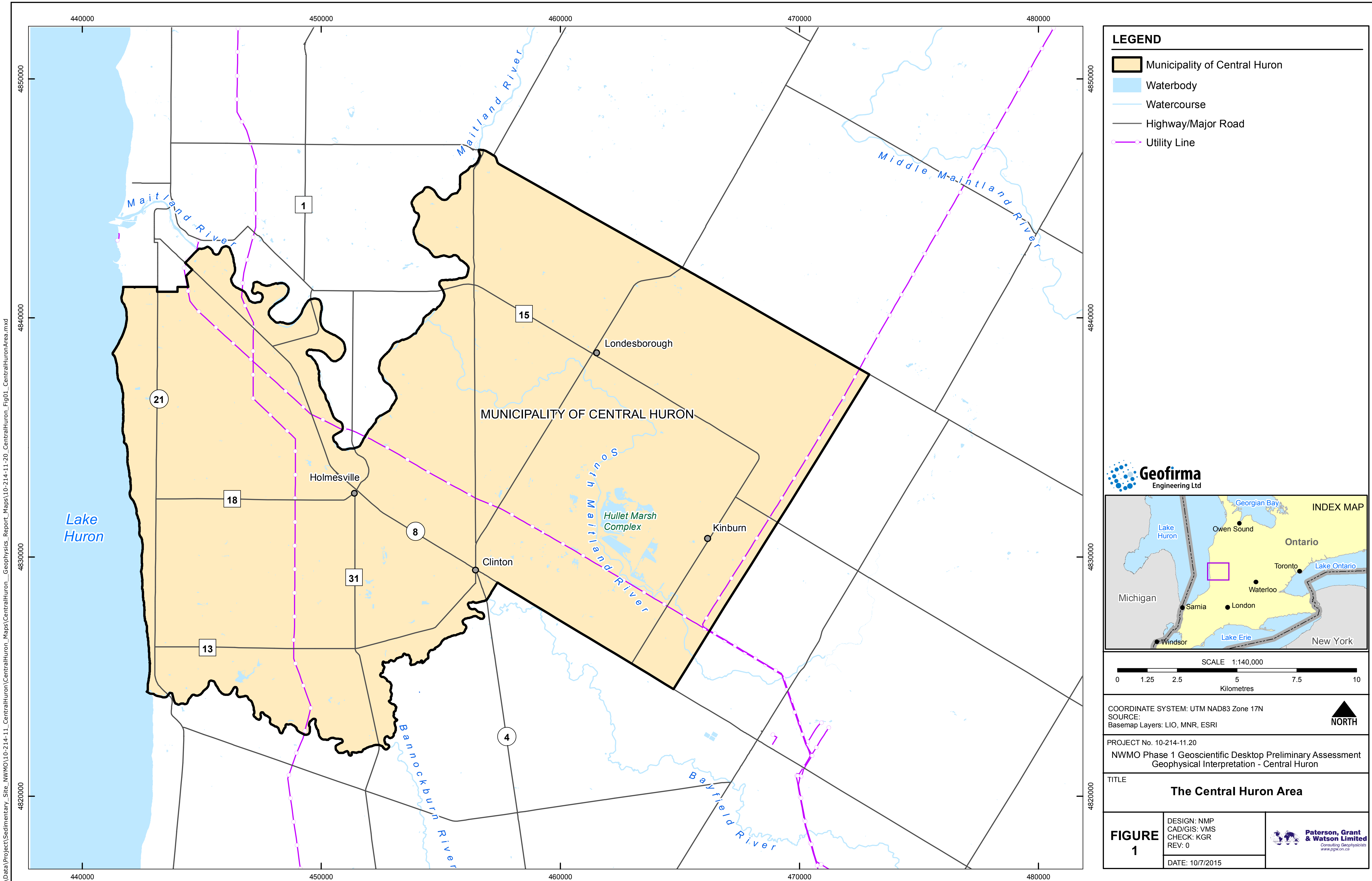
FIGURES



440000
450000
460000
470000
480000
4850000
4840000
4830000
4820000
Lake Huron
Maitland River
Middle Maitland River
South Maitland River
Bannockburn River
Bayfield River
Hullet Marsh Complex
MUNICIPALITY OF CENTRAL HURON
Londesborough
Holmesville
Clinton
Kinburn
1
15
21
18
8
31
13
4
LEGEND
Municipality of Central Huron
Waterbody
Watercourse
Highway/Major Road
Utility Line
Geofirma Engineering Ltd
INDEX MAP
Georgian Bay
Owen Sound
Lake Huron
Ontario
Toronto
Lake Ontario
Waterloo
Michigan
Sarnia
London
Lake Erie
Windsor
New York
SCALE 1:140,000
0 1.25 2.5 5 7.5 10
Kilometres
COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
NORTH
PROJECT No. 10-214-11.20
NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron
TITLE
The Central Huron Area
FIGURE 1
DESIGN: NMP
CAD/GIS: VMS
CHECK: KGR
REV: 0
DATE: 10/7/2015
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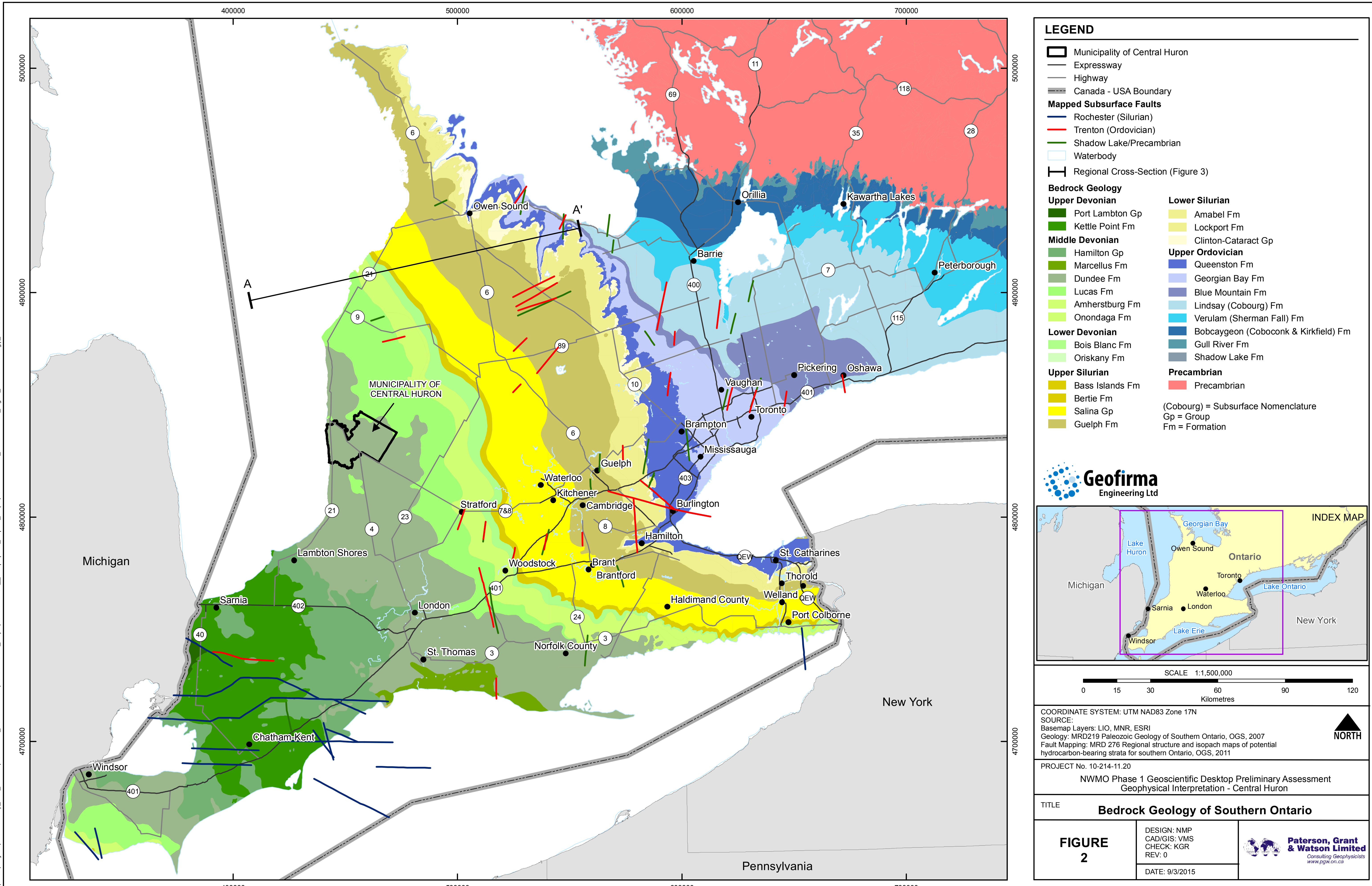
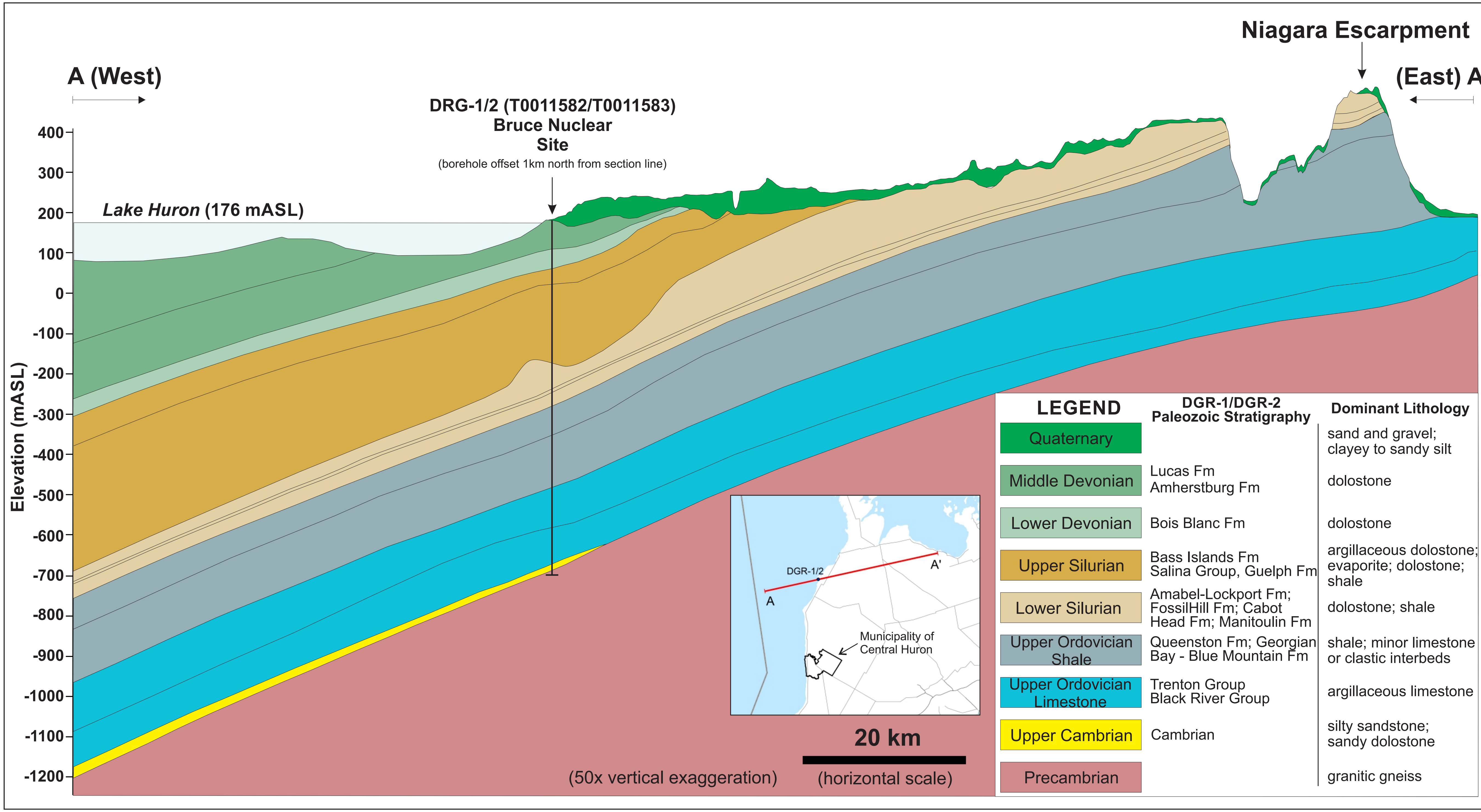


FIGURE 2
Bedrock Geology of Southern Ontario



Data Source: NWMO, 2011

FIGURE 3 - Regional Geological Cross-Section of the Eastern Flank of the Michigan Basin

PROJECT No: 10-214-11.20

NWMO Phase I Geoscientific Desktop Preliminary Assessment, Geophysical Interpretation - Central Huron

Prepared by: NMP/VMS
Reviewed by: KGR
Date: 04/12/2014

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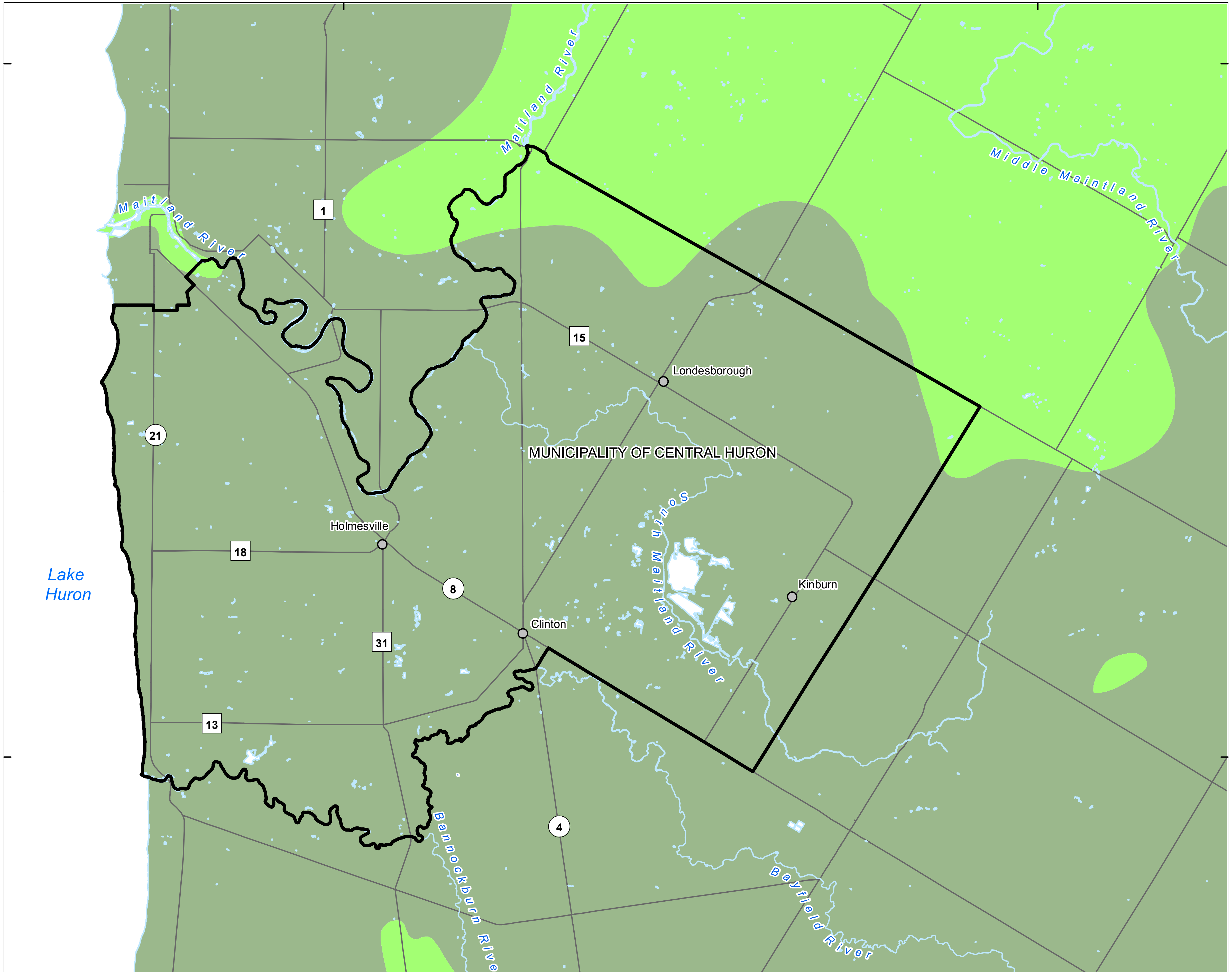

LEGEND

- Municipality of Central Huron
- Highway/Major Road
- Waterbody
- Watercourse

Bedrock Geology

Middle Devonian

- Dundee
- Lucas

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SCALE 1:140,000

0 1.25 2.5 5 7.5 10

Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N

SOURCE:

Basemap Layers: LIO, MNR, ESRI

Geology: MRD219 Paleozoic Geology of Southern Ontario, OGS, 2007

NORTH

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NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Bedrock Geology of the Central Huron Area

FIGURE 4

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

DATE: 9/10/2015

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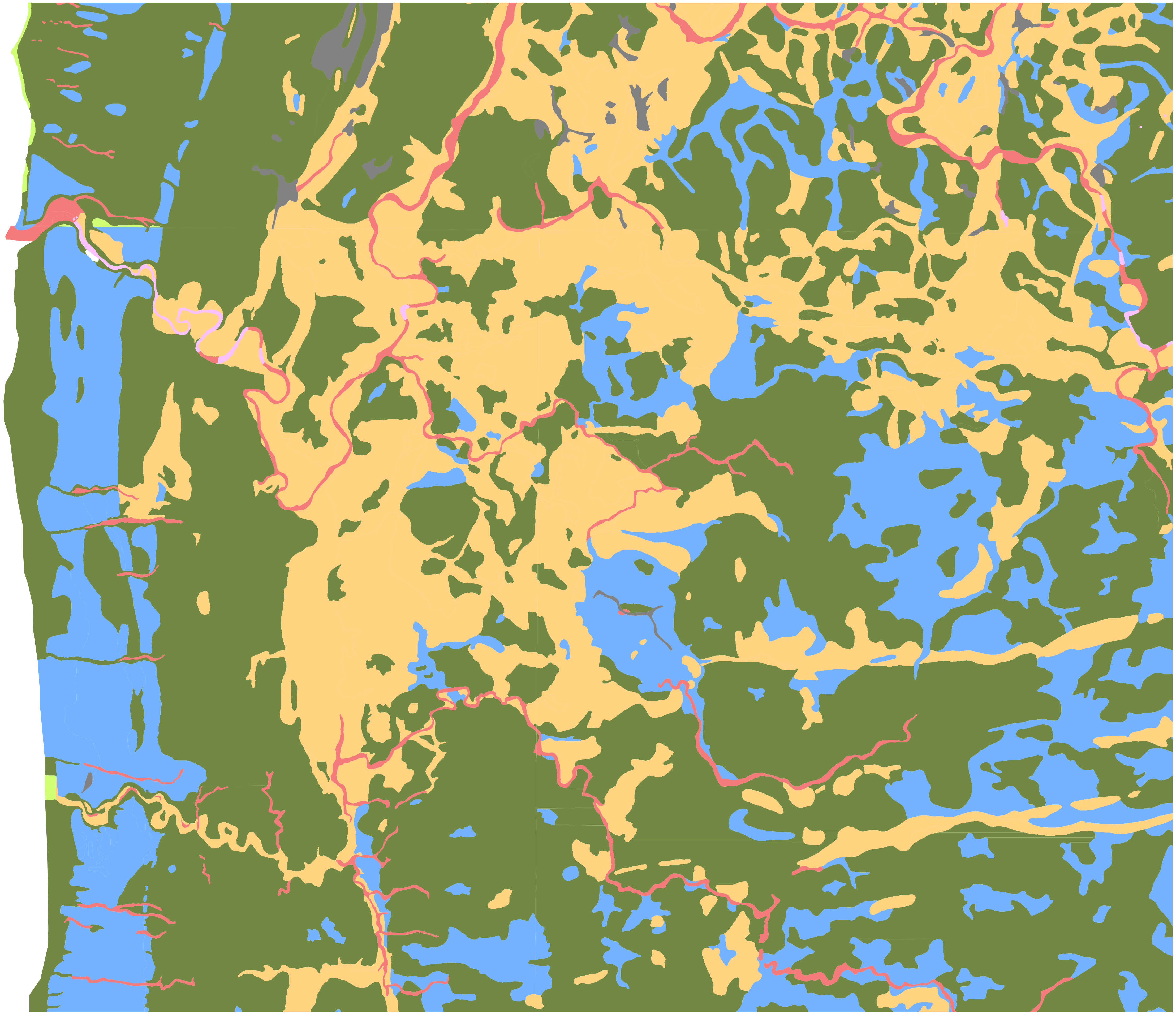

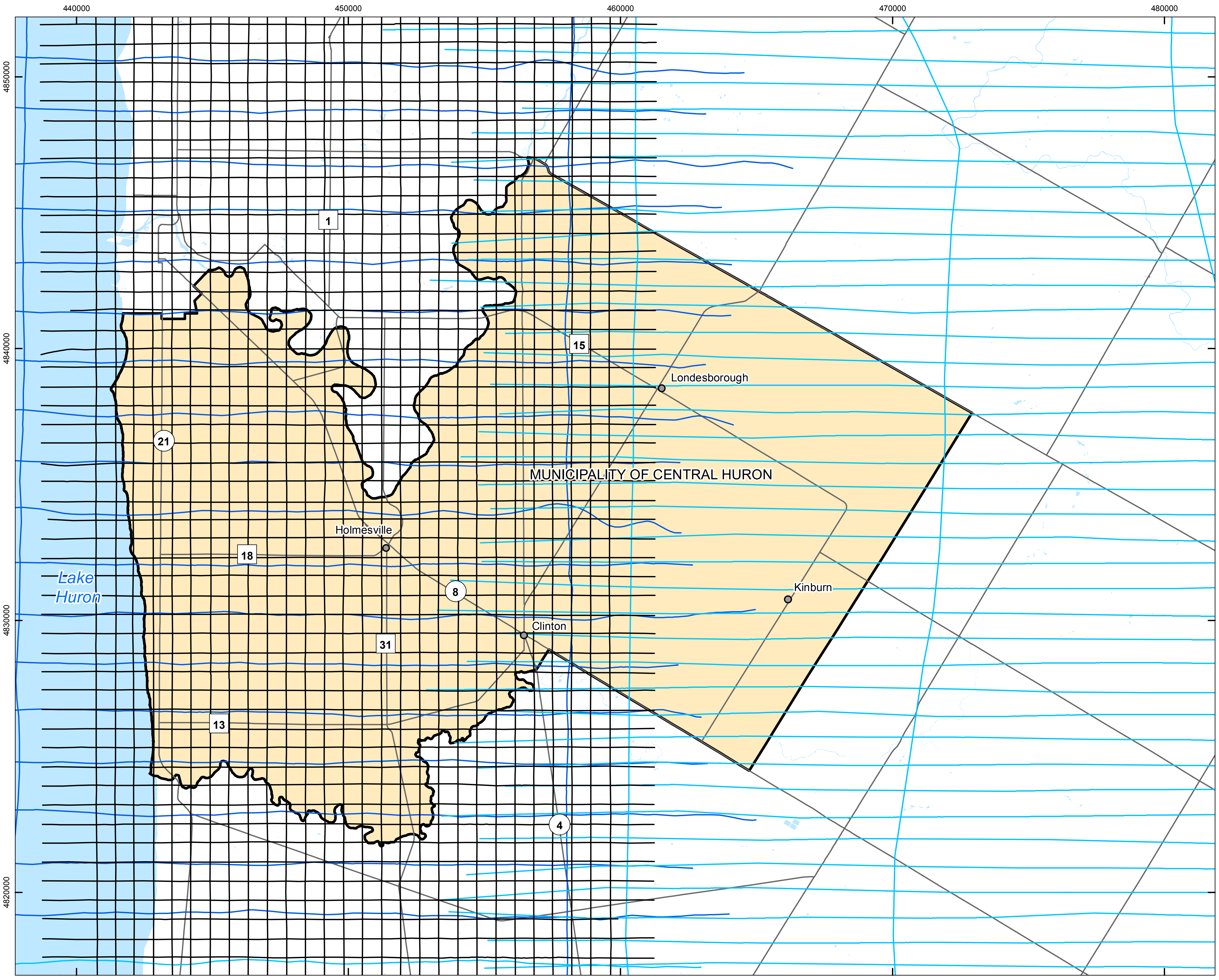

LEGEND

- Municipality of Central Huron
- Waterbody
- Highway/Major Road

GSC Survey

- Lake Huron GSC
- Waterloo GSC

Proprietary Survey

- Strathroy Survey

SCALE 1:140,000

0 1.25 2.5 5 7.5 10

Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE: LIO, MNR, ESRI
GSC Survey: GSC, 2014
Proprietary Survey: Spector, 1999

NORTH

PROJECT No. 10-214-11.20

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Geophysical Interpretation - Central Huron

TITLE

Airborne Geophysical Coverage of the Central Huron Area

FIGURE 6

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

DATE: 4/14/2015

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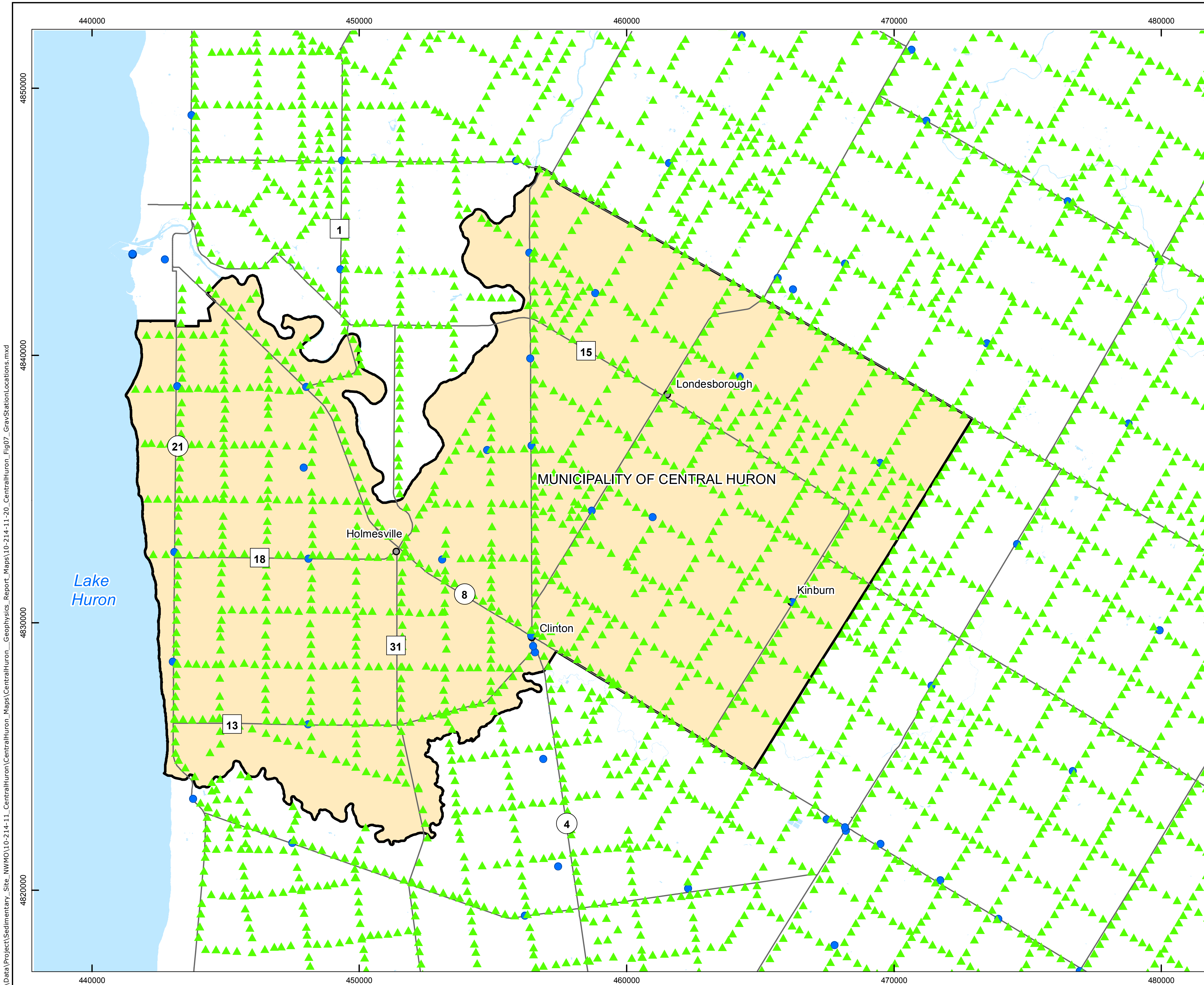

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LEGEND

- Municipality of Central Huron
- Waterbody
- Highway/Major Road
- GSC Gravity Station Location
- PGW Gravity Station Location

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SCALE 1:140,000

0 1.25 2.5 5 7.5 10

Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
Gravity Station Locations: GSC, 2014; PGW

NORTH

PROJECT No. 10-214-11

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Ground Gravity Station Locations of the Central Huron Area

FIGURE 7

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

DATE: 4/15/2015

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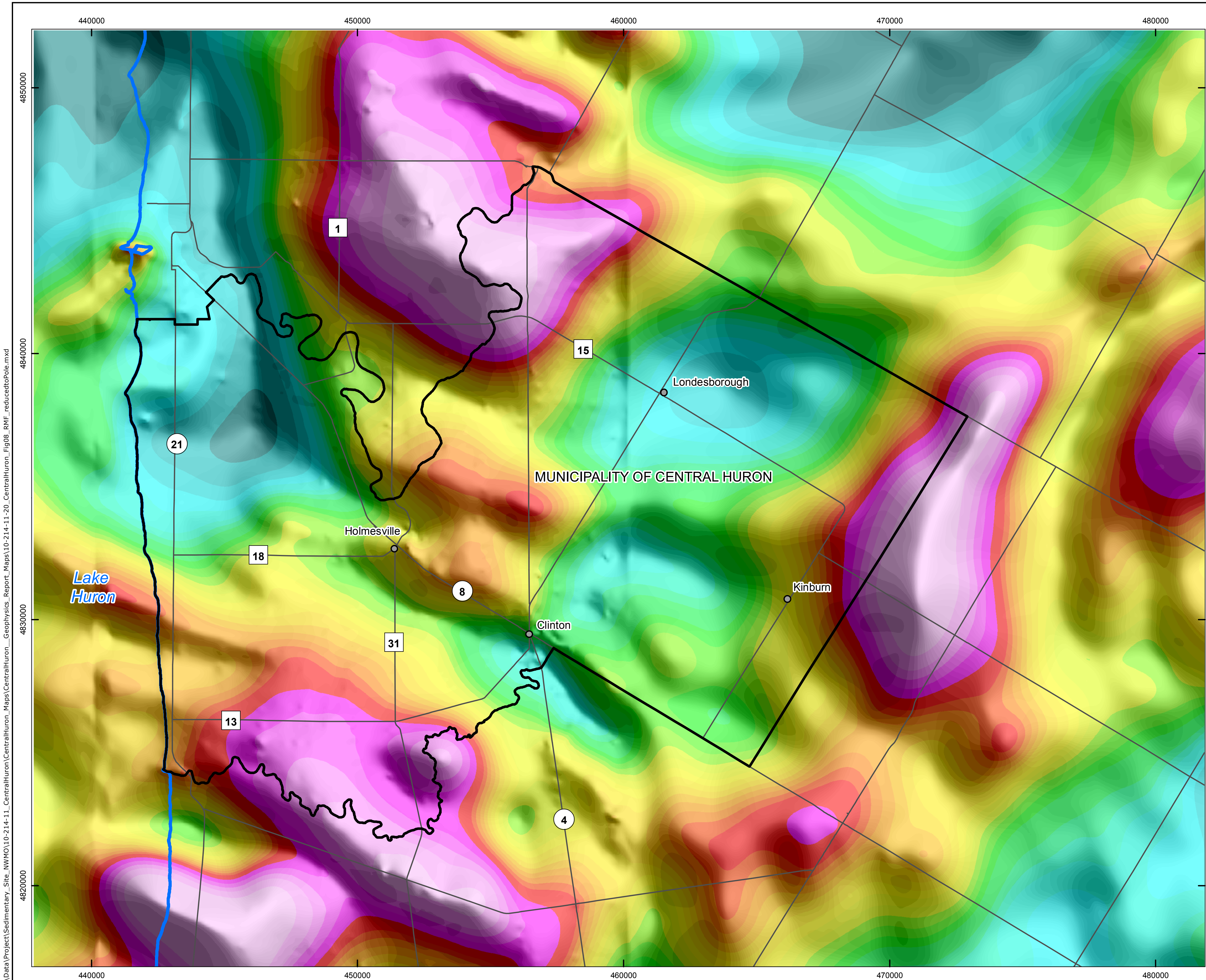

LEGEND

- Municipality of Central Huron
- Shoreline
- Highway/Major Road

RTP (nT)
10
-5
-15
-25
-35
-45
-50
-55
-60
-65
-70
-75
-80
-85
-90
-95
-100
-105
-115
-120
-125
-135
-145
-160
-185

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SCALE 1:140,000

0 1.25 2.5 5 7.5 10

Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
Proprietary Survey: Spector, 1999
GSC Survey: GSC, 2014

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Residual Magnetic Field Reduced to Pole

FIGURE 8

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

DATE: 4/14/2015

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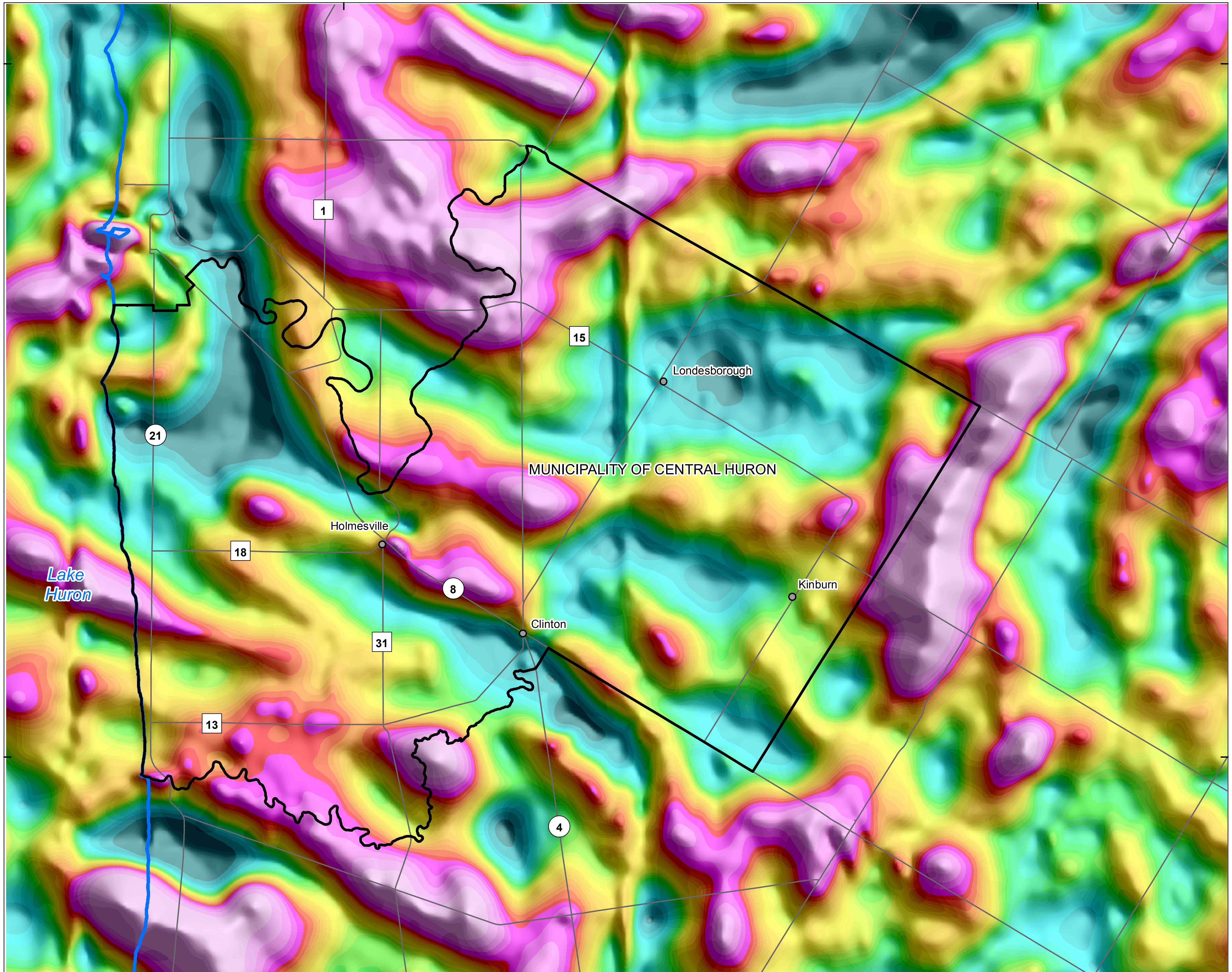

LEGEND

Municipality of Central Huron

Shoreline

Highway/Major Road

0.043
0.033
0.027
0.023
0.019
0.017
0.014
0.012
0.010
0.008
0.006
0.004
0.003
0.001
0.000
-0.002
-0.003
-0.005
-0.007
-0.008
-0.010
-0.013
-0.015
-0.018
-0.021
-0.026
-0.034

1VD of RTP
(nT/m)

Geofirma Engineering Ltd

SCALE 1:140,000

0 1.25 2.5 5 7.5 10
Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
Proprietary Survey: Spector, 1999
GSC Survey: GSC, 2014

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

First Vertical Derivative of the Pole Reduced Magnetic Field

FIGURE 9

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

DATE: 4/14/2015

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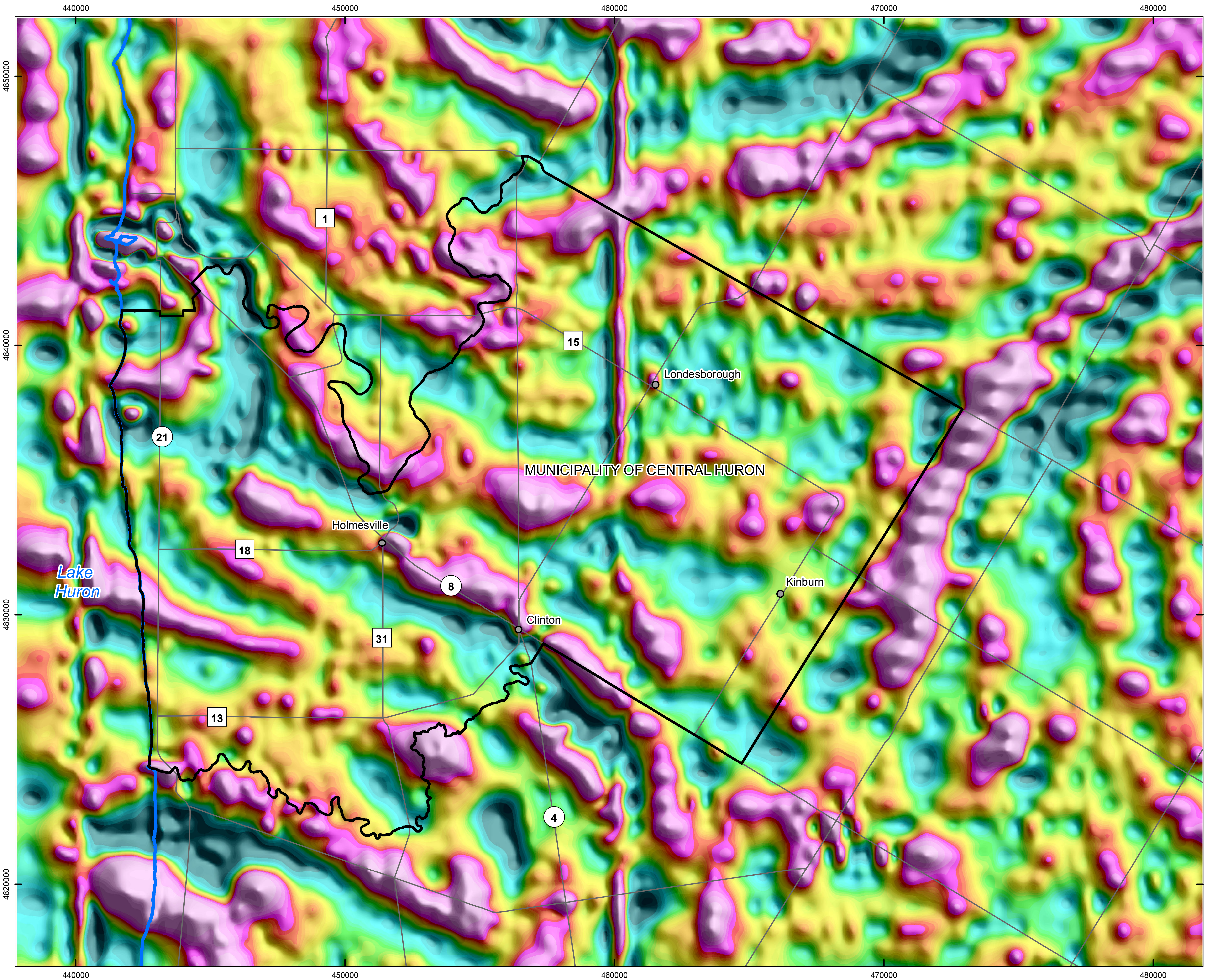

LEGEND

- Municipality of Central Huron
- Shoreline
- Highway/Major Road

2VD of RTP (nT/m^2)
0.000045
0.000033
0.000026
0.000022
0.000018
0.000016
0.000013
0.000011
0.000009
0.000007
0.000005
0.000004
0.000002
0.000000
-0.000001
-0.000002
-0.000004
-0.000006
-0.000008
-0.000010
-0.000012
-0.000014
-0.000016
-0.000019
-0.000022
-0.000025
-0.000030
-0.000039

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SCALE 1:140,000

0 1.25 2.5 5 7.5 10

Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
Proprietary Survey: Spector, 1999
GSC Survey: GSC, 2014

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Second Vertical Derivative of the Pole Reduced Magnetic Field

FIGURE 10

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

DATE: 4/14/2015

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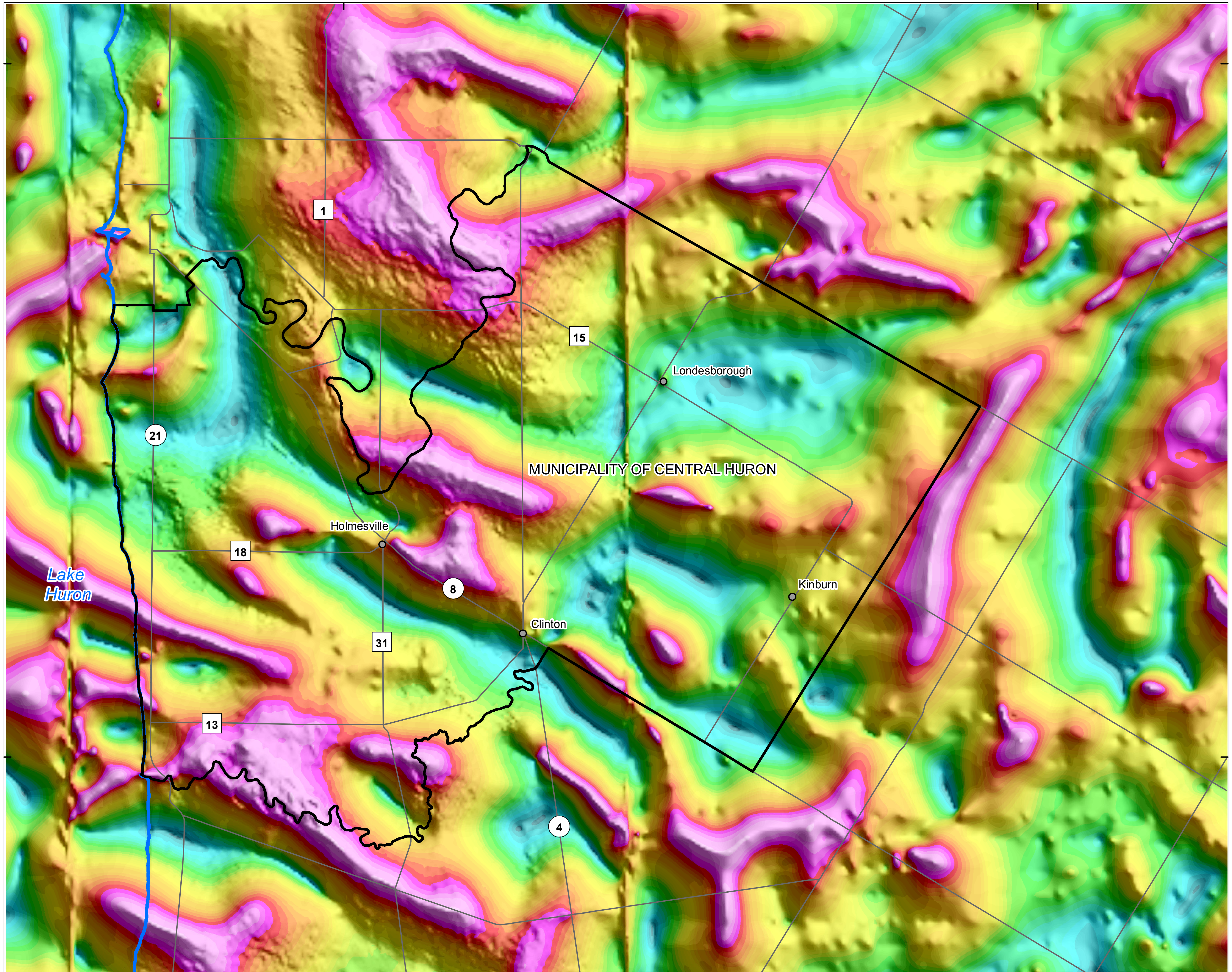
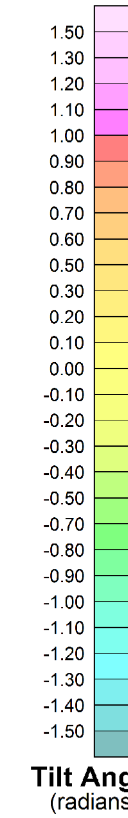


LEGEND

- Municipality of Central Huron
- Shoreline
- Highway/Major Road



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SCALE 1:140,000

0 1.25 2.5 5 7.5 10

Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
Proprietary Survey: Spector, 1999
GSC Survey: GSC, 2014

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Tilt Angle of the Pole Reduced Magnetic Field

FIGURE 11

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

DATE: 4/14/2015

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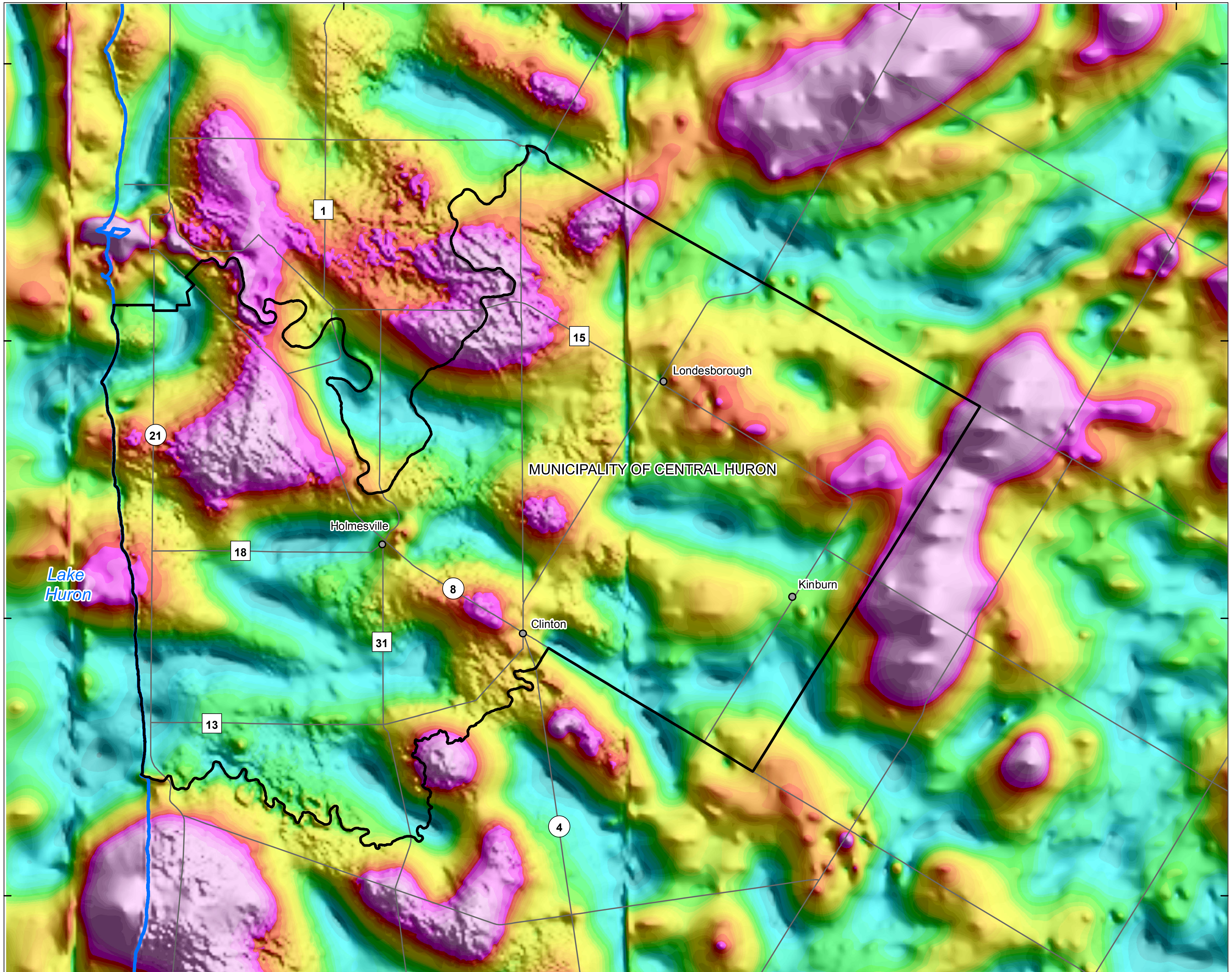

LEGEND

Municipality of Central Huron
Shoreline
Highway/Major Road

Analytic Signal (nT/m)
0.050
0.046
0.043
0.040
0.038
0.037
0.035
0.033
0.032
0.031
0.029
0.028
0.027
0.026
0.025
0.023
0.022
0.021
0.020
0.018
0.017
0.015
0.014
0.012
0.010
0.008
0.005
0.001

Analytic Signal
(nT/m)

Geofirma
Engineering Ltd

SCALE 1:140,000
0 1.25 2.5 5 7.5 10
Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
Proprietary Survey: Spector, 1999
GSC Survey: GSC, 2014

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Analytic Signal Amplitude of the Total Magnetic Field

FIGURE 12

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

DATE: 4/14/2015

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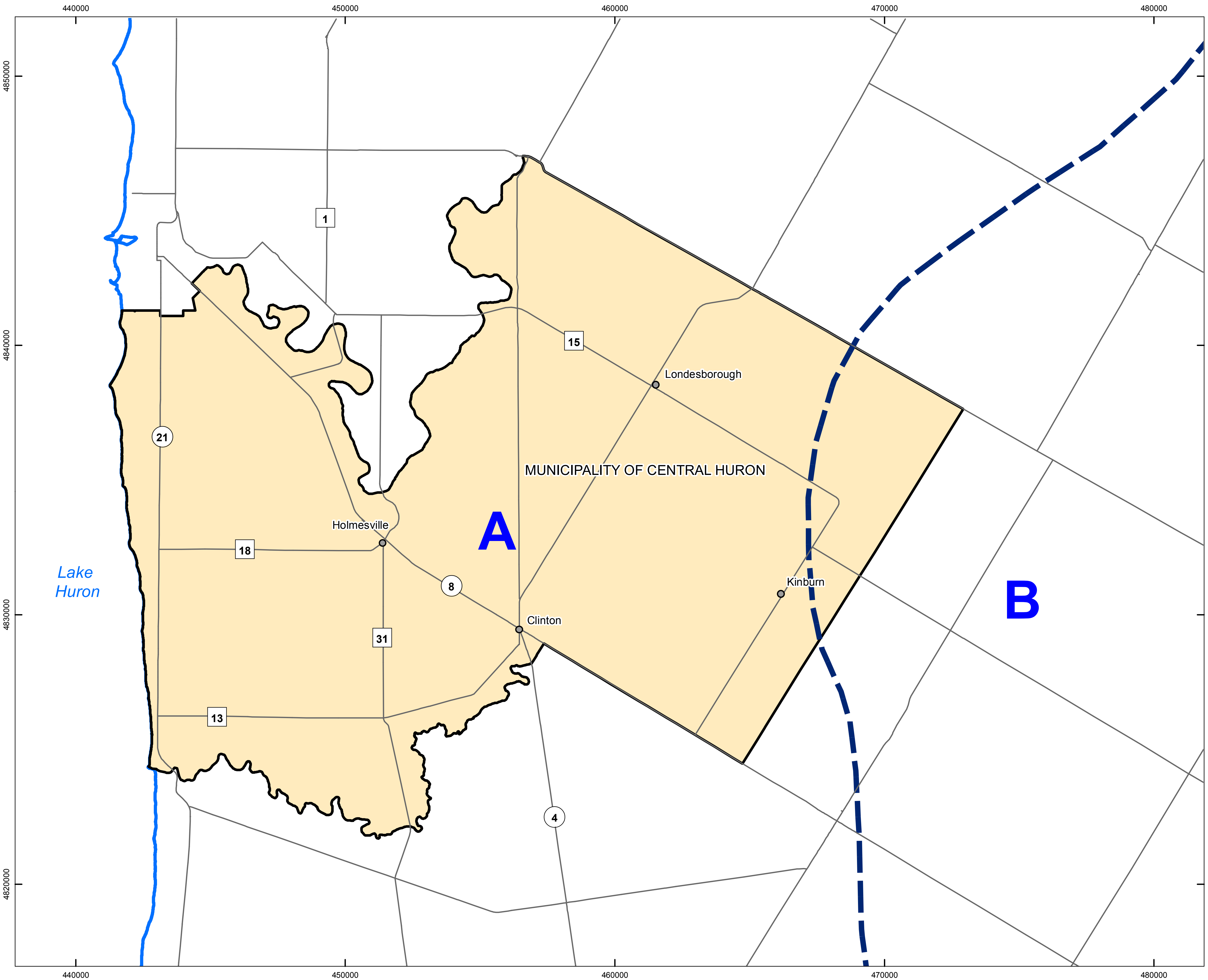

LEGEND

- Municipality of Central Huron
- Shoreline
- Highway/Major Road
- Interpreted Magnetic Domains

Geofirma Engineering Ltd

SCALE 1:140,000

0 1.25 2.5 5 7.5 10

Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Geophysical Interpretation of Magnetic Domains

FIGURE 13

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

DATE: 4/15/2015

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Consulting Geophysicists

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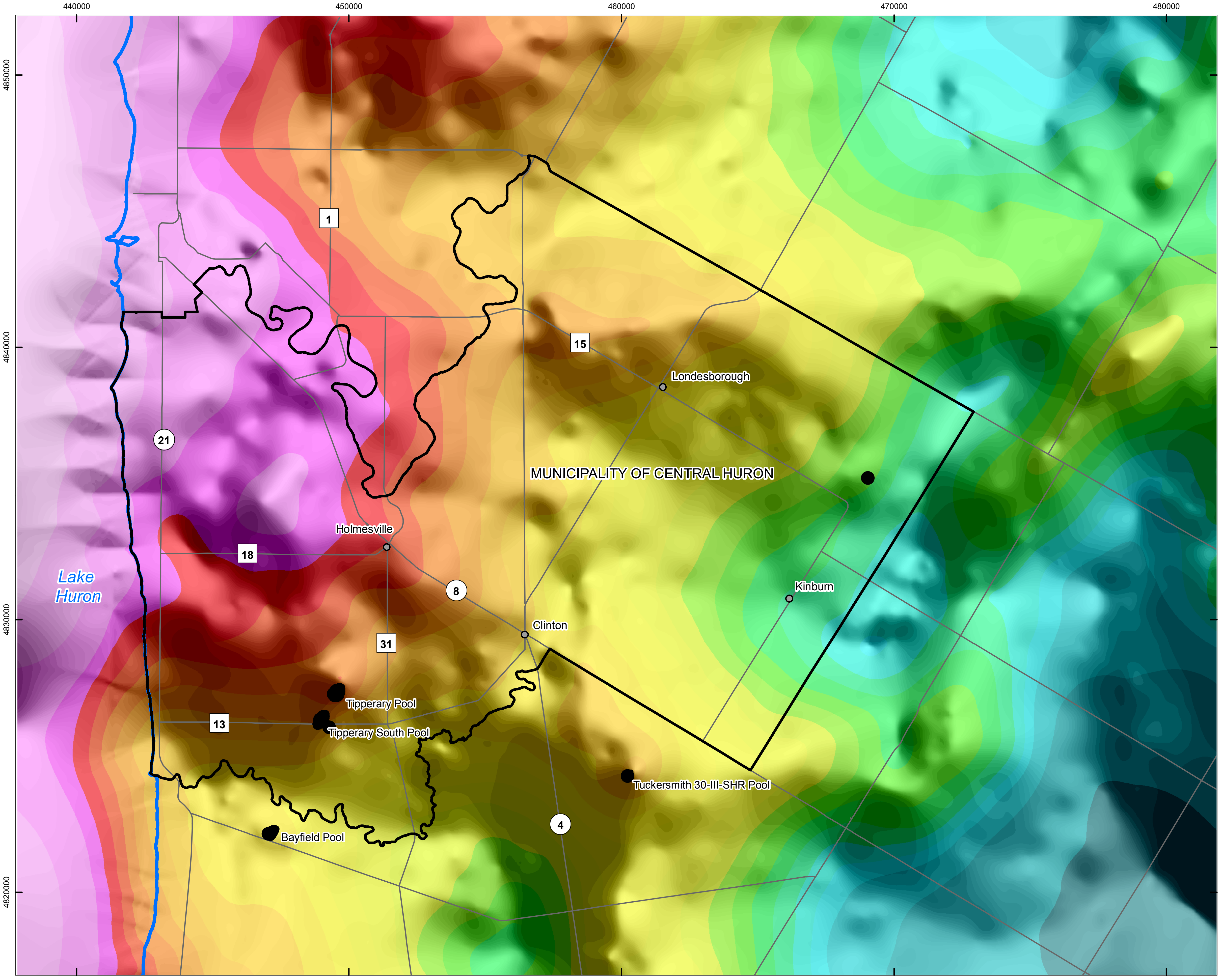

LEGEND

- Municipality of Central Huron
- Shoreline
- Highway/Major Road
- Pinnacle Reef / Oil and Gas Pool

Note: Labelled Pinnacle Reefs are Oil and Gas Pools

66.0
64.5
63.5
63.0
62.5
62.0
61.5
61.0
60.5
60.0
59.5
59.0
58.5
58.0
57.5
57.0
56.5
56.0
55.5
55.0
54.5
53.5
51.5

Bouguer Gravity
(mGal)

Geofirma Engineering Ltd

SCALE 1:140,000

0 1.25 2.5 5 7.5 10

Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
Proprietary Survey: PGW Coverage
GSC Survey: GSC, 2014
Pinnacle Reef: OGS, 2011

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Bouguer Gravity Field

FIGURE 14

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

DATE: 4/14/2015

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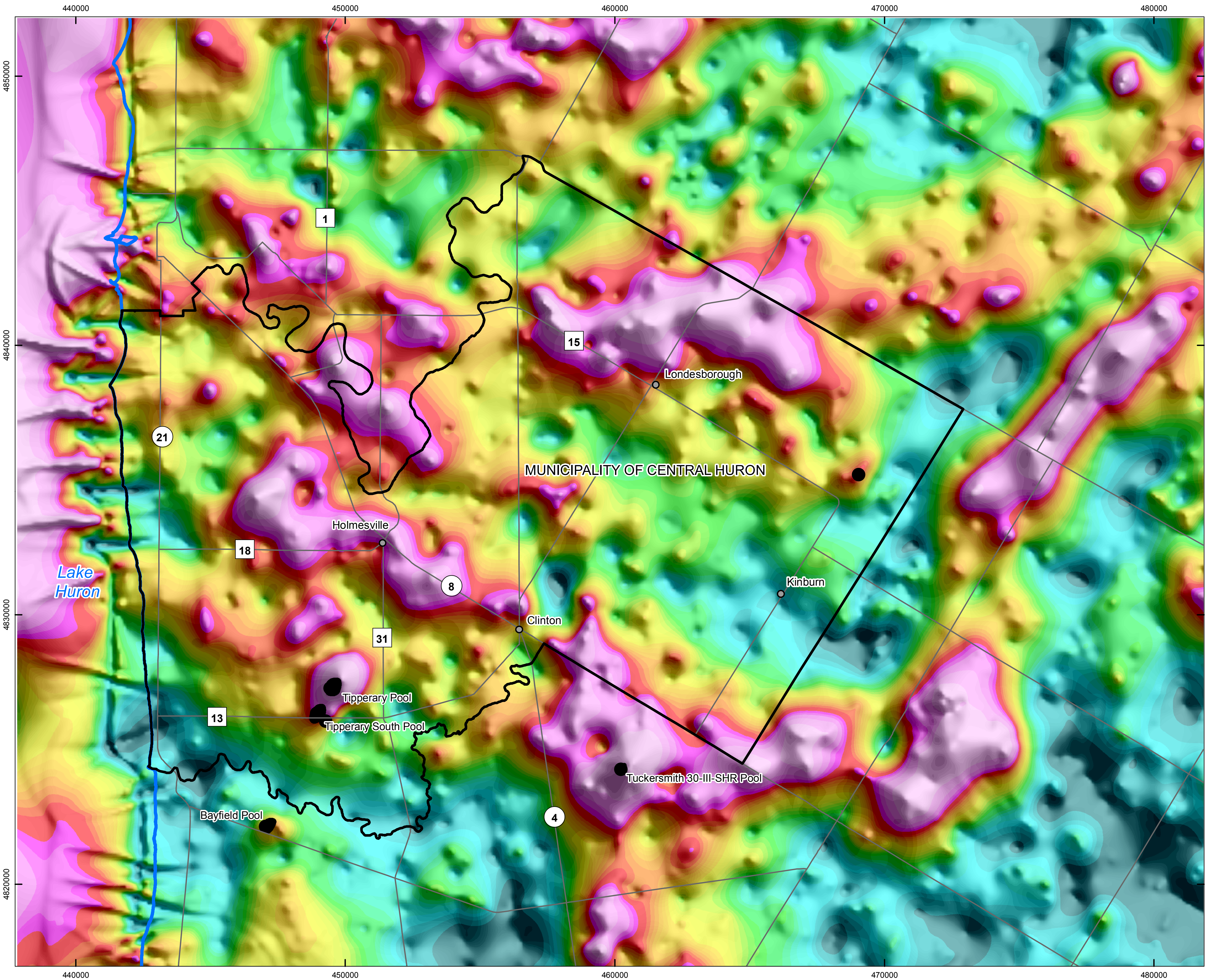

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LEGEND

Municipality of Central Huron
Shoreline
Highway/Major Road
Pinnacle Reef / Oil and Gas Pool

Note: Labelled Pinnacle Reefs are Oil and Gas Pools

0.00075
0.00060
0.00050
0.00045
0.00040
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
-0.00005
-0.00010
-0.00015
-0.00020
-0.00025
-0.00030
-0.00035
-0.00045
-0.00050
-0.00055
-0.00065
-0.00075
-0.00085
-0.00100

1VD of Bouguer Gravity (mGal/m)

Geofirma Engineering Ltd

SCALE 1:140,000
0 1.25 2.5 5 7.5 10
Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
Proprietary Survey: PGW Coverage
GSC Survey: GSC, 2014
Pinnacle Reef: OGS, 2011

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

First Vertical Derivative of the Bouguer Gravity Field

FIGURE 15

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

DATE: 4/14/2015

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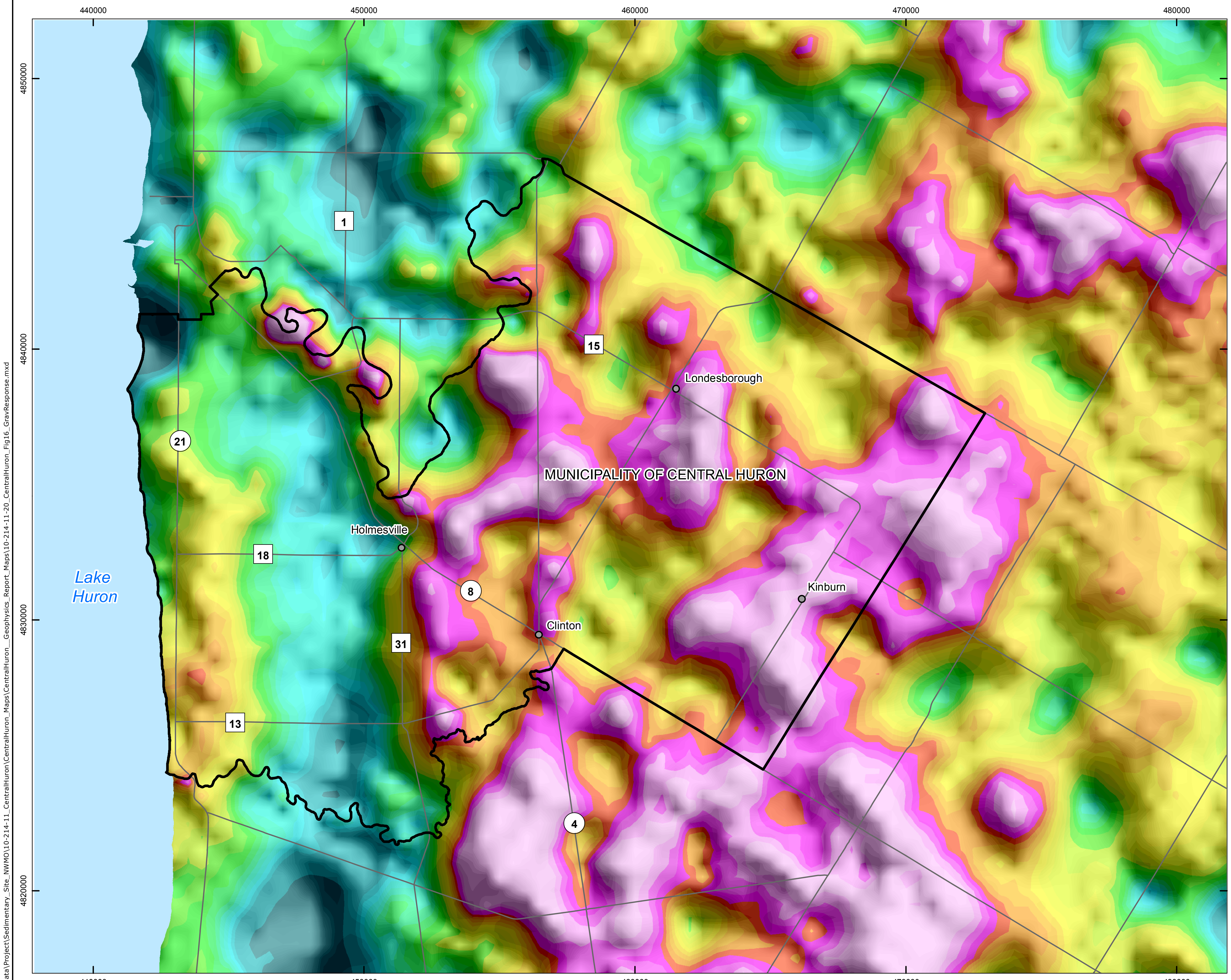

LEGEND

- Municipality of Central Huron
- Waterbody
- Highway/Major Road

3.65
3.60
3.55
3.50
3.45
3.40
3.35
3.30
3.25
3.20
3.15
3.10
3.05
3.00
2.95
2.90
2.85
2.80
2.75
2.70
2.50

Gravity (mGal)

Geofirma Engineering Ltd

SCALE 1:140,000

0 1.25 2.5 5 7.5 10
Kilometres

COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI

NORTH

PROJECT No. 10-214-11.20

NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron

TITLE

Modeled Bouguer Gravity from Overburden and Paleozoic Sedimentary Sequence

FIGURE 16

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

DATE: 4/14/2015

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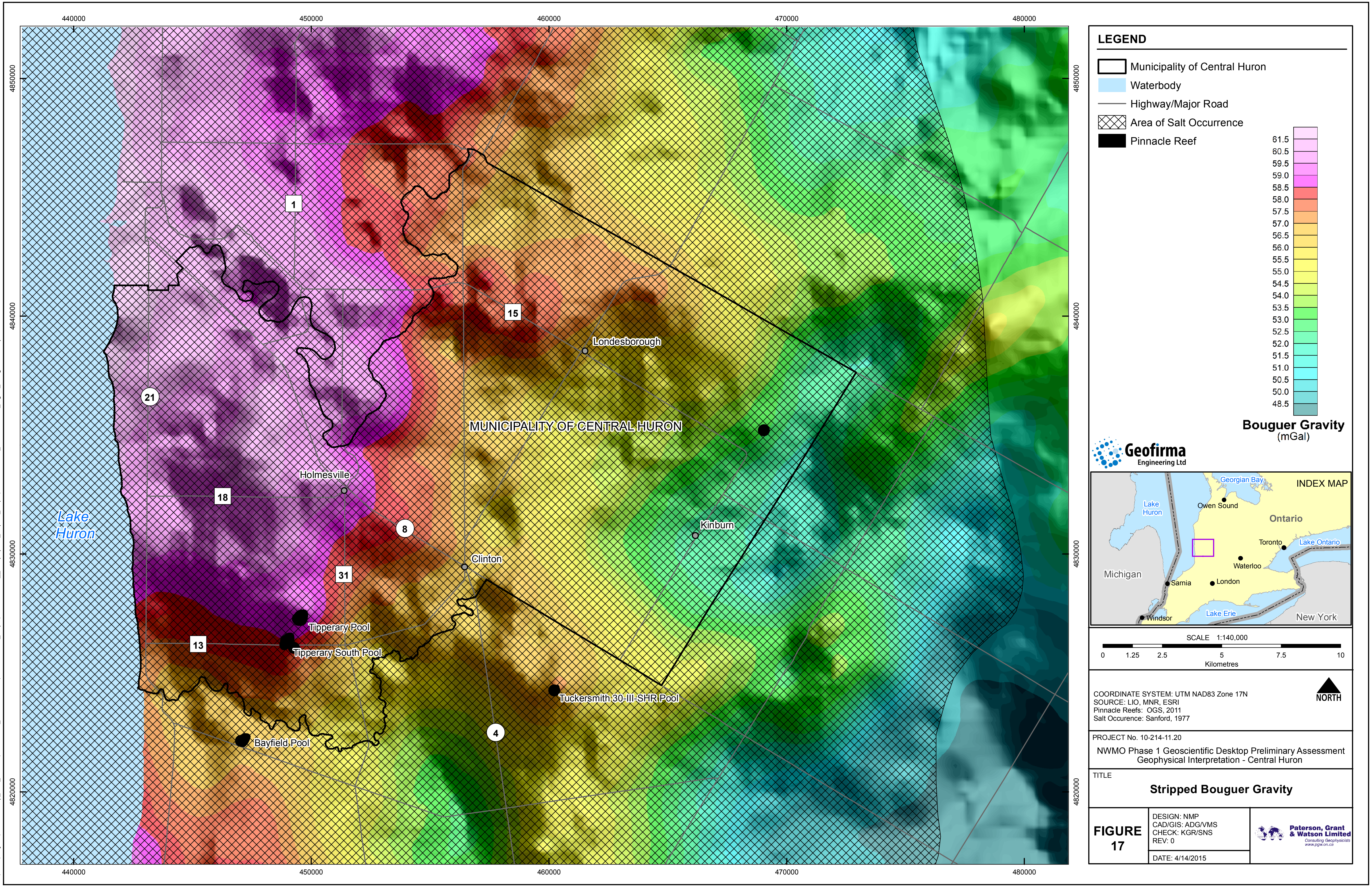
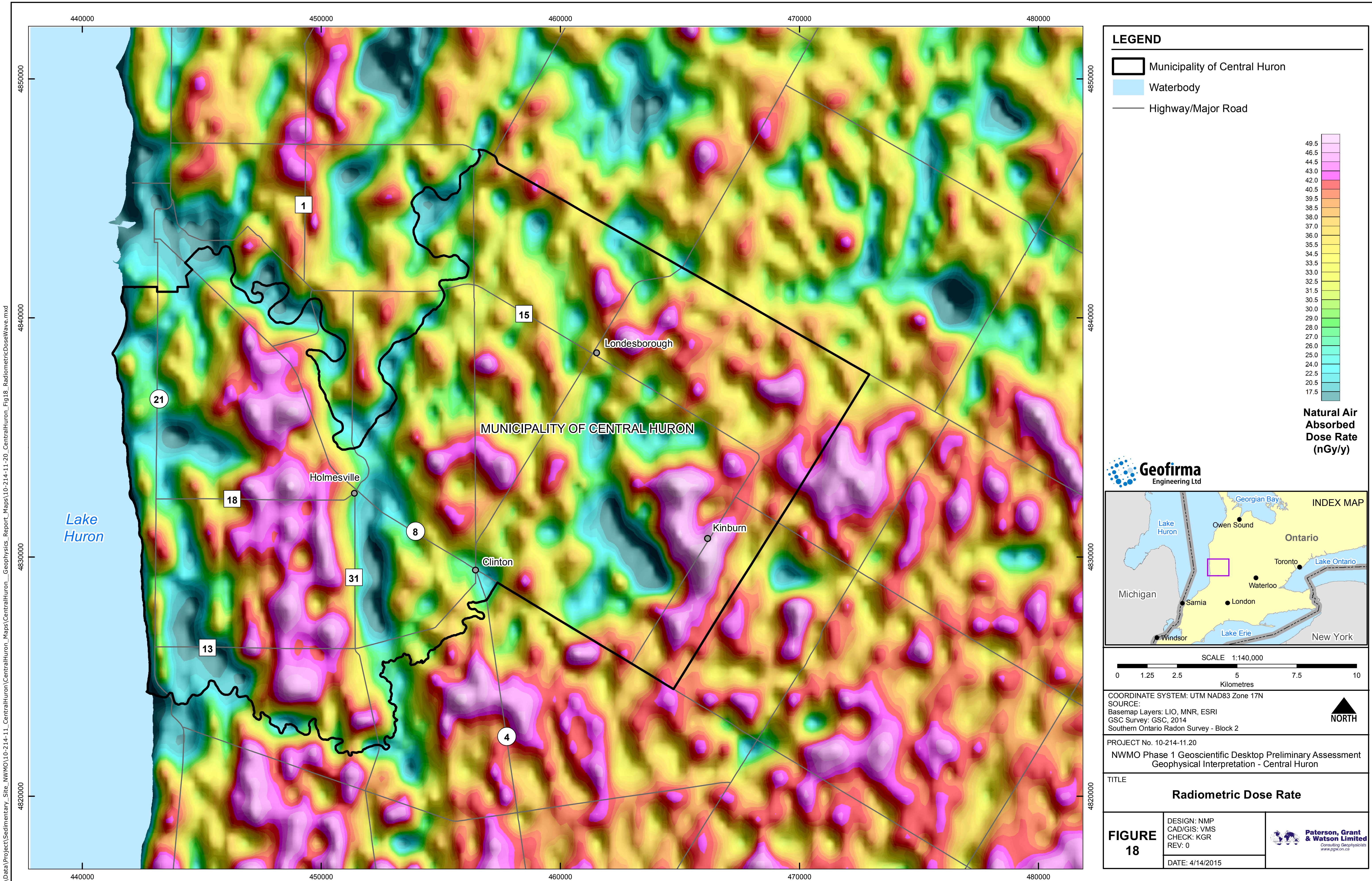


FIGURE 17

Stripped Bouguer Gravity



440000
450000
460000
470000
480000
4850000
4840000
4830000
4820000
Lake Huron
MUNICIPALITY OF CENTRAL HURON
Londesborough
Holmesville
Kinburn
Clinton
1
15
21
18
8
31
13
4
LEGEND
Municipality of Central Huron
Waterbody
Highway/Major Road
49.5
46.5
44.5
43.0
42.0
40.5
39.5
38.5
38.0
37.0
36.0
35.5
34.5
33.5
33.0
32.5
31.5
30.5
30.0
29.0
28.0
27.0
26.0
25.0
24.0
22.5
20.5
17.5
Natural Air Absorbed Dose Rate (nGy/y)
Geofirma Engineering Ltd
INDEX MAP
Georgian Bay
Lake Huron
Owen Sound
Ontario
Toronto
Lake Ontario
Waterloo
Michigan
Sarnia
London
Windsor
Lake Erie
New York
SCALE 1:140,000
0 1.25 2.5 5 7.5 10
Kilometres
COORDINATE SYSTEM: UTM NAD83 Zone 17N
SOURCE:
Basemap Layers: LIO, MNR, ESRI
GSC Survey: GSC, 2014
Southern Ontario Radon Survey - Block 2
NORTH
PROJECT No. 10-214-11.20
NWMO Phase 1 Geoscientific Desktop Preliminary Assessment
Geophysical Interpretation - Central Huron
TITLE
Radiometric Dose Rate
FIGURE 18
DESIGN: NMP
CAD/GIS: VMS
CHECK: KGR
REV: 0
DATE: 4/14/2015
Paterson, Grant & Watson Limited
Consulting Geophysicists
G:\Data\Project\Sedimentary_Site_NWMO\10-214-11_CentralHuron\CentralHuron_Maps\CentralHuron__Geophysics_Report_Maps\10-214-11-20_CentralHuron_Fig18_RadiometricDoseWave.mxd