NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Terrain and Remote Sensing Study

CITY OF ELLIOT LAKE, TOWN OF BLIND RIVER, TOWNSHIP OF THE NORTH SHORE AND TOWN OF SPANISH, ONTARIO

APM-REP-06144-0092

NOVEMBER 2014

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PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT

TERRAIN AND REMOTE SENSING STUDY

CITY OF ELLIOT LAKE, TOWN OF BLIND RIVER, TOWNSHIP OF THE NORTH SHORE AND TOWN OF SPANISH, ONTARIO

NWMO REPORT NUMBER:
APM-REP-06144-0092

October 2014

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EXECUTIVE SUMMARY

In November and December 2012, the City of Elliot Lake, the Town of Blind River, the Township of The North Shore, and the Town of Spanish expressed interest in continuing to learn more about the Nuclear Waste Management Organization nine-step site selection process, and requested that a preliminary assessment be conducted to assess the potential suitability of the area of the four communities safely hosting a deep geological repository (Step 3). This request followed the successful completion of initial screenings for each community conducted during Step 2 of the site selection process.

The preliminary assessment is a multidisciplinary desktop study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. The findings of the overall preliminary assessment are reported in an integrated report (NWMO, 2014a,b,c,d). The objective of the geoscientific desktop preliminary assessment is to determine whether the City of Elliot Lake, the Town of Blind River, the Township of The North Shore, and the Town of Spanish and surrounding areas, referred to as the "area of the four communities", contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

This report presents the findings of a terrain and remote sensing study completed as part of the geoscientific desktop preliminary assessment of the area of the four communities (Golder, 2014). The main information sources used include the CDED elevation model, the SPOT and Landsat satellite imagery, the maps and reports from the Northern Ontario Engineering Geology Terrain Study (NOEGTS), the maps and reports from OGS 1:50,000 scale surficial geology mapping, and borehole and water well data on overburden deposits. The study addresses the following seven objectives:

- Evaluate the nature, areal extent and depth of overburden materials;
- Delineate the areas of exposed bedrock or relatively thin overburden cover;
- Identify features that may preserve evidence of neotectonics;
- Establish the main site accessibility constraints;
- Determine and/or confirm watershed and sub-catchment boundaries;
- Infer groundwater recharge and discharge zones and divides; and
- Infer regional and local groundwater and surface flow directions.

The report provides an overview of the bedrock and Quaternary geology within the area of the four communities, including estimates of local overburden thickness. Surficial deposits outside of the valleys and other depressions are generally thin and discontinuous. The landscape is controlled almost entirely by bedrock topography, with major faults and other lineaments, and major bedrock hills and highlands forming the main landscape elements.

Drainage divides delineated in the provincial quaternary watershed file produced by the Ministry of Natural Resources (MNR) were confirmed and in some cases subdivided using the CDED surface model. All of the surface flow within the area of the four communities is eventually directed towards Lake Huron. Shallow groundwater flow, recharge and discharge will be controlled by topography and the distribution of surficial deposits. Shallow groundwater flow patterns will follow the local surface flow patterns suggested in the detailed watershed mapping.

The main accessibility constraint in the area of the four communities is the complex, steep and irregular morphology of the bedrock surface in many of the areas of thin drift cover. Highways 17, 810, 108, 546 and 129 represent paved highways that provide access to areas within the southern half and along the western margin of the area of the four communities. The most remote part of the area of the four communities is represented by a rectangular zone 40 by 125 km in extent in the northern part of the area. The network of local roads could provide access for preliminary site reconnaissance.

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1 INTRODUCTION

In November and December 2012, the City of Elliot Lake, the Town of Blind River, the Township of The North Shore and the Town of Spanish 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 area of the four communities for safely hosting a deep geological repository (Step 3). The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability; engineering; transportation; environment and safety; as well as social, economic and cultural considerations (NWMO, 2014a,b,c,d).

This report presents the findings of a terrain and remote sensing study completed as part of the geoscientific desktop preliminary assessment of Elliot Lake, Blind River, The North Shore, Spanish and surrounding area, which is referred to as the "area of the four communities" (Golder, 2014). The objective of the geoscientific desktop preliminary assessment is to determine whether the area of the four communities contains general siting areas that are potentially suitable for hosting a deep geological repository based on available geoscientific information and the geoscientific evaluation factors outlined in the NWMO site selection process. The study focused on the four communities and their peripheries.

1.1 OBJECTIVES

This report presents an analysis of the terrain in the area of the four communities using existing remote sensing and geoscientific information sources. The report provides information on the nature and distribution of overburden deposits in the area, and discusses the role of drift deposits in concealing and censoring the lengths of lineaments. The main information sources relied on in this terrain study are the Canadian Digital Elevation Data (CDED) elevation model, the SPOT and Landsat satellite imagery, the maps and reports from the Northern Ontario Engineering Geology Terrain Study (NOEGTS), and the maps and reports from 1:50,000 scale surficial geology mapping programs. Additional data sources included the Water Well Information System, the Ontario Drill Hole Database, the Assessment File Research Imaging (AFRI) database and lake depth data from the Ministry of Natural Resources. This study makes use of remote sensing and geoscientific information sources to address the following seven objectives:

- Evaluate the nature, areal extent and depth of overburden materials;
- Delineate the areas of exposed bedrock or relatively thin overburden cover;
- Identify features that may preserve evidence of neotectonics;
- Establish the main site accessibility constraints;
- Determine and/or confirm watershed and sub-catchment boundaries;
- Infer groundwater recharge and discharge zones and divides; and
- Infer regional and local groundwater and surface flow directions.

These objectives for the area of the four communities were addressed using the data and methodology described in Section 1.3.

1.2 AREA OF THE FOUR COMMUNITIES

The area of the four communities is approximately 114 km by 126 km in size, encompassing an area of about 14,450 km^2 (Figure 1), of which the communities of Elliot Lake, Blind River, The North Shore and Spanish make up 13%. The approximate western, northern, eastern and southern limits of the area of the four communities are (UTM Zone 15, NAD83): 318150, 52255490, 432490, and 5099140 m. The City of Elliot Lake is located in the south-central portion of the area of the four communities. The Town of Blind River is located in the southwestern portion of the area bordering the North Channel of Lake Huron. The Town of Spanish is located in the southeastern portion of the area bordering the North Channel. The Township of The North Shore is located in the southern portion of the area, bordering the North Channel.

1.3 DATA AND METHODS

This section summarizes the remote sensing and geoscientific data sources that were used in the terrain study for the area of the four communities, including an evaluation of the quality of the data. The data sets are all publically available. The processing of selected data sets is described in appropriate sections.

1.3.1 NOEGTS

Overburden deposits within the area of the four communities were mapped as part of a program undertaken between 1977 and 1980 entitled the Northern Ontario Engineering Geology Terrain Study (NOEGTS). These studies divided the landscape into a set of distinct terrain units within which the engineering characteristics are broadly predictable. The terrain units were delineated by identifying landforms from black and white air photos taken in the late 1960s and early 1970s at a scale of approximately 1:50,000. Interpreted terrain units were checked against published and unpublished maps and reports that documented previous field visits and observations. A limited amount of fieldwork was undertaken in 1978, which involved observing terrain conditions from roads in order to corroborate the aerial photo interpretation. The results of the terrain studies were intended to provide a framework for regional planning and a database on which to conduct site studies. In many areas of northern Ontario, including the area of the four communities, maps produced from these programs currently represent the best level of detail available for surficial geology mapping and descriptions of terrain conditions.

The Ontario Geological Survey (OGS) digitized the NOEGTS maps and published the digital data in the form of a miscellaneous release of data (OGS, 2005a). For the current study, JD Mollard and Associates (JDMA) clipped part of the NOEGTS digital map layer and then transformed it from geographic coordinates into Universal Transverse Mercator (UTM) projection (Zone 17).

Nine Northern Ontario Engineering Geology Terrain Studies (Gartner, 1980a,b; Roed and Hallett, 1979d, 1980a,b; VanDine, 1980a,b,c,d) along with ten maps at a scale of 1:100,000 (Gartner, 1978a,b,c; Roed and Hallett, 1979a,b,c; VanDine, 1979a,b,c,d) describe the terrain conditions in the area of the four communities. The reports provide background information on physiography, bedrock geology, Quaternary geology and descriptions of the occurrence and nature of the engineering geology terrain units outlined on the accompanying maps. The terrain reports include estimates of the distribution and thickness of overburden deposits. They also discuss the influence of the terrain conditions on general construction (e.g., location and construction of highways, town sites, waste disposal sites, cottage subdivisions, and airfields), aggregate resource potential (e.g., asphalt aggregate, traffic gravel, base course and sub-base for pavement structures) and groundwater resource potential.

1.3.2 OGS MAPS AND REPORTS

Detailed surficial mapping has been conducted within two of the twenty 1:50,000 scale map sheets that extend into the area of the four communities. Ford (1993b) mapped the surficial geology of the Rawhide Lake area (41 J/10) and provided a useful summary of the physiography and Quaternary geology of the area (Ford, 1991, 1993a). The Rawhide Lake area of Ford (1993b) has been plotted on Figure 3. Henderson and Halstead (1992) mapped and described the surficial geology of the Elliot Lake area (41 J/07), the extent of which has also been plotted on Figure 3. These 1:50,000 scale surficial maps have not been digitized at the time of preparation of this report. As a result, the detailed mapping has not been presented in this report.

1.3.3 CDED

This subsection describes the digital elevation model used to evaluate the terrain in this study. Section 4.2 describes the drainage basin analysis conducted in this study using the CDED elevation model as the representation of the landscape.

Canadian Digital Elevation Data, 1:50,000 scale, 0.75 arc second (20 m) elevation models (GeoBase, 2011a) served as important data sources for analyzing and interpreting the terrain in the area of the four communities. The digital elevation model (DEM) used for this study was constructed by Natural Resources Canada (NRCan) using data assembled through the Water Resources Information Program (WRIP) of the Ontario Ministry of Natural Resources (MNR). The source data were 1:20,000 scale topographic maps generated through the Ontario Base Map (OBM) program, which was a major photogrammetric program conducted across Ontario between about 1978 and 1995. Four main OBM data sets were used: OBM contours, OBM spot heights, the WRIP stream network, and lake elevations derived using the OBM spot heights and OBM water features. CDED data sets are provided in geographic coordinates, referenced horizontally using North American Datum 1983 (NAD83) and vertically based on the Canadian Geodetic Vertical Datum 1928 (CGVD28). Ground elevations are recorded in metres relative to mean sea level.

CDED generally provides a good quality representation of the land surface in high relief areas. However, relatively poor quality representation can be found in flat areas, where the elevation model is, in some instances, based on elevation values obtained from a single elevation contour, with large areas around the contour where elevation values must be interpolated. These areas display a distinct stair-step or terraced pattern in the DEM. Slope values are relatively steep along the margins of these steps, as the step represents an artificially abrupt shift in elevation.

The elevation matrices provided by GeoBase were converted from geographic coordinates to UTM projection using bilinear resampling, which assigns a value to each output cell based on a weighted average of the four nearest cells in the input raster. Compared with cubic convolution, bilinear resampling can sometimes produce a noticeably smoother surface, whereas cubic convolution can produce a sharper image. However, the differences between the two methods are generally trivial and the selection of bilinear resampling made here was arbitrary. After projection, each file was assembled into a single-band mosaic with a 20 m cell size and 32-bit pixel type.

Surface analyses were performed on the digital elevation model in order to characterize slope and relief. Slope was calculated using the standard grid-based method employed in ArcGIS, which involves fitting a plane to the elevation values of a three by three neighbourhood centered on the processing cell. Slope is defined as the maximum slope of that plane, which can also be thought of as the dip of the plane, and aspect is equivalent to the dip direction. Relief was calculated in two ways. The first was by subtracting the average elevation within a radius from the elevation value in the processing cell. The second was defined as the range in elevation within a circular window. The second relief calculation represents a high pass filter. The density of steep slopes was calculated as the number of points with a slope of at least 6° within a 2 km radius. The threshold of 6° was found to be effective in distinguishing between the rugged bedrock-controlled areas and the areas of gentle slope associated with thicker overburden cover.

1.3.4 SPOT

SPOT multispectral orthoimagery at a resolution of 20 m and panchromatic imagery at 10 m resolution formed an important information source for identifying features such as exposed bedrock and wetlands within the area of the four communities (GeoBase, 2011b). SPOT multispectral data consist of several 8-bit bands, each recording reflected radiation within a particular spectral range. SPOT 4 images were acquired using the HRV-IR sensor, while SPOT 5 imagers were acquired using the HRG sensor (Table 1). Each image covers a ground area of 60 km by 60 km.

For quality control, NRCan provides images that have a maximum of 5% snow and ice cover, 5% cloud cover and a maximum viewing angle of 15°. NRCan orthorectified the SPOT images using three data sources: 1:50,000 scale Canadian Digital Elevation Data (CDED), National Road Network, and Landsat 7 orthoimagery. The orthoimages are provided in GeoTIFF format, in UTM projection referenced to NAD83. A comparison of lake shorelines in the SPOT imagery with those delineated in the MNR waterbody file suggests that the georeference is generally accurate to within 20 to 40 m or better.

Nine SPOT images (or 'scenes') provided complete coverage for the area of the four communities (Table 2). The scenes are from the SPOT 4 and 5 satellites, with acquisition dates from 2006 and 2007. Seven of the images were captured during the summer (August), one in the spring (May) and one in the fall (September).

In addition to the use of SPOT imagery, more recent Google Earth imagery (2011) was viewed to assess the extent of exposed bedrock and to interpret the presence of other features such as roads and wetlands. The resolution of the Google Earth imagery available was highest in an area around the City of Elliot Lake and lower in the surrounding area.

Table 1 Characteristics of SPOT 4 and 5 multispectral bands.

Satellite, sensor, band no.	Wavelength (µm)	Pixel size (m)
SPOT 4, HRV-IR, B1	0.50-0.59 (Green)	20
SPOT 4, HRV-IR, B2	0.61-0.68 (Red)	20
SPOT 4, HRV-IR, B3	0.78-0.89 (Near-Infrared)	20
SPOT 4, HRV-IR, B4	1.58-1.75 (Shortwave-Infrared)	20
SPOT 5, HRG, B1	0.50-0.59 (green)	20
SPOT 5, HRG, B2	0.61-0.68 (red)	20
SPOT 5, HRG, B3	0.78-0.89 (near-infrared)	20
SPOT 5, HRG, B4	1.58-1.75 (shortwave-infrared)	20

Table 2 List of SPOT 4 and 5 images acquired.

Scene ID	Satellite	Date of image
S4_08223_4702_20070917	SPOT 4	Sep 17, 2007
S5_08141_4702_20070520	SPOT 5	May 20, 2007
S5_08152_4634_20070816	SPOT 5	Aug 16, 2007
S5_08203_4605_20070816	SPOT 5	Aug 16, 2007
S5_08234_4634_20070805	SPOT 5	Aug 05, 2007
S5_08246_4605_20070805	SPOT 5	Aug 05, 2007
S5_08306_4702_20060811	SPOT 5	Aug 11, 2006
S5_08318_4634_20060811	SPOT 5	Aug 11, 2006
S5_08331_4605_20060811	SPOT 5	Aug 11, 2006

1.3.5 LANDSAT

Cloud-free Landsat 2 coverage for the area of the four communities is available in one scene (NASA Landsat Program, 2013). The sensor onboard the Landsat 2 satellite was the Multispectral Scanner (MSS). Multispectral Scanner data consist of four multispectral bands with a pixel size of 60 m. The acquisition date of the Landsat MSS data was September 8th, 1976. To map rock outcrops using the Landsat MSS data, all four multispectral bands were used as input in a principal component analysis. Campbell (1987) provides more information on the use of principal component analysis in remote sensing. As outcrops could be identified as having high values on the second component, this component was reclassified to produce a preliminary outcrop map, which was then edited to remove roads, utility lines, wetlands, clearcuts and any other non-outcrop areas. Section 5 presents a map of bedrock outcrops derived from the Landsat MSS imagery.

1.3.6 DRILL HOLES AND WATER WELLS

A preliminary review was made of data on overburden thickness obtained from databases compiled by the OGS and the Ontario Ministry of the Environment (MOE). Section 5.1 summarizes the results of the subsurface information reviewed, and Section 5.2 makes further reference to these data in the description of the thickness and character of surficial deposits in the area of the four communities. As Ford (1991) found for the Rawhide Lake map area, the available subsurface data in the area of the four communities in general are far too sparse to enable the development of a comprehensive drift thickness map.

Water well records from the MOE Water Well Information System for the area of the four communities were acquired on 9 September 2013. There are 785 well records contained within the area of the four communities. Many of the wells were not advanced into bedrock or for other reasons the records did not contain data on depth to bedrock. About half (357) of the water well records contain reliable data on depth to bedrock (CODEOB = r). Most of the wells are located in the southern portion of the area of the four communities, concentrated along Highway 17 or within the City of Elliot Lake. The distribution of all water wells is presented in Golder (2014). The water wells were drilled between May 1953 and January 2013.

The Ontario Drill Hole Database was compiled by the Ontario Geological Survey from assessment files, with the most recent official release of the database in December 2005 (OGS, 2005b). A preliminary analysis of the drill hole database was completed during this study. Several assessment files were reviewed to check the drill hole locations and depth to bedrock data and to better understand the terrain conditions in the areas where drilling had taken place. Assessment files are stored in the Assessment File Research Imaging (AFRI) database held by the OGS. Some of the assessment files contain descriptions of overburden cover, site accessibility and other useful information, including photographs of work sites where overburden stripping had taken place. Some of the borehole logs included in the assessment files reported overburden types encountered.

OGS establishes the geographic coordinates of the drill holes using one of a variety of methods, including some approximate georeferencing methods, such as positioning the drill hole in the center of a claim for lack of additional supporting information. Some of the drill hole plans submitted in assessment files are very difficult to interpret. As a result, the location of the drill holes can be off by hundreds of metres in some cases. This makes interpreting the depth to bedrock information in light of terrain conditions interpreted from SPOT imagery difficult, as a distance of 100 to 200 m can mean the difference between a hilltop location and a location between rock ridges where drift would be expected to be thicker.

Within the area of the four communities, the Ontario Drill Hole Database (OGS, 2005b) contains 3,535 records. Most of the drillholes are located in the southern half of the area of the four communities with a distribution that follows the uranium-bearing lithostratigraphic units of the Huronian Supergroup (Golder, 2014). Many of the drillhole records do not contain information on overburden thickness. For example, some of the holes represent holes drilled underground, several do not report a dip angle, and several are missing borehole logs altogether. Some drill holes are known to have been drilled from lake ice platforms, resulting in an inflated depth to bedrock value due to inclusion of the water column in the reported casing length. Such records have been removed from the selection of drill holes summarized in Section 5.1.2.

2 SUMMARY OF GEOLOGY

A detailed discussion of the geological setting of the area of the four communities is provided in Golder (2014). The following sections on bedrock geology, geological and structural history, and Quaternary geology present a summary of that information.

The area of the four communities is underlain by bedrock of the Canadian Shield, a stable craton created from a collage of ancient plates and accreted juvenile arc terranes that were progressively amalgamated over a period of more than 2 billion years. The Canadian Shield forms the stable core of the North American continent, and is composed of several geological provinces of Archean age, which in the area of the four communities, is bordered by the younger Proterozoic-aged Southern Province.

The Superior Province covers an area of approximately 1,500,000 km^2 stretching from the Ungava region of northern Québec through the northern part of Ontario and the eastern portion of Manitoba, and extending south into Minnesota and the northeastern part of South Dakota. The Superior Province is divided into subprovinces, medium- to large-scale regions that are characterized by their similar rock-types, structural style, age, metamorphic grade and mineralization.

The area of the four communities, situated on the north shore of Lake Huron, is underlain by early Proterozoic rocks of the Southern Province and Archean rocks of the westernmost portion of the Abitibi Subprovince of the Superior Province of the Canadian Shield. The Abitibi Subprovince is bounded to the west by the Kapuskasing structural zone (KSZ) and Wawa Subprovince and to the north by the Opatica Subprovince. The southern boundary of the Abitibi Subprovince is overlain by metasedimentary and metavolcanic rocks of the Huronian Supergroup of the Southern Province. The Southern Province is bounded to the southeast by the Proterozoic Grenville Province. Numerous mafic dyke swarms and mapped faults transect the bedrock in the area of the four communities. Figure 2 shows the bedrock geology for the area of the four communities.

The Abitibi Subprovince is exposed in the northern half and much of the eastern side of the area of the four communities (Figure 2). The Abitibi Subprovince is a granite-greenstone-gneiss terrane that was developed between 2.8 and 2.6 billion years ago (Thurston, 1991). It is composed of low metamorphic grade volcanic rocks and granitoid plutonic and gneiss-dominated domains, the latter of which are predominant in the area of the four communities and are represented by the Ramsey-Algoma granitoid complex (e.g., Jackson and Fyon, 1991). The Ramsey-Algoma granitoid complex is a large heterogeneous group of granitic bodies that intruded the older metavolcanic and subordinate metasedimentary rocks of the Whiskey Lake and Benny Lake greenstone belts. Several smaller intrusive bodies are distributed throughout the area of the four communities, including the Cutler pluton, the Seabrook Lake intrusion, the Parisien Lake syenite, and the East Bull Lake intrusive suite, among others (Figure 2).

The Huronian Supergroup underlies the southern portion of the area of the four communities (Figure 2) and consists of a group of metasedimentary rocks (stratigraphically youngest) and lesser (stratigraphically oldest) metavolcanic rocks ranging in age from 2.5 to 2.2 billion years old. The Southern Province also includes the Sudbury Igneous Complex (ca. 1.85 billion years old) located to the east of the area of the four communities, and the metasedimentary and metavolcanic rocks of the Animikie and Sibley Groups that are exposed further to the west, beyond the assessment area, towards Thunder Bay.

2.1 BEDROCK GEOLOGY

Approximately two-thirds of the area of the four communities is underlain by the Ramsey-Algoma granitoid complex, which extends beyond this area to the east, west, and north (Figure 2). The bedrock in the southern third of this area is dominated by metasedimentary rocks and subordinated metavolcanic rocks of the Huronian Supergroup, and an inlier of the Ramsey-Algoma granitoid complex. Rocks of the Huronian Supergroup extend beyond this area to the east and west. Less areally extensive lithologies include thin slivers of greenstone belt affinity (Whiskey Lake and Benny Lake greenstone belts) distributed within the gneissic portion of the granitoid complex. In addition, mafic to ultramafic units of the East Bull Lake intrusive suite, the Parisien Lake syenite, and the Cutler pluton, among other small geological units, are present in the southern third of this area. As well, several generations of mafic dykes and brittle faults crosscut the area of the four communities with the former comprising a volumetrically significant portion of the total bedrock area. All mapped dykes post-date the older Archean rocks; however, as discussed further below, not all dykes post-date the metasedimentary rocks of the overlying Huronian Supergroup.

2.1.1 WHISKEY LAKE GREENSTONE BELT

The Whiskey Lake greenstone belt (Figure 2) consists of Archean metavolcanic and subordinated metasedimentary rocks that form an arcuate, easterly-striking, 10 km by 30 km, synclinal greenstone belt (Rogers, 1992). The greenstone belt has been subdivided into the Whiskey Lake greenstone belt for the portion south of the Folson Lake fault and a northern component named the Ompa greenstone belt (Easton, 2010) for the portion north of the Folson Lake fault. In the interest of simplicity and consistency with earlier nomenclature, the name Whiskey Lake refers to both components in this assessment. Radiometric (^{207}Pb/^{206}Pb) dating from greenstone rocks in the Joubin Township area, located 15 km west of the East Bull Lake intrusion, yielded ages of ca. 2.686 and 2.725 billion years, for upper and lower metavolcanic sequences (Easton, 2010; Easton and Heaman, 2011), while a similar age of 2.689 billion years was obtained from felsic metavolcanic rock of the northern portion of the greenstone belt (Easton, 2010). Drill holes in the Whiskey Lake greenstone belt in the vicinity of Folson Lake (AFRI # 41J08NW0001) indicate a thickness of at least 400 m for the greenstone rocks.

The Whiskey Lake greenstone belt is mostly composed of metavolcanic rocks in its eastern half. Metasedimentary rocks are more abundant in the western part of the greenstone belt. Although the greenstone belt is partly overlain by rocks of the Huronian Supergroup, there are large exposures of Archean greenstone rocks southeast and northwest of the easternmost portion of the Huronian Supergroup located in the vicinity of the City of Elliot Lake (Roscoe, 1969).

The eastern half of the Whiskey Lake greenstone belt consists of inter-layered tholeiitic and calc-alkalic metavolcanic rocks and rare, narrow horizons of bedded chert (Rogers, 1992). The tholeiitic rocks consist of massive and pillow basalt flows usually about 15 m thick. Mafic to felsic pyroclastic rocks, composing the calc-alkalic suite, occur as generally thin, less than 100 m thick, units of fine-grained tuff, exhibiting penetrative schistosity parallel to bedding (Rogers, 1992). These rocks are intruded by Archean gabbro dykes, sills, and stocks across the southern portion of the greenstone belt.

The mafic to intermediate metavolcanic portions of the greenstone belt are well-defined by discrete magnetic highs with a roughly east-west orientation; although, the widespread dyke activity makes it difficult to differentiate the more subtle responses of any felsic metavolcanic and metasedimentary rocks from adjacent rocks of the Ramsey-Algoma granitoid complex or the Huronian Supergroup. A slight gravity high is associated with the greenstone belt, which has a low radiometric response.

2.1.2 BENNY LAKE GREENSTONE BELT

The Benny Lake greenstone belt (Figure 2) consists of Archean metavolcanic and metasedimentary rocks that form an east-striking 40 km long by 5 km wide greenstone belt that extends from the Geneva Lake area to the Mink Lake area, some 70 km northeast of the City of

Elliot Lake. The greenstone belt extends approximately 10 km into the area of the four communities to its mapped termination south of Mink Lake. Card and Innes (1981) described the central part of the belt as consisting of intercalated mafic flows and pyroclastic rocks with intermediate tuffs and tuff-breccia with some volcanogenic metasedimentary rocks including tuffaceous greywake and siltstone, chert, and iron formation. The stratigraphic sequence in this part of the belt comprises cyclic repetitions of mafic, intermediate, and felsic metavolcanics, plus sulphide-bearing tuffs and tuffaceous metasedimentary rocks that commonly lie along contact zones between the metavolcanic units. Outliers of the Huronian Supergroup have also been mapped in the area south of the greenstone belt.

Felsic plutonic rocks are noted to surround and intrude the greenstone rocks. Card and Innes (1981) subdivided these rocks into an older gneissic, granodioritic complex that occurs mainly to the north of the greenstone belt and a younger, relatively massive, homogeneous quartz monzonite that forms most of the terrain to the south, based on mapping carried out in 1973-74. Quartz monzonite, as used in 1973-74, may overlap with a number of fields in the currently used International Union of Geological Sciences (IUGS) classification. Although there is no published information on the age of this greenstone belt, Easton (2010) noted that the ages obtained for the Whiskey Lake greenstone belt mentioned above were consistent with 2.690 to 2.685 billion year old volcanism in the southern part of the Abitibi Subprovince, including the Benny Lake greenstone belt and other greenstone belts in the subprovince.

The greenstone sequence dips steeply to the south with a schistosity subparallel to the primary stratification. Movements on major northwest and north-northwest trending faults such as those along the Spanish River have resulted in progressive northward displacement of the Benny Lake belt from east to west.

The Benny Lake greenstone belt exhibits a similar aeromagnetic response to that of the Whiskey Lake greenstone belt, with the mafic to intermediate metavolcanic portions of the greenstone belt defined by magnetic highs with a roughly east-west orientation. A slight gravity high is associated with the Benny Lake greenstone belt.

2.1.3 RAMSEY-ALGOMA GRANITOID COMPLEX

The Ramsey-Algoma granitoid complex is a large complex of granitoid and gneissic rocks divided in three large domains: Chapleau gneiss domain, Ramsey gneiss domain and Algoma plutonic domain (Jackson and Fyon, 1991). In the area of the four communities, the granitoid complex is dominated by the Algoma plutonic domain. Although some portions of the Algoma plutonic domain have been mapped in detail (e.g., Robertson, 1965a,b,c; Robertson and Johnson, 1965; Giblin, 1976; Giblin et al., 1977), the Algoma plutonic domain is generally not well studied. The Ramsey-Algoma granitoid complex is generally described in the literature as largely consisting of a massive to foliated granite-granodiorite suite intruding a tonalite-granodiorite suite. In addition, several narrow slivers of metavolcanic rock are mapped within the gneissic tonalite portion of the Ramsey-Algoma granitoid complex in the north part of the area of the four communities.

The Algoma plutonic domain consists of granitic and granodioritic rocks and granitic gneisses with numerous greenstone enclaves and massive to foliated granite, granodiorite, and syenite intrusions (Card, 1979); although, a variety of facies have been observed throughout the granitoid complex in the area of the four communities. For example, in the area of Rawhide Lake, about 15 km north of Elliot Lake, the Algoma plutonic domain consists generally of uniform, massive, medium to coarse-grained, equigranular granite (Ford, 1993). About 45 km northwest of Elliot Lake, in the area of Kirkpatrick Lake, the plutonic complex is reported to be predominantly composed of massive to foliated biotite-bearing to hornblende-bearing granitic rock with up to 30% amphibole. Minor, more leucocratic phases are typically quartz monzonite to granodiorite and trondhjemite. Further westward in the Wakomata Lake area, outcrops of pink to grey, equigranular, fine- to coarse-grained trondhjemite, quartz monzonite and granodiorite have been reported, of which grey, medium- to coarse-grained, leucocratic trondhjemite predominates (Siemiatkowska, 1977). Sage (1988) described granitic rock in the Seabrook Lake area as massive, medium- to coarse-grained, red to red-brown, leucocratic, granodiorite to quartz monzonite. In the area of East Bull Lake, Easton et al. (2004) reported mixtures of strongly foliated granitic gneiss and migmatitic facies enclosing mafic gneiss, whereas McCrank et al. (1989) described that area as comprising weakly to moderately foliated granodiorite and porphyroblastic granite. Lastly, Gordon (2012) noted massive, homogeneous syenogranite as the main plutonic phase in Otter Township, located just west of the area of the four communities.

The geophysical interpretation by PGW (2014), based largely on the aeromagnetic data, subdivides the Ramsey-Algoma granitoid complex into distinct anomalies with strongest magnetic responses predominantly associated with areas of mapped granite to granodiorite units, and slightly weaker response associated with the mapped gneissic tonalite units. The geophysical interpretation also identifies low magnetic response where the gneissic tonalite surrounds the Huronian Supergroup. Some of the contacts between the massive granodiorite to granite and the gneissic tonalite, based on the geophysical interpretation, are discordant relative to their mapped surface location. There is also uncertainty in the true location of contacts due to the presence of dykes masking the bedrock response, and the limitation of the data set resolution.

Geochronology for the Algoma plutonic domain includes an age of 2.716 billion years old in the Batchawana area, about 60 km west of the area of the four communities (Corfu and Grunsky, 1987), and 2.662 billion years for the area south of Ramsey, about 20 km northeast of the area of the four communities (van Breemen et al., 2006). Heather et al. (1995) reported a preliminary age of ca. 2.727 billion years for biotite tonalite from immediately south of the Swayze greenstone belt to the northeast of the area of the four communities. More recently, Easton (2010) obtained preliminary dates of 2.675 and 2.651 billion years for two samples of granite and granodiorite near Elliot Lake. The wide range of dates suggests that the Algoma-Ramsey granitoid complex contains distinct plutonic and gneissic lithologies emplaced over a period of 75 million years and possibly longer. This interpretation is supported by van Breemen et al. (2006) who subdivided granitic rocks in the Swayze area, around 120 km north of Elliot Lake, into the following five broad categories:

- Synvolcanic diorite and hornblende tonalite intrusions ranging in age from ca. 2.740 to 2.696 billion years old;
- A transitional suite of tonalite and quartz monzonite intrusions ranging from ca. 2.695 to 2.686 billion years old;
- Syntectonic hornblende granodiorite intrusions ranging from ca. 2.685 to 2.686 billion years old;
- A younger transitional suite of tonalite and quartz monzonite intrusions ranging from ca. 2.680 to 2.665 billion years old; and
- Non-foliated ca. 2.665 billion year old post-tectonic granite intrusions occurring within areas of synvolcanic and syntectonic intrusions.

Although the Swayze area is located further north, it shares a similar tectonic setting to the northern part of the area of the four communities. Van Breeman et al. (2006) may therefore offer an interpretative framework for the largely unmapped Ramsey-Algoma granitoid complex within the northern part of the area of the four communities. Heather et al. (1995) also described a large body of massive Algoma biotite granite in the area southwest of Ramsey that extends into the area of the four communities.

There is only limited data on the thickness of the Ramsey-Algoma granitoid complex in the area of the four communities. Cruden (2006) used gravity and seismic measurements to estimate the regional thickness of late Archean granites to be on the order of 1 to 3 km thick, with the lower value assuming wedge-shaped plutons and the higher value corresponding to a tabular morphology.

2.1.4 SEABROOK LAKE INTRUSION

The Seabrook Lake carbonatite intrusion is located within the northwest part of the area of the four communities some 80 km northwest of the City of Elliot Lake. Sage (1988) described the carbonatite as tadpole-shaped in plan-view, tapering to the south, and occupying an area of approximately 1.5 km^2. The northern portion is dominated by sovite and silicocarbonatite, while rocks of the ijolite suite dominate to the south. The intrusion occurs at the intersection of several regional lineaments, and Sage (1988) speculated that it may represent the southern limit of alkalic magmatism associated with faulting in the Kapuskasing structural zone which lies further to the north.

The carbonatite and ijolite are enclosed within an envelope of brecciated and fenitized granitic rock, which grades outward to an unbrecciated halo of fenitized granitic rocks up to 300 m wide. The granitic rocks are mapped as part of the Ramsey-Algoma granitoid complex and are described at this location (Sage, 1988) as typical of the late Archean granite diapirs found throughout the Canadian Shield. Texturally, the granite is massive, medium- to coarse-grained, red to red-brown, leucocratic, granodiorite to quartz monzonite with modal composition estimated as 35% quartz, 40 to 50% plagioclase, trace to 25% potassium feldspar, and up to 5% biotite. No petrographic evidence of recrystallization and/or metamorphism was noted by Sage (1988).

The granitic rocks enclosing the Seabrook Lake intrusion are crosscut by northwesterly-trending diabase dykes (Matachewan and Sudbury) but these dykes do not crosscut the carbonatite. The intrusion has been dated by K-Ar isotopic techniques at 1.109 and 1.107 billion years old (Gittins et al., 1967).

This intrusion is characterized by a central, east-northeast-striking, magnetic high and spotty magnetic highs beyond its mapped margin.

2.1.5 PARISIEN LAKE SYENITE

The Parisien Lake syenite is a late Archean, 2.665 billion year old (Krogh et al., 1984), elliptical intrusive stock located about 15 km east of the City of Elliot Lake, adjacent to the East Bull Lake intrusion. It measures approximately 13.5 km east-west and 3.3 km at its widest point north-south. The intrusion is composed of medium- to coarse-grained, pink, equigranular monzodiorite, monzonite and syenite (Rogers, 1992). Predominant minerals are K-feldspar phenocrysts, with interstitial amphibole, biotite, sphene, and magnetite, with a distinctive, locally developed K-feldspar alignment (McCrank et al., 1989). The Parisien Lake syenite is shown on Figure 2 as a diorite-monzonite-granodiorite suite. There is no readily available information on the thickness of this intrusion.

The Parisien Lake syenite, with its strong magnetic response, is clearly differentiated from the weakly magnetic East Bull Lake intrusion immediately to the north.

2.1.6 EAST BULL LAKE INTRUSIVE SUITE

The East Bull Lake intrusive suite is located east of the City of Elliot Lake. It consists of a series of east-northeast-trending, elongated gabbro-anorthosite intrusions that were emplaced into Archean metavolcanic and metaplutonic rocks of the Superior Province during the early Proterozoic ca. 2.490 to 2.470 billion years ago (Easton et al., 2004). These intrusions are shown as mafic and ultramafic intrusive rocks on Figure 2. The East Bull Lake intrusive suite comprises three intrusions: 1) the East Bull Lake intrusion, which includes the East Bull Lake pluton and the intrusions to the north of the pluton; 2) the Agnew Lake intrusion; and 3) the May Township intrusion, located near Highway 17 east of the Town of Spanish, which is a thin sheet-like intrusion near the contact between Archean granitic rocks and the Huronian Supergroup.

The elliptical East Bull Lake pluton, about 15 km east of the City of Elliot Lake, has surface dimensions of at least 13.5 km east to west, and a maximum north-south extent of 3.5 km (Figure 2). It is about 780 m thick in its central part (McCrank et al., 1989). The East Bull Lake pluton has a U-Pb isotopic age of 2.480 billion years old (Krogh et al., 1984), and it is divided into several large composite rock units distinguishable by variations in mineral composition, texture, and style of internal layering (McCrank et al., 1982; James et al., 1985; Ejeckam et al., 1985). Within the composite units, mineralogical grading produced layers that grade from gabbro to leucogabbro, rhythmic layers that grade upwards from clinopyroxenite and gabbro, to anorthosite layers and thin, centimetre-sized laminations of clinopyroxenite within gabbroic rock (McCrank et al., 1989).

The main mass of the Agnew Lake intrusion is located about 35 km east of the City of Elliot Lake. It is similar in age and size to the East Bull Lake intrusion, with an estimated U-Pb isotopic age of approximately 2.491 billion years old (Krogh et al., 1984), a thickness of 1 to 2.1 km, and an area of 50 km^2 (Vogel et al., 1998). The primary axis of the Agnew Lake intrusion is east-west, similar to the East Bull Lake intrusion, and is thought to reflect the orientation of the rift structure that permitted magma intrusion (Easton et al., 2004), and would have shaped the Agnew Lake and the East Bull Lake intrusions originally into funnel-like bodies (Vogel et al., 1998). The Agnew Lake intrusion is linked to the East Bull Lake intrusive suite on its northwest side by the Streich dyke, a 200 to 300 m wide gabbronoritic body with a strike length of approximately 10 km (not shown on Figure 2). The Agnew Lake intrusion is a product of four major magma pulses that produced an internal layered distribution of gabbronorite, olivine gabbronorite and leucogabbronorite in the intrusive body, each ranging in thickness from a few tens of metres to hundreds of metres. The Camp Eleven fault bisects the intrusion and exhibits 600 m of dextral displacement of this internal layering (Vogel et al., 1998). The Agnew Lake intrusion was wholly emplaced in granitoid rocks of the Algoma plutonic domain, while the top of this intrusion corresponds to a major disconformity separating the Agnew Lake intrusion from the Huronian Supergroup (Vogel et al., 1998). Also, potentially related to the East Bull Lake suite is the Tennyson sill (Prevec, 1993), an approximately 650 m thick body of medium-grained gabbro north of Massey. The Tennyson sill intruded Archean granodiorite, but is crosscut by Matachewan dykes. Easton (2010) interpreted the Tennyson sill to be a primitive phase of the East Bull Lake intrusive suite.

The East Bull Lake intrusion generally shows a low magnetic response, with some areas of higher intensity towards its west end, reflecting some internal inhomogeneity (Golder, 2014). The northern two lobes mapped for this intrusion show no magnetic contrast with the host rock and have not been separated in the interpretation. The Agnew Lake intrusion shows a local magnetic high in its southeast corner, but otherwise cannot be differentiated from the surrounding massive granodiorite to granite. Local gravity highs (Golder, 2014) are associated with both the East Bull Lake and Agnew Lake intrusions.

2.1.7 CUTLER PLUTON

The Cutler pluton is located south of the City of Elliot Lake (Figure 2) and extends west into Lake Huron (Giblin and Leahy, 1979). The pluton is an elongated muscovite-biotite granitic body with dimensions of approximately 3 km by 28 km. The pluton intrudes both metamorphosed rocks of the Huronian Supergroup and Nipissing intrusive rocks south of the Murray fault (Robertson, 1970; Card, 1978) along the axis of the doubly plunging Spanish anticline (Robertson, 1970). The pluton consists of different intrusive phases, medium- to coarse-grained, foliated quartz monzonite, granodiorite and tonalite. The Cutler pluton was emplaced approximately 1.75 billion years ago after the Penokean Orogeny (Wetherill et al., 1960). There is no readily available information on the thickness of this intrusion.

2.1.8 HURONIAN SUPERGROUP

The Huronian Supergroup (Figure 2) is a stratigraphic sequence that extends for about 450 km from the east shore of Lake Superior to northwest Quebec, with varying thickness of up to 12 km southwest of Sudbury, thinning northward against rocks of the Ramsey-Algoma granitoid complex (Bennett et al., 1991). The Huronian Supergroup surrounds the City of Elliot Lake and overlies rocks of both the Whiskey Lake greenstone belt and the Ramsey-Algoma granitoid complex over large areas. Deposition of the thick Huronian stratigraphic package in a rift setting started approximately 2.497 billion years ago (Rainbird et al., 2006), influenced by Archean tectonic activity and possibly an early Proterozoic extension event, and was later succeeded by a passive-margin setting (Bennett et al., 1991; Young et al., 2001). Deposition ceased sometime before 2.219 billion years ago (Corfu and Andrews, 1986).

The Huronian Supergroup consists of a succession of four lithostratigraphic groups: the Elliot Lake Group is at the base and is overlain, in ascending order, by the Hough Lake, Quirke Lake and Cobalt groups. The Elliot Lake Group forms an eastward-thinning volcano-sedimentary package of uranium-bearing conglomerate beds and sandstone sequences associated with the extensional rifting events (Bennett et al., 1991). The other three groups represent three sedimentary cycles deposited in a continental passive-margin setting, intercalated by periods of Neoproterozoic glaciations (Bennett et al., 1991; Young et al., 2001). Each metasedimentary cycle typically consists of conglomerate, overlain by either mudstone, siltstone or carbonate, and is capped by coarse, cross-bedded sandstone (Roscoe, 1969).

The Huronian Supergroup sequence underwent subgreenschist facies metamorphism that resulted in highly indurated, non-porous quartzite and arkose-greywacke strata. The sequence was gently folded through north–south compression prior to the emplacement of Nipissing diabase intrusions (2.2 to 2.1 billion years ago). The Huronian Supergroup is also intruded by the Cutler pluton (Bennett et al., 1991) and several groups of mafic dykes such as Nipissing, Sudbury and unclassified dykes (Lewis, 2013) described in the section below.

The Huronian Supergroup strata are generally magnetically transparent. The southern part of the Huronian Supergroup shows a slightly higher magnetic response than the northern part, corresponding to the shallower and deeper underlying basement reflected by the Chiblow anticline and the east-west Quirke Lake syncline axes respectively (Johns et al., 2003). Two prominent, broadly north-west trending magnetic highs are observed east of Elliot Lake. The larger of the two anomalies is referred to as the Pecors magnetic anomaly, known to exhibit resource potential. The north-west orientation of these anomalies tends to be broadly coincident with the strike of the Matachewan dyke swarm through the area. Magnetic inversion modelling suggests that the source of the magnetic anomaly is located within the Archean bedrock underlying the Huronian Supergroup units (Hawke, 2011). The east-southeast oriented gravity high, previously described, occurs near the center of the Huronian Supergroup and is aligned with the Quirke Lake syncline. The Huronian Supergroup strata show a mixture of radiometric responses, with higher responses in the Quirke Lake syncline, particularly north and east of Elliot Lake.

2.1.9 MAFIC DYKES

Mafic dykes and intrusions of diabase and gabbroic composition are widespread in and around the area of the four communities (Figure 2). Although the similar composition and texture of these intrusions has hampered the determination of their age and character, most of the studies carried out in the area of the four communities have historically assigned the mafic intrusions and dykes either to the Matachewan or Nipissing suites. More recent studies (Osmani, 1991; Phinney and Halls, 2001) indicate the presence of at least four distinct generations of mafic dyke emplacement: Matachewan swarm, Nipissing intrusions, Biscotasing swarm, Sudbury swarm, North Channel swarm, and younger unclassified dykes (in addition to the local occurrence of highly deformed unclassified mafic dykes of Archean age). The determination of age relationships is further hampered by the widespread occurrence of composite dykes, resulting from multiple injections of magma into the same fracture system (Easton, 2009). Finally, Easton (2010) noted that south of approximately 46°42′N, the Matachewan swarm diabase dykes lose their magnetic character, making their identification based on aeromagnetic response problematic.

The main generations of mafic dykes in the area of the four communities are described in the following subsections.

2.1.9.1 Matachewan dykes

Matachewan diabase dykes are early Proterozoic intrusions ca. 2.473 billion years old (Buchan and Ernst, 2004). These dykes form the oldest and most extensive dyke swarm, cutting the Archean Superior Province rocks, and are characterized by a north-northwest orientation and the display of large phenocrysts of plagioclase in an epidote-rich matrix (Robertson, 1977). Variations can be found in particular areas; for example, in the area of Albanel Township, located approximately 35 km northwest of Elliot Lake, these dykes are equigranular, fine- to medium-grained, composed predominantly of hornblende and plagioclase, and vary in width from 2 to 20 m (Lewis, 2013). In the Pecors-Whiskey Lake area, Easton (2010) noted dyke widths of up to 150 m and identified two compositional groups: non-phyric and plagioclase-phyric with phenocrysts up to 3 mm in size. The majority of the mafic dykes cutting the Archean terrane beneath the northern half of the area of the four communities and south and east of the Quirke Lake syncline are considered to be Matachewan dykes, which have also been related to the East Bull Lake intrusive event and may be related to the basal Thessalon Formation basaltic flow deposits (Vogel et al., 1998; Easton, 2009). The Matachewan dykes in the East Bull Lake area trend northwestward through the Archean terrain of the northern half of the area of the four communities (Figure 2). Easton (2010) noted that in the area south of Elliot Lake, Matachewan dykes constitute roughly 60 to 75% of the mafic dykes exposed in outcrop with this percentage rising to approximately 90% in the Whiskey Lake area. The Matachewan dykes predate the deposition of the sedimentary rocks of the Huronian Supergroup, but they may have served as feeders for the volcanic rocks of the Huronian Supergroup (Buchan and Ernst, 2004), given their similar age and geochemical affinity (Vogel et al., 1998).

2.1.9.2 Nipissing intrusions

The Nipissing intrusions consist of early Proterozoic mafic bodies of irregular sill-like and dyke-like geometry, approximately 2.21 billion years old (Corfu and Andrews, 1986; Palmer et al., 2007). These intrusions post-date the Matachewan dykes and cut both the Archean basement and the folded Huronian Supergroup. In the area of the four communities, mapped Nipissing intrusions are confined to the Huronian Supergroup and adjacent crystalline rocks of the Ramsey-Algoma granitoid complex. These undulating sill-like intrusions are up to around 460 m thick, and roughly parallel the regional east-west structural-stratigraphic trends (Lovell and Caine, 1970; Card and Pattison, 1973; Card, 1976), predominating over much less frequent dyke-like intrusions of tens of metres wide, and other intrusive bodies interpreted as cone sheets (Palmer et al., 2007).

Most of the Nipissing intrusions consist of uniform, undifferentiated quartz diabase; nevertheless, more differentiation exists in the area of the four communities, as quartz diabase and two-pyroxene gabbro appear to be the most common Nipissing intrusive rock type (Lightfoot et al., 1993). Other varieties of Nipissing intrusive rocks consist of olivine gabbro, hornblende gabbro, feldspathic pyroxenite, leucogabbro, granophyric gabbro and granophyre (Card and Pattison, 1973). In the Iron Bridge area (at the intersection of Highway 17 and Highway 546), steeply dipping, metagabbro bodies are dominant (Bennett et al., 1991). The gabbros are massive, but commonly display weak foliations near their contacts with other rocks. Some sills are altered mainly by hydrous fluids produced by the elevated temperature and pressure of regional metamorphism (Card, 1964).

The Nipissing intrusions seem to have been emplaced during at least two magmatic pulses from approximately 2.209 to 2.218 billion years ago (Buchan et al. 1989; Palmer et al., 2007). No major tectonic event has been identified to be the source of the Nipissing intrusive rocks (Bennett et al., 1991), but subduction of oceanic crust with some continental crustal contribution could possibly account for their emplacement (Lightfoot et al., 1993), or a second extensional event (Jackson, 2001). More recently, however, Palmer et al. (2007) suggested that coeval Seneterre dykes acted as feeders for the Nipissing intrusions, mostly based on measurements of anisotropy of magnetic susceptibility and age correlation, but apparently also supported by geochemical affinities.

2.1.9.3 Biscotasing dykes

Biscotasing dykes are prominent, regional northeasterly-trending vertical features that have been identified within the northern half of the assessment area, where they cut rocks of the Archean basement, and further south where they transect the Huronian Supergroup. At the regional scale these dykes extend from the Flack Lake syncline northeast several hundred kilometres to the Lake Abitibi area. The dykes have been dated at 2.167 billion years old (Buchan et al., 1993). These dykes, also formerly referred to as the Preissac dykes, are quartz tholeiitic features usually 50 to 100 m in width, with fine-grained chilled margins and medium- to coarse-grained interiors (Buchan et al., 1993; Halls et al., 2008), which were emplaced along fault structures that possibly pre-date the dykes. Compositionally, the Biscotasing dykes are composed of approximately 50% plagioclase, 30% pyroxene, up to 10% quartz, and several percent magnetite–ilmenite intergrowths. Alteration of the dykes is highly variable from one dyke to another and within individual dykes (Buchan et al., 1993).

2.1.9.4 Sudbury dykes

Archean rocks in the area of the four communities in the vicinity of East Bull Lake intrusive suite are themselves intruded by Proterozoic, post-Nipissing mafic dykes that correlated with the 1.238 to 1.235 billion year old Sudbury dyke swarm (Krogh et al., 1987). These younger dykes typically range in composition from olivine diabase, amphibole diabase, diabase, magnetite-bearing diabase to lamprophyre diabase. All have in common a narrow width, generally less than 10 m, and a west-northwest orientation; they appear to have filled the space of older northwest-trending faults (Easton, 2009). Dykes of this age and composition are scarce or absent within a prism-shaped area of approximately 150 km^2 centered on Elliot Lake (Robertson, 1968; Easton, 2009).

2.1.9.5 North Channel dykes

A suite of west-northwest striking mafic dykes occurs along the southern portion of the area of the four communities. Previously mapped as part of the Nipissing dyke swarm, these dykes are now considered to represent a separate phase of intrusion and they are mapped separately in the most recent seamless geology coverage of Ontario (OGS, 2011) which gives an age range from 1.6 to 2.5 billion years old.

2.1.9.6 Younger dykes

Archean rocks in the area of the four communities are also intruded by younger post-Sudbury dykes including olivine lamprophyres (Siemiatkowska, 1977). These late intrusions were mapped crosscutting the Seabrook carbonatite intrusion (Sage, 1988) suggesting an emplacement age that post-dates ca. 1.1 billion years ago. Easton (2010) also recognized several intrusions in the area of the four communities that could not be confidently assigned to the extensive Nipissing intrusions, one of which seem to correlate with that observed more recently by Lewis (2013) in the Albanel Township area.

2.1.10 FAULTS

Mapped structures in the area of the four communities include large-scale folds, several mafic dyke swarms of different age and orientation, and a mosaic of brittle faults (Figure 2). Their complex present day geometrical arrangement is attributed to the protracted history of tectonic events that has overprinted the area, as described in Section 2.2. At the broader regional scale, additional prominent structures include the Sudbury Igneous Complex, the Kapuskasing structural zone and the Grenville Front tectonic zone. The following paragraphs provide additional details on these structural features.

During the Penokean Orogeny and earlier deformational periods, both the Archean basement and Huronian Supergroup were affected by different degrees of folding, deformation and faulting. The synformal structure of the Whiskey Lake greenstone belt and its belt-parallel foliation is evidence of early structural overprinting related to the Archean amalgamation of the Superior Province. The development of the Quirke Lake syncline, Chiblow anticline and Flack Lake syncline (Figure 2) occurred between approximately 2.219 and 1.8 billion years ago in response to northward compression that included tectonic events attributed to the Penokean Orogeny (e.g., Zolnai et al., 1984; Easton, 2013). The regional scale folding is also evident in the map pattern of the gneissic tonalite suite of the Ramsey-Algoma granitoid complex wrapping around a massive granodioritic to granitic core (e.g., Figure 2).

Several distinct mafic dyke swarms form some of the most prominent geological features within the area of the four communities (Figure 2). These include the northwesterly trending intrusions corresponding to the ca. 2.473 billion year old Matachewan dyke swarm (Buchan and Ernst, 2004). Volumetrically, these are the most prominent dyke swarms in the region and their mapped spacing of about 1 to 3 km may not be indicative of their detailed distribution, as suggested by detailed mapping studies undertaken elsewhere (e.g., Halls, 1982). The Matachewan dykes are orthogonally crosscut by the approximately east-west trending ca. 2.22 billion year old Nipissing intrusions (Corfu and Andrews, 1986); the younger, less frequent, northeasterly trending ca. 2.167 billion year old Biscotasing dykes (Buchan et al., 1993); and the east-northeast trending 2.1 billion year old Kapuskasing/Marathon dykes (not mapped within the area of the four communities). Later emplacement of the ca. 1.238 billion year old Sudbury dyke swarm (Krogh et al., 1987), and a suite of mafic dykes of uncertain affinity and unknown age (ca. 2.5 to 1.6 billion years old) referred to as the North Channel dyke swarm (OGS, 2011), provide evidence of the long and complicated crustal deformation that has occurred in the area of the four communities.

The various mafic dyke swarms are associated with, and overprinted by, regional and local scale brittle fractures or fault systems that are also evident throughout the area of the four communities. The faults include northwest-trending strike-slip faults (e.g., the Spanish American, Pecors Lake and Horne Lake faults) that cut the Huronian Supergroup, and the parallel Nook Lake fault within the Archean basement directly north of the Quirke Lake syncline (Robertson, 1968). These faults locally offset diabase dyke intrusions across some fault traces (Spanish American and Horne Lake faults), and offset diabase sills across others (Pecors Lake fault). Thrust faults also occur in the sedimentary sequence parallel to the axis of the syncline and over-thrusting toward the north such as the Quirke Lake fault (Robertson, 1968).

The regional scale arcuate east-trending Flack Lake fault (Figure 2) extends for about 150 km and transects both the Huronian Supergroup rocks and the Ramsey-Algoma granitoid complex. The Flack Lake fault is interpreted as a north-directed listric thrust that reactivated an earlier normal fault. Its movement history may be related to post-Nipissing and Penokean events (Bennett et al., 1991).

The Murray fault (referred to in the literature by some as the Murray fault zone) is a major east-trending structure that can be traced a few hundred kilometres from Sault Ste. Marie to Sudbury (Robertson, 1967). Within the area of the four communities, the Murray fault parallels the shoreline of Lake Huron (Figure 2) where it is a steeply south-dipping fault zone with approximately 15 to 20 km of reverse sense offset (Zolnai et al., 1984). It records both dextral (Bennett et al., 1991), and sinistral (Abraham, 1953) movement. The Murray fault appears to have been initiated prior to deposition of the Huronian Supergroup, but periodic reactivation occurred synchronous with and after sediment deposition (Reid, 2003; Dyer, 2010). As discussed in Section 2.2, the most recent movement of the Murray fault was during the Grenville Orogeny (Robertson, 1970; Card, 1978; McCrank et al., 1989; Piercy, 2006). North of the fault, the Huronian Supergroup deposits are largely fluvial and accumulated to depths of about 5 km, while south of the fault the deposits are dominated by turbidites that accumulated to depths of 15 to 20 km as reflected by their higher metamorphic grade (Bennett et al., 1991). North of the Murray fault, the Huronian Supergroup is considered largely unmetamorphosed, ranging from sub-greenschist to lower greenschist (Bennett et al., 1991). South of the Murray fault, metamorphism increases to middle greenschist and upward to amphibolite facies (Bennett et al., 1991; Jackson, 2001).

Detailed mapping at the East Bull Lake pluton (Ejeckam et al., 1985) highlights the northwest-trending Folson Lake and East Bull Lake faults, and the east-trending Parisien Lake deformation zone. The Folson Lake fault offsets the East Bull Lake intrusion with approximately 3 km of dextral movement and the fault lineament is traceable for approximately 45 km trending northwest (McCrank et al., 1989). Cataclastic zones up to 10 m wide associated with various episodes of movement and dyke injection were identified and drilling difficulties were experienced where these zones were intersected at depth (McCrank et al., 1989). Some evidence gained from dyke-fault relationships suggests that the Folson Lake fault may have been active prior to the injection of the East Bull Lake intrusion while potassium feldspar (adularia) from a hydrothermal vein suggests reactivation ca. 940 million years ago during a later stage of the Grenville Orogeny. Additional fractures and minor faults occur in several preferred orientations, the most common being subparallel to the Folson Lake fault, to mafic dykes and to topographic lineaments (McCrank et al., 1989). The contact between the East Bull Lake pluton and the Huronian Supergroup seems to be faulted, but this has not been confirmed (Easton et al., 2004). In the Whiskey Lake area, at least some of these faults have been inactive since the Archean Eon as shear zones are cut by Archean granitoid rocks that do not appear to be affected by subsequent deformation (Easton, 2010).

Proximal to the area of the four communities, there are several tectonic features of importance. The north-northeast-trending KSZ is an approximately 150 km wide by 500 km long fault-bounded block, located to the northwest of the area of the four communities, which subdivides the Superior Province into eastern and western halves (Percival and West, 1994). The KSZ consists of Archean granulite facies metasedimentary rocks derived from a lower crustal environment (high pressure and temperature) that was brought to higher levels in the crust along the major westward dipping thrust fault and shear zones during the Penokean Orogeny (Percival and West, 1994). The maximum uplift along the fault zone is in the order of 30 to 40 km based on the granulite metamorphic facies of the zone being brought into juxtaposition with greenshist facies rock. Continued tectonic activity in proximity to the KSZ is evidenced by the emplacement of alkalic complexes as recently as ca. 1.1 billion years ago (Sage, 1991). The ca. 1.85 billion year old Sudbury Igneous Complex, located east of the area of the four communities, is generally considered to represent the scar of a meteorite impact event that occurred during the Penokean Orogeny (Young et al., 2001). The Grenville Front tectonic zone, located to the southeast of the area of the four communities represents the mapped northwestern boundary of rocks affected by the Grenville Orogeny. While acknowledging their existence, it is unclear what effect the development of these regional structures had on the local structural complexity of the area of the four communities.

2.1.11 METAMORPHISM

Studies on metamorphism in Precambrian rocks across the Canadian Shield have been summarized in several publications, including Fraser and Heywood (1978), Kraus and Menard (1997), Menard and Gordon (1997), Berman et al. (2000), Easton (2000a,b), Holm et al. (2001) and Berman et al. (2005). The thermochronologic record for major parts of the Canadian Shield is given in a number of studies such as those by Berman et al. (2005), Bleeker and Hall (2007), Corrigan et al. (2007), and Pease et al. (2008). Overall, most of the Canadian Shield, outside of unmetamorphosed late tectonic plutons, contains a complex episodic history of tectonometamorphism largely of Neoarchean age with broad tectonothermal overprints extending from the Paleoproterozoic to the end of the Grenville Orogeny approximately 0.95 billion years ago.

The Superior Province largely preserves low pressure – low to high temperature Neoarchean metamorphism from ca. 2.710 to 2.640 billion years ago, but there is a widespread tectonothermal overprint of the Archean crust by Paleoproterozoic deformation and typically amphibolite facies metamorphism across the Churchill Province through northernmost Ontario under the northern Hudson Bay Lowland, western Manitoba, northern Saskatchewan and Nunavut (e.g., Skulski et al., 2002; Berman et al., 2005).

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

Subgreenschist facies metamorphism in the Superior Province is restricted to limited areas, notably within the central Abitibi greenstone belt (e.g., Jolly, 1978; Powell et al., 1993) and locally within the Uchi Subprovince (Thurston and Paktunc, 1985). Most late orogenic shear zones in the Superior Province experienced lower to middle greenschist retrograde metamorphism. Post-metamorphic events along faults in the Abitibi greenstone belt show a drawn-out record through $^{40}Ar/^{39}Ar$ dating to ca. 2.50 billion years ago (Powell et al., 1995). The distribution of contrasting grades of metamorphism is a consequence of relative uplift, block rotation and erosion from Neoarchean orogenesis and subsequent local Proterozoic orogenic events and broader epeirogeny during Proterozoic and Phanerozoic eons.

Metamorphic grade in the area of the four communities is largely of subgreenschist facies north of the Murray fault, east and north of Blind River. South of the fault (Piercey, 2006), metamorphism increases to localized lower amphibolite facies extending eastward between Blind River, Sudbury and the Grenville Front (Riller et al., 1999). Most authors (e.g., Zolnai et al., 1984) have considered the medium grade metamorphism reached south of the Murray fault to be a product of tectonothermal burial. However, Jackson (2001) pointed out that the high temperature-low pressure metamorphism reached could not be solely the result of burial, and he advanced the alternative of a second period of crustal extension in the area of the four communities. This hypothesis would not only account for the required heat for medium grade metamorphism but would also explain the emplacement of Nipissing intrusions. Holm et al. (2001) suggested that peak Penokean Orogeny metamorphism occurred ca. 1.835 billion years ago, based on monazite ages. More recently, Piercey (2006) pointed out that the Penokean Orogeny was only the first of several accretionary events that impinged on the southern Laurentide margin and presented evidence of a younger and more significant, ca. 1.7 billion year old, metamorphic event possibly related to the Yavapai tectonothermal pulse. This event may have affected the metamorphic conditions in the area of the four communities and possibly increased the metamorphic overprint to greenschist facies, at least in the area proximal to the Cutler pluton, on the north side of the Murray fault. Also north of the Murray fault, Fedo et al. (1997) pointed out that a ca. 1.7 to 1.75 billion years ago metasomatic event is evident in potassic and sodic alterations of the Huronian Supergroup. This event is probably what replaces most metamorphic minerals in the Huronian Supergroup with white mica and is presumably related to fluid-flow driven by post-orogenic uplift of the Penokean Orogeny. Minor contact metamorphism exists in the metavolcanic rocks of the greenstone belt near some of the large Proterozoic mafic intrusions (Rogers, 1992).

2.2 GEOLOGICAL AND STRUCTURAL HISTORY

The geological and structural history of the area of the four communities spans almost 3 billion years and includes both Archean and Proterozoic orogenic events, periods of intense felsic and mafic intrusive activity, and complex brittle deformation. The geological history is moderately well understood in the south where the Huronian Supergroup is exposed, but is less well constrained for the underlying Archean Ramsey-Algoma granitoid complex further to the north and east. The geologic and structural history is discussed below and summarized in Table 3. The discussion integrates the results from studies undertaken mainly within and proximal to the Huronian Supergroup, augmented by studies within the Swayze area (van Breemen et al., 2006), approximately 120 km north of Elliot Lake, to present an integrated geological and structural history for the area of the four communities.

The oldest rocks in the area of the four communities include the isolated greenstone belt slivers of the ca. 2.725 to 2.686 billion year old Whiskey Lake and Benny Lake greenstone belts, which are themselves intruded by and deformed with the Ramsey-Algoma granitoid complex. Geochronology for the Ramsey-Algoma granitoid complex spans the period between ca. 2.716 and ca. 2.651 billion years (Corfu and Grunsky, 1987; Easton, 2010), indicating that these rocks were emplaced and deformed during the same cratonization event that is characteristic of the regional scale deformation history of the Superior Province.

At the beginning of the Proterozoic Eon, approximately 2.5 billion years ago, an Archean supercontinent (Williams et al., 1991) began fragmentation into several continental masses, including the Superior craton, caused by a widespread and voluminous magmatic event that took place in the Lake Superior region (Heaman, 1997). This magmatic event is associated with rifting and intracratonic development of basins in many areas across the Lake Superior region. Major regional-scale faults such as the Murray and Flack Lake faults were likely formed during the rifting event or represent pre-existing structures reactivated during rifting.

Continental extension at the southern margin of the Superior craton, particularly in the Lake Huron area, allowed intrusion of coeval and comagmatic, mafic-ultramafic geological units such as the ca. 2.49 to 2.47 billion year old Agnew Lake and East Bull Lake intrusions, and contemporaneous to slightly younger (ca. 2.473 billion year old) Matachewan dyke swarm (Vogel et al., 1998; Buchan and Ernst, 2004; Easton, 2009). The timing of intrusion of the mafic and ultramafic units is also approximately contemporaneous with deposition of the basal volcanic rocks of the Huronian Supergroup (Rainbird et al., 2006) upon the Archean basement. The current areal extent of the intrusions likely represents the deformed and erosional remnants of one or more sill-like bodies that may originally have formed an extensive and interconnected mafic sheet (Vogel et al., 1998); similarly, the original extent of the volcanic rocks was much greater than that which is exposed today (Easton, 2010).

The area of the four communities was overprinted by a poorly understood tectonic event, the Blezardian Orogeny, during deposition of the metavolcanic and overlying metasedimentary rocks of the basal portion of the Huronian Supergroup from source regions to the east and northeast

(Rainbird et al., 2006). The Blezardian event is interpreted to represent a short-lived orogenic pulse within a larger extensional tectonic setting (Schneider and Holm, 2005). The Blezardian Orogeny is interpreted to have been underway between ca. 2.47 and 2.4 billion years ago (Riller et al., 1999), and ended before ca. 2.30 billion years ago (Raharimahefa et al., 2011; Hoffman, 2013). It was characterized by the development of rifted and structurally-controlled depressions that themselves controlled the deposition of the basal portion of the Huronian Supergroup (Riller et al., 1999; Young et al., 2001). The Blezardian Orogeny is also thought to have initiated the map-scale thick-skinned folding of the Archean basement and rocks within the basal portion of the Huronian Supergroup (Riller et al., 1999).

The rift setting ultimately evolved into a passive margin setting, reflective of a more advanced stage of ocean-opening conditions of a Wilson cycle (Young et al., 2001; Bekker et al., 2005) during deposition of the remainder of the Huronian Supergroup. Deposition continued until between ca. 2.22 and 2.10 billion years ago (Corfu and Andrews, 1986) when rocks of the Archean basement and the Huronian Supergroup were pervasively intruded by the ca. 2.2 to 2.1 billion year old Nipissing intrusions (Lightfoot et al., 1993). The area of the four communities was subsequently overprinted by the Penokean Orogeny that occurred ca. 1.89 to 1.84 billion years ago (Sims et al., 1989). At the regional scale, the Penokean Orogeny is marked first by the beginning of ocean closure and development of the Pembina-Wasau volcanic arc terrane ca. 1.889 to 1.860 billion years ago (Sims et al., 1989), which was later accreted to the southern margin of the Superior craton in the Lake Superior area (ca. 1.860 billion years ago). This was followed by indentation of the Marshfield terrane ca. 1.840 billion years ago in what is today part of Wisconsin and Illinois (Sims et al., 1989; Schulz and Cannon, 2007). Whether either the Pembina-Wasau terrane or the Marshfield terrane extended to the Lake Huron area, or whether in this latter area the oceanic crust was subducted, remains unknown (Riller et al., 1999). In the Lake Huron area, the Penokean Orogeny involved the reactivation of pre-existing listric normal faults, such as the Murray and Flack Lake faults, enhancement of the pre-existing (Blezardian) folds in the basement and cover rocks, and the northward thrust of rocks of the Huronian Supergroup. Together, these deformation events produced burial depths of up to 15 km for the basal rocks of the Huronian Supergroup (Zolnai et al., 1984). An associated metamorphic overprint was insignificant to the north of the Murray fault, where sub-greenschist facies assemblages are preserved. Amphibolite facies were reached southward of the Murray fault (Piercey, 2006), but seem to be associated with younger tectonothermal pulses such as the Yavapai Orogeny, which occurred ca. 1.75 billion years ago (Piercey, 2006).

In addition, there may be structural overprinting along the eastern part of the area of the four communities resulting from the ca. 1.85 billion year old emplacement of the Sudbury Igneous Complex. The Sudbury Igneous Complex is generally considered to represent the scar of a meteorite impact event that occurred during the Penokean Orogeny (Young et al., 2001). Breccias within metamorphosed argillites of the Huronian Supergroup are known from the Whitefish Falls area approximately 70 km southwest of Sudbury and slightly to the southeast of the area of the four communities. These are attributed (Parmenter et al., 2002) to the Sudbury impact event and their distance suggests a diameter in excess of 200 km for the entire impact ring structure. Similar estimates are given by Thompson and Spray (1996) who inferred an original diameter of as much as 250 km for the Sudbury structure based on the distribution of pseudotachylyte. This distance encompasses the eastern third of the area of the four communities and structures related to the Sudbury impact may therefore be present within the area.

Around 1.238 to 1.235 billion years ago, a swarm of dykes intruded the bedrock in the area of the four communities. These are the Sudbury swarm mafic dykes which crosscut all bedrock units in the area of the four communities. The effects of later orogenic events, such as the Grenville Orogeny (ca. 1.250 to 0.980 billion years ago), remain unknown in the area of the four communities; although, towards the Grenville Front (the northwesternmost boundary of the area defining the Grenville Orogeny), the pre-existing mafic dykes are deformed and disrupted from their through-going nature further away from this young orogenic belt.

Around ca. 1.1 billion years ago, a continental-scale rifting event in the Lake Superior area produced the Midcontinent Rift structure (Van Schmus, 1992) that extends southward via an eastern branch down through Minnesota, and via a western branch from Sault Ste. Marie to central Michigan. The rifting event included deposition of large volumes of volcanic rocks and voluminous emplacement of mafic intrusions (Heaman et al., 2007).

Uplift and erosion of bedrock occurred over a protracted period following the rifting event such that at the end of the Precambrian Eon (ca. 540 million years ago), the folded and faulted terrain of the area of the four communities had been eroded to a peneplain roughly approximating the bedrock surface seen today over much of the area. Resistant strata of the Huronian Supergroup formed topographic ridges that persist to the present time, such as the La Cloche Mountains near Espanola. During the Paleozoic Era, commencing in the late Cambrian to early Ordovician Periods, most, perhaps all, of the area of the four communities was submerged beneath shallow seas and overlain by flat-lying carbonate and shale formations. Subsequent uplift and erosion during the late Paleozoic/Mesozoic eras stripped the Paleozoic cover from the area of the four communities. Weathering and erosion of the re-exposed Precambrian surface continued throughout the Cenozoic Era.

Table 3 Summary of the geological and structural history of the area of the four communities.

Approximate Time Period (billion years ago)	Geological Event
2.72 to 2.651	Kenoran Orogeny: • Emplacement and deformation of the ca. 2.72 to 2.68 billion year old Whiskey Lake and Benny Lake greenstone belts and ca. 2.716 to 2.651 billion year old Ramsey-Algoma granitoid complex. Intrusion of the ca. 2.665 billion year old Parisien Lake syenite. • Development of folds and east-trending foliation in the greenstone belts (ca. 2.72 to 2.70 billion years ago). [D_1]
<2.651 to 2.5	• Early (re)activation of NE-, ENE-, WNW- and NW-striking faults (e.g., Murray and Flack Lake faults) [D_2]
2.497 to 2.47	Onset of continental break-up [D_3]; rifting in many areas across Lake Superior. • Deposition of volcanic rocks and basal sedimentary rocks of the Huronian Supergroup. • Reactivation, or continued activity, of WNW- to NW- and E-striking faults. Widespread mafic magmatism, and emplacement of: • Agnew Lake intrusion and East Bull Lake intrusion 2.49 to 2.47 billion years; ca. 2.473 billion years Matachewan dyke swarm.
2.47 to > 2.3	Blezardian Orogeny. [D_4] • Thick-skinned folding of Archean basement and basal rocks of the Huronian Supergroup. Initiation of Quirke Lake syncline and Chiblow anticline.
< 2.3 and > 2.1	Transition to passive margin setting; • Continued deposition of sedimentary rocks of Huronian Supergroup. • Emplacement of ca. 2.2 to 2.1 billion year old Nipissing diabase intrusions and ca. 2.17 to 2.15 billion year old Biscotasing dyke swarm.
2.10 to 1.89	Denudation of bedrock and formation of peneplain.
1.89 to 1.84	Penokean Orogeny. [D_5] • Crustal shortening and development of thrust-and-fold belt in rocks of the Huronian Supergroup, buckling and faulting of Archean basement. • Subgreenschist and amphibolite grade metamorphic overprint to north and south of Murray fault, respectively. • Emplacement of the Sudbury Igneous Complex ca. 1.85 billion years ago.
1.75 to 1.7	Emplacement of ca. 1.7 billion years Cutler pluton and metamorphic overprint south of Murray fault. Ca. 1.75 to 1.7 billion years ago, a metasomatic event of the Huronian Supergroup (Fedo et.al., 1997).
1.238 to 1.235	Emplacement age of Sudbury dyke swarm and related intrusions of unclassified olivine diabase dykes.
1.25 to 0.98	Grenville Orogeny (overprint in area of the four communities is unclear) • Development of Midcontinent Rift (ca. 1.1. billion years ago) (D_6)
< 1.1 to present	ca. 1.1 to 0.54 billion years ago: denudation of bedrock, formation of peneplain (continuation of D_6). Post-0.54 billion years ago: sedimentation, erosion, ingression and regression of sea water, shallow sea, glaciations. Exhumation of peneplain.

The area of the four communities was glaciated during the Pliocene-Pleistocene ice ages when a series of continental ice sheets moved southward across the area (Barnett et al., 1991; Reid, 2003). The advance of the ice sheets and subsequent outwash of meltwaters during glacial retreat scoured the bedrock surface, removing residual soil and weathered rock, and exposing fresh polished bedrock surfaces. Glacial erosion may have enhanced the numerous geological linear features that characterize the area of the four communities where deeper residual soils and weathered rock occurred in association with faults, dykes and formational contacts (e.g., greenstone/granite contacts) of contrasting hardness. This erosion established drainage patterns and lakes which tend to follow the various structural lineaments.

The structural history in the area of the four communities is complex. Recent geologic investigations within the area of the four communities and its vicinity conclude that the region has undergone complicated polyphase deformation (e.g., Card et al., 1972; Young, 1983; Riller et al., 1999; Jackson, 2001; Easton, 2005). The most comprehensive studies on the structural geology of the area of the four communities and its vicinity have been carried out by Zolnai et al. (1984), Riller et al. (1999) and Jackson (2001). These and other investigations documenting the structural geology of particular portions of the area of the four communities (e.g. Easton, 2005) support the existence of two main deformation events which have overprinted all bedrock lithologies. These have been assigned to the aforementioned Blezardian and Penokean orogenies. It should be noted, however, that the occurrence of the Penokean Orogeny in the area of the four communities remains controversial with some authors (e.g. Davidson et al., 1992; Piercey et al. 2003).

It is understood that there are potential problems in applying a regional deformation numbering (Dx) system into a local geological history. Nonetheless, the following summary offers an initial interpretation for the area of the four communities, which may be modified in future if site-specific information is collected.

The earliest deformation phase (D_1) is associated with ca. 2.72 to 2.7 billion year old penetrative deformation of rocks of the Whiskey Lake greenstone belt. According to Jensen (1994), this penetrative deformation is represented by foliation closely paralleling the strike and dip of the metavolcanic and metasedimentary strata composing the greenstone belt. The foliation was likely developed concurrent with folding which is expressed by a west-northwest-trending, isoclinal syncline that strikes about 110^{o}E and dips approximately 70^{o}NE. Recently, Easton (2010) reported the existence of an east-trending shear zone apparently overprinting only the greenstone rocks. Later truncation of the foliation by plutonic material indicates that much of this deformation occurred prior to at least the youngest phase of emplacement of the ca. 2.716 to 2.651 billion year old Ramsey-Algoma granitoid complex (Jensen, 1994).

Subsequent to emplacement of the Ramsey-Algoma granitoid complex, a series of northeast-striking sinistral strike-slip faults and later subvertical, east-northeast-striking faults exhibiting sinistral-oblique movement were formed along the margins of the greenstone belts. The earliest activation along regional east-trending faults, such as the Murray and Flack Lake faults, is attributed to this deformation. This early faulting episode, defined herein as the D_2 event, is poorly constrained to have occurred between ca. 2.651 and 2.5 billion years ago.

Subsequently, a large-scale rifting event (D_3) overprinted the area of the four communities in association with the ca. 2.497 to 2.47 billion year old break-up of the Superior Craton (Williams et al., 1991). This deformation event also involved continued activation along regional faults, including the Murray and Flack Lake faults, and overlapped in time with the deposition of the basal volcano-sedimentary rocks of the Huronian Supergroup (Jensen, 1994). These faulting episodes also involved dextral, west-northwest- to northwest-striking fault reactivation crosscutting the earlier formed structures throughout the Huronian Supergroup (Jackson, 2001). These younger faults also cut the Archean basement and the Murray fault (Jackson, 2001). Alternatively, Jensen (1994) and Jackson (2001) suggested that some of the faults in the area of the four communities may have initiated as Archean structures that subsequently experienced a long history of reactivation during and post-dating the Penokean Orogeny.

D_3 also overlaps in time with the widespread emplacement of mafic intrusions such as the Agnew Lake intrusion and the East Bull Lake intrusive suite (Vogel et al., 1998; Easton, 2009), as well as the pervasive Matachewan dyke swarm. Numerous, narrow, discontinuous shear zones that range from east-northeast to east-southeast in strike, cut the volcanic rocks of the Huronian Supergroup suggesting that east-trending faulting continued during the period of volcanism (Jensen, 1994). As well, the Flack Lake fault and the Murray fault continued as down-to-the-south syn-sedimentary growth faults during the formation of the Huronian Supergroup (Zolnai et al., 1984) while the Neoarchean dextral, west-northwest to northwest faults were reactivated.

The Blezardian Orogeny is assigned as the fourth deformation event, D_4, in the area of the four communities. The Blezardian Orogeny produced steeply south-dipping reverse faults and upright, kilometre-scale folds (Zolnai et al., 1984). Riller et al. (1999) interpreted the initial development of the Quirke Lake syncline and the Chiblow anticline to be attributed to the Blezardian event. As mentioned, the timing of the Blezardian Orogeny is poorly constrained. It is thought to have occurred between ca. 2.4 (possibly as early as 2.47 billion years ago), and 2.3 billion years ago (Riller et al., 1999; Raharimahefa et al., 2011).

The ca. 1.89 to 1.84 billion year old Penokean Orogeny represents a fifth deformation event, D_5. Riller et al. (1999) contended that the Penokean Orogeny in the area of the four communities involved dextral shearing and horizontal shortening. Jensen (1994) also noted that east-northeast faults in the Archean basement and Huronian Supergroup near the Whiskey Lake greenstone belt were reactivated at this time. Crustal shortening and fault reactivation enhanced the previously buckled (Blezardian) structure of the Archean basement and further compressed, folded and faulted rocks of the Huronian Supergroup, so that overlapping thrusted blocks stacked up to possibly 15 km in burial thickness (Zolnai et al., 1984). Penetrative deformation features, included cleavage, stretching lineation and rotation of tectonic fabric to a near-vertical orientation, and development of medium to high grade metamorphic assemblages (south of the Murray fault) were developed at this time (Zolnai et al., 1984). Northwest-trending strike-slip faults such as the Spanish American, Pecors Lake and Horne Lake faults that cut the Huronian Supergroup sequence and the parallel Nook Lake fault within the Archean basement directly north of the Quirke Lake syncline (Robertson, 1968), may have been formed during the Penokean Orogeny, or they may be reactivated Archean faults as suggested by Jackson (2001). The effect that the syn-Penokean meteorite impact, which produced the Sudbury Igneous Complex, had on the geological and structural evolution of the area of the four communities is unclear.

Deformation associated with the Grenville Orogeny, ca. 1.250 to 0.98 billion years ago, is considered the next major deformation episode, D_6, in the area of the four communities. In spite of the scarcity of evidence and problems of deformation overprinting and fault reactivation, it seems that the Murray fault remained active or was reactivated during this orogeny (Robertson, 1970; Card, 1978; McCrank et al., 1989; Piercey, 2006). The Midcontinent Rift (ca. 1.1 to 1.0 billion years ago) was developed contemporaneously with the long-lived Grenville Orogeny and is also included as part of D_6, although its effect on the area of the four communities is not known. There is poor control on any subsequent fault reactivation in the area of the four communities. Therefore all possible post-Grenville fault reactivation is included as part of a protracted D6 event.

2.3 Quaternary Geology

The Quaternary geology of the area of the four communities is dominated at surface by different types of glacial deposits that accumulated with the progressive retreat of the ice sheet during the end of the Wisconsinan glaciation. This period of glaciation began approximately 115,000 years ago and peaked about 21,000 years ago, at which time the glacial ice front extended south of Ontario into what is now Ohio and Indiana (Barnett, 1992).

Overburden deposits within this area were mapped as part of the Northern Ontario Engineering Terrain Study (NOEGTS), a program undertaken between 1977 and 1981 (Gartner, 1978a,b,c; 1980a,b; Roed and Hallet, 1979a,b,c,d; 1980a,b; VanDine, 1979a,b,c,d; 1980a,b,c,d; Gartner et al., 1981). These studies divided the landscape into a set of distinct terrain units within which the engineering characteristics are broadly predictable. Major landforms mapped by the NOEGTS program are shown on Figure 3. The area of the four communities is dominated by exposed bedrock or bedrock having only a thin mantle of unconsolidated sediments. Quaternary deposits are predominantly located in bedrock-controlled valleys. Figure 3 also illustrates several east-west trending morainic belts postulated by Boissonneau (1968), which mark successive positions of the ice front. In the area of the four communities, these include the Whiskey Lake, Rawhide Lake, Cartier I, Cartier II, Cartier III (not shown) and Obabika Lake moraines.

Data on ice flow direction compiled from the literature (Karrow, 1987) reveal that glacial ice flowed in a generally southwesterly direction across the area of the four communities from the Hudson Bay basin. Ford (1993a) recognized two dominant orientations in glacial striations, lunate fractures, drumlinoid features, and till flutings in the Rawhide Lake area to the north of the City of Elliot Lake. These are recorded as 175° (165 to 180°) and 195° (190 to 210°). At three sites, older 100 to 120° striations were found intersecting either the 175 or 195° sets.

The most widely occurring and oldest known stratigraphic unit in the area is a silty sand to sandy silt till found overlying bedrock in low relief areas and along the flanks of topographic lows. It is typically thin and discontinuous and is coarse-textured, unsorted, and boulder-rich, although there are some areas of compact, massive to fissile and gravelly to silty and sandy till (Barnett et al., 1991). Glaciolacustrine sediments have more limited distribution and are limited to only very small, mappable, surficial units (Ford, 1993a) largely along river valleys. These units, typically composed of laminated silt and fine sand and silt-clay rhythmites, may be related to the series of postglacial lakes of the Lake Huron basin.

Deposits of glaciofluvial outwash and ice-contact stratified drift are commonly encountered along valleys in the area of the four communities. Ice contact deposits are composed of variable quantities of sand, gravel, and boulders, locally with minor silt and/or till in the form of small moraines. Glaciofluvial outwash is common in low-lying areas and occasionally in esker ridges with the local formation of terraces related to changing lake levels in the Lake Huron basin. Thick deposits of alluvial sand and gravel are found along many of the rivers in the region. Recent swamp, lake, and stream deposits are also common throughout the area.

The northward retreat of the ice sheet in the area of the four communities started approximately 12,000 years ago between the Onaway Advance (11,800 years ago) and the Marquette Advance (10,000 years ago). Ice retreat took place as Lake Algonquin spread northward, leaving a series of shorelines during isostatic uplift and opening of the sequence of outlets near North Bay, Ontario.

The high water level associated with Lake Algonquin has been mapped between 309 and 312 m above present day sea level (Cowan, 1976; 1985). Lower strand sequences are interpreted as recessional strands representing falling Lake Algonquin water levels as the retreating Laurentide ice sheet exposed a series of outlets south of North Bay. These recessional beaches are believed to have formed between about 10,400 and 10,000 years ago, and some strands may actually represent single storm events (Cowan and Bennett, 1998). After the opening of a very low-level outlet at North Bay after 10,000 years ago, water levels in the Huron-Michigan basin dropped to more than 100 m below present levels, creating two smaller water bodies: Lake Stanley in the main Huron basin and Lake Hough in Georgian Bay (Eschman and Karrow, 1985).

Over time, isostatic uplift continued to raise the North Bay outlet, and by about 7,500 years ago, the Huron-Michigan and Superior basins became confluent again. The St. Marys River thus became the St. Marys Strait connecting the three upper Great Lakes. Ongoing uplift closed the North Bay outlet around 5,500 years ago, restoring high-level outlets at Chicago and Port Huron and initiating the Nipissing phase in the upper Great Lakes. The Nipissing transgression is marked by buried wood and peat 7,300 to 5,900 years old and by the development of a prominent shoreline above the present lake level. Information on the thickness of Quaternary deposits in the area of the four communities was largely derived from a small number of water well records for rural residential properties, a small number of water well records along the highways, and from diamond drill holes. Diamond drill hole records and water well records in the area show overburden thickness to be between zero and 137 m.

3 TOPOGRAPHY

Topography is an important aspect of the terrain, as it plays a role in controlling surface water and groundwater flow directions and it is an important factor to consider in the routing of roads or the siting of surface structures. The topography in this area is largely bedrock-controlled (Ford, 1991; Henderson and Halstead, 1992), with bedrock hills and ridges and structurally-controlled valleys acting as the main landscape elements, and, as a result, it can reveal much about the bedrock structure and distribution of overburden deposits. The following descriptions of the topography in the area of the four communities rely heavily on the representation of the landscape by the CDED digital elevation model.

3.1 ELEVATION

The pattern of elevation across the area of the four communities controls the overall pattern of drainage and provides definition of the primary physiographic features. Overall, the northern part of the area is a highland and the southern part is a lowland. Boissonneau (1968) described the narrow lowland along this part of the north shore of Lake Huron as one characterized by wave-washed bedrock knolls interspersed with local pockets of glaciolacustrine sediments. The elevation gradient from north to south is from 612 to 176 m, with this elevation drop occurring over a distance of approximate 90 km. The highest point in the area of the four communities is within the highlands north of the Aubinadong River, in the northwest corner of the area. The lowest point is defined by the surface of Lake Huron, which has a chart datum of 176.0 m (Canadian Hydrographic Service, 2014).

The northeast quadrant of the area of the four communities features a large contiguous area of high elevation, as shown on the Figure 4 inset map. The local summits within this feature reach elevations of 530 to 560 m or more. This major highland divides flow between three of the four tertiary watersheds included within the area of the four communities, known as the Spanish, Upper Mississagi and Lower Mississagi watersheds (Section 4.3). It forms the headwaters of many watercourses, including the Boland, Little White, Wakonassin, Mozhabong rivers and the River aux Sables.

The northwest quadrant of the area of the four communities also contains abundant areas of high elevation, but the areas are distributed as isolated blocks of high ground rather than as a large contiguous area as in the northeast quadrant. One of the larger highlands in the northwest quadrant is the oval-shaped area west of the Kindiogama River. Another is located in the northwesternmost corner of the area of the four communities, forming a highland around the Aubinadong and Little Aubinadong rivers.

3.2 RELIEF

As described in Section 1.3.3, relief within a radius was calculated in two ways, as the range in elevation and as the departure from the average elevation. An important relief calculation in this study was the calculation of topographic departure, as topographic prominence plays an important role in controlling the distribution of overburden deposits and water features. The thickest overburden deposits and the largest waterbodies are located in the depressions, and the thinnest drift and most exposed bedrock is located on the highlands and hills. Section 6 presents a map of depressions, plains and highlands created using a combination of the relief calculations described below to facilitate a discussion on groundwater flow directions, and areas of recharge and discharge.

A map of departures from the average elevation within a 20 km radius (Figure 5) provides definition of high and low ground within the area of the four communities beyond that shown by the raw elevation map. For instance, the heavily entrenched aspect of the major river valleys is much more apparent in Figure 5 than in Figure 4. The valleys of the Aubinadong, Mississagi, Little White, and Spanish rivers are significant in this regard, as are the valleys of the Boland, Kindiogama and Wakonasin rivers. The topographically depressed aspect of these areas would have resulted in them being key basins for the accumulation of Pleistocene and Holocene sediment. Figure 5 also shows broad areas of topographic prominence. For example, an inset map provided on Figure 5 shows the areas that are at least 15 m higher than average at this scale of calculation. These local highlands are responsible for dividing surface flow between watersheds, and they are expected to represent key recharge zones for shallow bedrock and surficial aquifers, as described in Section 6. In Figure 5, the broad topographic high in the northeast quadrant of the area, as also seen in Figure 4, is represented as a complex of smaller local highlands.

Topographic prominence calculated at a local scale is a variable that can provide a reasonable image of the areas where overburden deposits are relatively thin on the tops of bedrock-controlled hills. Figure 6 shows the departure in elevation from the mean elevation calculated within a 2 km radius. An inset map in this figure shows the areas with at least 15 m of topographic prominence. In virtually all cases, the areas delineated in the inset map are expected to represent bedrock hills, such as the cuestas and hogback ridges around the Boland and Little White rivers formed by the

Nipissing intrusions as described in Section 2.1.9.2. None of the surficial deposits in the area of the four communities display topographic prominence of this magnitude. The surficial deposits that display the greatest relief in the area of the four communities are eskers and recessional moraines, and Henderson and Halstead (1992) found that these deposits rarely display more than 5 m of topographic prominence in the Elliot Lake area. As a result, the hills at least 15 m high are expected to delineate the places where overburden deposits are most likely to be thin or absent.

Further to the discussion above, “outcrops” were mapped as part of the 1:20,000-scale bedrock map of Easton (2013) covering the Pecors Lake – Whiskey Lake area shown in Figure 3, where “outcrops” covered 27% of the 390-km^2 map area. The outcrops represent areas where overburden deposits are thin or absent. Outcrops generally followed the outlines of bedrock hills. Similarly, the highlands and hills at least 15 m high shown in the inset maps of Figure 5 and Figure 6 cover 34% of the portion of the area of the four communities not covered by Lake Huron.

In contrast to the above discussion, there are low-relief areas near the shores of Lake Huron where wave action during the recession of glacial lakes has stripped the overburden deposits leaving exposed bedrock on the tops of low bedrock hills. The small extent and height of these hills are impossible to resolve using the 1:50,000 digital elevation model. However, even in these areas, the zones delineated as hills using CDED are observed to display greater exposed bedrock in the SPOT imagery than the areas not delineated as hills.

A map showing the range in elevation within a 250 m radius (Figure 7) provides an indication of the location and extent of high and low relief zones within the area of the four communities. The upper limit of relief calculated at this scale is about 260 m, which is reflective of mountainous terrain. Many of the areas with at least 150 m of relief at this scale are underlain by Proterozoic rocks or are located near the contact with Proterozoic rocks in the south-central portion of the area and along the Lake Huron shoreline at the La Cloche Mountains. The inset map in Figure 7 shows the areas with at least 50 m of relief calculated at this scale.

3.3 SLOPE

The distribution of slope within the area of the four communities is highly skewed towards values less than about 10°, with values below this cutoff representing about 83% of the data. Only about 33% of the area is represented by a slope value of at least 6° (Figure 8). Part of the reason for this is the presence of lakes represented in the digital elevation model as flat areas; however, the flatness of the area is not restricted to the lakes. Even the rugged bedrock terrain is made up of areas of gentle slope interrupted only at the margins of bedrock hills and trenches. The tops of some bedrock hills display gentler slopes than what is represented around their flanks.

As indicated above, areas of steep slope form the margins of many of the rugged landforms in the area of the four communities, such as bedrock ridges and hills. As steep slopes in the area of the four communities are often associated with irregularities in the bedrock topography, the absence of steep slopes can be an approximate indicator of heavy overburden cover. Many of the extensive areas lacking steep slopes are relatively flat due to the presence of drift filling lows in the bedrock topography.

A map showing the density of steep (≥6°) slopes within a 2 km radius was prepared to provide a general indication of the areas where the thickness of overburden might be relatively low and conversely where the surficial deposits could be thicker (Figure 9). The inset map in Figure 9 displays a classified version of the slope density map, showing that the main areas of low slope density are concentrated along the northern limit of the area of the four communities and along the Lake Huron shoreline. The former area is associated with extensive overburden deposits, as shown in Figure 3. The latter area is also partly associated with overburden deposits, but is also associated with the low-relief lowland bordering onto the north shore of Lake Huron.

The presence of thick drift will obstruct the identification and characterization of surface structures, such as lineaments. For example, areas of low slope density can be expected to be areas of low surface lineament density due to masking of the surface expression of lineaments by drift. In addition, thick drift can hinder bedrock-mapping activities, which can result in less confidence in the geologic model developed for the area.

The areas of low slope density shown on Figure 9 are areas where SPOT and CDED could be less reliable in identifying the presence or absence of a lineament. These are the areas where the presence of thick overburden makes it impossible to identify lineaments. The use of low slope density as an indicator of low confidence in identifying the presence or absence of a lineament also accounts for the areas covered by lakes, as the lakes are represented as flat surfaces in the digital elevation model.

4 DRAINAGE

Drainage and the distribution of surface water are important factors to consider in the preliminary assessment. The larger lakes, some of which are 5 km or more across, can conceal geological structures, and drainage is a useful indicator of groundwater flow at shallow depth. Section 4.1 provides information on the size, distribution and depth of lakes and wetlands in the area of the four communities. Section 4.2 describes the existing watershed map file and the drainage analysis conducted by JDMA, and Section 4.3 describes surface drainage within the area of the four communities.

4.1 WATERBODIES AND WETLANDS

The area of the four communities contains a large number of lakes of various sizes, twenty-four of which are larger than 10 km^2 and ten of which are larger than 20 km^2, with 21% (3,049 km^2) of the area occupied by water bodies, 11% of which is represented by Lake Huron (Figure 10 and Table 4). Waterbodies cover 11.5% of the portion of the area of the four communities not covered by Lake Huron. The large lakes are sufficiently large to conceal geological structures up to about 5 km in length, and clusters of small lakes can conceal structures, especially when the lakes are located in areas covered by overburden.

Wetlands depicted on Figure 10 are from the Wetland Unit map file produced by the Ministry of Natural Resources (MNR). The wetlands contained in this file are from two main sources: Forest resource Inventory (FRI) and Ontario Base Maps. Wetlands cover 738 km^2 (or 5.1%) of the area of the four communities, or 5.7% of the portion not covered by Lake Huron. According to the attribute information provided in the FRI file, the FRI wetlands are of three types: open wetland, treed wetland, and brush and alder. Open wetland represents wet areas of mosses, grasses, sedges and small herbaceous plants, often interspersed with small areas of open water. Treed wetland represents areas of dry or wet muskeg on which stunted trees occur as widely spaced individuals or in small groups. Areas mapped as brush and alder represent areas covered with non-commercial tree species or shrubs.

The general paucity of extensive wetlands in much of the area of the four communities is associated with a general absence of thick and extensive overburden deposits over much of the area. The largest wetland complexes in the area are expected to be associated with some of the thickest overburden deposits. The location and size of several of these are described below.

Table 4 Largest lakes in the area of the four communities.

Lake[1]	Perimeter (km)	Area (km^2)
Dunlop Lake	61.9	10.3
Ten Mile Lake	52.7	10.4
White Owl Lake	70.1	10.4
Sinaminda Lake	108.1	10.5
Birch Lake	51.0	10.6
Kirkpatrick Lake	65.1	11.2
La Cloche Lake	57.2	11.7
Lac aux Sables	59.9	11.7
Bright Lake	27.3	12.2
Tunnel Lake	74.6	15.8
Aubrey Lake	139.7	17.2
Indian Lake	178.9	18.1
Mozhabong Lake	134.9	18.7
Bark Lake	135.3	18.9
Chiblow Lake	50.9	20.0
Quirke Lake	60.0	20.7
Lauzon Lake	101.6	22.1
Wakomata Lake	46.0	24.9
Basswood Lake	48.8	27.0
Agnew Lake	196.4	27.4
Matinenda Lake	156.8	41.4
Rocky Island Lake	280.8	45.0
Ramsey Lake	373.6	48.2
Lake Huron[2]	1202.9	1567.8

[1]Metrics obtained from LIO OHN Waterbody file

[2]Metrics reported for portion of Lake Huron within area of the four communities

A large (7.4 km^2) wetland complex exists in the low-relief basin surrounding the West Abinette River near the north boundary of the area of the four communities. Another large (5.3 km^2) wetland complex exists within the Boland River watershed south of Rawhide Lake. This wetland complex is located within the drift-filled bedrock basin formed between Boland Hill and the escarpment of the Flack Lake fault in the central part of the area. The floodplain and terraces of a lower 16 km-long reach of the Potomac River contain a large (9.3 km^2) wetland complex 8 km south of Chiblow Lake. The glaciolacustrine delta formed at the mouths of the Blind and Mississagi rivers supports a large (3.1 km^2) wetland known as the Marshy Bay wetland complex, which is designated as a provincially significant wetland. Another large (3.5 km^2) provincially significant wetland is located on the islands at the mouth of the Spanish River, also associated with a glaciolacustrine delta.

The MNR completed depth surveys of selected lakes in the late 1960s and early 1970s. The resulting bathymetry maps consist of contour plots based on soundings, with summary information in the map margin, such as maximum and mean depth. Figure 10 indicates the lakes within the area of the four communities for which bathymetry data exist. The greatest known lake depth is 117.4 m, which was measured in Ten Mile Lake (Table 5), which is located in the center of the area of the four communities. This great depth is associated with differential erosion of a weakness zone associated with a mapped west-northwest trending mafic dike (Figure 2). The depth of any surficial deposits accumulated into this deep structurally controlled valley is unknown. The maximum depth of the other lakes ranges from 12.2 to 73.2 m. Lake Huron reaches about 60 m depth near the southwest boundary of the area of the four communities.

Table 5 Lake depths in the area of the four communities.

Lake[1]	Area (km^2)	Max depth (m)	Mean depth (m)
Cutler Lake	1.2	12.2	N/A
Maple Lake	1.5	12.2	N/A
Dean Lake	2.4	14.9	6.4
Depot Lake	2.2	18.3	N/A
Birch Lake	10.6	27.4	10.3
La Cloche Lake	11.7	30.5	16.2
Big Lake	1.7	32.0	9.9
Esten Lake	4.8	33.5	N/A
Matinenda Lake	41.4	33.5	19.4
Williamson Lake	2.3	33.5	12.1
Denman Lake	6.4	38.1	17.3
Big Moon Lake	5.2	41.8	18.1
Mozhabong Lake	18.7	45.7	12.1
Mashagama Lake	6.8	65.5	19.1
Basswood Lake	27.0	73.0	38.6
Wakomata Lake	24.9	73.2	31.1
Ten Mile Lake	10.4	117.4	31.2

[1]Area from LIO OHN Waterbody file; depth values from MNR depth maps

4.2 WATERSHEDS

A watershed, also known as a catchment, basin or drainage area, includes all of the land that is drained by a watercourse and its tributaries. The best available watershed delineation for the area of the four communities is the quaternary watershed file produced by the MNR. JDMA subdivided some of the quaternary watersheds in the area of the four communities to add detail to the watershed delineation. The delineation of drainage divides can be useful for determining drainage directions and contributing to an initial understanding of the shallow groundwater flow system.

According to the metadata for the MNR quaternary watershed file, a quaternary watershed is a polygon feature that identifies a subdivision of a tertiary watershed (MNR tertiary watersheds are generally equivalent to the sub-sub-division of drainage areas produced by the Water Survey of Canada). The boundaries of the quaternary watersheds were created based on the Provincial DEM and Enhanced Flow Direction products released between 2006 and 2008. The watershed boundaries are generally consistent with the regional hydrology available for Ontario. The horizontal positional accuracy of the quaternary watershed boundaries is variable depending on the nature and spatial distribution of the raw DEM information, and thus cannot be quantified without on-site investigation and verification. In general, positional accuracy in northern Ontario is within 400 m, but there is no statistical level of confidence available.

JDMA modelled the movement of water over the landscape using the watershed analysis function in the program TNTmips with the CDED elevation model as the surface model. The CDED digital elevation model used for this study was created by NRCan (Section 1.3.3) using the same provincial data on which the Provincial DEM was constructed. As a result, the DEM used here is comparable with that used by the MNR to construct the quaternary watersheds. The result of the drainage analysis is a single set of lines and polygons, which represents a merged watershed file (Figure 11). The inset map on Figure 11 illustrates the tertiary watersheds in the area of the four communities.

4.3 SURFACE FLOW

The area of the four communities is contained entirely within the St. Lawrence Drainage Area, which drains towards the Atlantic Ocean through the St. Lawrence River. The St. Lawrence Drainage Area covers parts of the provinces of Ontario and Quebec, and the states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, Vermont and Wisconsin.

Surface water drainage within the area of the four communities is directed towards the North Channel of Lake Huron through the Mississagi, Blind, Serpent and Spanish Rivers. The inset map in Figure 11 shows the division of the area of the four communities into tertiary watersheds, illustrating how the Mississagi River in this area contains upper and lower watersheds.

The Mississagi River drains the northwest and west parts of the area of the four communities. Within the Lower Mississagi watershed, the Mississagi River is fed by the Little White, Little Rapid and Sharpsand rivers, of which the Little White River is the major tributary. The Boland, Sister, Kindiogama, and West Little White rivers are the main tributaries to the Little White River. Within the Upper Mississagi watershed, the Aubinadong, Wenebegon, Maskuti and Abinette rivers are the main tributaries to the Mississagi River. The Aubinadong River is fed by the West Aubinadong and Little Aubinadong rivers. The West Aubinadong River is located west of the northwest corner of the area of the four communities. The Wenebegon River is fed by the Burntwood and Embarrass rivers (located north of the area of the four communities). The Abinette River receives flow from the North and West Abinette rivers.

The Serpent watershed drains the south-central part of the area of the four communities, including the City of Elliot Lake. This watershed is drained by the Blind and Serpent rivers. The Blind River flows through Matinenda and Chiblow lakes before being fed by the Potomac River. The Serpent River flows through Quirke and Whiskey lakes, controlled by the Quirke Lake syncline, before receiving flow from the Marshland and Little Serpent rivers.

The Spanish watershed drains the eastern part of the area of the four communities. The Spanish River receives flow from the River aux Sables and the Vermillion, Wakonassin, Agnes, Mogo, East Spanish and Mozhabong Rivers. The Vermillion and Mogo rivers are located east of the area of the four communities. In the northeast corner of the area of the four communities, surface flow directions are towards the north. However, surface water flows through Ramsey and Biscotasi Lakes beyond the area of the four communities, prior to joining the Spanish River that flows south towards the North Channel.

Within the area of the four communities, the Upper Mississagi watershed is the only tertiary watershed underlain entirely by Archean rocks. A mix of Proterozoic and Archean rocks underlies the Lower Mississagi and Serpent watersheds. Watersheds feeding the Blind River are underlain almost entirely by Proterozoic rocks, whereas a greater proportion of Archean rocks exist in watersheds feeding the Serpent River. Apart from the southern portion of the watershed, Archean rocks underlie much of the Spanish watershed in the area of the four communities.

5 TERRAIN CHARACTERISTICS

An understanding of the distribution and thickness of overburden within the area of the four communities is essential for interpreting the distribution of lineaments mapped from satellite imagery and topographic surface data (JDMA, 2014), particularly with respect to lineament length and density. Thick drift deposits are able to mask the surface expression of lineaments. In areas of sporadic drift deposits, the drift can conceal minor lineaments, producing low apparent lineament density, and it can censor the lengths of major structures. In areas of thick and extensive overburden, major structures could exist that would be completely undetected from SPOT and CDED, particularly if these areas also contain large lakes.

Areas of exposed bedrock or thin drift are more readily amenable to site characterization as such locations would enable further investigation of the potentially suitable bedrock formations through outcrop mapping of bedrock structures and preliminary rock mass characterization. Due to the importance of areas of thin drift or exposed bedrock for site characterization, Section 5.2.1 provides a critical discussion of the distribution of these areas based on NOEGTS mapping, topographic analysis (Section 3.2), outcrop mapping presented in a detailed bedrock map (Easton, 2013) and on analysis of satellite imagery.

The purpose of this section is to provide information to help enhance the understanding of overburden deposits in the area of the four communities generated through the NOEGTS program (Figure 3). Information generated from 1:50,000-scale surficial mapping programs are also used in Section 5.2 to characterize the surficial deposit types and terrain conditions found in the area. Section 5.1 presents a preliminary review of water well and drill hole data on overburden thickness in the area of the four communities. Details on the expected composition, distribution and thickness of surficial deposits within the terrain units are presented in Section 5.2.

5.1 DRILL HOLE AND WATER WELL DATA

Drift thickness in the area of the four communities is highly variable, and the unevenly distributed available subsurface data do not allow for the development of a comprehensive drift thickness map (Ford, 1991). Data on overburden thickness from water well records collected by the MOE and from diamond drill holes compiled by the OGS were reviewed to supplement the information on overburden deposits compiled from the NOEGTS reports and 1:50,000-scale surficial mapping programs (Section 5.2).

5.1.1 Water Well Information System

Section 1.3.5 provided a summary of the available water well records within the area of the four communities. There are 357 water well records with reliable data on depth to bedrock contained within the area of the four communities. Most of the wells are located in the southern portion of the area of the four communities, concentrated along Highway 17 or within the City of Elliot Lake. These data indicate depths to bedrock ranging from zero to 136.8 m with an average of 13.2 m. Because of the large number of well records for the area, only a specific subset is shown on Figure 3 to maintain clarity in the Quaternary mapping. The subset includes well records that indicate drift thicknesses of 30 m or more. These wells are located along Highway 17 in the lowland bordering onto Lake Huron, where the main glaciolacustrine deposits shown in Figure 3 have been mapped. Some of these wells are located in areas mapped as bedrock terrain. Two records indicating drift thickness exceeding 100 m are located within the valley of the Spanish River in an area of extensive glaciolacustrine deposits east of Massey.

The group of water wells in the City of Elliot Lake includes 29 well records that contain data on depth to bedrock. Drift thickness indicated by these wells ranges from zero to 19.2 m with an average of 5.6 m.

5.1.2 Ontario Drill Hole Database

Section 1.3.6 provided a summary of the available drill hole records within the area of the four communities. As described in Section 1.3.6, there are some issues with the drill hole records which would bias any statistical summaries made from the data. For example, an unknown number of the boreholes were drilled from lake ice platforms, thereby inflating the depth to bedrock value through inclusion of the height of the water column into the reported casing length. Furthermore, the locations of many drill holes are only accurate to within several hundreds of metres, making it tenuous to provide a systematic drift thickness summary for each of the deposit types mapped in the area (Figure 3). In any case, summary information is drawn from these data below and then further reference is made to the drill hole records in Section 5.2 in the description of specific surface deposits. Within the area of the four communities, a total of 2,617 drill hole records were considered to provide useful information on drift thickness and these data indicate drift thicknesses ranging from zero to 95.7 m with an average of 3.5 m.

Due to the large number of drill holes in this area, it was determined that to maintain clarity in Figure 3, only drill holes indicating depths to bedrock of at least 40 m would be plotted. There are 23 drill holes with depth to bedrock ranging from 40 to 80 m, and three with values in excess of

80 m. Two of the three holes with values greater than 80 m were advanced through overburden deposits located along or a short distance south of the Whiskey Lake Moraine (as proposed by Boissonneau, 1968), and the third was drilled within a basin covered by an extensive organic deposit located near Stag Lake. These three drill holes are described below. In addition, a set of drill holes less than a kilometre east of the area of the four communities is described in Section 5.1.2.3, providing an indication of the thick sediments infilling the Spanish River valley.

5.1.2.1 Big Moon Lake

A drill hole southeast of Big Moon Lake encountered 95.7 m of overburden before intersecting bedrock. Another hole in this area indicated a depth to bedrock of 61.5 m. These drill holes are located within one of the most extensive morainal deposits mapped in the area of the four communities (Figure 3), being mapped as a complex of ground moraine and end moraine. Boissonneau (1968) referred to this area as a drumlin field and indicated that it represents the most prominent drumlin field in the 89,350 km^2 portion of northeastern Ontario included within his study. The exact locations of drill holes are generally difficult to establish in order to determine whether they are located on top of hills or within the lows between hills. However, it is suspected that the large depth to bedrock values reported in this area are associated with overburden deposits filling the lows between the streamlined hills. Henderson and Halstead (1992) suggested that the group of broad elongated hills oriented parallel to ice flow in the area south and west of Elliot Lake represent predominantly bedrock features that were glacially moulded and contain only a discontinuous veneer of till. They mapped the hills in this area as exposed bedrock, bedrock-drift complex or till, and the depressions were mapped as outwash, glaciolacustrine or organic deposits. Unfortunately, drill logs provided no descriptions of the overburden deposits in this area.

5.1.2.2 Pecors Lake

A drill hole located within an east-west trending creek valley east of the north tip of Pecors Lake indicated a depth to bedrock of 85.3 m. The creek valley was mapped as ground moraine in Figure 3. No information on the nature of the overburden deposits was provided in the drill log. It is possible that some of the overburden intersected by this drill hole is related to an ice contact deposit associated with the Whiskey Lake Moraine, a feature that was initially proposed by Boissonneau (1968) and then described further by Henderson and Halstead (1992).

5.1.2.3 Agnew Lake

Thick glaciofluvial sediments are indicated in the borehole logs of a set of holes advanced into drift deposits on the floor of Agnew Lake, located just east of the eastern boundary of the area of the four communities. The drill holes in this area were drilled from lake ice platforms, with the height of the water column amounting to about 10 m. Agnew Lake is formed within the valley of the Spanish River. Figure 3 shows that overburden deposits around its shores have been mapped as outwash, ground moraine and organic deposits. Two holes advanced into deposits beneath the lake reported mud, sand and gravel to great depths, suggesting thick outwash deposits. One hole indicated 92.3 m of overburden before intersecting bedrock, and another hole indicated 97.2 m of overburden and did not intersect bedrock.

5.1.2.4 Stag Lake

The last of the occurrences of thick overburden deposits indicated by drill hole data that will be described in this section is found within the deep basin formed within the valley of the Boland River near Stag Lake (Figure 3). This basin is bounded to the south by the scarp of the Flack Lake fault, and to the north by what Ford (1991) described as the eastward extension of Boland Hill along the south shore of Rawhide Lake. Boland Hill represents a prominent rock ridge associated with Nipissing diabase sills. Eight drill holes in this basin indicated overburden deposits thicker than 70 m with the greatest thickness reported as 82.9 m. Ford (1993b) mapped the surface of this part of the Boland River valley as being characterized dominantly by organic and outwash deposits with lesser areas of ice-contact stratified drift, till, and modern alluvium. All of the holes drilled through the organic deposit near Stag Lake indicate fine to coarse sand in the upper 60 to 75 m with this material underlain by gravel and boulders. One hole indicated 9.1 m of humus material and black muck at the top of the hole. Ford (1991) describes the organic deposit here as a large bog containing the only significant area of peat accumulation in the Rawhide Lake map area.

5.2 TERRAIN UNITS

Except for the narrow lowland along the north shore of Lake Huron, which was mapped as wave-washed bedrock with local pockets of glaciolacustrine deposits, Boissonneau (1968) mapped the rest of the area of the four communities as moderately rolling terrain characterized by thin till deposits over bedrock with local morainal and outwash deposits. Overburden deposits in the area of the four communities have been mapped at the scale of 1:100,000 as part of the Northern

Ontario Engineering Geology Terrain Studies. Bedrock terrain has been mapped over 76% of the area not covered by Lake Huron. Of the areas mapped as overburden deposits, morainal and glaciofluvial deposits make up the largest areas.

5.2.1 BEDROCK TERRAIN

In general, much of northern Ontario has been mapped as bedrock terrain (Gartner et al., 1981), where overburden deposits are suggested to be thin to absent. Northern Ontario Engineering Geology Terrain Studies in the area of the four communities (e.g., Gartner, 1980b; Roed and Hallett, 1980b; VanDine, 1980a) suggest that the bedrock surface is generally below a mantle of ground moraine in the areas mapped as bedrock (Figure 3). The till in these areas is expected to be generally less than 1 m over the crest of hills, but it can increase to several metres on the flanks of hills or in the lows between hills. The till is silty to sandy in texture and generally contains cobbles and boulders. Local depressions within the areas mapped as bedrock commonly contain organic, ground moraine, outwash, esker or ice-contact deposits that were too small to map explicitly.

The areas mapped as bedrock within the area of the four communities amount to 76% of the area not covered by Lake Huron. Within these areas, drift deposits are thinnest on the bedrock hills and ridges scattered throughout the landscape, and local drift deposits too small to map explicitly at the scale of 1:100,000 exist within depressions. Inset maps provided in Figure 5 and Figure 6, respectively, presented images of highlands and hills in the area of the four communities defined using the 1;50,000 digital elevation model. The highlands and hills presented in these inset maps have been combined in Section 6 to represent a subset of the areas mapped as bedrock terrain where drift deposits are expected to be thinnest (Figure 13).

Bedrock outcrops were mapped using Landsat MSS imagery, and the outcrops are shown on Figure 12. The pattern of exposed bedrock suggested in this image is of a greater amount of exposed bedrock in the southern part of the area of the four communities, particularly in the area between Highway 546 and Highway 108. Some of the outcrops within the lowland along the north shore of Lake Huron are expected to represent areas where the overburden deposits were eroded by wave erosion during glacial and postglacial high stands of the Lake Huron basin, leaving the bedrock exposed. The total extent of bedrock outcrops suggested by the Landsat MSS interpretation is about 8% of the portion of the area of the four communities not covered by Lake Huron.

The Northern Ontario Engineering Geology Terrain Studies described the significance of the bedrock terrain in terms of such considerations as groundwater resource potential and general construction capability. Groundwater within areas mapped as bedrock is contained within fractures, faults and other discontinuities, which renders the occurrence of aquifers unpredictable and the overall potential for groundwater resources poor. The complex, steep and irregular morphology of the bedrock surface is a major constraint for construction in bedrock areas. Excavations for foundations generally require blasting, but foundation conditions are excellent. Route alignments will require extensive rock cut-and-fill operations. Due to the shallow drift cover and complex bedrock topography, development activities are more difficult and expensive than in areas of thicker overburden. Construction will be extremely difficult in areas with high, steep rock slopes and steep bedrock hills (VanDine, 1980b).

5.2.2 Morainal deposits

Areas underlain by thicker, more continuous deposits of ground moraine have been mapped in various locations in the area of the four communities, particularly in the southern part of the area (Figure 3). Areas mapped as ground moraine are expected to contain a mantle of sandy, stony, bouldery till from 1 to 5 m thick (Gartner, 1980b; VanDine, 1980a). Relief is generally subdued in these areas due to the thicker layer of till filling lows in the bedrock topography. Organic deposits too small to map explicitly are expected in depressions in areas mapped as ground moraine. Small eskers, kames, and recessional moraines not delineated in Figure 3 are also expected locally.

Henderson and Halstead (1992) described the till in the area as commonly massive and consisting of a compact to moderately compact, grey-brown sandy diamicton with angular to subangular clasts ranging from granules to boulders several metres in diameter. The pebble fraction is reported to range from 15 to 40% and thin horizontal sand stringers have been recognized in the unit locally. Ford (1991) divided the till in the area into two lithofacies. A darker-coloured lodgement facies consisting of a compact, fissile, relatively uniform matrix with 5 to 10% clasts overlies a lighter-coloured meltout facies characterized by a loose to moderately compact matrix with sand lenses and stringers and a substratified appearance with up to 40% clasts.

End moraine has been mapped as discontinuous patches in parts of the area of the four communities (Figure 3). Boissonneau (1968) postulated several east-west trending morainic belts in northeastern Ontario, which mark successive positions of the ice front. In the area of the four communities (Figure 3), these include the Whiskey Lake, Rawhide Lake, Cartier I, Cartier II, Cartier III (not shown) and Obabika Lake moraines. Henderson and Halstead (1992) describe the area mapped in Figure 3 as end moraine north of Gullbeak Lake. The surface of the deposit is characterized by irregular hummocks up to 5 m high. The deposit itself is composed of a loose, apparently massive, grey-brown, stony, sandy diamicton overlain by a discontinuous mantle of poorly-sorted pebbly sand. They also describe ridges of sand and gravel north of Gullbeak Lake, which they suggested could be eskers or recessional moraines. South of Gullbeak Lake, these authors reported many low hummocks and small ponds or swamps interpreted as kames and kettles in the area mapped as end moraine in Figure 3. In general, Henderson and Halstead (1992) suggest that ice recessional features in the area are limited to short eskers and other ice-contact deposits, particularly subaqueous fans. The small recessional moraines mapped in the Rawhide Lake area (Ford, 1991) were suggested to be composed of either very bouldery material or largely of sand.

Drill hole data described in Sections 5.1.2.1 and 5.1.2.2 indicated that drift deposits found along or a short distance south of the Whiskey Lake Moraine can display thicknesses exceeding 80 m. Being dominantly mapped as morainal terrain in Figure 3, the impression given is that the extensive area of ground moraine and end moraine mapped south and west of Elliot Lake is dominantly composed of till. However, Henderson and Halstead (1992) remapped much of this area as glaciofluvial ice-contact stratified drift and outwash.

The engineering significance of ground moraine and end moraine are slightly different owing to the different deposit types found in these areas. In areas of ground moraine, large boulders, patches of poorly drained ground, and the possibility of near-surface bedrock are the main difficulties expected (Roed and Hallett, 1980b). Although boulders and near-surface bedrock can result in construction problems associated with rock excavation and grading, areas of ground moraine are generally superior to areas of bedrock terrain for route construction due to lower grades and fewer chances of the necessity for rock blasting. The till found in areas of ground moraine can be suitable for use in embankments required for roads. Groundwater resources are expected to be scarce in ground moraine due to the absence of appreciable granular deposits. In contrast to ground moraine, areas mapped as end moraine are more likely to contain granular materials, resulting in somewhat better potential for aggregate and groundwater resources, although material texture is expected to be highly variable (Gartner, 1980b).

5.2.3 GLACIOFLUVIAL DEPOSITS

Outwash plains generally deposited as valley trains composed of stone-free to slightly stony sand cover small parts of northeastern Ontario (Boissonneau, 1968). Glaciofluvial deposits dominantly composed of outwash are mapped over 10% of the portion of the area of the four communities not covered by Lake Huron (Figure 3). Outwash deposits in the valleys of the Mississagi, Little White and Spanish rivers were included on the regional map of Boissonneau (1968). Outwash deposits are found in low-lying areas, such as valleys and other depressions. Laterally extensive outwash deposits not confined to a deep valley exist, including along the northern margin of the area of the four communities near White Owl Lake and south of Red Pine Lake. The surface of outwash deposits is generally of low relief but can be pitted, terraced and channelled (VanDine, 1980a). Boreholes advanced through deposits on the floor of Agnew Lake (Section 5.1.2.3) indicated in the order of 80 to 90 m of sand and gravel filling the Spanish River valley.

Ford (1991) described the contrasting outwash systems of the Little White and Boland river valleys. These outwash systems represent the most significant systems in the Rawhide Lake area. The terraced outwash along the Little White River is composed dominantly of pebble and cobble gravels, with the terraces indicating a series of erosional events. In contrast, the Boland River outwash is mainly fine to coarse sand, and terraces are notably absent except locally. Boreholes in the Boland River valley near Stag Lake (Section 5.1.2.4) indicated as much as 70 to 80 m of drift composed of fine to coarse sand underlain by gravel and boulders.

Henderson and Halstead (1992) indicate that outwash is widespread in the Elliot Lake map area. This is in contrast to what is suggested by Figure 3, which shows a virtual absence of outwash deposits delineated in the Elliot Lake map area of Henderson and Halstead (1992). According to these authors, the most significant outwash accumulations are located in the northern and central portions of the map area: south of Dunlop Lake, and south and west of Gullbeak and Elliot lakes. The outwash is composed of discontinuous beds of horizontally stratified pebble to boulder gravel, pebbly sand and coarse to medium sand in varying proportions. The surface expression of the outwash is horizontal with subdued relief.

As described above, borehole data described in Section 5.1.2.4 indicated up to 83 m of sand and gravel in the valley of the Boland River and more than 90 m of sand and gravel in the valley of the Spanish River. In addition, drill holes indicating drift thicknesses exceeding 40 m also exist along the valleys of the Little White and Potomac rivers (Figure 3). These drilling results illustrate the great thickness of overburden deposits that can be found within the river valleys in the area of the four communities.

The glaciofluvial deposits have the best potential for sand and gravel of any of the deposits mapped in the area of the four communities (Gartner, 1980b; VanDine, 1980a). Potential reserves of aggregate and groundwater are high in the areas mapped as outwash, such as along the Mississagi, Little White, Boland and Spanish rivers and the River aux Sables. The good foundation conditions and abundance of suitable borrow and granular materials make these landforms ideal for transportation routes, building sites, forest management staging areas, and airport locations. The low-relief surface expression of most outwash deposits is relatively favourable for transportation routes, pipelines, and air strips as compared with eskers or kames (Roed and Hallett, 1980b). High water tables in some outwash deposits can necessitate dewatering during excavations (VanDine, 1980b).

5.2.4 GLACIOLACUSTRINE DEPOSITS

Glaciolacustrine deposits have been mapped over 2% of the portion of the area of the four communities not covered by Lake Huron, occurring in two main belts within the lowland bordering onto Lake Huron: surrounding and west of Blind River, and surrounding and east of Spanish (Figure 3). The vast majority (76%) of the glaciolacustrine deposits mapped in the area of the four communities are located over the Proterozoic rocks, with a much smaller amount (15%) located over the Archean rocks (Figure 3). Within the two belts mentioned above, waters of a post-Algonquin glacial lake washed the till from many of the bedrock highs and redeposited the sediment as sand to sandy silt glaciolacustrine plain deposits between the highs (Gartner, 1980b; VanDine, 1980b,c). These low-relief sandy silt plains represent the dominant glaciolacustrine deposits mapped in the area of the four communities. Glaciolacustrine beach and nearshore deposits composed of gravelly sand are present in the two main lacustrine belts in this area, particularly between Thessalon and Blind River (VanDine, 1980c). Boissonneau (1968) indicated that well-developed raised beaches are uncommon along the north shore of Lake Huron and east shore of Lake Superior, and where they occur they can be followed for only short distances. The only glaciolacustrine delta mapped within the area of the four communities in Figure 3 is at the mouth of the Mississagi River.

In the Elliot Lake map area of Henderson and Halstead (1992), the glaciolacustrine deposits were divided into either sandy or silt and clay deposits. Although glaciolacustrine deposits are present mainly in the southern half of the Elliot Lake map area, sandy deposits thought to be associated with an inland proglacial lake are present south of Dunlop and Quirke lakes. Glaciolacustrine silts and clays within the map area were found only at elevations below 320 m, commonly found within sequences of stratified sands, silts and clays. The thickest deposits of stratified glaciolacustrine silt and clay (2 to 4 m thick) observed in the map area are found in the southwest part of the area and along the shores of Matinenda Lake.

In the Rawhide Lake map area, Ford (1991) indicates that glaciolacustrine sediments generally do not form a mappable unit partly because they are buried beneath glaciofluvial sediments. For example, silt-clay rhythmites were found below glaciofluvial sediments in several sections in the Little White River valley and at one site north of the Boland River. As a result, glaciolacustrine ponding had evidently occurred in the Little White River valley and in the area near Stag Lake within the Boland River valley.

Glaciolacustrine plain deposits have little potential as sources of sand and gravel, and groundwater resources are generally scarce within the fine-grained materials (VanDine, 1980d), especially where the materials form only a veneer over bedrock (Gartner, 1980b). However, limited groundwater supplies can be found if coarser materials are located between the fine-grained glaciolacustrine materials and the underlying bedrock (VanDine, 1980d). Construction conditions can be difficult within silt and clay glaciolacustrine deposits. The geotechnical properties of silts and clays are usually poor, with low shear strengths that decrease with depth, poor bearing capacities, and high frost susceptibility (Gartner et al., 1981). These materials can have high moisture contents and can be difficult to handle and compact. Glaciolacustrine plains are often associated with poor drainage and organic terrain.

5.2.5 ALLUVIAL DEPOSITS

Alluvial plains occur along most rivers and creeks in the area, but modern alluvium has been mapped only along the trunks of the major rivers forming only 2% of the portion of the area of the four communities not covered by Lake Huron (Figure 3). The modern alluvium generally takes on the texture of the local Pleistocene sediments contained within the valley (VanDine, 1980c). For example, alluvial deposits along the Boland River are mainly sandy in association with the nearby sandy outwash deposits, and well-sorted gravels form the dominant texture of the alluvium along the Little White River in association with the gravelly outwash found locally (Ford, 1991). Sandy to silty alluvium exists along several river valleys bordering onto Lake Huron, where the rivers flow through silty to sandy glaciolacustrine sediments (VanDine, 1980c). Alluvium along the River aux Sables is generally composed of gravelly sand (VanDine, 1980b). Modern rivers are also forming deltas where they drain into lakes such as Big Moon and Matinenda lakes (Henderson and Halstead, 1992).

Foundation conditions are generally poor in fine-grained saturated alluvial sediments. Structures built on alluvial plains will be subject to flooding, and the potential for erosion and slope instability exists along stream banks (Roed and Hallett, 1980b). Groundwater potential in alluvial sediments is best in the coarser deposits and poor in the fine-grained deposits.

5.2.6 ORGANIC DEPOSITS

Deposits of peat, muck and organic-rich silt have been mapped as organic terrain in Figure 3, with no attempt to distinguish between marsh, swamp, bog, or fen (Gartner et al., 1981). Organic deposits occur throughout the area of the four communities, with most of them too small to map at the scale of 1:100,000. Organic deposits mapped in Figure 3 cover about 3% of the portion of the area of the four communities not covered by Lake Huron. An alternate image of the organic deposits in the area of the four communities can be obtained from the distribution of wetlands shown in Figure 10. Wetlands shown in Figure 10 cover 5.7% of the portion of the area of the four communities not covered by Lake Huron. Within most organic terrain, stagnant drainage or wet surface conditions are common. These deposits are generally found in association with poorly-drained alluvial, outwash, glaciolacustrine or ground moraine deposits or in depressions within the bedrock terrain (VanDine, 1980a, c; Ford, 1991; Henderson and Halstead, 1992).

In the Rawhide Lake area, Ford (1991) indicates that small swamp deposits of muck and organic-rich silt are common in bedrock-controlled depressions and along small streams, but bog deposits of sphagnum-derived peat are far less common. The only significant area of peat accumulation in the map area is located near Stag Lake. One diamond drillhole advanced through this deposit indicated 9.1 m of humus material and black muck at the top of the hole (Section 5.1.2.4).

Exceptionally poor engineering characteristics can be found within areas mapped as organic terrain (Gartner et al., 1981). Peat and muck have very low shear strength and high compressibility. Groundwater tables are at or near the surface in organic terrain and flooding is common.

6 GROUNDWATER

Regional groundwater flow is discussed here based largely on topography, surficial geology and additional information presented in the literature. Golder (2014) provides further discussion on the hydrogeology of the area of the four communities.

6.1 SHALLOW GROUNDWATER FLOW

The occurrence and movement of shallow groundwater in the area of the four communities is expected to be controlled mainly by topography and the distribution of surface materials. Shallow groundwater flow patterns should largely follow the general pattern of surface flow suggested in Figure 11. The major surficial aquifers are the outwash deposits, which are located within depressions throughout the area (Figure 3). The major discharge areas are the waterbodies, watercourses, and wetlands (Figure 10).

As topographic prominence plays a critical role in controlling the distribution of water features and surface materials in the area of the four communities, a relief map can be useful to facilitate a discussion of the hydrological cycle and groundwater flow, recharge and discharge. Figure 13 divides the area into highlands, depressions and plains based on the calculation of topographic prominence described in Section 3.2. Specifically, the depressions shown in Figure 13 represent depressions with depths of at least 15 m delineated using search radii of both 20 km (Figure 5) and 2 km (Figure 6). Similarly, the highlands were defined based on a minimum of 15 m of topographic prominence. The “plains” are simply the inconspicuous areas of normal elevation not delineated as depressions or highlands.

The highlands and hills shown in Figure 13 extend a minimum of 15 m, on average 30 to 40 m and as much as 150 to 200 m above the nearby terrain. The hills and highlands represent a subset of the areas mapped in Figure 3 as bedrock terrain. The subset is expected to outline in detail the rock-controlled hills and highlands where overburden deposits are expected to be thinnest and bedrock exposure relatively abundant. These hills and highlands form about 34% of the portion of the area of the four communities not covered by Lake Huron (Section 3.2). A thin layer of sandy till should be the most common deposit type found in these areas. Precipitation and snowmelt should infiltrate into the generally shallow surficial deposits and into structural and lithological discontinuities daylighting in the exposed or thinly covered bedrock. Where there is an abundance of steep slopes, runoff will be favoured over infiltration, whereas local depressions will facilitate storage of surface water in the form of ponds, wetlands or small lakes. Highlands represent the headwaters of creek and river basins where groundwater divides would be located. Groundwater within highland bedrock aquifers will be similar to that described for the bedrock terrain in general. That is, the occurrence of groundwater is unpredictable (Gartner, 1980a, b), but will generally be associated with interconnected fracture networks and fault zones (Roed and Hallett, 1979d).

Overburden deposit types and thicknesses, and the consequent potential for significant surficial aquifers should be highly variable in the plains shown in Figure 13. Exposed bedrock can be found in some of these areas, such as east and west of Highway 108 near Lake Huron where wave-washed bedrock knolls are scattered across the plain, but the extent of exposed bedrock is generally much less significant in the plains than in the highlands and hills.

The depressions shown in Figure 13 are entrenched a minimum of 15 m, on average 25 to 35 m and as much as 115 to 150 m below the surrounding landscape. All of the largest lakes and major rivers in the area of the four communities are located within these low-lying areas. The largest and deepest outwash deposits, which have the greatest potential for groundwater supplies in the area (Gartner, 1980a,b; Roed and Hallett, 1979d; VanDine, 1980d), are found within these valleys.

Boreholes advanced through sand and gravel valley fill deposits in this area (Sections 5.1.2.3 and 5.1.2.4) in combination with topographic analysis indicates that there are known potential groundwater resources in surficial aquifers extending to depths of 150 to 200 m below the adjacent highlands. For example, the Boland River valley near Stag Lake contains a deposit of fine to coarse sand underlain by gravel and boulders more than 80 m thick, with the surface of the deposit located 75 to 125 m below the general elevation of the adjacent upland. The Flack Lake fault forms the southern margin of the valley in this location. The groundwater potential of the Flack Lake fault is unknown, as is the hydrogeological connection between the fault and the overlying, deep outwash aquifer. Ten Mile Lake provides another example. The lake reaches a maximum depth of 117 m in association with a west-northwest trending mafic dyke. The lake floor is located about 150 m below the surface of the surrounding upland and any surficial deposits beneath the lake floor would probably display depths of perhaps 10 to 50 m.

The connections between highland and lowland aquifers and water features are generally expected to be uncomplicated. In many cases, discharge from highland bedrock and surficial aquifers is expected to recharge overburden aquifers within valleys. In other cases, highland bedrock and surficial aquifers could discharge directly into lowland waterbodies and watercourses. Groundwater contained within lowland surficial aquifers will generally discharge into nearby lakes, rivers and creeks. Groundwater flow from highland bedrock aquifers in some cases could recharge lowland bedrock aquifers. For example, groundwater that infiltrated into a permeable mafic dyke on a highland could be transmitted to a fault zone within a nearby valley.

6.2 DEEP GROUNDWATER FLOW

Topographic influence on groundwater flow systems in the area of the four communities is expected to persist for depths of several tens of metres to maybe even hundreds of metres below the surface. Deep groundwater flow systems in bedrock are controlled by the distribution and properties of major structures in the bedrock, such as faults, fracture zones, dykes or stratigraphic horizons. Golder (2014) summarizes some information on groundwater occurrence at typical repository depths (approximately 500 m) in the Canadian Shield, including information on the occurrence of brines found in crystalline rocks at depth (e.g., Frape et al., 1984).

7 NEOTECTONIC FEATURES

Repeated cycles of glaciation and deglaciation throughout the Quaternary have induced stresses by sequentially loading and unloading the Earth's crust. The loads associated with glaciation are sufficient to depress the crust by hundreds of metres. Crustal rebound takes place once the weight of the ice is removed and rebound continues to occur today in this area, albeit slowly. The greatest rates of rebound typically occur near the ice-centres.

The stresses associated with cycles of ice loading and unloading, overprinted onto the tectonic stress regime, may result in seismic events related to displacements along ancient discontinuities in the bedrock. In addition, the advance of the ice sheet may also exert stresses near the bedrock surface during its motion across the landscape, resulting in movement along existing discontinuities.

The study of neotectonic features is important because any examples of late- or post-glacial faulting that can be found in the area could provide information on the magnitude and timing of paleo-seismic events. No information on the presence of late- or post-glacial faulting in the area of the four communities has been described in the literature, and no such features were identified from the available remote sensing data. Air photo interpretation could help with identifying possible features, such as deformed surficial landforms like eskers or recessional moraines extending across major faults, but any identified features would need to be checked in the field.

Sandy and silty sediments such as some outwash and glaciolacustrine deposits could display liquefaction-induced deformation associated with late- or post-glacial faulting. Aggregate pits containing layers of fine grained sediment could be checked for seismically induced distortions. Wave-washed bedrock exposures in the lowland bordering Lake Huron could be checked for fault-related offsets of glacially striated and sculpted bedrock surfaces.

It is important to note that even after extensive future searching for seismically-induced distortions in sandy silty sediments throughout the area of the four communities, the lack of such features does not necessarily imply that late- or post-glacial faulting has not occurred, because the sandy and silty sediments would only be susceptible to liquefaction if they were saturated at the time.

8 ACCESSIBILITY CONSTRAINTS

Highways 17, 810, 108, 546 and 129 represent paved highways that provide access to areas within the southern half and along the western margin of the area of the four communities. The inset map in Figure 14 shows a distance plot to the nearest point on a main road. In the southern part of the area of the four communities, there are zones located 10 km or more from the nearest main road (e.g., the area midway between Highways 108 and 810). The most remote part of the area of the four communities is represented by a rectangular zone 40 by 125 km in extent in the northern part of the area where distances to the nearest main road range from 10 to 50 km. In detail, 62% of the Archean rock in the area of the four communities is located further than 10 km from the nearest point on a main road, 30% is further than 20 km, and 12% is further than 30 km.

Most of the local roads shown on Figure 14 are from the MNR road segment file obtained from Land Information Ontario (LIO). The MNR road segment file contains resource access roads constructed for and used by conventional street legal vehicles. It includes winter roads, and it contains roads not under the jurisdiction of the MNR sourced from the Ontario Road Network. Recreation trails and short-term forest operation roads or forest fire management roads are not included in the file. An evaluation of the MNR road segment file against roads displayed in the SPOT imagery indicates that the coverage is quite good, although JDMA coarsely delineated some unmapped roads that have been included on Figure 14. Some of the roads mapped by JDMA could represent old logging roads or recreation trails.

The background image in Figure 14 is a distance plot to the nearest point on any of the roads in the MNR road segment file, not including roads shown on Figure 14 designated as mapped by JDMA. This image highlights parts of the area of the four communities that are least accessible using the existing road network.

The complex, steep and irregular morphology of the bedrock surface in many of the areas of thin drift cover in the area of the four communities will pose a major constraint for construction and route alignments, which will require extensive rock cut-and-fill operations (VanDine, 1980b). Due to the shallow drift cover and complex bedrock topography, development activities are more difficult and expensive than in areas of thicker overburden. Construction will be extremely difficult in areas with high, steep rock slopes and steep bedrock hills. Waterbodies and wetlands will also pose obstacles for road routing and construction.

9 SUMMARY

This report presents an analysis of the terrain in the area of the four communities using available remote sensing and geoscientific information sources. The main information sources relied on in this study are the CDED elevation model, SPOT and Landsat satellite imagery, maps and reports from the Northern Ontario Engineering Geology Terrain Study (NOEGTS), and maps and reports from the OGS 1:50,000 scale surficial mapping programs. Additional information sources included the Ontario Drill Hole Database, the Water Well Information System, Assessment File Research Imaging (AFRI) database, and several files on drainage features, lake depths, aggregate pits, and roads obtained from Land Information Ontario (LIO).

A map and descriptions of the Quaternary deposits are presented based on the 1:100,000 scale NOEGTS mapping and the 1:50,000 scale surficial mapping. Surficial deposits outside of the valleys and other depressions are generally thin and discontinuous. Apart from local areas where drift deposits obscure bedrock surface irregularities and, consequently, where low surficial lineament density would be expected (Section 3.3), the landscape is controlled almost entirely by bedrock topography, with major faults and other lineaments, and major bedrock hills and highlands forming the main landscape elements. The NOEGTS mapping (Figure 3) suggested that thin drift characterizes about 76% of the area of the four communities, whereas a refined delineation of the most likely areas of thin drift forming about 34% of the area was generated through the delineation of highlands and hills using the 1:50,000 scale digital elevation model (Figure 13). Rock outcrops mapped using Landsat data indicated that exposed bedrock can be found over about 8% of the portion of the area of the four communities not covered by Lake Huron.

All Quaternary deposits in the area of the four communities are believed to be Wisconsinan or Holocene in age. The Laurentide Ice Sheet advanced to the south-southwest across the area during the last glacial maximum depositing a thin layer of sandy bouldery till over much of the area. Although several east-west trending morainic belts are postulated in the area, temporary ice sheet stabilization during deglaciation did not produce major laterally continuous end moraine deposits like those observed elsewhere in northern Ontario. Ice recessional features are limited to short eskers and other ice-contact deposits, particularly subaqueous fans. Extensive glaciolacustrine deposits associated with high levels of the Lake Huron basin during and following deglaciation are found in two main belts along the lowland bordering Lake Huron: one extends along the Spanish River from Espanola to Spanish; the other extends along a coastal plain between Blind River and Thessalon. Sandy glaciolacustrine deposits found at higher elevations have been interpreted as forming within inland proglacial lakes formed between the ice sheet and local bedrock highs.

The thickest surficial deposits and the largest lakes in the area of the four communities are mostly located within depressions associated with valleys and other low-lying areas, with some deposit thicknesses reported in the available water well and borehole data exceeding 90 to 130 m. Borehole data indicating overburden deposits exceeding 80 m in thickness were reviewed in Section 5.1.2. Even with the unevenly distributed available borehole data, examples have been found of valleys that extend 200 m or more below the nearby uplands, with sandy valley fill deposits 80 to 100 m thick resting on top of the fault zones and other structural and lithological discontinuities beneath the valleys. In contrast, drift deposits are described as being thin (less than 1 m thick) to absent on top of rock-controlled hills in the area.

Drainage divides delineated in the provincial quaternary watershed file produced by the Ministry of Natural Resources (MNR) were confirmed using the CDED surface model. In some instances, the quaternary watersheds were subdivided based on the presence of continuous highlands dividing flow within the watersheds. An updated watershed file was produced including drainage divides not present in the MNR quaternary watershed file. All of the surface flow within the area of the four communities is directed towards Lake Huron. The Mississagi, Blind, Serpent and Spanish rivers and their tributaries are the major watercourses that drain the area, with drainage occurring generally from north to south.

Shallow groundwater flow, recharge and discharge are expected to be mainly controlled by topography and the distribution of surficial deposits. Shallow groundwater flow patterns will follow the local surface flow patterns suggested in the detailed watershed map (Figure 11). In the hills and highlands forming the headwaters of creek and river basins (Figure 13), precipitation and snowmelt will infiltrate into shallow sandy till aquifers and into bedrock discontinuities daylighting where drift deposits are absent. Groundwater from the highlands will recharge the major aquifers found in the valleys and other depressions, and the valley aquifers will discharge into local lakes, rivers and wetlands. Sandy valley fill deposits with potential as major surficial aquifers have been found to extend at least 200 m below the height of nearby uplands. Apart from the latter observation, this study found no information beyond what was presented in the initial screening study (Geofirma Engineering Ltd., 2012a-d) on groundwater flow at repository depth (about 500 m).

No information on the presence of late- or post-glacial faulting in the area of the four communities has been described in the literature, and no such features were identified from the available remote sensing data. Features to consider in a future search for evidence of late- or post-glacial faulting have been suggested. Air photo interpretation could help with identifying possible features, such as deformed eskers or recessional moraines extending across major faults, but any identified features would need to be checked in the field. Sandy and silty sediments such as some outwash and glaciolacustrine deposits could display liquefaction-induced deformation associated with late- or post-glacial faulting. Aggregate pits located near mapped faults could be checked for seismically induced distortions of any fine-grained sediments that may be present. Wave-washed bedrock exposures in the lowland bordering Lake Huron could be checked for fault-related offsets of glacially striated and sculpted bedrock surfaces.

Highways 17, 810, 108, 546 and 129 represent paved highways that provide access to areas within the southern half and along the western margin of the area of the four communities. The most remote part of the area of the four communities is represented by a rectangular zone 40 by 125 km in extent in the northern part of the area where distances to the nearest main road range from 10 to 50 km. In detail, 62% of the Archean rock in the area of the four communities is located further than 10 km from the nearest point on a main road, 30% is further than 20 km, and 12% is further than 30 km. The network of local roads could provide access for preliminary site reconnaissance. The complex, steep and irregular morphology of the bedrock surface in many of the areas of thin drift cover in the area of the four communities will pose a major constraint for construction and route alignments, which will require extensive rock cut-and-fill operations (VanDine, 1980b). Due to the shallow drift cover and complex bedrock topography, development activities are more difficult and expensive than in areas of thicker overburden. Construction will be extremely difficult in areas with high, steep rock slopes and steep bedrock hills. Waterbodies and wetlands will also pose obstacles for road routing and construction.

The terrain analysis provides information on the distribution of overburden deposits and large lakes that can play a role in generating a background of structural and lithological uncertainty in certain areas. The role of overburden deposits in concealing minor structures and censoring the lengths of major structures is apparent when comparing the observed lineament densities (JDMA, 2014) to the areas of thick overburden as determined through the current terrain analysis. Areas of low slope density described in Section 3.3 are areas where a low density of surficial lineaments would be expected due to drift filling the lows in the bedrock topography.

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REPORT SIGNATURE PAGE

J.D. Mollard and Associates (2010) Limited

David van Zeyl, M.Sc.

Lynden Penner, M.Sc., P.Eng., P.Geo.

FIGURES

LEGEND

- Settlement
- Communities of Elliot Lake, Blind River, The North Shore and Spanish
- Main road
- Waterbody
- Watercourse
- First Nations reserve
- Provincial Park

Data sources:
Road: Selected from MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse

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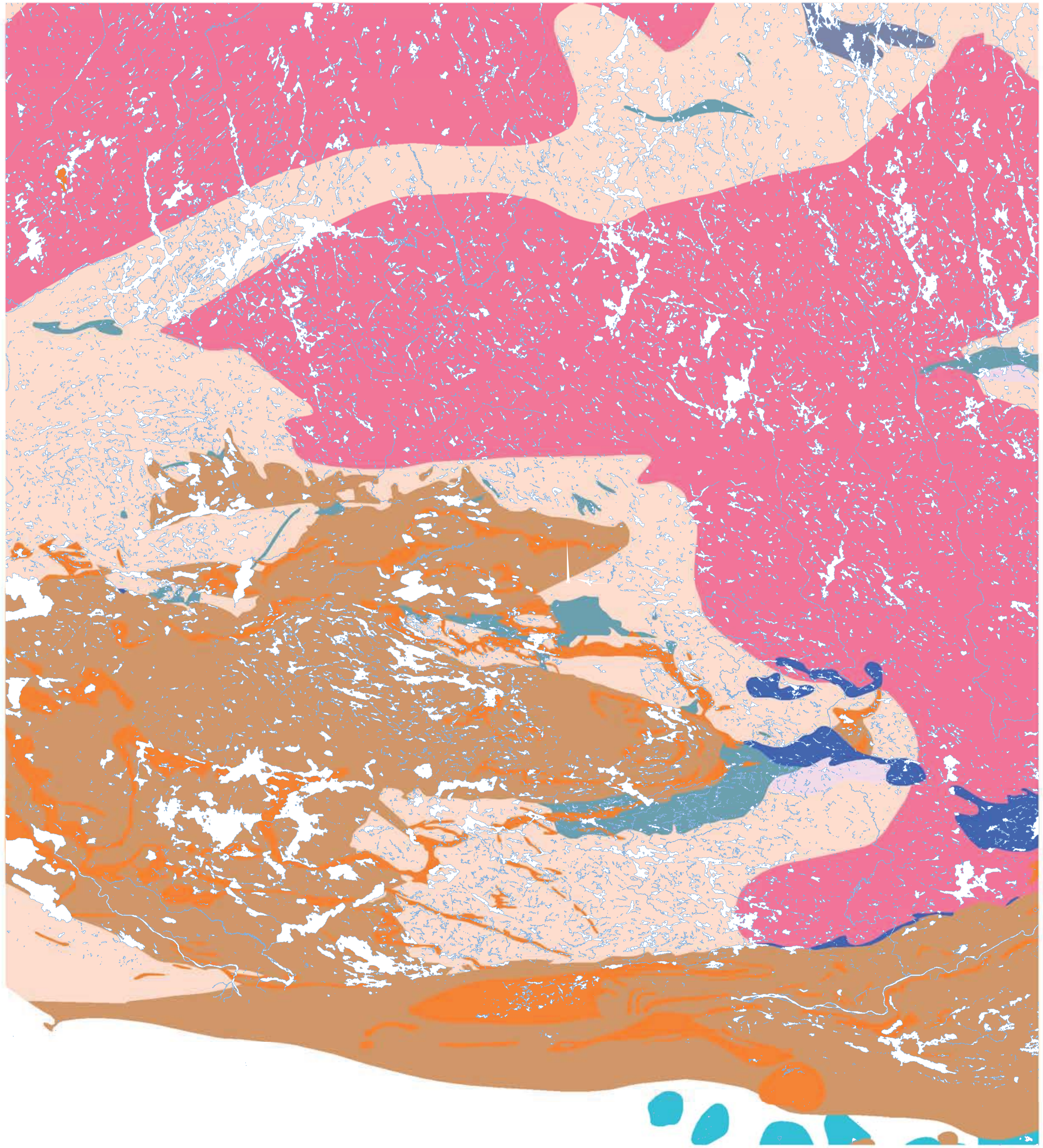
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE
Tthe area of the four communities

DESIGN	DVZ	25 JUN 2012	FIGURE 1	REVISION 3
GIS	DVZ	23 JUN 2014		UTM ZONE 17
CHECK	LAP	26 JUN 2014		NAD 1983
REVIEW	GS	27 JUN 2014		1:550,000



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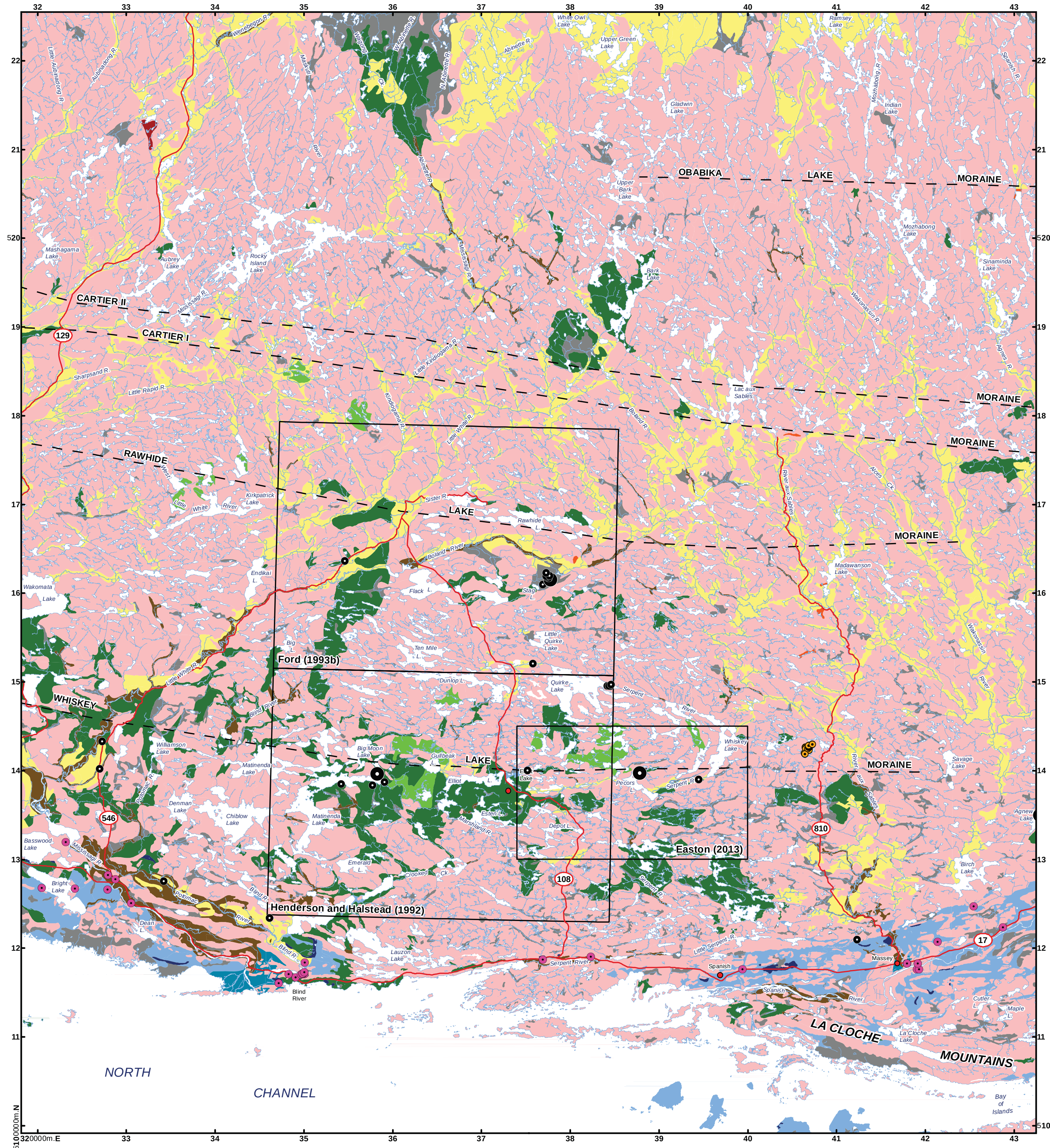


LEGEND

- Settlement
- Main road
- East Bull Lake drill hole
- Morainic belt
- Map outline
- Waterbody
- Watercourse

Depth to bedrock

Drillhole

- 40 - 80 m
- > 80 m

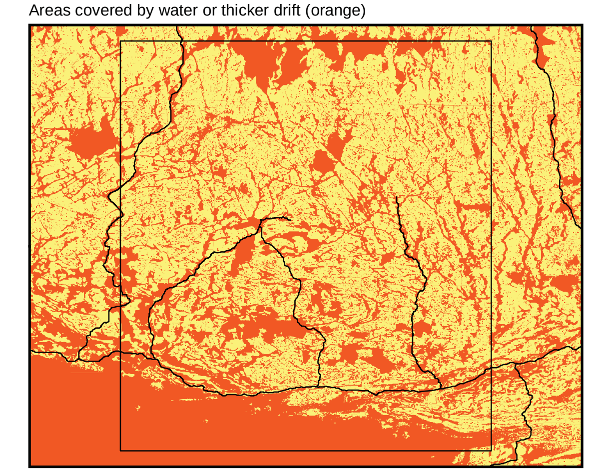
Water well

- > 30 m

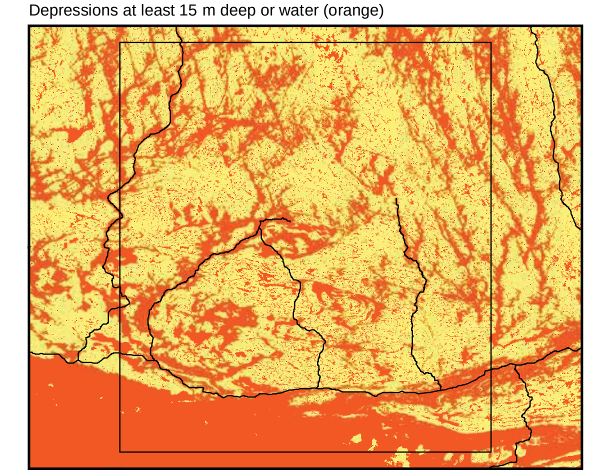
Surficial geology

- Ground moarine
- End Moraine
- Glaciofluvial kame
- Glaciofluvial esker
- Glaciofluvial outwash
- Glaciolacustrine delta
- Glaciolacustrine plain
- Glaciolacustrine beach
- Alluvial
- Organics
- Bedrock

Areas covered by water or thicker drift (orange)



Depressions at least 15 m deep or water (orange)



Data sources:
NOEGTS: OGS MRD 160
Road: Selected from MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Drillhole: OGS Ontario Drillhole Database
Water well: MOE Water Well information System

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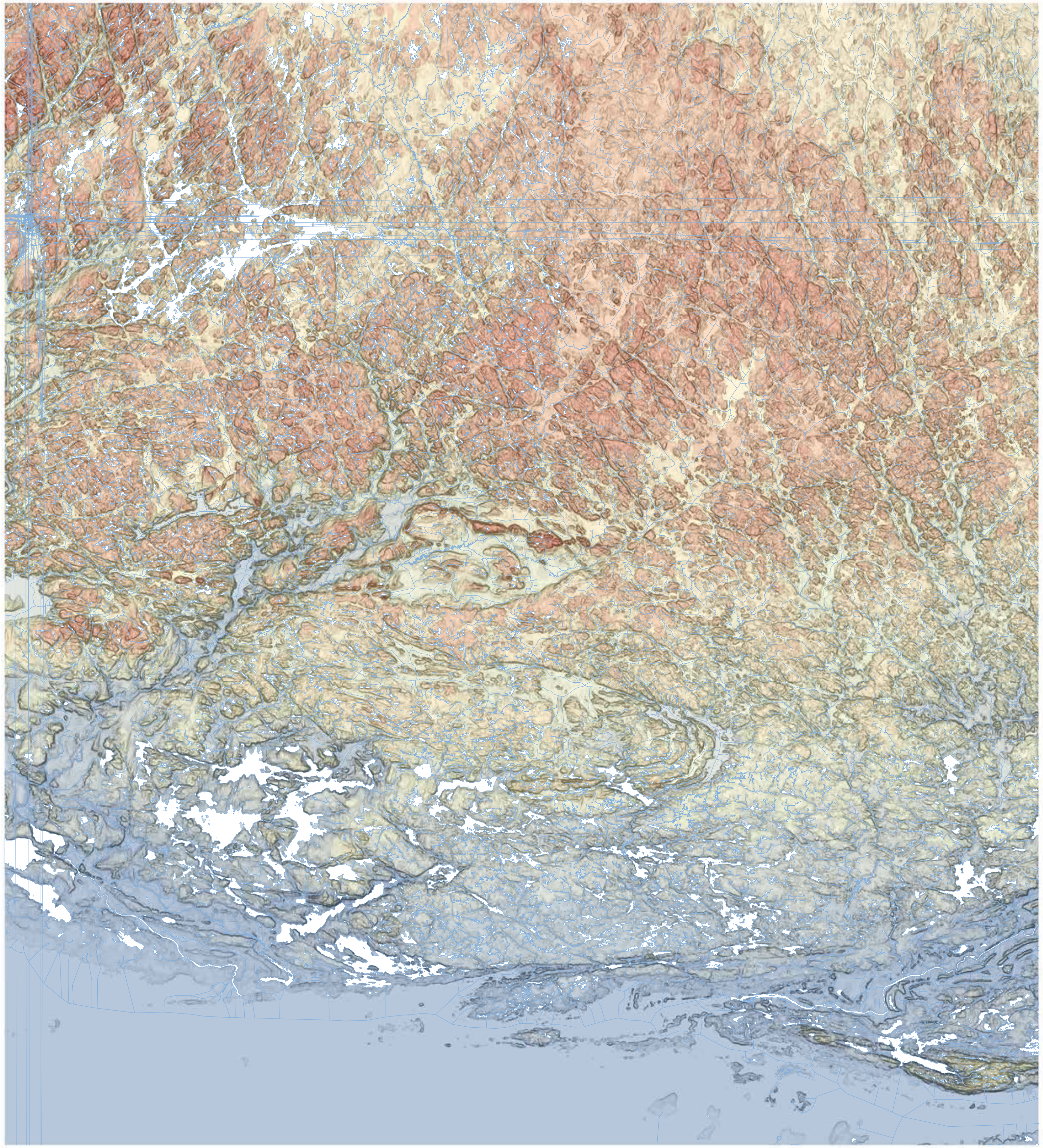
PROJECT PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE Surficial geology of the area of the four communities

DESIGN	DVZ	02 MAY 2013	FIGURE 3	REVISION 2
GIS	DVZ	23 JUN 2014		UTM ZONE 17
CHECK	LAP	26 JUN 2014		NAD 1983
REVIEW	GS	27 JUN 2014		1:550,000



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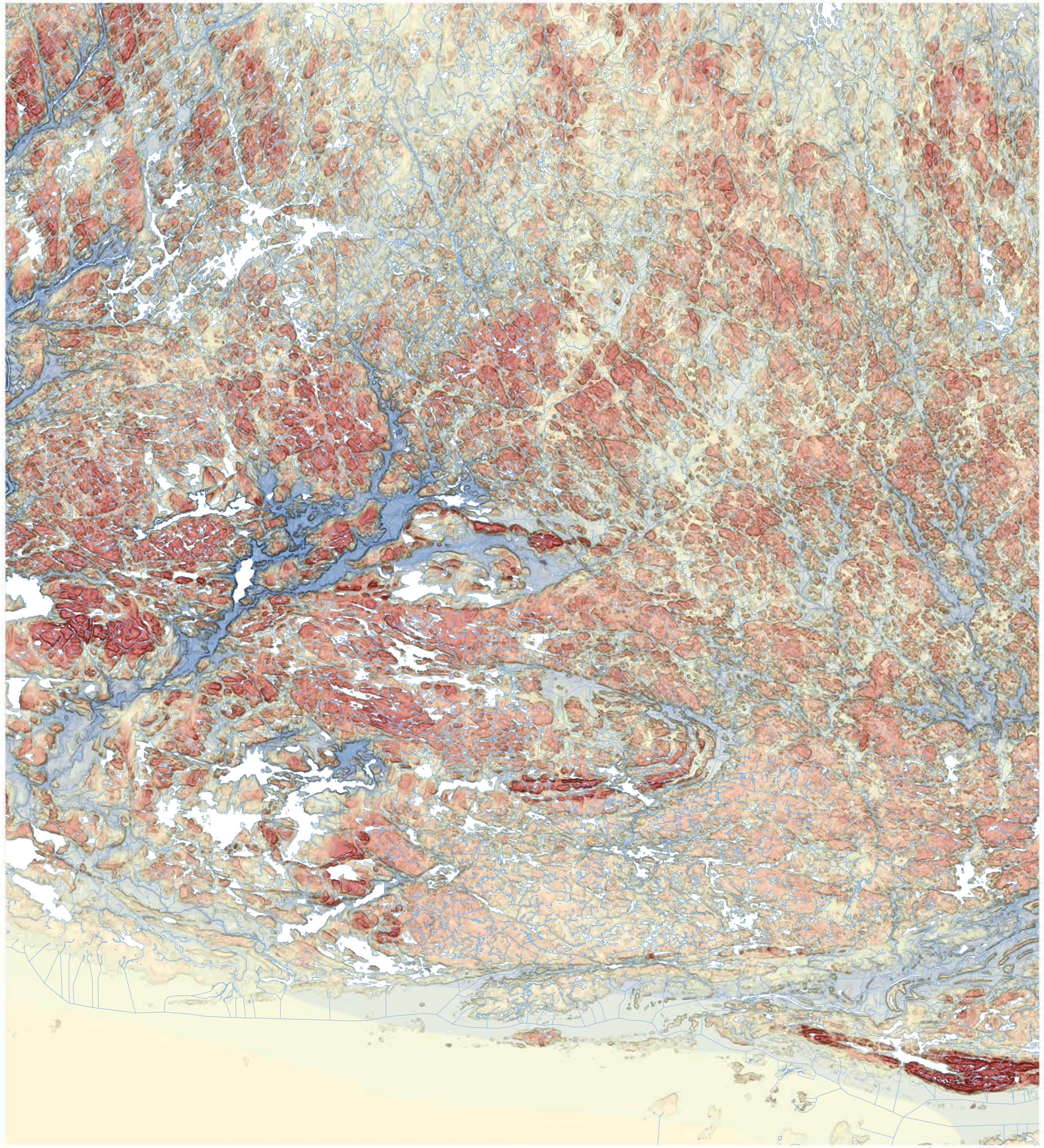

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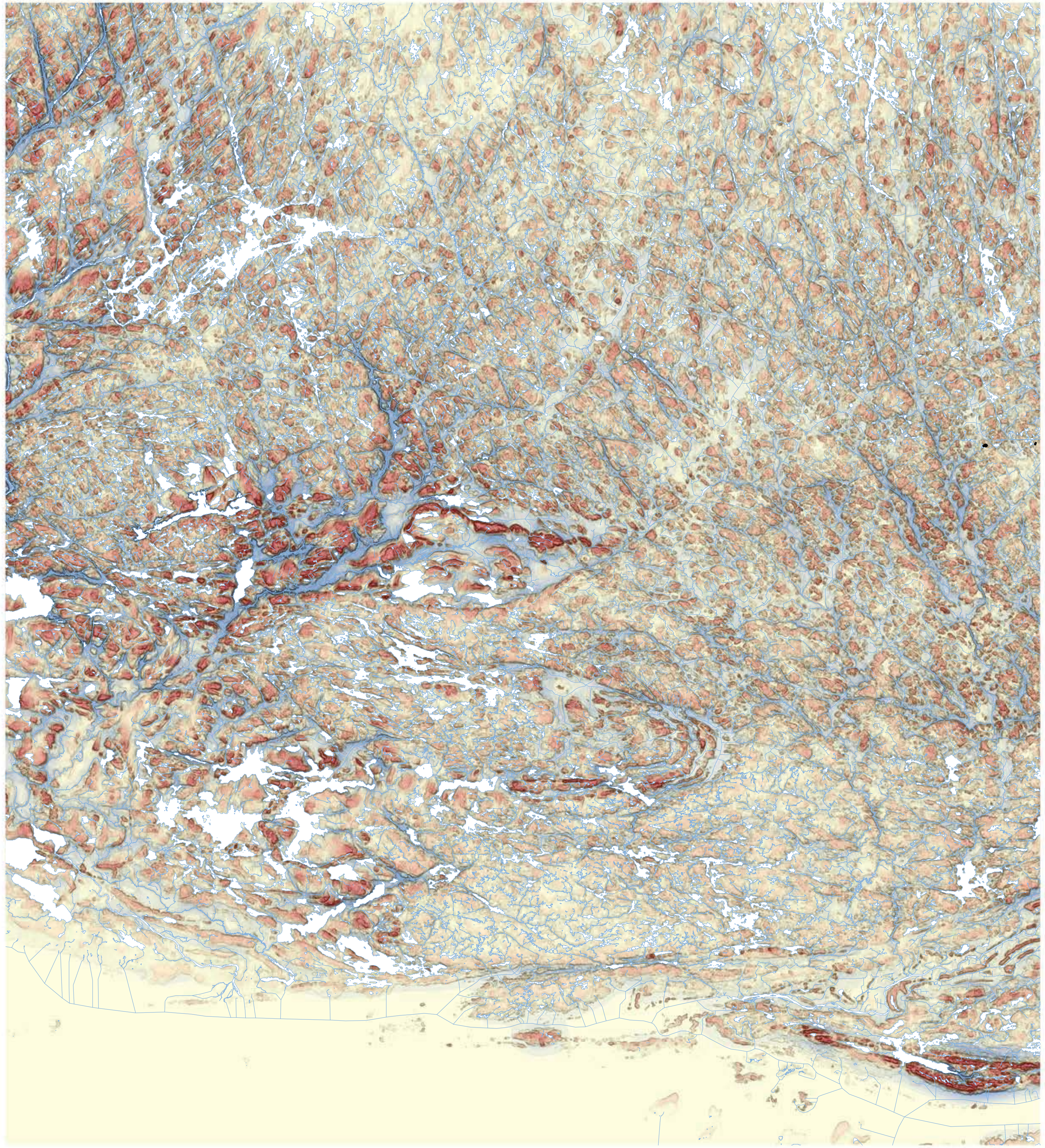

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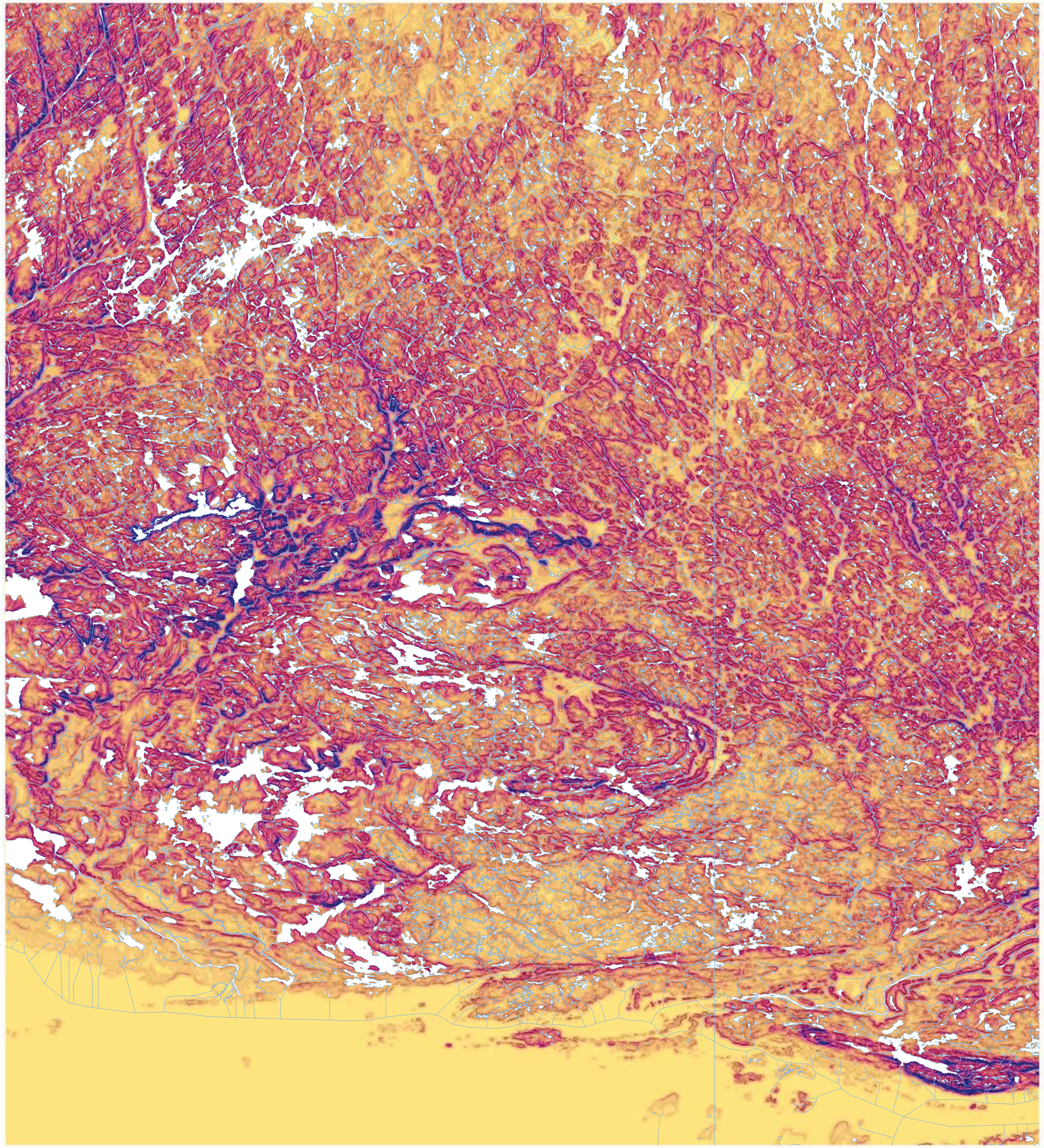

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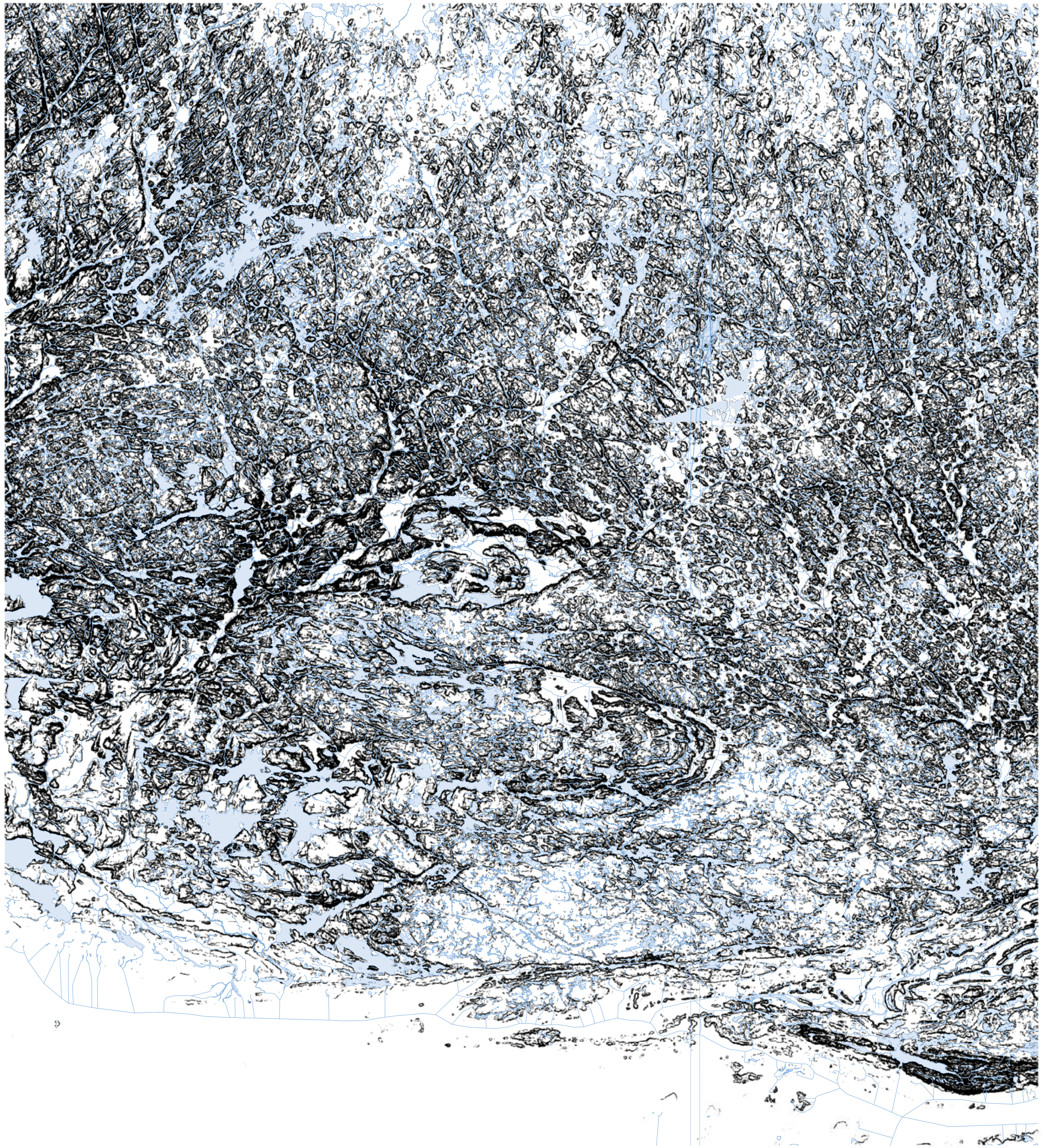

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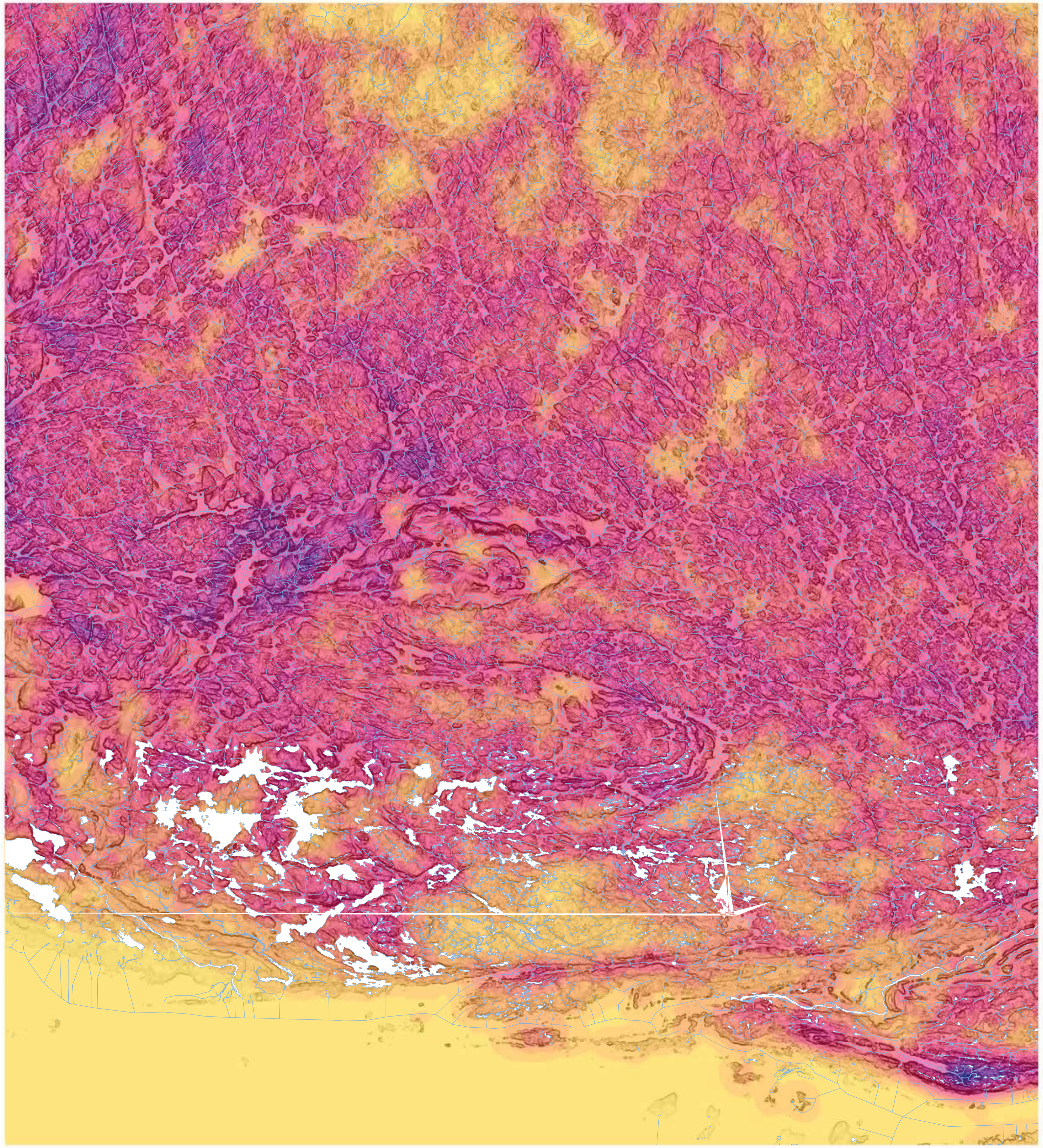

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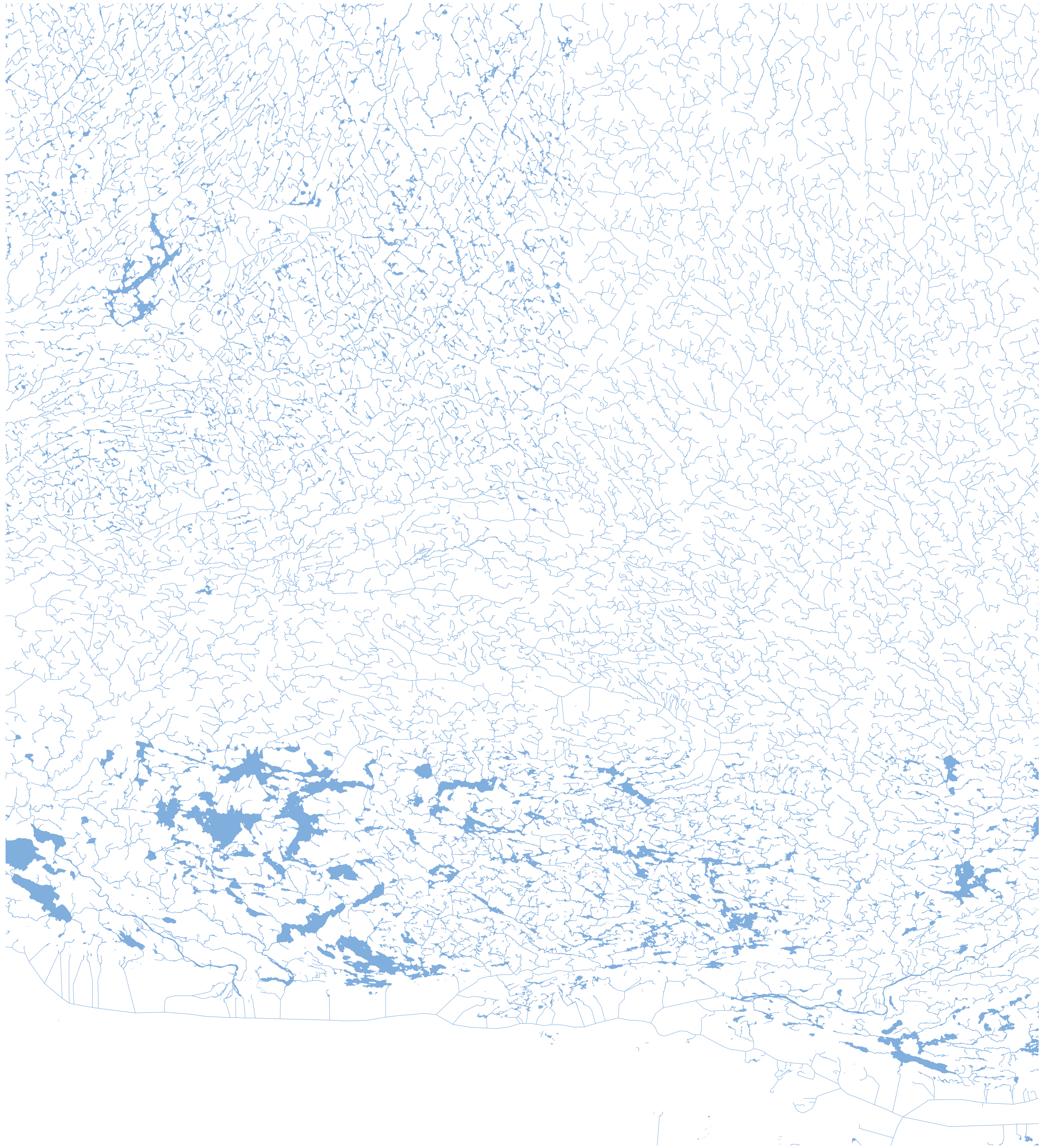

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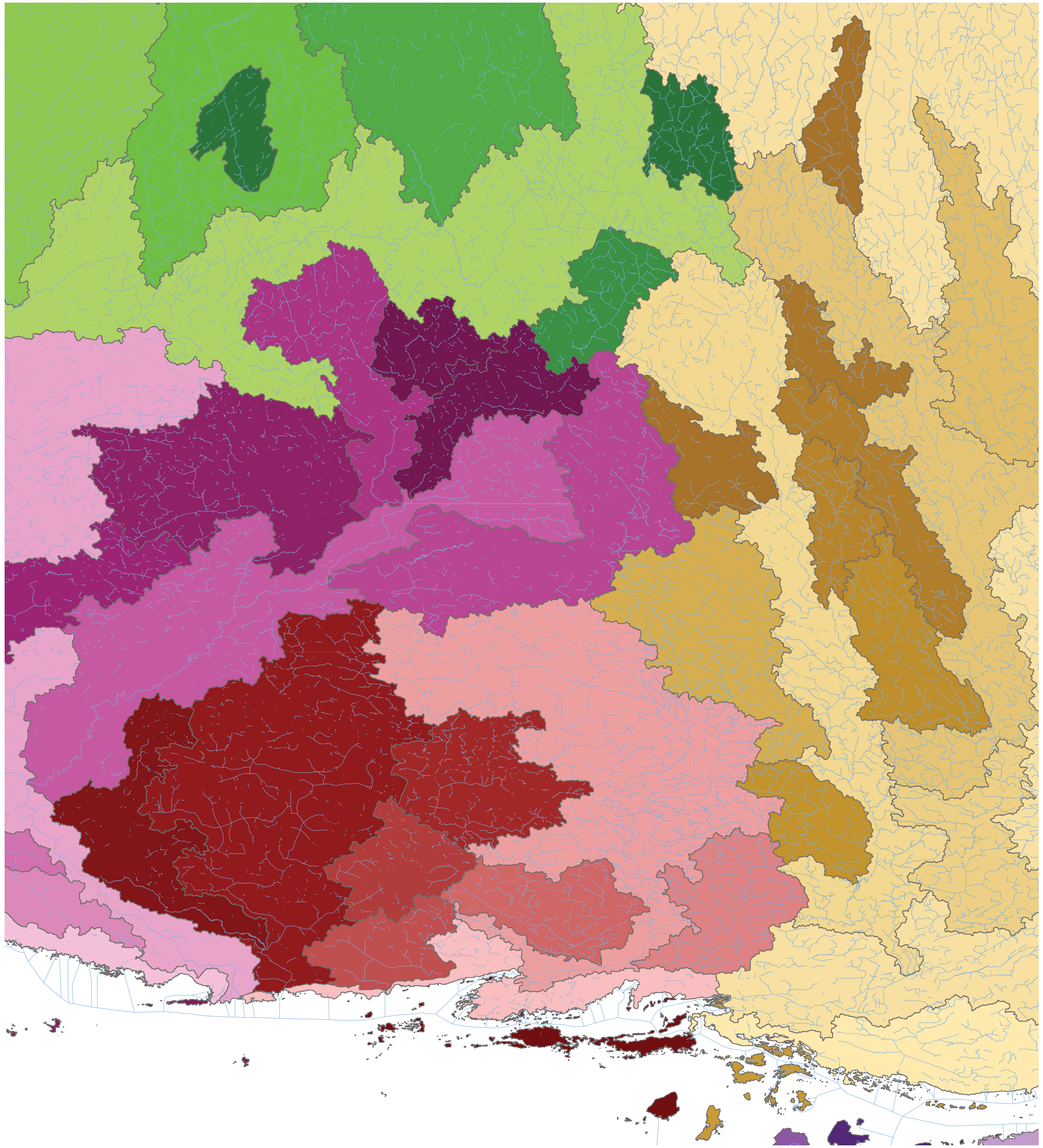

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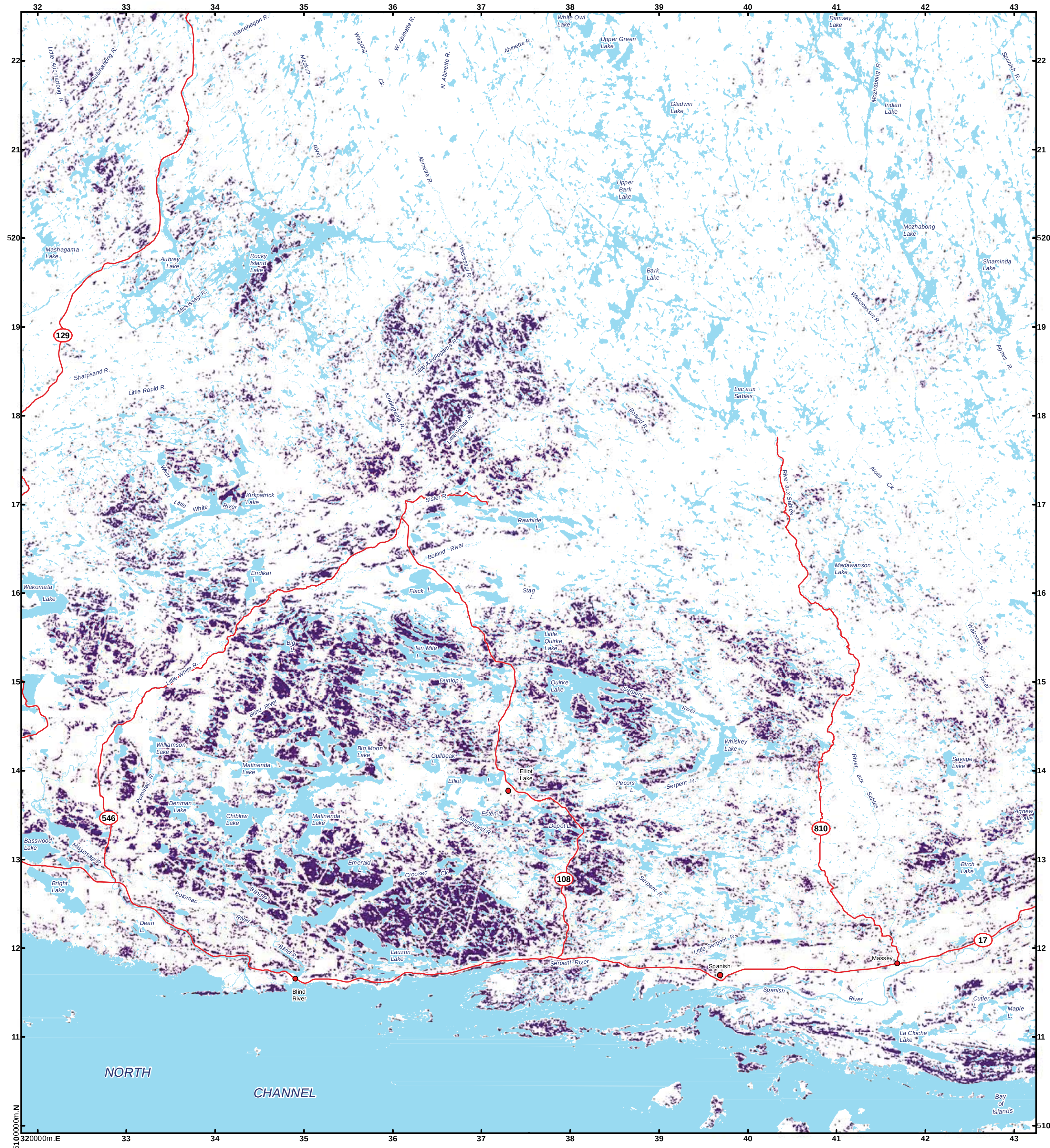

LEGEND

- Settlement
- Main road
- Waterbody
- Bedrock outcrop

Data sources:
Road: Selected from MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse

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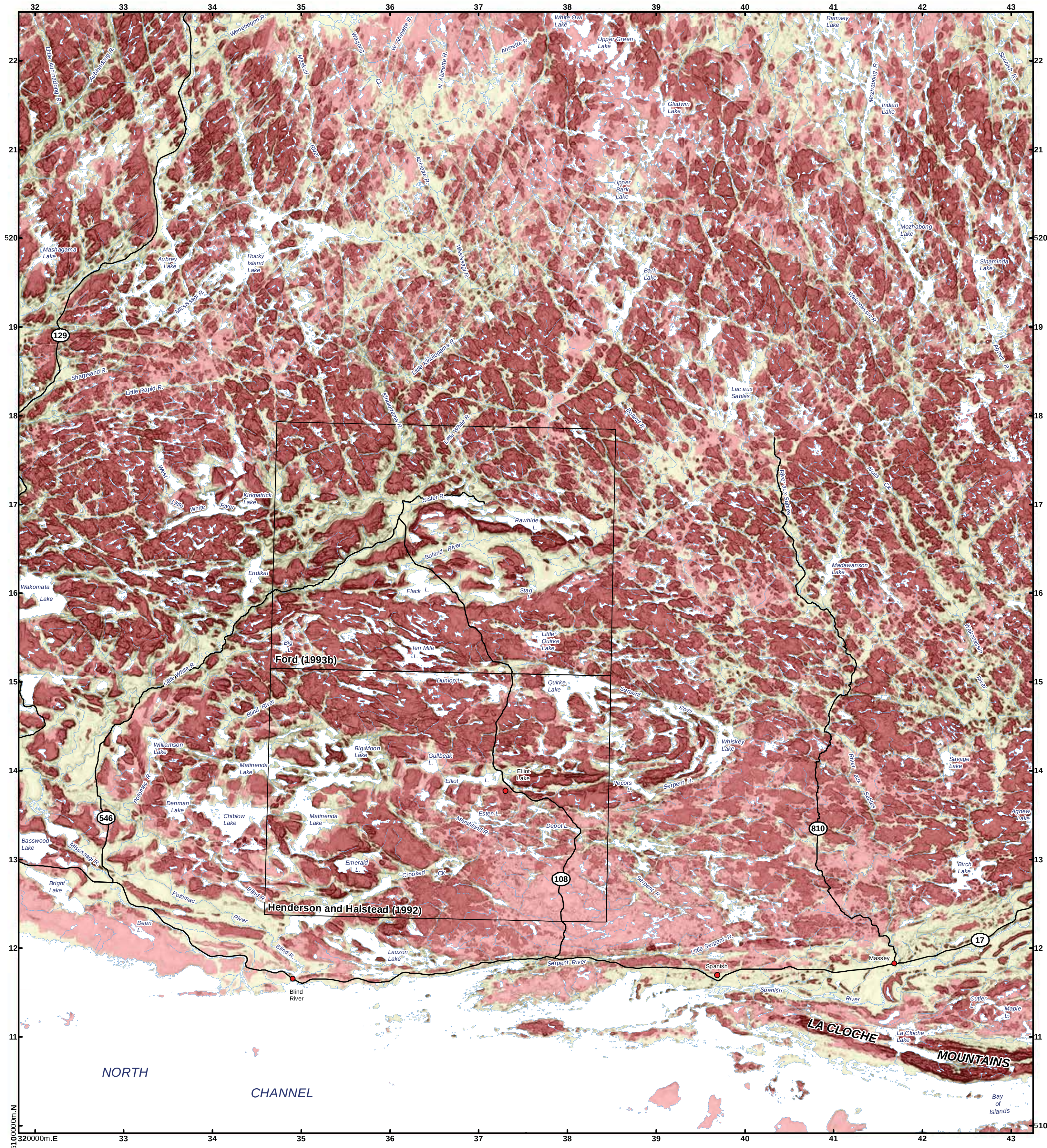
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE
Bedrock outcrops mapped from Landsat MSS imagery

DESIGN	DVZ	02 MAY 2013	FIGURE 12	REVISION 1
GIS	DVZ	23 JUN 2014		UTM ZONE 17
CHECK	LAP	26 JUN 2014		NAD 1983
REVIEW	GS	27 JUN 2014		1:550,000

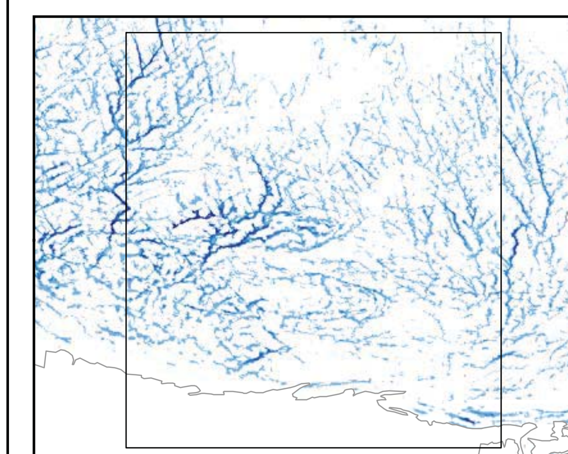


LEGEND

- Settlement
- Main road
- Map outline
- Waterbody
- Watercourse
- Highland/hill
- Plain
- Depression

Slope (°)

- 0 - 1
- 1.1 - 3.7
- 3.8 - 6.3
- 6.4 - 9
- 9.1 - 11.6
- 11.7 - 14.2
- 14.3 - 16.9
- 17 - 67.4



Depression depth (m)

- -116.3 - -80
- -79.9 - -60
- -59.9 - -40
- -39.9 - -20
- -19.9 - 160

Data sources:
Road: Selected from MNR road segment
Waterbody: NTDB Waterbody 1:250,000
Watercourse: NTDB Watercourse 1:250,000
Highlands, plains, depressions: See Section 6

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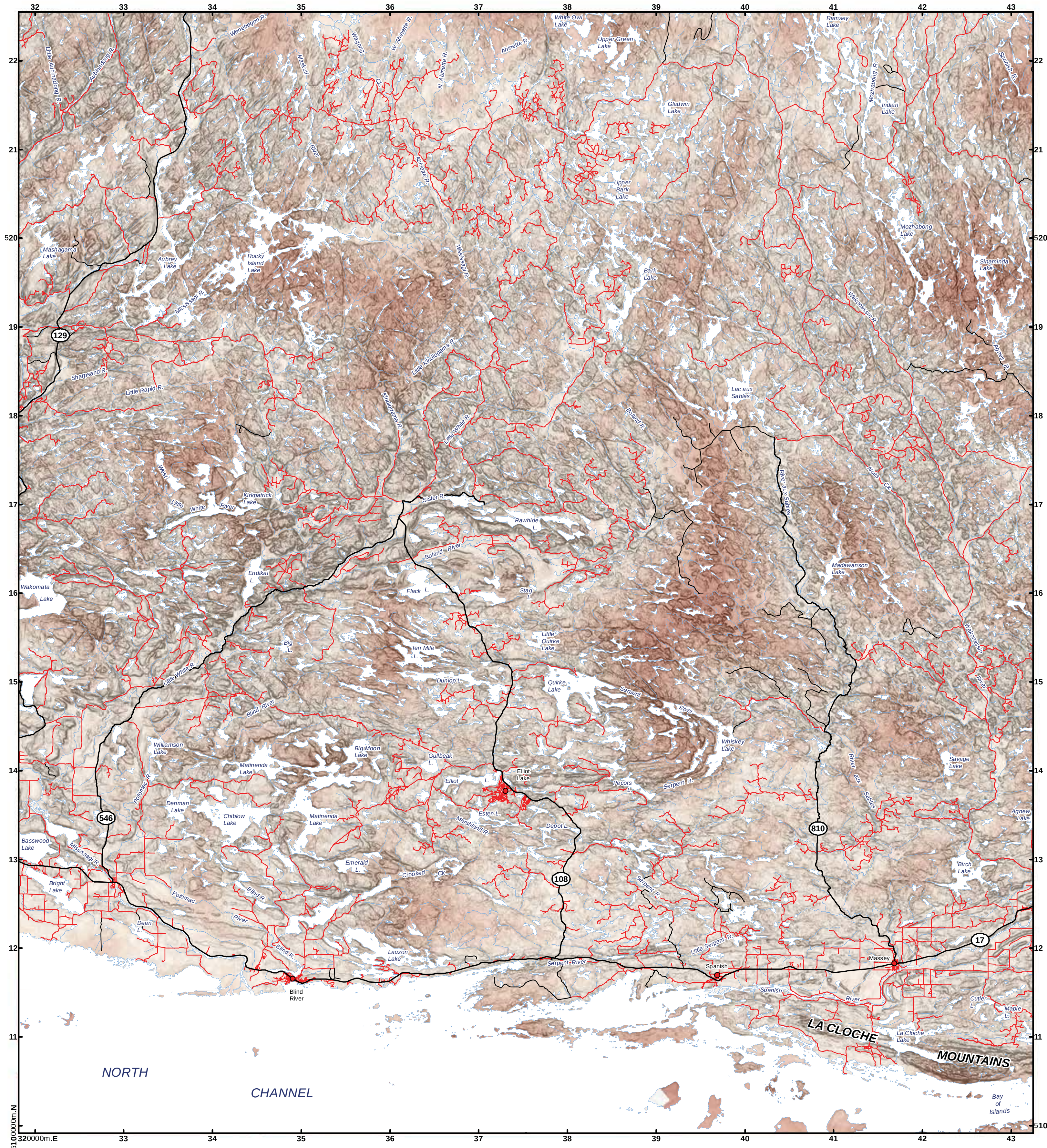
PROJECT: PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE: Relief map used to facilitate groundwater discussion

DESIGN	DVZ	21 MAY 2013	FIGURE 13	REVISION 2
GIS	DVZ	23 JUN 2014		UTM ZONE 17
CHECK	LAP	26 JUN 2014		NAD 1983
REVIEW	GS	27 JUN 2014		1:550,000



LEGEND

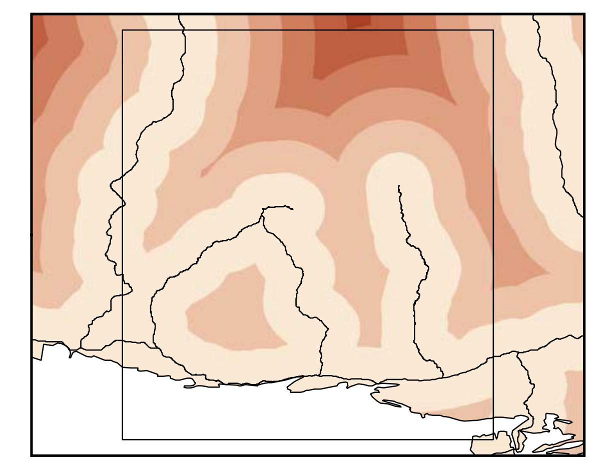
- Settlement
- Main road
- Local road (JDMA)
- Local road (MNR)
- Waterbody
- Watercourse

Slope (°)

- 0 - 1
- 1.1 - 3.7
- 3.8 - 6.3
- 6.4 - 9
- 9.1 - 11.6
- 11.7 - 14.2
- 14.3 - 16.9
- 17 - 67.4

Distance to nearest road (m)

- 0 - 1,000
- 1,001 - 2,000
- 2,001 - 3,000
- 3,001 - 4,000
- 4,001 - 5,000
- 5,001 - 6,000
- 6,001 - 7,000
- 7,001 - 8,000
- 8,001 - 9,000
- 9,001 - 10,000
- 10,001 - 11,000



Distance to nearest main road (m)

- 0 - 10,000
- 10,001 - 20,000
- 20,001 - 30,000
- 30,001 - 40,000
- 40,001 - 50,000
- 50,001 - 60,000

Data sources:
DEM: CDED 1:50,000
Road: MNR road segment
Waterbody: NTDB 1:250,000
Watercourse NTDB 1:250,000

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PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE
Road network and distances to nearest roads

DESIGN	DVZ	02 MAY 2013	FIGURE 14	REVISION 2
GIS	DVZ	23 JUN 2014		UTM ZONE 17
CHECK	LAP	26 JUN 2014		NAD 1983
REVIEW	GS	27 JUN 2014		1:550,000