NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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

## MUNICIPALITY OF WAWA, ONTARIO

**APM-REP-06144-0028**

**NOVEMBER 2013**

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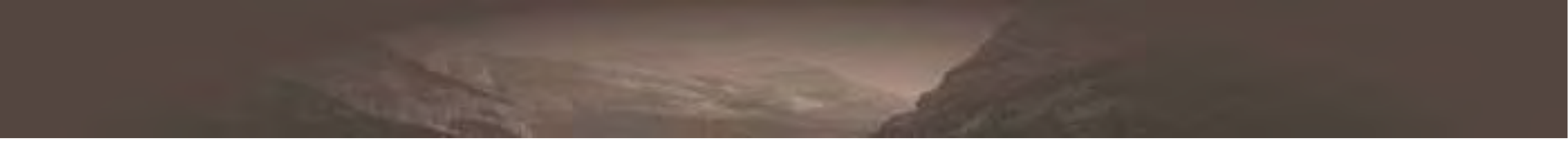

**PHASE 1 DESKTOP GEOSCIENTIFIC PRELIMINARY ASSESSMENT**

# TERRAIN AND REMOTE SENSING STUDY

## MUNICIPALITY OF WAWA, ONTARIO

November 2013

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## EXECUTIVE SUMMARY

In December, 2011, the Municipality of Wawa, Ontario expressed interest in continuing to learn more about the Nuclear Waste Management Organization nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess the potential suitability of the Wawa area for safely hosting a deep geological repository (Step 3). This request followed the successful completion of an initial screening conducted during Step 2 of the site selection process.

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

This report presents the findings of a terrain and remote sensing assessment completed as part of the desktop geoscientific preliminary assessment of the Wawa area (Geofirma, 2013). The main information sources used include the Canadian Digital Elevation Data (CDED) elevation model, the multispectral SPOT 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 mapping by the Ontario Geological Survey (OGS).

The study addresses the following seven objectives:

- Evaluate the nature, areal extent and depth of overburden materials;
- Delineate 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 Wawa area, including estimates of overburden thickness. Maps and descriptions of surficial deposits are presented in this report based on the 1:100,000-scale NOEGTS mapping and the 1:50,000-scale

OGS mapping. Comparisons between the two maps indicated that the NOEGTS mapping underestimated the extent of thicker overburden deposits. The detailed mapping indicated that thicker overburden deposits covered about 40% of the area, whereas NOEGTS suggested 20%. Drainage divides delineated in the provincial quaternary watershed file produced by the Ministry of Natural Resources were confirmed and some watersheds were subdivided using the CDED surface model. An updated watershed file was produced that specifies the drainage divides delineated in this study not present in the quaternary watershed file. Based on the available topographic and drainage information, groundwater in the Wawa area can be conceptualized as being recharged in the highlands of the northwest, northeast and southeast parts of the Wawa area with Lake Superior representing the regional discharge zone. Regional groundwater flow in the bedrock will be locally affected by the presence of faults and major structural and lithological discontinuities that have hydraulic properties different from that of the bulk bedrock.

Conclusive identification of features indicative of reactivation of ancient bedrock structures due to cycles of glacial loading and unloading cannot be identified using the information sources available in the current study. Field investigations would be required to identify such features.

Existing highways generally provide access only to low-lying, drift-covered parts of the potentially suitable geological formations within the Wawa area.

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# 1 INTRODUCTION

In December 2011, the Municipality of Wawa, Ontario expressed interest in continuing to learn more about the Nuclear Waste Management Organization nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the Wawa area for safely hosting a deep geological repository (Step 3). The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations (NWMO, 2013).

This report presents the findings of a terrain and remote sensing assessment completed as part of the desktop geoscientific preliminary assessment of the Municipality of Wawa and its periphery, referred to as the “Wawa area” (Geofirma, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Wawa area contains general areas that have the potential to meet NWMO’s geoscientific site evaluation factors.

## 1.1 OBJECTIVES

This report presents an analysis of the terrain in the Wawa area using existing remote sensing and geoscientific information sources. The information will enhance and expand upon that presented in the initial screening report (Geofirma, 2011) prepared for the Nuclear Waste Management Organization (NWMO) as part of the Adaptive Phased Management (APM) project for the long term management of Canada’s used nuclear fuel. The main information sources relied on in this assessment are the Canadian Digital Elevation Data (CDED) surface model, the multispectral SPOT satellite imagery and the maps and reports completed through the Northern Ontario Engineering Geology Terrain Study (NOEGTS) in the late 1970s and by the Engineering and Terrain Geology Section of the Ontario Geological Survey in the 1990s. Additional data sources included the Water Well Information System, the Ontario Drill Hole Database, and the Assessment File Research Imaging (AFRI) database.

This assessment makes use of remote sensing and geoscientific information sources to address the following five objectives:

- Evaluate the nature, areal extent and depth of overburden materials;
- Delineate 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 objectives above were addressed for the Wawa area described in Section 1.2 using the data and methodology described in Section 1.3.

## 1.2 WAWA AREA

The main part of the Wawa area is a rectangular area approximately 80 km by 53 km in size, encompassing an area of about 4,274 $km^2$ (Figure 1). The approximate western, northern, eastern and southern limits of the Wawa area are (UTM Zone 16, NAD83): 633000, 5341500, 712850, and 5288000 m. The settlement area of Wawa is located near the intersection of Highway 17 and Highway 101.

## 1.3 DATA AND METHODS

This section summarizes the remote sensing and geoscientific data sources available for the Wawa area, including an evaluation of the quality of the data.

### 1.3.1 NOEGTS

Overburden deposits within the Wawa area were mapped as part of a program undertaken between 1977 and 1980 entitled the Northern Ontario Engineering 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 1:54,000. 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, maps produced from this program currently represent the best level of detail available for surficial geology mapping and descriptions of terrain conditions.

Three main Northern Ontario Engineering Geology Terrain Studies (Gartner and McQuay, 1979a, b; McQuay, 1980) along with three maps at a scale of 1:100,000 (McQuay, 1979a, b, c) describe the terrain conditions in the Wawa area. These reports provide background information on the bedrock and Quaternary geology, followed by 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 discuss the influence of the terrain conditions on general construction (e.g., location and construction of highways, transmission lines, timber storage sites, town sites, work camp sites, waste disposal sites, cottage subdivisions, airfields), aggregate resource potential (e.g., asphalt aggregate, traffic gravel, base course and sub base for pavement structures) and groundwater resource potential.

Recently, 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 assessment, JDMA clipped part of the NOEGTS digital map layer and then transformed it from geographic coordinates into Universal Transverse Mercator (UTM) projection (Zone 16).

### 1.3.2 OGS MAPS AND REPORTS

The Engineering and Terrain Geology Section of the Ontario Geological Survey mapped the surficial deposits in the northeast part of the Wawa area at a scale of 1:50,000 (Morris, 1990, 1991, 1992a, b). The mapping was conducted to provide a framework for exploration programs using overburden as an exploration media and to complement bedrock mapping of the Michipicoten greenstone belt and surrounding area. Glacial landforms were mapped using Landsat imagery and black and white air photographs at scales of 1:15,480 and 1:50,000. Fieldwork leading up to the production of two compilation maps (Morris, 2001a, b) and an open file report (Morris, 2001c) was conducted over four summers in 1990, 1991, 1994 and 1996.

JDMA obtained the digital MicroStation (.dgn) files for the two maps of Morris (2001a, b) provided by the Ontario Geological Survey and converted them to a single shapefile. A layer file was created that coloured the various surficial units based on the colours shown on the accompanying map legends. This approach was also taken for the bedrock geology maps of Johns and McIlraith (2002) and Santaguida (2001).

### 1.3.3 CDED

This subsection describes the digital elevation model used to evaluate the terrain in this assessment. Section 4.1 describes the drainage basin analysis conducted in this assessment using the CDED surface raster as the representation of the landscape.

Canadian Digital Elevation Data (CDED), 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 Wawa area. The digital elevation model (DEM) used for this assessment was constructed by NRCan using provincial data created through the Water Resources Information Program (WRIP) of the Ontario Ministry of Natural Resources (OMNR). The data represented 1:20,000 source data acquired through the Ontario Base Mapping (OBM) program, which was a major photogrammetric program conducted across Ontario between 1978 and 1995. Four main OBM datasets were used: OBM contours, OBM spot heights, WRIP stream network, and lake elevations derived using the OBM spot heights and OBM water features. CDED datasets 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 representation of the land surface that is reasonable for the scale of the data and the underlying photogrammetric method used to generate the elevation data. 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 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.

JDMA converted the elevation matrices provided by GeoBase 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 centred 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 first relief calculation represents a high pass filter, and it can highlight the areas of topographic prominence where thin drift and abundant bedrock exposure are typically located. This high pass filter can also delineate depressions in the landscape, which often represent preferentially eroded damage zones associated with major structures, and these depressions are prone to infilling of Quaternary sediments.

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. As a result, areas of low slope density are areas where the lineament interpreter should expect a low density of lineaments mapped from CDED and to a lesser extent from SPOT.

### 1.3.4 SPOT

SPOT multispectral orthoimagery at a resolution of 20 m formed an important information source for identifying exposed bedrock within the Wawa area (GeoBase, 2011b). SPOT multispectral data consist of several bands, each recording reflected radiation within a particular spectral range. SPOT 5 images 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 (NRN), and Landsat 7 orthoimagery. The orthoimages are provided in GeoTIFF format, projected using Universal Transverse Mercator (UTM) projection referenced to the North American Datum 1983 (NAD83).

Four SPOT images (or 'scenes') provided complete coverage for the Wawa area (Table 2). The scenes are from the SPOT 4 and 5 satellites with one image acquired in June 2005, one in June 2006, and two in May 2007.

**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 multispectral images acquired in this assessment.**

| Scene ID | Satellite | Date of image |
|---|---|---|
| S5_08531_4760_20050621 | SPOT 5 | June 21, 2005 |
| S4_08410_4760_20070510 | SPOT 4 | May 10, 2007 |
| S5_08450_4760_20060901 | SPOT 5 | June 1, 2006 |
| S5_08419_4731_20070503 | SPOT 5 | May 3, 2007 |

In order to assist with the interpretation of the location and extent of bedrock outcrops in the Wawa area, JDMA performed principal component analysis on the SPOT multispectral data. Prior to performing this analysis, water bodies were removed from the SPOT images in order to maximize contrast in the dry areas. This was accomplished by removing values from the shortwave-infrared band (band 4) that were below a threshold. The shortwave band displays a bimodal histogram with one high-valued mode representing dry land surfaces that reflect shortwave radiation, and a low-valued mode for areas that largely absorb shortwave radiation. The latter generally represents water bodies, but can also represent dark forest areas or shadows in front of north facing cliffs where sunlight is absorbed.

Principal component analysis based on all four SPOT bands was found to generate composite images that provided the best definition of the various land cover types thereby enabling optimal interpretation of the presence of bedrock exposures. For that purpose, principal component analysis produced composite images that were superior to those produced by combining any of the raw SPOT bands. For each image, the first three of the four components were used to generate the composite image, which is referred to here as the PCA composite image. Campbell (1987) provides more information on the use of principal component analysis in remote sensing.

An unsupervised classification aimed at mapping bedrock exposures was attempted, but was eventually abandoned and is only described below for reference. Unsupervised classification generates distinct unimodal groups from the four SPOT bands using an iterative self-organizing (ISO) cluster procedure employed within ArcGIS. The ISO cluster algorithm is an iterative process that computes the minimum Euclidean distance when assigning each candidate cell to a cluster. The first step that JDMA took in the unsupervised classification was to classify the four SPOT bands into fifteen classes and to interpret the fifteen classes in light of the features (e.g., bedrock outcrops, clearcuts) interpreted in the PCA composite image. If a set of the fifteen classes delineated the interpreted bedrock exposures exclusively, then this completed the classification and these classes were used to generate a map depicting bedrock exposures. However, in many cases the classes mapping bedrock exposures also mapped wetlands and clearcuts. The next step was to mask the four SPOT bands in order to exclude areas that were both distinctly unrelated to bedrock exposures and effectively delineated by a set of classes, such as areas with a high vegetation index. The cluster analysis was then performed a second time on the masked data.

After some effort in attempting to produce good results from the unsupervised classification, it was found that, generally, the only areas where this type of technique could be used in a straightforward way was in the areas undisturbed by the forest industry in recent decades. It is difficult to make an accurate appraisal of the extent of bedrock exposure within fresh clearcuts. Some of the exposed land within fresh clearcuts represents exposed mineral soil rather than bedrock. Even in the areas not disturbed by the forest industry, there remain challenges in using unsupervised classification to map the exposed bedrock accurately and reliably. For instance, certain parts of wetlands can exhibit similar spectral characteristics as exposed bedrock. Alluvial sediments exposed in creek valleys also display similar spectral properties. Additional issues contribute to the unreliability of this technique. As a result, the identification of bedrock exposure from SPOT imagery in this assessment (Section 5.2.1) has relied on the PCA composite images.

### 1.3.5 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. Section 5.1 summarizes the results of the subsurface information reviewed. Additional subsurface information that could be available from the OGS Resident Geologist Program has not been reviewed.

Water well records from the Ministry of the Environment (MOE) Water Well Information System for the Wawa area were acquired (MOE, 2012). Of the 71 well records within the Wawa area, 14 records were found to contain data on depth to bedrock, most of which are located near the settlement area of Wawa. The wells were drilled between 1962 and 2004.

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 assessment. Some 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.

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 centre of a claim for lack of additional supporting information. 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.

Drill holes in the Wawa area are concentrated primarily in the Michipicoten greenstone belt, which extends from Lake Superior northward and separates the Western batholith and Whitefish Lake batholith. There is a smaller concentration of drill holes in the Mishibishu greenstone belt, located on the north shore of Lake Superior. Most of these drill holes occur in areas mapped as bedrock terrain in the NOEGTS mapping. Only about 10% of the drill holes were oriented vertically. As a result, the vertical depth to bedrock had to be calculated from the recorded dip angle and length of drill hole to bedrock.

Data on depth to bedrock obtained from the Ontario Drill Hole Database must be interpreted carefully. Drilling often is carried out in areas where extensive stripping of the overburden has taken place, and some drill sites might be preferentially located in areas of thin overburden, biasing the drift thickness data to low values.

# 2 SUMMARY OF GEOLOGY

The Wawa area, shown in Figure 1, is underlain by a thin veneer of glacial soils and approximately 3.0 to 2.6 billion year old bedrock of the Superior Province of the Canadian Shield – a stable craton that forms the core of the North American continent (Figure 2). The Canadian Shield is an assemblage of Archean-age plates and accreted juvenile arc terranes and sedimentary basins of Proterozoic age that were progressively amalgamated over geologic time scales.

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

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

## 2.1 BEDROCK GEOLOGY

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

Figure 2 shows the general bedrock geology and main structural features of the southeastern part of the Wawa Subprovince, where the Wawa area is located. The bedrock geology is composed predominantly of irregularly distributed Archean greenstone belts (Michipicoten, Gamitagama, and Mishibishu) surrounded by granitic bodies of various compositions and sizes, with smaller mafic intrusive rocks locally present. The Michipicoten greenstone belt makes a regional reference point, and the surrounding granitoid terranes are named differently on its southern and northern flanks.

To the south, between the Michipicoten greenstone belt and the Kapuskasing structural zone, the granitoid terrane is referred to as the Wawa Gneiss domain (Thurston et al. 1977; Moser, 1994). The granitoid terrane to the west of the Michipicoten greenstone belt is generally referred to as the Western batholith (Card and Poulsen, 1998). The Western batholith and Wawa Gneiss domain, along with the Whitefish Lake and Brulé Bay batholiths (Figure 2) were identified as geological formations with geoscientific characteristics that are potentially suitable for hosting a deep geological repository within the Wawa area (Geofirma Engineering Ltd., 2011). Mafic (diabase) dykes, largely of Proterozoic age, occur in “swarms” across the entire region, including in the Wawa area (Figure 2).

### 2.1.1 WESTERN BATHOLITH

The Western batholith is located in the northwestern corner of the Wawa area (Figure 2). The composition of the Western batholith is based largely on OGS mapping (Reilly 1991, Reid et al. 1991, and Vaillancourt et al., 2005b) covering different sections of the batholith and adjacent greenstone belts. The Western batholith (part of the Pukaskwa batholith of Reid et al. 1991) has been subdivided into areas dominated by three compositionally distinguishable plutonic suites: gneissic tonalite; foliated tonalite, granodiorite and quartz diorite; and massive granite, granodiorite, quartz diorite to local diorite. All the suites are approximately 20 to 30 km long and 10 to 15 km wide. There is no information available on the thickness of these units, although based on lateral map extent they are anticipated to be several km thick. Turek et al. (1984) dated the gneissic tonalite suite at approximately 2.698 billion years old.

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

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

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

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

### 2.1.2 WAWA GNEISS DOMAIN

The Wawa Gneiss domain (Figure 2) was mapped and described by Moser (1994 and references therein) in a region just east of the Wawa area. It is a 10 to 15 km thick array of tonalitic and granodioritic orthogneiss and plutons surrounding extensive bodies of amphibolite- to granulite grade mafic gneiss and paragneiss (Jackson and Sutcliffe, 1990; Percival, 1990; Moser, 1994). The gneiss domain is dominantly composed of tonalite to granodiorite gneiss and foliated tonalite but, within the Wawa area, it has not been adequately mapped to provide much insight. East of the Wawa area the gneisses are northwest-trending and curvi-planar (Bursnall et al., 1994). West of the eastern limit of the Wawa area the foliation trend in the gneisses is west to southwest (Moser 1994, p.1067). East of the greenstone belt and Hawk Lake, the gneiss domain is composed of a mix of quartz diorite to tonalite with one U-Pb zircon age of approximately 2.746 billion years, comparable to the age of the second cycle (Wawa assemblage) in the greenstone belt (Turek et al. 1982). Evidence of similar comparable ages, within adjacent granitoid terrains, to volcanic assemblages reflects the widespread presence of synvolcanic magma chambers preserved within external batholiths of relatively older metamorphosed tonalite to quartz diorite.

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

### 2.1.3 WHITEFISH LAKE / BRULÉ BAY BATHOLITH

The Whitefish Lake batholith (Williams et al. 1992) is a massive granodiorite to granite intrusion within the Wawa Gneiss domain, making up much of the central eastern portion of the Wawa area (Figure 2). This intrusion has been dated at approximately 2.694 billion years old (Turek et al. 1984). South of the extension of the Michipicoten greenstone belt which bisects the batholith, the batholith has previously been referred to as the Brulé Bay batholith (McCrank et al. 1981). The Whitefish Lake-Brulé Bay batholith covers an approximate elongated area with northeast and southwest axes of approximately 62 km by 15 km, respectively. No specific information was found on the thickness of these two granitic bodies, though as part of the regional granitoid terrane, they would likely exceed several km in thickness (Percival, 1990).

There has been very little mapping related to the Whitefish Lake-Brulé Bay batholiths and surrounding Wawa Gneiss domain. Williams et al. (1992) note that reconnaissance mapping by Card (1979, 1982) attempted to subdivide the granitoid complexes into older tonalitic bodies and younger granodiorite to granite intrusions, some of which are batholith in size. Thus, the Whitefish Lake batholith and Brulé Bay batholith, as outlined by Johns and McIlraith (2002), are derived from the east-central sheet, Bedrock Geology of Ontario Map 2543 (OGS 1991), which in turn bases the batholiths on Card (1979, 1982) who conducted regional reconnaissance roadside outcrop visits. Hence, the general subdivisions of the granitoid regions in the Wawa Gneiss domain and enclosed batholiths are largely based on reconnaissance mapping.

### 2.1.4 GREENSTONE BELTS

There are three greenstone belts within the Wawa area: the Michipicoten, Gamitagama and Mishibishu greenstone belts (Figure 2). These greenstone belts are supracrustal assemblages formed by mafic to felsic volcanic cycles between approximately 2.9 and 2.7 billion years ago. The economic and regional geology, as well as structural setting of the Michipicoten, Mishibishu and Gamitagama greenstone belts are summarized by Williams et al. (1992). The Michipicoten greenstone belt is a structurally and stratigraphically complex assemblage of volcanic, sedimentary and intrusive rocks, metamorphosed to greenschist facies and localized amphibolite facies (Williams et al., 1992; Sage, 1994).

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

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

### 2.1.5 MAFIC DYKES

Mapping of the swarms of mafic diabase dykes in the Wawa area was compiled by Santaguida (2001) and Johns and McIlraith (2002). There are two main sets of diabase dykes that intrude all rock types in the Wawa area (Figure 2). The first set consists of the dominant northwest-trending and subvertically-dipping Matachewan swarm of dykes (Bates and Halls, 1991; West and Ernst, 1991; Phinney and Halls, 2001). The Matachewan dykes, reaching up to 40 m in width, were emplaced between approximately 2.473 and 2.446 billion years ago in the area between Lake Superior and James Bay (Phinney and Halls, 2001). The approximately 1.141 billiion years old Abitibi (Ernst and Buchan, 1993), and approximately 2.167 billion years old Biscotasing (Hamilton et al., 2002) dyke swarms comprise subvertical, northeast-trending structures. A potential origin of the northeast-trending diabase dykes in relation to uplift of the Kapuskasing structural zone has been posed by Halls and Davis (2004). Others of this northeast-trending set are related to the approximately 2.126 to 2.101 billion year old Marathon swarm (Halls et al., 2008). Both northwest and northeast-trending sets of dykes are compositionally indistinguishable.

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

### 2.1.6 FAULTS

Faults are a common feature of the bedrock in the Wawa area (Figure 2), with eleven named and numerous other unnamed faults included in the OGS bedrock geology database. In general, there are three main orientations of mapped faults, trending northwest, north and northeast (McGill and Shrady, 1986; Sage, 1994; Manson and Halls, 1997). The relative ages of regional faulting across the Wawa area suggest that the oldest faults (which are largely unmapped) tend to trend east, overprinted by northwest and northeast-trending faults, followed by late north-trending faults.

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

North-trending structures include the Agawa Canyon fault and similarly oriented McEwan Lake fault (Halls and Mound, 1998), and the much shorter Loon Skin Lake fault. The Agawa Canyon fault, sometimes referred to as the McVeigh Creek fault, extends across the Wawa area approximately 10 km to the east of the Municipality of Wawa (Figure 2). This fault can be traced many kilometres south of the Michipicoten greenstone belt, and its northerly orientation is uncommon in the area. The fault is considered to be post-Keweenawan in age (i.e., younger than approximately 1.1 billion years), and associated with the Mid-continent Rift (Manson and Halls, 1997). It is generally considered to have a normal, east-side-down movement history (e.g., Renault, 1962). The McEwan Lake fault is an approximately 30 km long, north-trending structure located approximately 30 km east of the Agawa Canyon fault and south of Hwy 101 in the eastern part of the Wawa area (Figure 2). This fault, which is not mapped by the Ontario Geological Survey, is reported to be related to the Kapuskasing structural zone and is assumed to be of a similar age as the Agawa Canyon fault.

Northeast-trending faults include the Wawa Lake, Hawk Lake, Manitowik Lake, Old Woman River, Mishewawa and Firesand River faults (Figure 2). The largest of these northeast-trending structures, the combined Wawa Lake, Hawk Lake and Manitowik Lake fault crosses the entire Wawa area and is commonly genetically associated with major dextral offset along the Kapuskasing structural zone (Sage, 1994). This large fault has also been interpreted as a reactivated structure with an Archean origin (Turek et al., 1992; Sage, 1994). The Firesand River carbonatite was emplaced approximately 1.084 billion years ago (Sage, 1979) in the junction of the Wawa Lake and Hawk Lake faults. The presence of this type of intrusive rock in the Wawa Lake-Hawk Lake fault would imply a deep root for this fault, probably reaching lower crust or upper mantle depth (Sage, 1994).

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

### 2.1.7 Metamorphism

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

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

Sub-greenschist facies metamorphism in the Superior Province is restricted to limited areas, notably within the central Abitibi greenstone belt (e.g., Jolly, 1978; Powell et al., 1993). Most late orogenic shear zones in the Superior Province and Trans-Hudson Orogen experienced lower to middle greenschist retrograde metamorphism. Post-metamorphic events along faults in the

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

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

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

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

### 2.1.8 Geological and Structural History

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

The geological and structural history of the Wawa area can be summarized as a tectonic succession of seven deformation events (D1 to D7), that occurred between approximately 2.9 and 1.0 billion years ago, and comprised three major episodes of volcanism and sedimentation, as recorded in the Michipicoten greenstone belt (Turek et al., 1984; Sage, 1994). These episodes were coeval with the emplacement of synvolcanic plutons and batholiths that later became exposed during regional orogenic deformation and associated tectonic uplift. Syn-orogenic activity also included emplacement of diatreme breccias, and alkali plutons within or marginal to the greenstone belts (e.g., Stott et al., 2002). Major folding, refolding and thrusting of the strata were followed by, or concurrent with, the aforementioned uplift of the external batholiths.

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

It is understood that there are potential problems in regional correlation of specific structural events within a Dx numbering system and in the application of such a system to the local geological history of the Wawa area. Nonetheless, this summary represents an initial preliminary interpretation for the Wawa area, which may be modified after site-specific information has been collected.

Table 3 provides a simplified summary of the geological history of the Wawa area.

**Table 3 Summary of the geological and structural history of the Wawa area.**

| Time period (Ga) | Geological event |
|---|---|
| ca. 2.89 to 2.88 | First cycle of volcanism and coeval emplacement of the Hawk Lake granitic complex along the eastern margin of Michipicoten greenstone belt (Sage, 1994). |
| ca. 2.75 to 2.72 | Formation of most of the greenstone belts of the Wawa Subprovince (Ketchum et al., 2008). Second cycle of volcanism and synvolcanic plutonism in the Michipicoten greenstone belt (Turek et al., 1992), including Jubilee stock (2.745 to 2.742 Ga) and Jostle Lake tonalite (2.721 Ga) emplacement in the Western batholith southwest of the Michipicoten greenstone belt. |
| ca. 2.701 to 2.694 | Onset of the collision of the Wawa-Abitibi terrane against the Superior Superterrane.<br>Third cycle of volcanism and sedimentation in Michipicoten greenstone belt, including deposition of Catfish assemblage between 2.701 and 2.698 Ga and deposition in basin in-fill of 'Doré conglomerates' as early as 2.698 Ga. Emplacement of external granitoids surrounding greenstone belts, including the Western batholith at 2.698 Ga and the Whitefish Lake batholith at 2.694 Ga. |
| ca. 2.682 | $D_1$ nappe-style and $D_2$ folding and thrusting deformation events. $D_2$ was characterized by southward-vergent (northward dipping) refolding and thrust imbrication of a major $D_1$ nappe fold (Corfu and Sage 1992). |
| ca. 2.679 to 2.674 | Crystallization of mafic to ultramafic, heterolithic, diamondiferous diatreme breccias and shoshonitic lamprophyre dykes that intrude Michipicoten greenstone belt (Vaillancourt et al., 2005a; Stott et al., 2002). Lamprophyre dyke emplacement reflects an episode of crustal extension, possibly during late-stage termination of relatively flat subduction of oceanic plateau crust and slab breakoff (Wyman et al., 2006; 2008). |
| ca. 2.677 | Termination of the penetrative effects of Archean orogenesis in the Wawa area (end of regional $D_2$). Emplacement of the Dickenson Lake stock in the Michipicoten greenstone belt 2.677 Ga. |
| ca. 2.671 to 2.662 | Emplacement of a suite of felsic intrusive stocks, including Maskinonge Lake and Troupe Lake stocks (2.671 Ga) and Lund Lake stock (2.662 Ga) along the northern part of the Michipicoten greenstone belt. These intrusions postdate the penetrative regional $D_1$ and $D_2$ deformation events and thereby constrain the dominant record of belt-scale recumbent $D_1$ nappe folding and $D_2$ thrust imbrication and refolding (Arias and Helmstaedt, 1989) to between 2.682 and 2.671 Ga.<br>East-trending $D_3$ dextral shear zones are concurrent with or postdate this suite of alkalic to calc-alkalic plutons. Subsequent late tectonic crustal cooling and residual collisional stresses created a generation of $D_4$ brittle-ductile to brittle faults and brittle fractures of undetermined late orogenic age. The cooling and exhumation of late tectonic plutons produced brittle fractures within the plutons, collectively treated as $D_5$ features. There is a probable overlap in timing between regional $D_4$ and $D_5$ structures.<br>Emplacement of one of the youngest (2.662 Ga) granitic felsic plutons in the Wawa area (Turek et al., 1984). |
| ca. 2.45 | Intrusion of the Matachewan diabase dyke swarm which radiates northwestward from a plume centre near present day Sudbury, Ontario. |
| ca. 2.17 | Intrusion of the northeast-trending Biscotasing quartz tholeiite dyke swarm. |
| ca. 2.11 | Intrusion of the northeast-trending Marathon/Kapuskasing dyke swarm from a plume centre south of Lake Superior (Halls et al., 2008). |
| ca. 1.92 to 1.9 | Brittle ($D_6$) reactivation of regional-scale faults during the Trans-Hudson Orogeny. About 1.9 Ga uplift of the Kapuskasing structural zone was contemporaneous with dextral movements on northeast-trending faults, and sinistral movements on north- to northwest-trending faults, and a twenty three-degree rotation of the western Superior Province relative to the eastern Superior Province (Halls et al., 1994; Percival and West, 1994; Evans and Halls, 2010). |
| ca. 1.141 | Intrusion of the northeast-trending Abitibi dyke swarm extending from the Mid-continent Rift along Lake Superior (e.g., Ernst and Buchan, 1993). |
| ca. 1.1 | Keweenawan Mid-continent Rift gabbro and tholeiitic basalt were emplaced south and southwest of Wawa, with local felsic intrusions derived by melting of Archean crust, including emplacement of Firesand River carbonatite 1.048 Ga. |
| ca. 1.0 to 0.95 | Late ($D_7$) north-trending or northwest-trending crustal shortening and reverse fault movement during the Grenville Orogeny (Manson and Halls, 1994). |

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

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

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

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

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

## 2.2 QUATERNARY GEOLOGY

Quaternary sediments within the Wawa area were deposited during the Late Wisconsin glaciation through advance and retreat of the Labrador sector of the Laurentide Ice Sheet. Morris (1990, 1991, 2001a, b, c) provides the best available information on the Quaternary history and surficial deposits of the Wawa area. Section 5.2 presents a discussion of the nature, distribution and thickness of the surficial deposits mapped in the Wawa area as shown in Figure 3 (McQuay, 1979a, b, c) and Figure 4 (Morris, 2001a, b).

A south to southwest (160 to 240°) flowing ice sheet was responsible for depositing the veneer (less than 1 m thick) of compact and massive lodgement till that drapes the bedrock surface and represents the most common map unit in the part of the Wawa area covered by the 1:50,000 scale mapping (Figure 4). A later, weaker ice flow to the southwest and west (220 to 290°) was formed during the latter stages of glaciation as the ice sheet began to thin and bedrock topography began to influence the direction of ice flow (Morris, 2001c).

Deglaciation produced a variety of depositional landforms in the Wawa area (Figure 4). Recessional moraines 1-3 m in height formed of flow till (ablation till) were deposited by debris flowing off the ice sheet during temporary still-stands as the ice retreated (Morris, 2001c). Esker and outwash deposits associated with flowing meltwater are dominantly located within bedrock controlled valleys where meltwater is concentrated, with the two deposit types often forming outwash-esker complexes (Gartner and McQuay, 1979a). Kettles and kames formed of stratified sediments were deposited in areas where large blocks of ice had detached from the ice sheet and melted in place.

Meltwater flowing into the Lake Superior basin or into local basins further inland formed between topographic barriers and the ice sheet was responsible for depositing generally coarse-grained glaciolacustrine materials in the Wawa area. Seven prominent glacial and postglacial stages of the Lake Superior basin have been recognized. Glacial Lake Minong was the maximum stage, with a water level of about 308 m elevation reached at 9,750 ±170 years B.P. (Morris, 2001c). Deltas within the Magpie and Michipicoten river valleys and at the northeast end of the Wawa Lake basin record deposition into Glacial Lake Minong.

Modern alluvial deposits formed as rivers eroded through the glaciolacustrine and glaciofluvial deposits within the valleys (Morris, 2001c), particularly the Magpie, Michipicoten and Doré river valleys (Figure 4). Swamp and organic deposits have accumulated in poorly drained depressions, such as bedrock depressions, kettles, and floodplains.

# 3 TOPOGRAPHY

Topography is an important component of the terrain, as it plays an important role in controlling surface and groundwater flow and reveals much about the geological structure of the Wawa area. The following descriptions of the topography rely heavily on the representation of the landscape by the CDED surface raster.

## 3.1 ELEVATION

Elevation within the Wawa area ranges from about sea level on the floor of Lake Superior to as much as 607 m within the bordering highlands (Figure 5), resulting in about 600 m of ground surface relief across the area. Disregarding bathymetry, the lowest elevation in the Wawa area would be the surface of Lake Superior, which has a chart datum of 183.2 m. During the period 1918 to 2012 water levels on Lake Superior have fluctuated between 183.01 m (in 2007) to 183.86 m (in 1952) (Canadian Hydrographic Service, 2013). The maximum elevation of 607 m occurs on a hill about 6.5 km south of Gould Lake (Figure 5).

The most extensive highlands in the northwest and southeast corners of the area are associated with the Western batholith and the Wawa Gneiss domain, respectively (Figure 2). There is a central low-lying area associated mainly with the valleys of the Magpie and Michipicoten rivers, but also extending south into the low area around Anjigami Lake. These depressions are likely associated with widespread structural weakening.

The highlands in the northwest, which are largely underlain by the Western batholith (Figure 2) appear to be broken into three north-trending ridges centred on Warpula, Andre, and Bailloquet townships (respectively listed as A, B, and C on Figure 5 inset). The Ministry of Northern Development and Mines (MNDM, 2013) indicates that these ridges were selected in 2008 as sites for potential wind farms (Figure 5 inset).

The highland in the southeast part of the Wawa area is underlain by the Wawa Gneiss domain (Figure 2). It extends through Roy, Sampson and Pawis townships, and it appears to be the most extensive highland in the area (shown as D on Figure 5 inset). This highland is bounded to the north and south by west-southwest trending metavolcanic belts expressed on the surface as trenches. This highland has also been selected for the potential siting of a wind farm (Figure 5 inset).

The pronounced trenches and troughs bounding the ridges in the central part of the Wawa area give the strongest impression of ridges representing distinct blocks bounded by faults (Figure 5). There are four large ridges within the Whitefish Lake batholith, with one centred on each of Lastheels, Fiddler and Debassige townships and one extending through the north part of Isaac Township (respectively listed as E, F H and G on Figure 5 inset map). These ridges have dimensions of about 4 by 8 km with heights of 200 m above the surrounding trenches.

## 3.2 RELIEF

Relief is a metric that can be defined in different ways, and the calculated value of relief depends on the horizontal dimension considered in the calculation. Relief was calculated in two ways. The first was by subtracting the average elevation within a certain radius from the elevation value in the processing cell (termed departure), providing an indication of the degree to which a point is expressed negatively or positively. The second was defined as the range in elevation within a circular window, providing an indication of the maximum relief, or roughness within the window.

As described above, the total change in elevation across the Wawa area is about 600 m, or about 424 m if the bathymetry of Lake Superior is neglected, and some of the large rock ridges rise 200 m or more from the surrounding trenches. Relief of more than about ten to thirty metres over short ground distances (e.g., 100 m) within the Wawa area is expected in virtually all instances to reflect irregularities in the bedrock surface. The greatest relief associated with drift deposits in the Wawa area occurs where meltwater and river erosion has formed terraces as high as 30 m or more composed of deltaic sediments, such as near the mouth of the Magpie River.

A map of departures from the average elevation within a 20 km radius (Figure 6) provides an image of rock ridges throughout the Wawa area that is refined compared with that shown in Figure 5. The Figure 6 inset shows areas with at least 15 m of topographic prominence. These areas are probably indicative of relatively favourable rock mass conditions, as compared with areas of strong negative relief, which likely indicate the surface expression of damage zones associated with geological structures. In addition, these blocks of high ground are generally the main areas of thin drift and abundant bedrock exposure as shown in the surficial geology maps and SPOT imagery. As such, blocks of high ground could be relatively favourable for site characterization purposes.

A map of departures from the average elevation within a 2 km radius (Figure 7) highlights local summits and trenches within the broader ridges shown in Figure 6. The most common surficial deposit in the Wawa area consists of a till veneer that is non-existent over bedrock highs, thickens slightly in bedrock depressions, and occurs preferentially on the stoss (up-ice) side of bedrock knolls and ridges (Morris, 1990). The large rock ridges in the Wawa area are generally the areas of thinnest drift, and within these large rock ridges, the areas of positive relief shown in Figure 7 are likely areas of even thinner drift.

A map showing the range in elevation within a 250 m radius (Figure 8) provides an indication of the location and extent of high and low relief areas. The upper limit of relief at this scale is about 240 m, reflecting mountainous topography. Considering that some of the lakes in the area have depths of 100 m or more (Section 4.1), the actual relief in some areas could be 300 m or more. Figure 8 also shows the extent of low relief areas within the blocks of high ground delineated in Figure 5 and Figure 6. The inset map of Figure 8 illustrates the distribution of high relief areas, defined as > 50 m within a 250 radius.

### 3.3 SLOPE

Areas of steep slope form the margins of many of the rugged landforms in the Wawa area, such as rock ridges and trenches (Figure 9). The tops of the larger rock ridges in the area contain areas of gentle slope.

As steep slopes on the surface of the Precambrian Shield are often associated with irregularities in the bedrock topography, with some notable exceptions (e.g., end moraines, kames, eskers), the presence of steep slopes in the Wawa area can be an approximate indicator of minimal 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. However, others are related to low-relief bedrock topography associated with greenstone belts or to areas of even bedrock topography on the tops of large ridges. 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, consequently, where the lineament interpreter should expect low lineament density (Figure 10).

The density of steep slopes within nearly the entire Wawa area (Figure 10) is at least 200 points/km$^2$, which is believed to be a strong indication of an absence of widespread, thick drift deposits. However, a few areas of low slope density exist where thicker overburden deposits have been mapped. The best example is in Dolson Township, located in the northeast corner of the Wawa area, where Morris (1990) suggests that the presence of outwash and glaciolacustrine deposits (Figure 4) have subdued the bedrock topography. The greenstone belts often occupy depressed positions in the landscape, rendering them prone to sedimentation during deglaciation.

Other areas of low slope density where extensive drift deposits have been mapped include the areas along the Jackpine River in Quill Township, along Highway 17 in Menzies and Musquash townships, and along Highway 651 in Miskokomon and Nadjiwon townships.

The largest areas of highest density exceed 1,500 points/km$^2$ and are located predominantly along the slopes flanking Lake Superior, near Dog River and Old Woman Bay, with names given to some of the more impressive local features, such as Mountain Ash Hill, Bare Summit, Peat Mountain, and Burlé Hill. Inland areas of highest density are associated with west-southwest trending steep-walled canyons and escarpments. Examples include a canyon 2 km wide and more than 150 m deep on Dossier Creek in Peterson Township, and one that rises more than 200 m from the Kinniwabi River in the southeast corner of Maness Township.

# 4 DRAINAGE

The distribution of surface water and surface water drainage are important factors to consider in the preliminary assessment. Surface drainage can be a useful surrogate for shallow groundwater flow. Except for Lake Superior, the lakes within the Wawa area are confined within structurally controlled linear depressions, providing a clear indication of the underlying bedrock structure.

## 4.1 WATERBODIES AND WETLANDS

Aside from Lake Superior, which is the largest freshwater lake in the world, most of the lakes within the Wawa area represent small water bodies (less than 1-2 km$^2$) positioned outside of the major river valleys (Figure 11). The largest lakes occupy the major structurally controlled river valleys, which were pointed out as the major topographic lows in Section 3.1. About 20% (878 km$^2$) of the Wawa area is occupied by water, with two-thirds of that area accounted for by Lake Superior (Table 4). All of the other lakes cover only about 7% of the area.

Manitowik Lake, Hawk Lake and Wawa Lake occupy the linear topographic depression formed by the Wawa-Hawk-Manitowik Lake fault, which is associated with the Kapuskasing structural zone (Sage, 1994). Similarly, Whitefish Lake and Anjigami Lake occupy northeast-trending topographic depressions.

The wetlands mapped in the Wawa area (Figure 11) are all very small (less than 1.0 km$^2$). The lack of extensive wetlands is a product of the absence of extensive and thick poorly drained overburden deposits. Most of the wetlands are elongate features located within linear depressions in the bedrock.

Bathymetric maps illustrate the vertical extent of lake basins. The MNR completed depth surveys of selected lakes in the late 1960s and early 1970s. The depth maps consist of contour plots based on soundings. Figure 11 indicates the lakes within the Wawa area for which bathymetric data exist. Excluding Lake Superior, the greatest known lake depth in the Wawa area is 119 m in Manitowik Lake (Table 5). In the Wawa area, the maximum depth of Lake Superior is about 180 m, as water levels are typically at about 183 m above sea level and the floor of Lake Superior has an elevation of around sea level in the southwest corner of the Wawa area. During the period 1918 to 2012, water levels on Lake Superior have fluctuated between 183.01 m (in 2007) to 183.86 m (in 1952) (Canadian Hydrographic Service, 2013).

**Table 4 Size of lakes larger than 10 km² in the Wawa area.**

| Lake | Perimeter (km) | Area (km²) |
|---|---|---|
| Lake Superior[1] | 140 | 610 |
| Manitowik Lake | 77 | 24 |
| Whitefish Lake | 71 | 17 |
| Anjigami Lake | 43 | 11 |

Metrics obtained from LIO OHN Waterbody file
[1]Lake Superior values apply to area within Wawa area

**Table 5 Maximum and mean depths of lakes in the Wawa area.**

| Lake | Max depth (m) | Mean depth (m) |
|---|---|---|
| Lake Superior[1] | 180 | |
| Manitowik Lake | 119 | 38 |
| Wawa Lake | 33 | 15 |
| Catfish Lake | 40 | 12 |

Depth values obtained from summary data in margin of MNR depth maps
[1]Depth within Wawa area taken from bathymetric data in Google Earth

## 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. JDMA conducted a drainage analysis in order to confirm and, where possible, partition the most detailed available mapping of watersheds by the MNR. The delineation of drainage divides st several scales assists with inferring regional and local surface water flow and shallow groundwater flow directions.

The best available catchment delineation for the Wawa area is the quaternary watershed file produced by the MNR. According to the metadata for this 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 that the MNR 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 onsite 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 assessment was created by NRCan using the same 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 procedure that JDMA followed in the drainage analysis was to confirm the boundaries in the quaternary watershed file and then to subdivide the quaternary watersheds where possible. It is important to note that the quaternary watersheds do not represent the smallest catchments that can be delineated in most areas, as local ridges and highland complexes are present within many of the quaternary watersheds that serve to divide surface flow directions within the basin. The drainage analysis was conducted with no *a priori* knowledge of the quaternary catchments. Rather, only the tertiary catchments were examined during the drainage analysis.

The result of the drainage analysis is a single set of lines and polygons, which represents a merged watershed file (Figure 12). Where drainage divides created by JDMA matched reasonably with the quaternary watershed boundaries, the procedure was to accept the existing quaternary watershed boundary. Newly delineated drainage divides were then used to subdivide the quaternary watersheds. In some instances, the quaternary watershed file contained a drainage divide that was not delineated by JDMA during the drainage analysis. JDMA made an effort to ensure that the newly delineated drainage divides honoured the existing watercourse map file.

### 4.3 SURFACE FLOW

The Wawa area drains into northeast Lake Superior through three river systems: the White River, the Michipicoten River and the Agawa River. The extent of tertiary scale watersheds associated with these rivers in the Wawa area are shown in the inset map of Figure 12. The boundaries of the basins in the Wawa area are generally formed by ridges. The Michipicoten and Magpie rivers are the two major systems, each emptying into Michipicoten Bay southwest of the settlement area of Wawa.

The western flank of the Wawa area is drained, from west to east, by the Dog River, Jimmy Kash River, Mawka River, and Doré River, which flow directly to Lake Superior. The eastern flank is drained by the Old Woman River into Old Woman Bay. The quaternary watersheds along the Lake Superior shoreline include small rivers and streams that drain directly towards the lake. Runoff in the southeast corner of the Wawa area flows both to the south towards the Agawa River and to the north towards the Michipicoten River via the tributaries of the Anjigami River, Sponge

Creek and the Jackpine River. Sponge Creek drains the eastern part of the Anjigami basin and the Jackpine River drains a large part of the eastern margin of the Wawa area. Its basin is a generally low-relief basin with thicker drift deposits.

# 5 TERRAIN CHARACTERISTICS

Based on 1:50,000 scale surficial mapping (Figure 4), extensive and relatively thick overburden deposits are expected within about 40% of the Wawa area. As these drift deposits fill lows in the bedrock topography, they are capable of concealing the surface expression of geological structures of various sizes. Valleys and other low-lying areas associated with thicker drift represent areas where the surface expression of geological structures is limited. A higher degree of confidence can be obtained in identifying lineaments from the CDED and SPOT datasets in the remaining 60% of the Wawa area where relatively thin overburden deposits are expected.

The main reason for investigating the surficial deposits in the Wawa area is to delineate areas of exposed bedrock, or thin overburden cover, which are more readily amenable to site characterization. A location with good outcrop exposure would enable further investigation of the potentially suitable bedrock formations through outcrop mapping of bedrock structures and preliminary rock mass characterization. The distribution of overburden deposits is also important for understanding groundwater flow systems.

This section describes the expected composition, distribution and thickness of surficial deposits in the Wawa area mapped through the NOEGTS program (Figure 3). Detailed surficial mapping exists (Morris, 2001a, b) for the Michipicoten greenstone belt and for parts of the batholiths and Wawa Gneiss domain (Figure 4), but this mapping covers only part of the Wawa area. Section 5.2 is divided based on the NOEGTS map units. Discrepancies in the deposit types delineated in the two mapping programs are described to illustrate some limitations of the NOEGTS data, such as the typical underestimation of the extent of drift deposits implicit to the generalized NOEGTS delineation of bedrock. The section begins with a preliminary review of the water well and drill hole data on overburden thickness.

## 5.1 DRILL HOLE AND WATER WELL DATA

Data on overburden thickness from water well records collected by the Ministry of the Environment (MOE, 2012) and from diamond drill holes compiled by the Ontario Geological Survey (OGS, 2005b) have been included here to supplement the information on overburden deposits compiled from Morris (2001a, b) and Gartner and McQuay (1979a) presented in Section 5.2. The spatial distribution of the subsurface data does not allow for the interpolation of a continuous grid of drift thickness across the Wawa area.

### 5.1.1 WATER WELL INFORMATION SYSTEM

Water well records from the Ministry of the Environment (MOE) Water Well Information System for the Wawa area were acquired (Section 1.3.5). The database contained 71 records within the area, which are mostly located within areas mapped as sand and gravel near the mouths of the Magpie and Michipicoten rivers. Only 14 of the water wells contained information on depth to bedrock, and these wells have been plotted on Figure 3. Depth to bedrock in these wells ranges from zero to 86.3 m (Table 6). It is unclear whether some of the greatest depths recorded are reliable, but no further investigation of these well records has been carried out.

**Table 6 Ministry of the Environment water well data on drift thickness.**

| Well ID | Date | Elevation (m) | Depth to bedrock (m) |
|---|---|---|---|
| 1100781 | 30/06/1962 | 285 | 78.6 |
| 1100783 | 10/12/1962 | 284 | 86.3 |
| 1100784 | 10/01/1965 | 285 | 82.3 |
| 1101716 | 11/08/1973 | 186 | 25.6 |
| 1102684 | 05/11/1979 | 191 | 8.5 |
| 1102726 | 15/05/1980 | 231 | 0 |
| 1102925 | 06/06/1980 | 205 | 7.6 |
| 1102924 | 10/06/1980 | 205 | 62.8 |
| 1107338 | 15/07/2004 | 186 | 0 |
| 1107303 | 22/07/2004 | 288 | 0 |
| 1107304 | 04/08/2004 | 323 | 0 |
| 1107305 | 05/08/2004 | 323 | 0 |
| 1107306 | 08/08/2004 | 320 | 0 |
| 1107307 | 09/08/2004 | 311 | 0 |

### 5.1.2 ONTARIO DRILL HOLE DATABASE

The drill hole database for the Wawa area (Section 1.3.5) contains 1978 records with information on depth to bedrock (Figure 3). Drill holes in the Wawa area are mostly concentrated in the Michipicoten greenstone belt, with a smaller concentration in the Mishibishu greenstone belt (Figure 2). The maximum depth to bedrock recorded was 79.3 m and the average thickness of overburden is about 2 m, with 93% of the holes reporting overburden less than 5 m thick and 97% less than 10 m thick. Table 7 summarizes the minimum, maximum and mean depth to bedrock from drill holes reported from AFRI files containing ten or more drill holes in the Wawa area. Most of the drill holes with depth to bedrock greater than 20 m are located within topographic lows.

**Table 7 Selected OGS drill hole data on depth to bedrock in the Hornepayne area.**

| | Drift thickness (m) | | | |
|---|---|---|---|---|
| **AFRI FID[1]** | **Count** | **Min** | **Max** | **Mean** |
| 41N15NE0055 | 10 | 0.0 | 4.0 | 2.6 |
| 41N15NW0146 | 10 | 0.9 | 17.1 | 7.8 |
| 41N14NE0008 | 12 | 0.6 | 2.1 | 1.4 |
| 42C02SE0059 | 12 | 0.0 | 1.2 | 0.7 |
| 41N14NE0015 | 13 | 0.4 | 6.7 | 2.0 |
| 42C02SE0301 | 14 | 0.0 | 11.0 | 2.5 |
| 41N15NW0147 | 15 | 1.2 | 4.3 | 2.5 |
| 42C02NE0001 | 15 | 0.3 | 8.2 | 2.0 |
| 42C02SE8868 | 20 | 1.2 | 5.3 | 2.8 |
| 41N14NE0007 | 21 | 0.6 | 23.8 | 6.9 |
| 42C02SE0002 | 23 | 1.2 | 10.2 | 3.1 |
| 42C02SE0021 | 23 | 0.0 | 2.4 | 0.6 |
| 42C02SE0500 | 24 | 0.6 | 7.9 | 2.6 |
| 42C02SE0605 | 24 | 0.0 | 21.3 | 3.2 |
| 42C02SE0049 | 26 | 0.0 | 20.1 | 4.6 |
| 42C02SE0043 | 27 | 0.0 | 2.1 | 0.7 |
| 42C02NE8839 | 30 | 0.0 | 2.4 | 0.8 |
| 42C02SE0727 | 30 | 0.0 | 3.7 | 1.1 |
| 41N15NW0080 | 31 | 0.0 | 71.5 | 13.8 |
| 42C02SE0093 | 34 | 1.5 | 16.8 | 3.3 |
| 41N15NE0054 | 38 | 0.9 | 6.1 | 1.9 |
| 42C02SE0103 | 42 | 0.0 | 7.6 | 2.3 |
| 42C02SE0082 | 43 | 0.0 | 9.8 | 1.9 |
| 41N14NE0003 | 52 | 0.1 | 8.2 | 0.8 |
| 42C01NW8820 | 64 | 0.0 | 6.6 | 1.7 |
| 41N15NE0016 | 65 | 0.0 | 3.4 | 0.9 |
| 42C02SE8831 | 98 | 0.0 | 11.0 | 2.5 |
| 42C02SE0084 | 127 | 0.0 | 15.6 | 2.0 |
| 42C02SE0024 | 130 | 0.0 | 19.8 | 2.6 |
| 42C02SE9043 | 174 | 0.0 | 13.7 | 1.8 |
| 42C02SE0105 | 360 | 0.0 | 64.0 | 2.9 |

Data provided for AFRI files with 10 or more drill holes.
[1]AFRI = Assessment File Research Imaging

## 5.2 NOEGTS TERRAIN UNITS

This section describes the expected composition, distribution and thickness of surficial deposits in the Wawa area as mapped in Figure 3 and Figure 4.

### 5.2.1 BEDROCK

Bedrock is the most widespread terrain unit in the Wawa area, with bedrock expected to make up about 60% of the area. The NOEGTS mapping delineated about 80% of the Wawa area as bedrock (Figure 3). However, the detailed surficial mapping (Figure 4) delineated two types of bedrock terrain depending on the amount of exposed bedrock (Morris, 2001a, b): bedrock (>50% exposed bedrock) and bedrock-drift complex (<50% exposed bedrock). Comparison of the two surficial geology maps illustrates the typical underestimation of the extent of drift deposits implicit to the generalized NOEGTS delineation of bedrock. Note, for instance, that some of the areas mapped as bedrock in Figure 3 are delineated as till in Figure 4 (e.g., Bailloquet, Menzies and Musquash townships). Similarly, glaciofluvial, glaciolacustrine and till deposits in the west half of Dolson Township (Figure 4) were mapped as bedrock in Figure 3. Only about 60% of the Wawa area with detailed surficial geology coverage (Figure 4) was delineated as bedrock or bedrock-drift complex, whereas NOEGTS mapped about 80% of this area as bedrock.

Apart from isolated patches in the Western and Whitefish batholiths, all bedrock mapped in Figure 4 is located within the Michipicoten greenstone belt, and most of it is within an area about 6 km wide and more than 30 km long extending east of the Magpie River. The MNR lists this area as the “Fume Kill” restricted fire zone, as the lack of vegetation is due to a history of forest fires related to emissions from the ore sintering plant once located near the settlement of Wawa. Drill hole data located within areas mapped as bedrock in Figure 4 indicate overburden thickness ranging from zero to about 20 m, with a mean of 2 m.

Bedrock-drift complex was the second type of bedrock terrain delineated in the detailed surficial geology mapping. Section 5.2.2 describes the surficial deposits found within this map unit.

Areas delineated as bedrock in the NOEGTS mapping were described as areas where ground moraine less than 1 m thick draped the bedrock surface over the tops of bedrock hills, with thicknesses reaching 3 m or more on lower slopes and in valleys between hills (McQuay, 1980). Gartner and McQuay (1979a) suggested that in areas mapped as bedrock (Figure 3), relief is high, the landscape is rugged and well drained, and ground moraine and organic deposits often cover the margins of the bedrock hills and the valleys between hills.

Drill hole data in areas mapped as bedrock or bedrock-drift complex in Figure 4 indicate drift thickness ranging from zero to about 35 m and a mean of 2 m (n = 1106). In contrast, data from the other map units indicate drift thickness from zero to about 80 m and a mean of 4 m (n = 759).

Due to shallow drift and the irregular bedrock surface, development activities will be more difficult and expensive in bedrock terrain (McQuay, 1980). Construction could be extremely difficult in areas of high rock cliffs and steep bedrock hills. Road routing in bedrock terrain is complicated by severe grades, expensive cut-and-fill operations, and the presence of steep slopes can put serious constraints on the siting of buildings.

### 5.2.2 MORAINAL

Surficial deposits of till in the Wawa area can be found within four of the map units shown in the surficial geology maps. Thin till deposits exist within areas mapped as bedrock in Figure 3 and in areas mapped as bedrock-drift complex in Figure 4. Thicker till deposits have been mapped as ground moraine in Figure 3 and as till in Figure 4. Comparison of the two maps suggests that Figure 3 could fail to map as much as two thirds of the thicker till deposits expected to exist. Thicker till deposits are expected to make up about 6% of the Wawa area.

Till deposits in areas mapped as ground moraine in Figure 3 are expected to be as much as 5 to 10 m thick (Gartner and McQuay, 1979a). In these areas, the terrain is a subdued version of that in the areas mapped as bedrock, with the topography usually undulating to rolling (McQuay, 1980). The conditions in these areas are variable, with swamps occupying low areas between hills and exposed bedrock found on top of hills.

Two types of till deposits have been identified in the Wawa area. Morris (2001c) suggests that a southwest flowing ice sheet was responsible for depositing the veneer of lodgement till that drapes the bedrock surface in many areas, which his map depicts as bedrock-drift complex and which makes up the most common map unit in the part of the Wawa area covered by the 1:50,000 scale mapping (Figure 4). This till is compact and massive and can be thicker on the up-ice (stoss) side of small bedrock knobs and hills (Morris, 1990). These areas consist of thin, discontinuous drift deposits covering more than 50% of the bedrock surface, with the drift generally less than 1 m thick. In addition to the thin till in these areas, glaciofluvial deposits and organic deposits are also common drift types. In contrast, areas that Morris (2001c) mapped as till (Figure 4) contain flow till (ablation till) typically thicker than one metre, which was deposited during ice recession in the form of minor recessional moraines 1-3 m in height found as isolated patches in the headwaters of outwash systems or along the margins of former glacial lake basins.

### 5.2.3 GLACIOFLUVIAL

During retreat of the Laurentide Ice Sheet, meltwater systems produced outwash and esker deposits within many of the valleys in the Wawa area (Figure 3). Glaciofluvial deposits in the Wawa area were classified in Figure 3 as outwash or esker deposits and as outwash or ice-contact stratified drift in Figure 4. Modern alluvial deposits have also been delineated in both maps.

Large eskers, depicted as black lines on Figure 3 and Figure 4, are confined to valleys where subglacial meltwater was concentrated (Morris, 2001c). Although esker thickness is difficult to establish due to other drift deposits covering the esker flanks (Morris, 2001c), some of the larger esker ridges in the area are over 20 m in height (McQuay, 1980). Esker and outwash deposits are often connected. For example, Gartner and McQuay (1979a) describe the sediments within the Magpie River valley as an outwash-esker complex.

Outwash deposits exist within many of the topographically depressed parts of the Wawa area. Several of the sandy outwash deposits mapped in Figure 3 were re-interpreted as coarse-grained glaciolacustrine deposits in Figure 4, such as in Dolson Township and at the mouths of the Magpie and Michipicoten rivers. The materials consist primarily of sand, but texture depends on location within the meltwater channel or position within the outwash fan. Outwash thickness is variable and is a function of the bedrock topography, with thickness ranging from less than one metre to more than 17 m (Morris, 2001c). Well logs in gravel pits in the area indicate that outwash deposits can exceed 20 m in thickness (McQuay, 1980).

Minor recessional moraines up to about three metres in height associated with glaciofluvial and glacial deposits in the Wawa area are depicted as blue lines in Figure 4. The recessional moraines in this area can extend more than 1 km in length, and many of them are not composed of till, but are made up of stratified materials. Morris (2001c) describes a recessional moraine at least 7 m thick near Wawa formed of ice-contact stratified drift.

Ice stagnation features associated with the melting of blocks of ice detached from the ice sheet are present within the areas mapped as ice-contact stratified drift in Figure 4 and in other deposit types as indicated, for example, by the distribution of kettles shown in Figure 4. These deposits consist dominantly of stratified materials (Morris, 2001c).

Larger glaciofluvial deposits have the potential to represent significant regional aggregate or groundwater supplies. 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.

### 5.2.4 GLACIOLACUSTRINE

The only glaciolacustrine deposits mapped in Figure 3 were classified as raised beaches along the Lake Superior shoreline (Figure 3). However, many of the outwash deposits mapped in Figure 3 were re-interpreted as coarse-grained glaciolacustrine deposits in Figure 4, such as in Dolson Township and at the mouths of the Magpie and Michipicoten rivers. Although, rhythmically-bedded silt and clay (fine-grained) deposits formed within deep-water glaciolacustrine environments were observed along the shores of Manitowik Lake (Morris, 2001c), most of the glaciolacustrine deposits mapped in the Wawa area are coarse-grained and represent deltas formed either in high stands of the Lake Superior basin or in inland proglacial lakes impounded between the ice sheet and topographic barriers.

Extensive glaciolacustrine deposits formed in proglacial lakes impounded between the retreating ice margin and topographic barriers have been mapped in Quill and Dolson townships (Figure 4). In the case of the deposits in Dolson Township, located in the northeast corner of the Wawa area, the topographic barrier was the ridge forming the contact of the Whitefish Lake batholith (Figure 2 and Figure 5).

The thickest overburden deposits in the Wawa area are generally found within the major valleys at elevations below about 310 m, which was the maximum level of Glacial Lake Minong, the highest of seven prominent stages of the Lake Superior basin recognized in the Wawa area (Morris, 2001c). Water well and drill hole data from these areas indicates drift deposits as thick as 60 to 86 m. Morris (2001c) describes a 32 m thick deltaic sequence of sediments exposed in the terraces of the Magpie River near Wawa consisting of 28 m of stratified foreset sands between a sand and gravel topset and a silt and clay bottomset.

Glaciolacustrine material deposited within linear topographic depressions in the bedrock have been mapped in parts of the Wawa area (Figure 4). It is expected that stratified glaciolacustrine sediments associated with local ponding of meltwater were deposited within some of the lineaments exposed at the surface, more so than is mapped in Figure 4. These deposits are referenced in Section 7 as they could record evidence of neotectonic activity in the area.

Due to the coarse texture of most of the glaciolacustrine deposits mapped in the Wawa area (Figure 4), the engineering implications of these deposits are much like those described above for glaciofluvial deposits. For example, these deposits have the potential to represent regional aggregate or groundwater supplies.

### 5.2.5 ORGANIC

Virtually all of the organic deposits in the Wawa area represent small features confined to narrow, poorly-drained topographic depressions (Figure 3 and Figure 4), with a distinct absence of extensive organic deposits noted. Organic deposits can be found within bedrock-controlled depressions, kettle holes, between esker ridges, and within floodplains bordering onto lakes and rivers. The organic deposits develop through the accumulation of decaying mosses, rushes and woody materials, and most of the swamp and organic deposits probed in the area were found to be 1 to 1.5 m thick (Morris, 2001c).

Swamp and organic deposits mapped in Figure 4 range in size from about 100 $m^2$ to 1 $km^2$ with an average of 50,000 $m^2$. A more complete image of swamp and organic deposits in the Wawa area can be obtained from the distribution of wetlands delineated on the map of surface drainage features (Figure 11). Some of the largest wetlands are associated with floodplains on the lower reaches of the Magpie and Doré rivers or associated with poorly drained overburden deposits in Quill and Dolson townships (Figure 11).

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

A detailed discussion of the hydrogeology of the Wawa area is provided by Geofirma Engineering Ltd. (2013). Only a brief summary of likely groundwater recharge and discharge conditions and local and regional groundwater flow is provided here.

Steep slopes and the general absence of thick overburden deposits in the areas mapped as bedrock terrain should promote surface runoff and minimize groundwater recharge. Thicker drift deposits are present in the valleys and trench bottoms, and these deposits are expected to represent the most significant local discharge zones with discharge into creeks, rivers, lakes and wetlands.

Bedrock aquifers are likely shallow with recharge occurring through discontinuities such as joints and fractures. Gartner and McQuay (1979a, 1979b) and McQuay (1980) suggest that groundwater occurs in fractures and along fault zones in the bedrock terrain, but this terrain unit is considered to have only poor to fair potential for groundwater supplies. The permeability of the bedrock can vary from impermeable to highly permeable, depending on the spacing, depth and aperture of discontinuities in the bedrock.

Regional groundwater flow in the Wawa area was assessed using surface water elevations, surface drainage directions and ground surface elevations based on the expectation that the regional groundwater table will be a subdued reflection of topography. Due to the large amount of exposed bedrock in the Wawa area, the groundwater table for most of the area will be present within the bedrock, likely within several metres of ground surface. Exceptions to this assumption will occur within the overburden-filled bedrock valleys of the major rivers as they approach the regional groundwater discharge location of Lake Superior. In these areas of thick permeable overburden, the groundwater table is present within the overburden and the overburden will act as a local discharge area for bedrock groundwater.

Based on the available topographic and drainage information, groundwater in the Wawa area is conceptualized as being recharged in the bordering highlands of the northern and eastern parts of the Wawa area with flow predominantly southward and westward via local discharge through lakes and river valleys to the regional discharge location of Lake Superior. These estimates of regional groundwater flow conditions in the bedrock will be locally affected by the presence of faults and major structural and lithological discontinuities that have hydraulic properties different from that of the bulk bedrock.

# 7 NEOTECTONIC FEATURES

Neotectonics refers to deformations, stresses and displacements in the Earth's crust of recent age or which are still occurring. These processes are related to tectonic forces acting in the North American plate as well as those associated with the numerous glacial cycles that have affected the northern portion of the plate during the last million years (Shackleton et al., 1990; Peltier, 2002).

The movement and interaction of tectonic plates creates horizontal stresses that result in the compression of crustal rocks. The mean of the current major horizontal principal stress orientation in central North America, based on the World Stress Map (Zoback, 1992), is northeast (063° ± 28°). This orientation coincides roughly with both the absolute and relative plate motions of North America (Zoback, 1992; Baird and McKinnon, 2007), and is controlled by the present tectonic configuration of the North Atlantic spreading ridge (Sbar and Sykes, 1973), which has likely persisted since the most recent Paleocene-Eocene plate reorganization (Rona and Richardson, 1978; Gordon and Jurdy, 1986).

Repeated cycles of glaciation and deglaciation throughout the Quaternary have induced additional 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, such as around the margins of Hudson Bay.

The stresses associated with cycles of ice loading and unloading, interacting with the tectonic stresses, may result in seismic events related to displacements along ancient discontinuities in the bedrock. The assessment of neotectonic features in the area may reveal the timing and magnitude of glacially-induced seismic activity and deformations. Conclusive identification of features indicative of reactivation of ancient bedrock structures due to cycles of glacial loading and unloading could not be made using the available information sources. Field investigation would be required to identify such features. Under the appropriate conditions, glaciolacustrine deposits may preserve neotectonic features indicative of paleo-seismic activity. As stated in Section 5.2.4, several small glaciolacustrine deposits are mapped within linear topographic lows associated with lineaments (Figure 4). If rhythmically bedded silt and clay deposits can be found within the trenches forming the surface expression of lineaments, it is possible that postglacial reactivation of the underlying structure could have deformed the primary structures displayed in the walls of trenches excavated into these deposits. It is expected that many of the lineaments within the areas mapped as bedrock-drift complex (Figure 4) contain minor unmapped glaciolacustrine deposits associated with local ponding of meltwater during deglaciation. Lineaments with creeks that have eroded through such deposits could be a starting point for exploration of this possible type of evidence for neotectonic activity.

# 8 ACCESSIBILITY CONSTRAINTS

Existing highways generally provide access only to low-lying (Figure 4), drift-covered (Figure 3) parts of the potentially suitable geological formations within the Wawa area (i.e., the batholiths and Wawa Gneiss domain; Figure 2). Two main existing resource roads provide additional access into areas of thin drift and abundant exposed bedrock within the Wawa Gneiss domain and the Western batholith. Respectively, these roads extend through Noganosh and Roy townships, and through Menzies, Macaskill and Levesque townships (Figure 1).

Section 5 provided information to accompany the maps showing areas of thin drift and abundant exposed bedrock (Figure 3 and Figure 4), which represent areas that are more readily amenable to site characterization. A location with good outcrop exposure would enable further investigation of the potentially suitable bedrock formations through outcrop mapping of bedrock structures and preliminary rock mass characterization. Section 3.2 identified eight remote blocks of high ground where thin drift and abundant exposed bedrock are expected (labelled ‘A’ to ‘H’ in Figure 6 inset). Although areas of thin drift are relatively amenable to site characterization, road building and site construction within these areas can be challenging. Due to shallow drift and the irregular bedrock surface, development activities will be more difficult and expensive in bedrock terrain (McQuay, 1980). Construction could be extremely difficult in areas of high rock cliffs and steep bedrock hills. Road routing in bedrock terrain is complicated by severe grades, expensive cut-and-fill operations, and the presence of steep slopes can put serious constraints on the siting of buildings. The relief and slope maps presented and described in Section 3 can be used to assess the suitability of general areas, and these maps indicate the presence of mountainous topography with steep slopes and high relief in many parts of the Wawa area.

Major highways traverse through the central parts of the Wawa area. The Trans-Canada Highway (Highway 17) is the major highway connecting Wawa with southern Ontario. Highway 17 extends through or near the margins of the Western and Brulé Bay batholiths (Figure 2). Highway 101 is a two-lane paved highway that provides direct access into a remote, low-lying, dominantly drift-covered corridor of the Wawa Gneiss domain. Highway 101 also provides access to the margins of the large ridges on the Whitefish Lake batholith in Lastheels and Fiddler townships. Highway 651 is a remote secondary highway that extends through the Wawa Gneiss domain in the eastern part of the Wawa area.

The Ministry of Natural Resources (MNR) road segment file is used in Figure 1 to illustrate the distribution of resource roads in the Wawa area. This file contains resource access roads constructed for and used by conventional street legal vehicles, including winter roads and those roads not under the jurisdiction of the MNR (municipal roads and provincial highways) that are sourced from the Ontario Road Network. Recreation trails and short-term forest operation roads (skidder trails) or forest fire management roads (e.g., rehabilitated fire trail) are not included in the MNR road segment file. From the point of view of the geoscientific preliminary assessment, the resource roads could represent options for field reconnaissance. An evaluation of the road segment file revealed that it contains many of the resource roads visible in the Wawa area from the SPOT imagery, but that there are still many roads not included in the road segment file. JDMA mapped some additional roads from the satellite imagery, particularly on the Western batholith, west of Highway 17 shown on Figure 1.

The eight blocks of high ground delineated in Section 3.2 where thin drift and abundant exposed bedrock are expected (labelled ‘A’ to ‘H’ in Figure 6 inset), represent remote locations within the Wawa area that could be difficult to access. The large highland in the southeast part of the Wawa area (labelled ‘D’ in Figure 6 inset) contains a road that extends south from Highway 101 to the Agawa River and further south. The high ground west of Catfish Lake (labelled ‘C’ in Figure 6 inset) is located within about 5 km of Highway 17 a short distance north of Wawa. Of the eight blocks of high ground delineated in the Figure 6 inset, areas A, B, G and H are the most remote.

If wind farms were developed on any of the blocks of high ground in the Western batholith and Wawa Gneiss domain (Section 3.1) where wind farm applications have been filed, then this would involve the construction of new access roads or improvement of the existing road network in these areas. However, according to staff at the Wawa MNR office, the wind farm applications for these areas were filed in 2008 and no further developments have occurred since then. The main transmission line extending from the southeast to northwest parts of the Wawa area is apparently at capacity but will be upgraded in the future, which could result in renewed interest in the potential for wind power projects in the Wawa area.

# 9 SUMMARY

This report presents an analysis of the terrain in the Wawa area using available remote sensing and geoscientific information sources. The information enhances and expands upon that presented in the Wawa initial screening report (Geofirma, 2011). The main information sources relied on in this assessment are the Canadian Digital Elevation Data (CDED) elevation model, the multispectral SPOT 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 mapping by the Ontario Geological Survey (OGS). Additional data sources included the Water Well Information System, the Ontario Drill Hole Database, and the most up to date and detailed map data on waterbodies, wetlands and watersheds available from the Ministry of Natural Resources.

This report provides an overview of the Quaternary geology and surficial deposits within the Wawa area. Maps and descriptions of surficial deposits are presented in this report based on the 1:100,000-scale NOEGTS mapping and the more detailed 1:50,000-scale OGS mapping. Comparisons between the two maps indicated that the NOEGTS mapping underestimated the extent of thicker overburden deposits identified in the detailed mapping program. The detailed mapping indicated that thicker overburden deposits covered about 40% of the area, whereas the NOEGTS mapping suggested 20%.

With about 60% of the Wawa area characterized by thin overburden deposits and abundant exposed bedrock, the digital elevation model provides a valuable image of linear topographic depressions associated with structural features expressed in the bedrock topography. The thickest overburden deposits are located within and only partially fill the major structurally controlled valleys in the area. As a result, the overburden does not conceal the fact that the valleys must have been formed along weak zones in the bedrock. However, thick glacial, glaciofluvial and glaciolacustrine deposits are also located outside of the major river valleys, such as in Quill and Dolson townships. These deposits would mask the surface expression of irregularities in the bedrock topography associated with geological structures and result in low apparent lineament density from surface mapping. The tops of the hills in the Wawa area are generally the locations with the thinnest overburden cover, which is an attribute that would facilitate site characterization. Eight large ridges were identified in the Wawa area (Section 3.2) where thin drift and abundant exposed bedrock are expected. Maps of relief, slope and slope density provide an image of the distribution of flat areas that would be more amendable to site characterization and road routing.

Drainage divides delineated in the provincial quaternary watershed file produced by the Ministry of Natural Resources 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 that identifies the drainage divides delineated in this assessment, but not present in the quaternary watershed file. Most of the runoff in the Wawa area flows into the northeast part of Lake Superior through the Michipicoten – Magpie sub-sub basin. Runoff in southern portions of the Wawa area flows through the Agawa sub-sub basin into Lake Superior to the south of the Wawa area.

Based on the available topographic and drainage information, groundwater in the Wawa area can be conceptualized as being recharged in the highlands of the northwest, northeast and southeast parts of the Wawa area with flow predominantly southward and westward via local discharge through lakes and river valleys to the regional discharge location of Lake Superior. These estimates of regional groundwater flow conditions in the bedrock will be locally affected by the presence of faults and major structural and lithological discontinuities that have hydraulic properties different from that of the bulk bedrock. This assessment found no information beyond what was presented in the initial screening (Geofirma, 2011) on groundwater flow at repository depth.

Estimates of overburden thickness within the Wawa area were largely derived from reports produced by two surficial mapping programs. The NOEGTS map delineated about 80% of the Wawa area as bedrock, which was described as being characterized by thin discontinuous drift deposits generally less than one metre thick with drift thickness up to 3 m in depressions. The OGS surficial map delineated an equivalent unit called bedrock-drift complex, which is described as having less than 50% exposed bedrock and consisting of drift that is mostly a veneer (less than 1 m thick) of sandy lodgement till with lesser ice-contact stratified drift and organic deposits. Drift deposits in areas mapped as ground moraine in the NOEGTS map were expected to be as much as 5 to 10 m thick (Gartner and McQuay, 1979a). Similarly, materials mapped as till in the OGS map are expected to contain ablation till generally greater than one metre thick and up to about 10 m thick where minor recessional moraines have formed. Outwash and esker deposits within valleys and depressions could be 20 m thick or more. The thickest overburden deposits known in the Wawa area are located within the valleys of the major rivers below an elevation of about 310 m, where water well and drill hole data indicate depths up to 60 to 86 m. Terraces near the mouth of the Magpie River expose 32 m of deltaic sediments deposited in Glacial Lake Minong.

Conclusive identification of features indicative of reactivation of ancient bedrock structures due to cycles of glacial loading and unloading cannot be identified using the information sources available in the current assessment. Field investigations would be required to identify such features.

Existing highways generally provide access only to low-lying, drift-covered parts of the potentially suitable geological formations within the Wawa area. Areas of thin drift and abundant exposed bedrock are more readily amenable to site characterization as they would would enable further investigation of the potentially suitable bedrock formations through outcrop mapping of bedrock structures and preliminary rock mass characterization. Although areas of thin drift are relatively amenable to site characterization, road building and site construction within these areas can be challenging. Due to shallow drift and the irregular bedrock surface, development activities will be more difficult and expensive in bedrock terrain. Construction could be extremely difficult in areas of high rock cliffs and steep bedrock hills. Road routing in bedrock terrain is complicated by severe grades, expensive cut-and-fill operations, and the presence of steep slopes can put serious constraints on the siting of buildings. The relief and slope maps presented and described in Section 3 can be used to assess the suitability of general areas, and these maps indicate the presence of mountainous topography with steep slopes and high relief in many parts of the Wawa area.

Major highways traverse through the central parts of the Wawa area. The Trans-Canada Highway (Highway 17) is the major highway connecting Wawa with southern Ontario. Highway 17 extends through or near the margins of the Western and Brulé Bay batholiths (Figure 2). Highway 101 is a two-lane paved highway that provides direct access into a remote, low-lying, dominantly drift-covered corridor of the Wawa Gneiss domain. Highway 101 also provides access to the margins of the large ridges on the Whitefish Lake batholith in Lastheels and Fiddler townships. Highway 651 is a remote secondary highway that extends through the Wawa Gneiss domain in the eastern part of the Wawa area.

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## REPORT SIGNATURE PAGE

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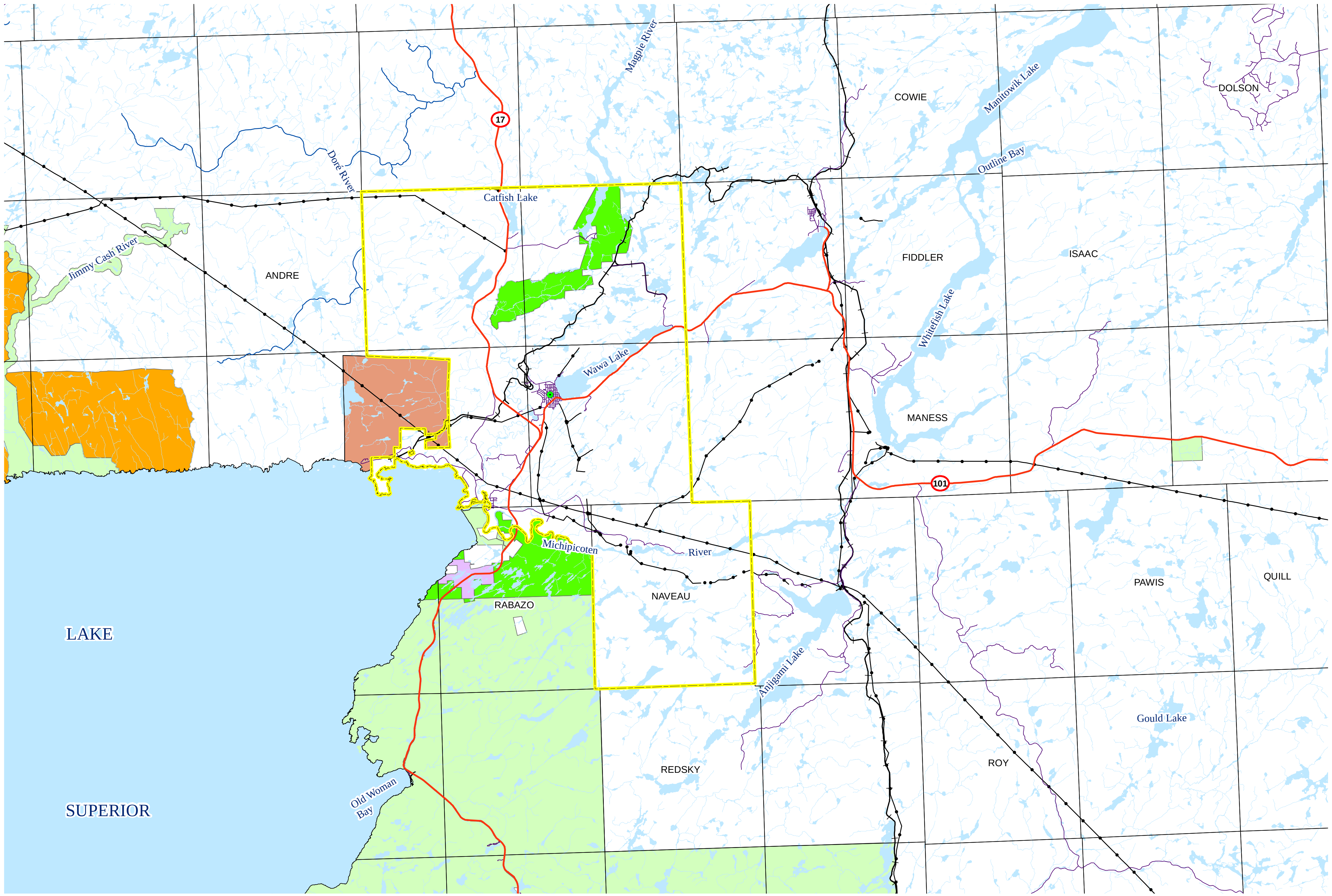
David van Zeyl, M.Sc.

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

# FIGURES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ANDRE
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Whitefish Lake
Wawa Lake
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101
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River
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Gould Lake
REDSKY
ROY
SUPERIOR
Old Woman Bay

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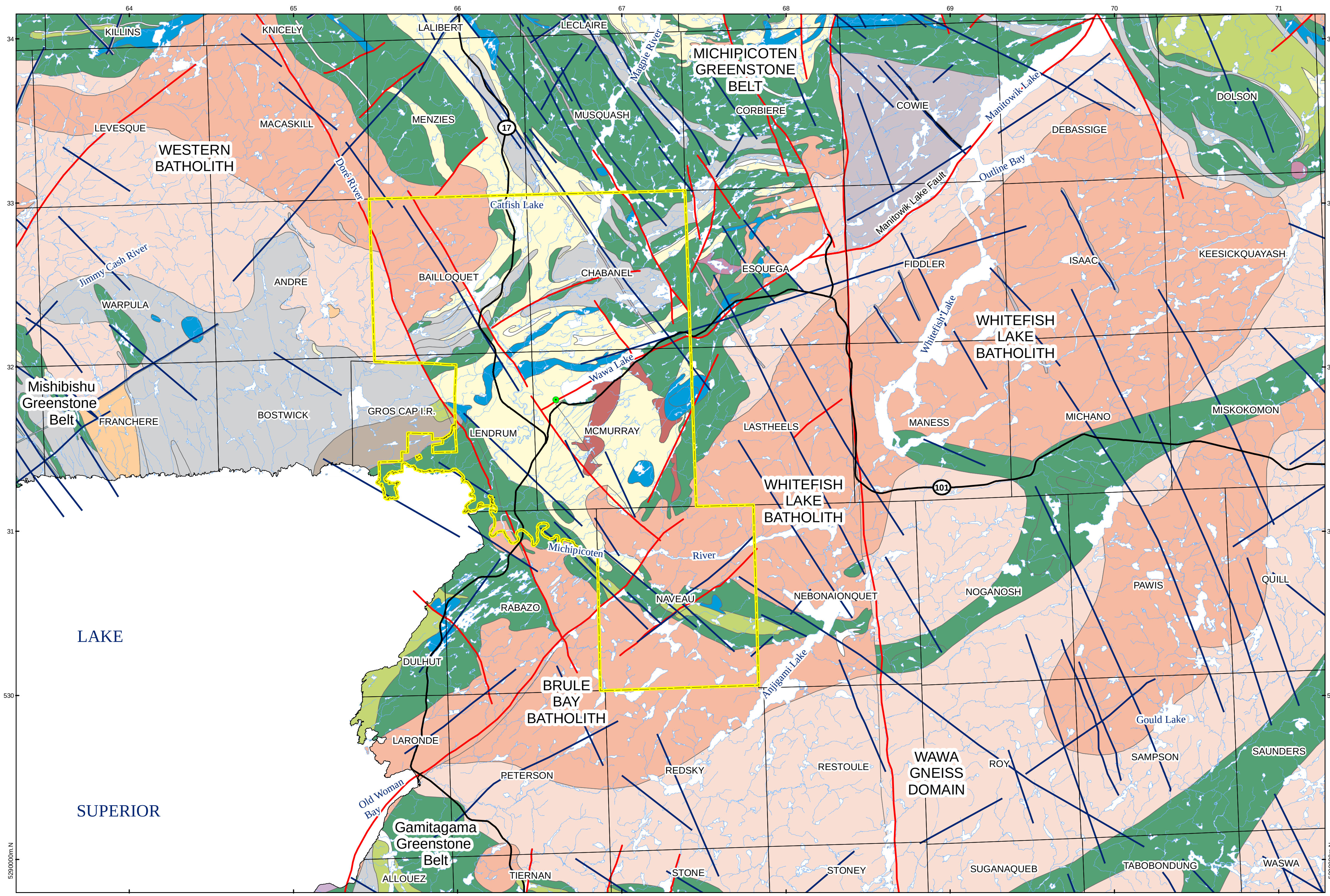


**LEGEND**

- Municipality of Wawa
- Geographic township
- Settlement of Wawa
- Main road
- Dyke
- Fault
- Waterbody
- Watercourse

**Bedrock geology**

- 2 Mafic volcanic
- 3 Felsic-intermediate volcanic
- 4 Felsic volcanic
- 5 Metasedimentary
- 6 Metasedimentary
- 7 Ultramafic plutonic
- 8 Gabbro dike
- 9 Gneissic tonalite
- 10 Foliated tonalite
- 12 Diorite-monzonite-granodiorite
- 13 Granite-granodiorite
- 17 Hough Lake Group
- 21 Gunflint Formation
- 24 Felsic intrusive
- 99 Iron formation

Data sources:
Bedrock: OGS map 2669 (1:250,000)
Roads: Selected from LIO MNR Road Segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse

NORTH
5 km

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PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, WAWA AREA, ONTARIO

TITLE
Bedrock geology of the Wawa area

| | | | | |
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| DESIGN | DVZ | 14 SEP 2012 | FIGURE 2 | REVISION 3 |
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| CHECK | DVZ | 22 AUG 2013 | | NAD 1983 |
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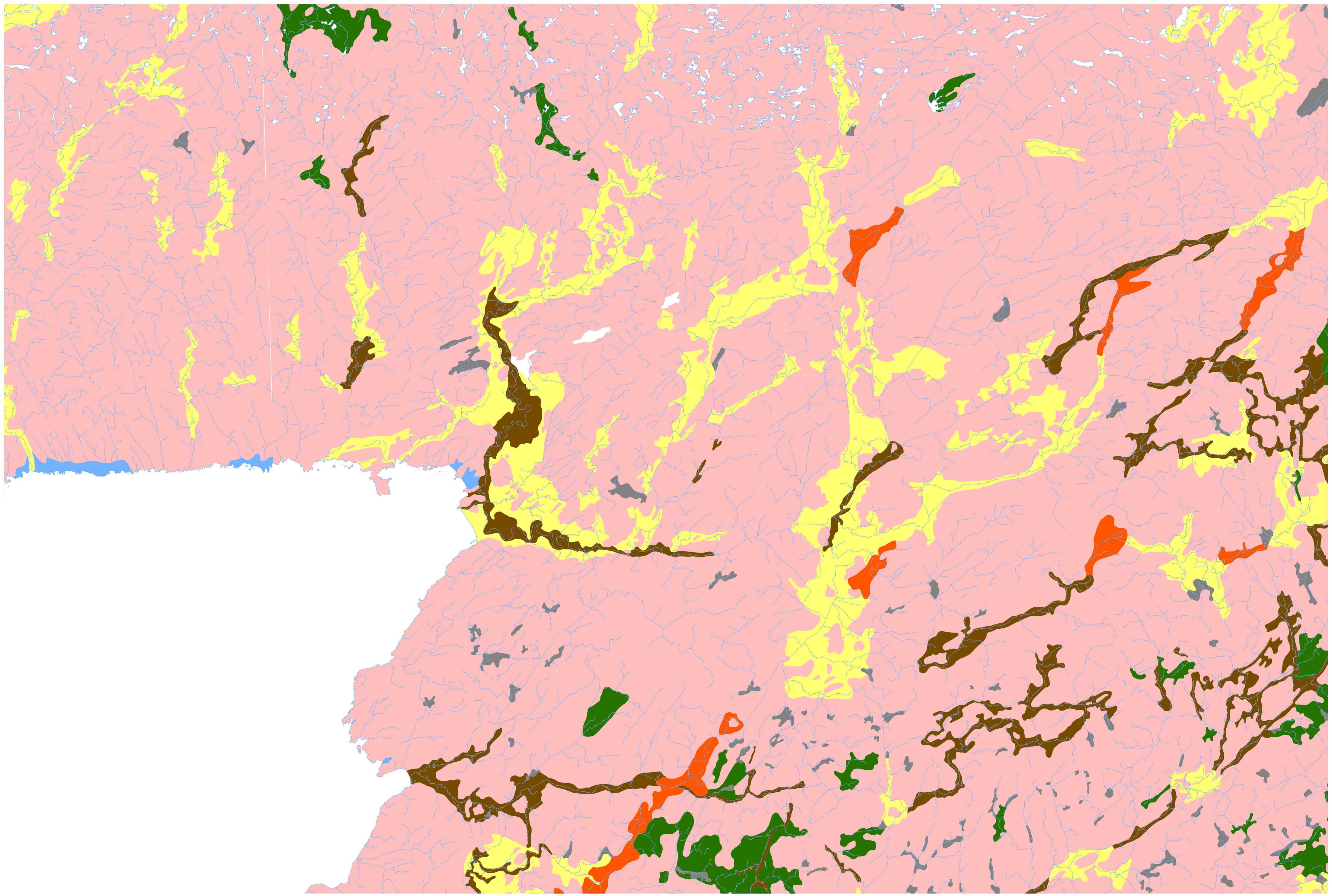

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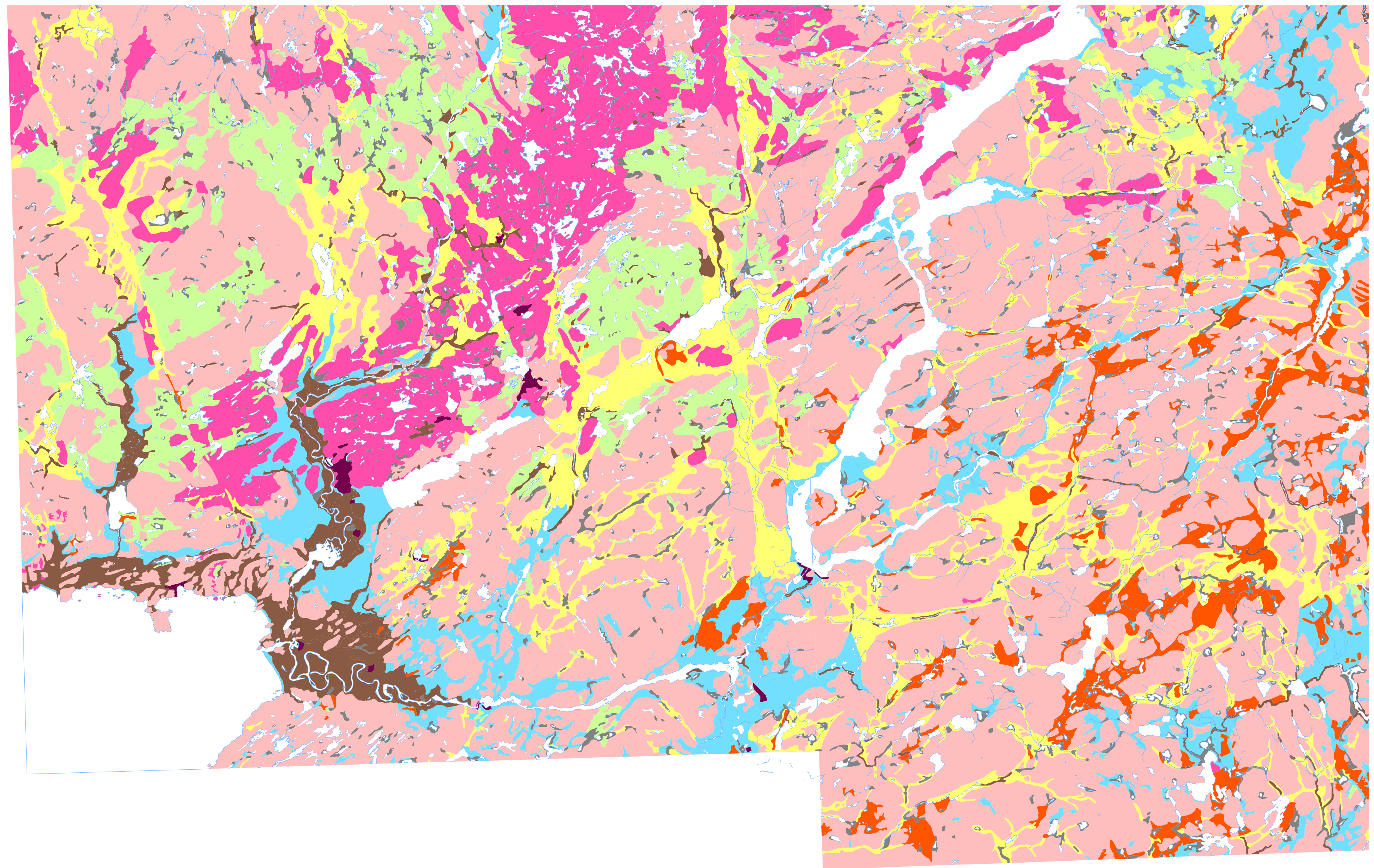

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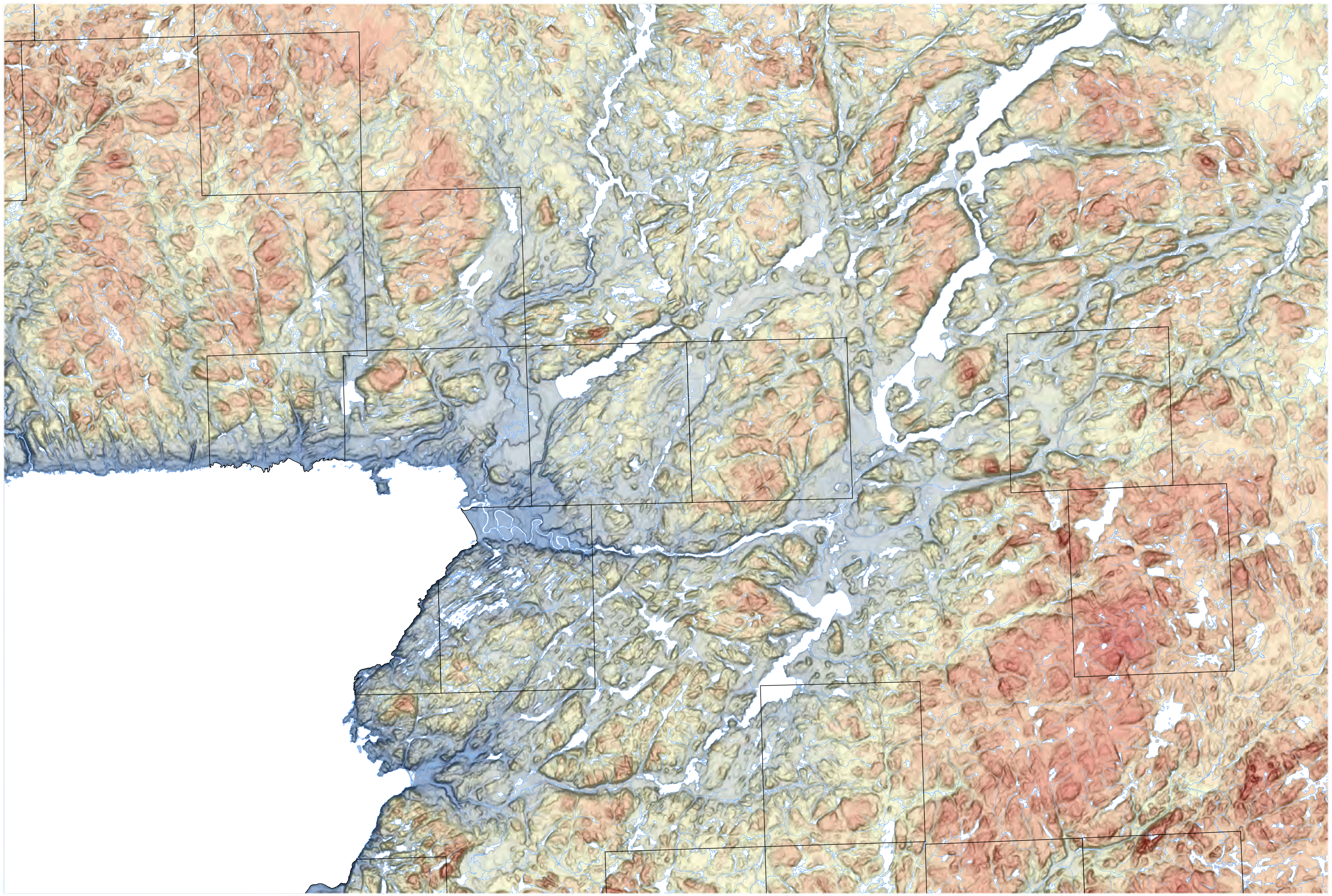

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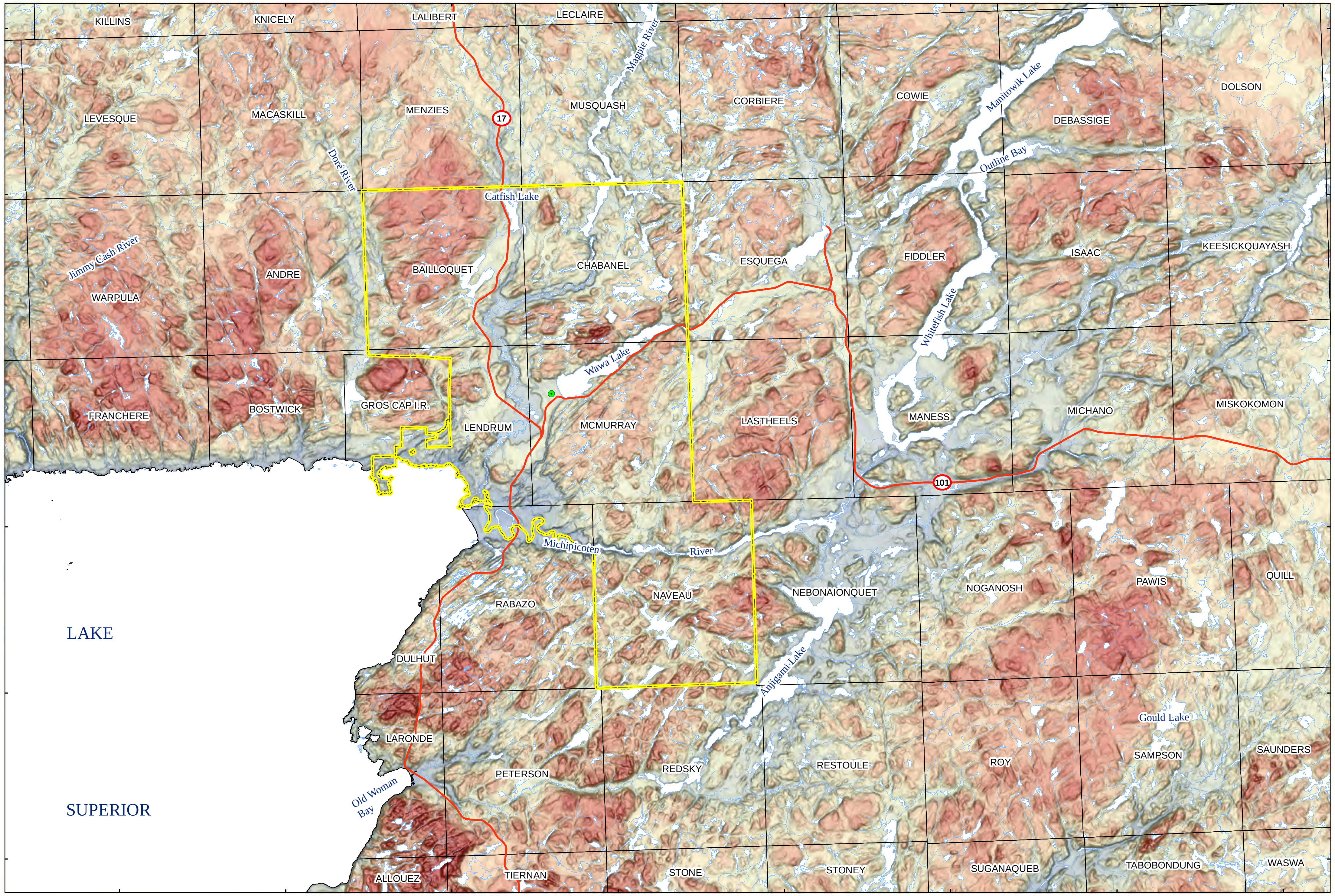
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MUSQUASH
CORBIERE
COWIE
Manitowik Lake
DEBASSIGE
DOLSON
Dore River
Outline Bay
Catfish Lake
Jimmy Cash River
BAILLOQUET
CHABANEL
ESQUEGA
FIDDLER
ISAAC
KEESICKQUAYASH
ANDRE
WARPULA
Whitefish Lake
Wawa Lake
GROS CAP I.R.
FRANCHERE
BOSTWICK
LENDRUM
MCMURRAY
LASTHEELS
MANESS
MICHANO
MISKOKOMON
101
Michipicoten
River
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NOGANOSH
PAWIS
QUILL
RABAZO
LAKE
DULHUT
Anjigami Lake
Gould Lake
LARONDE
PETERSON
REDSKY
RESTOULE
ROY
SAMPSON
SAUNDERS
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TIERNAN
STONE
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SUGANAQUEB
TABOBONDUNG
WASWA

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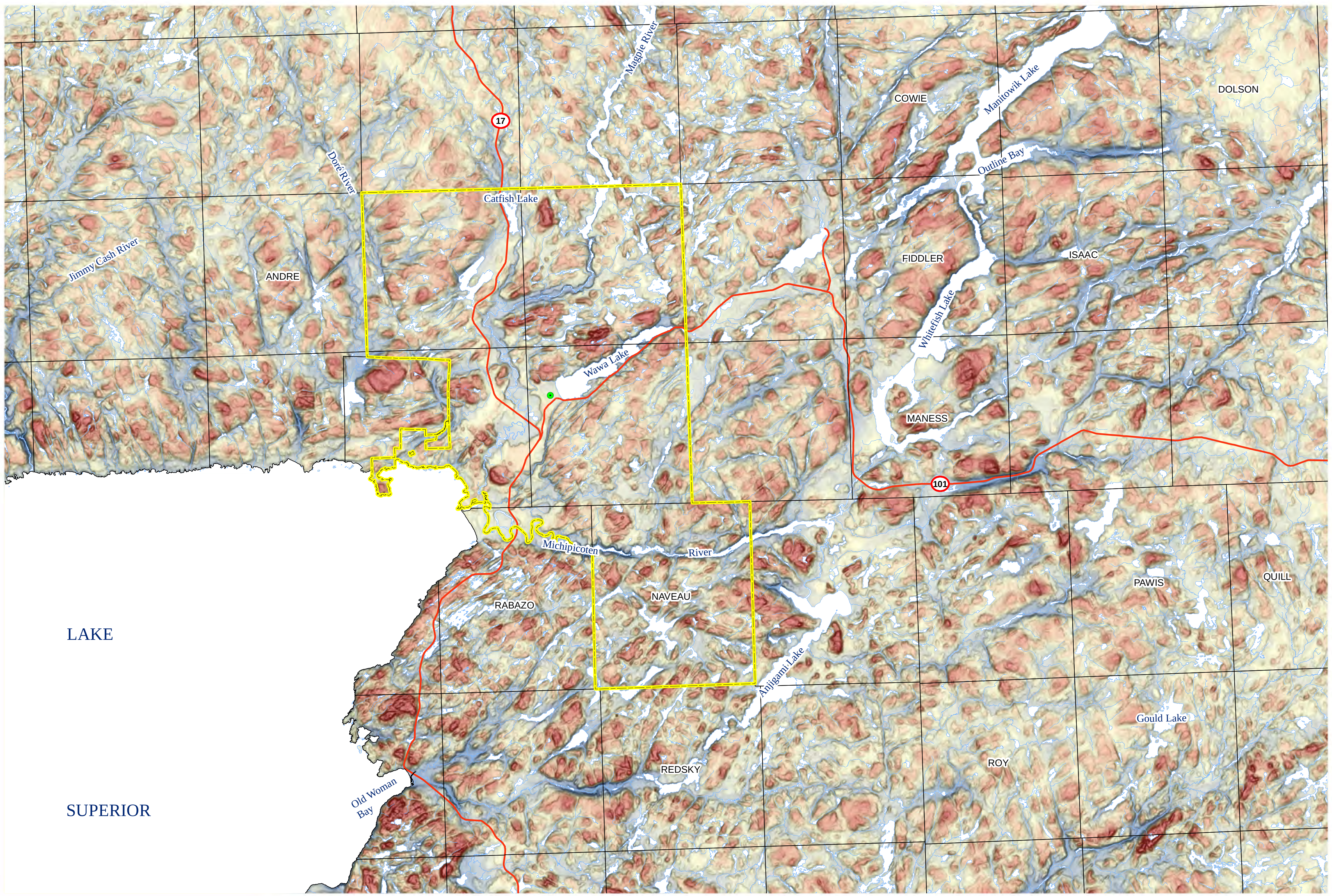
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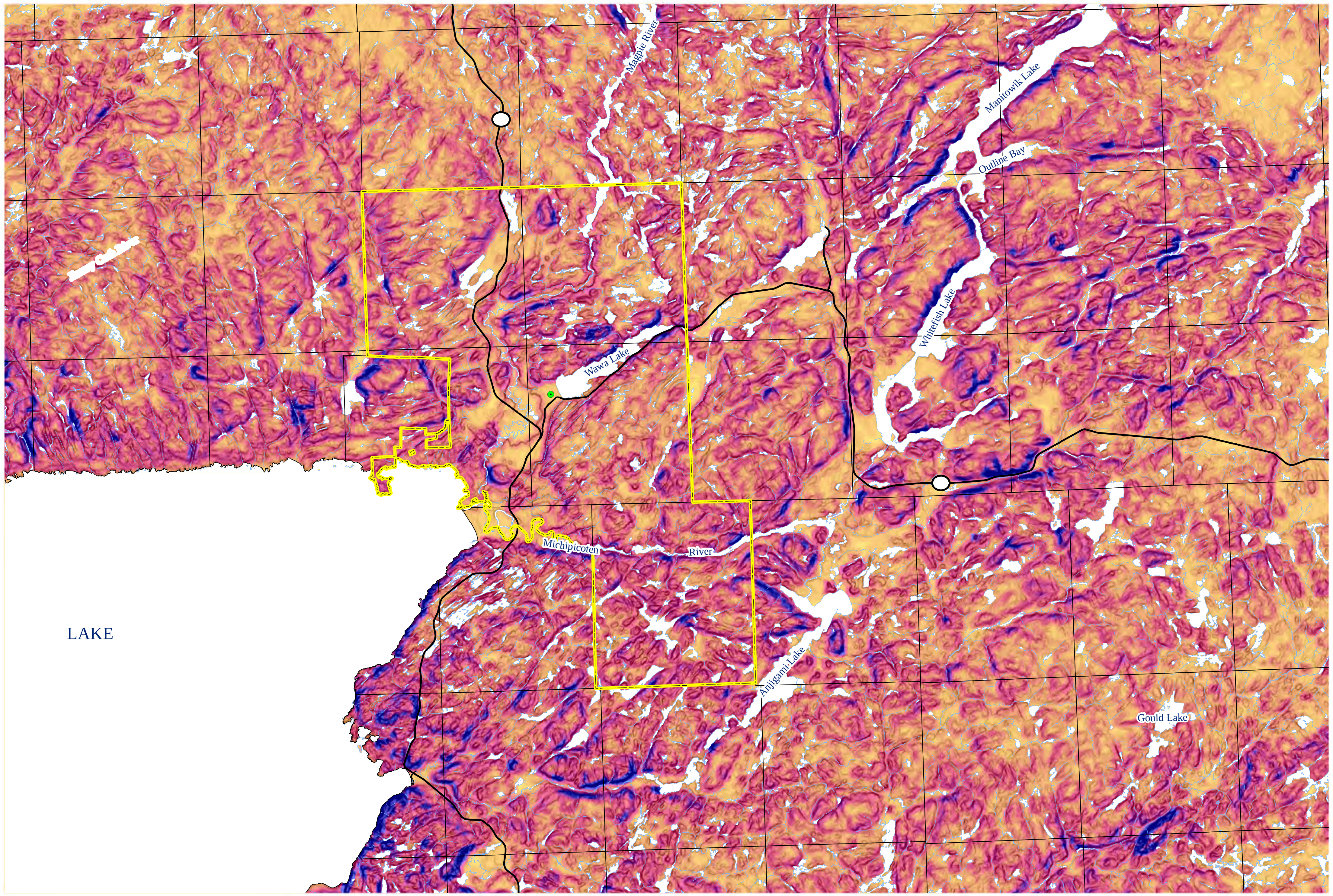

Magpie River
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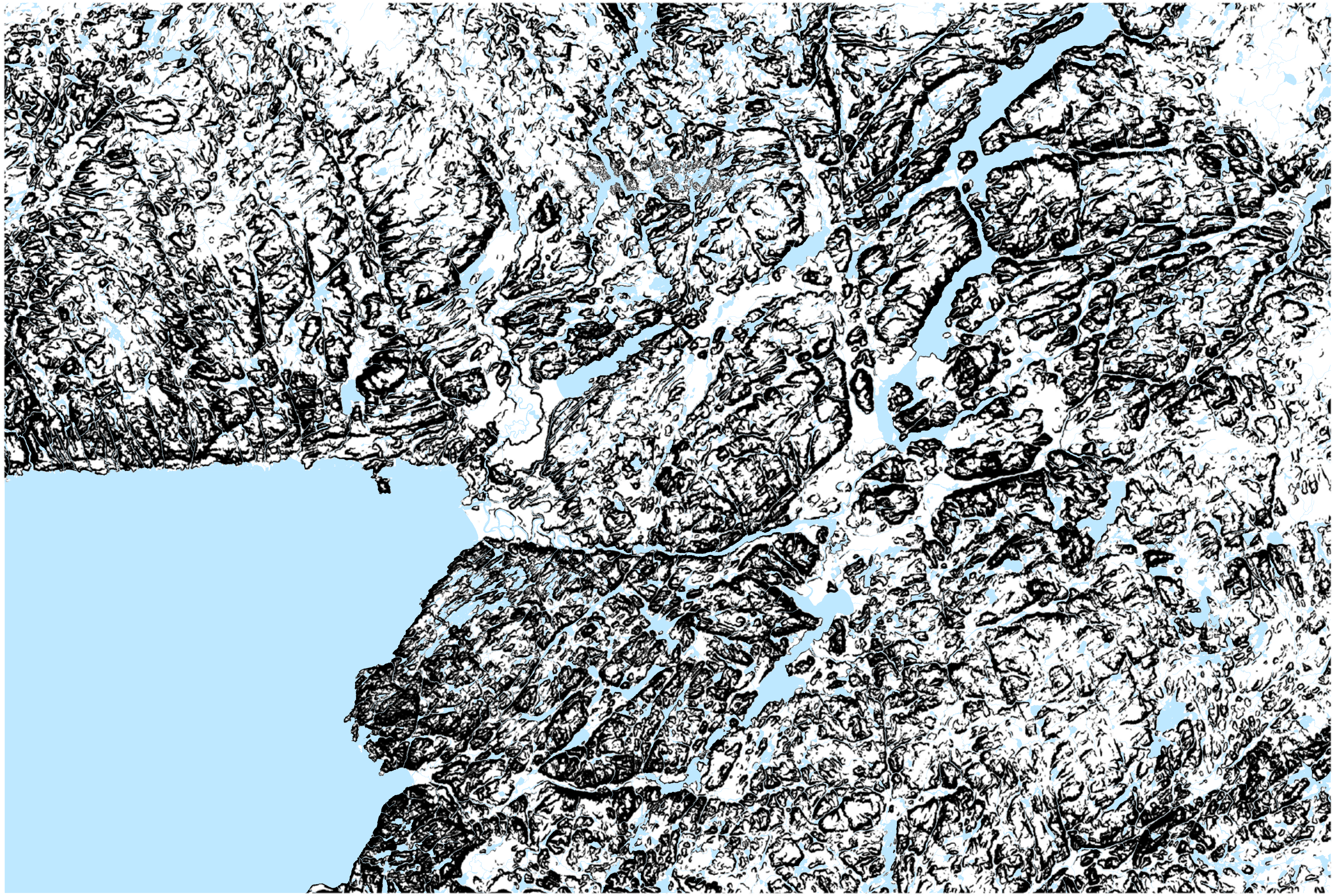

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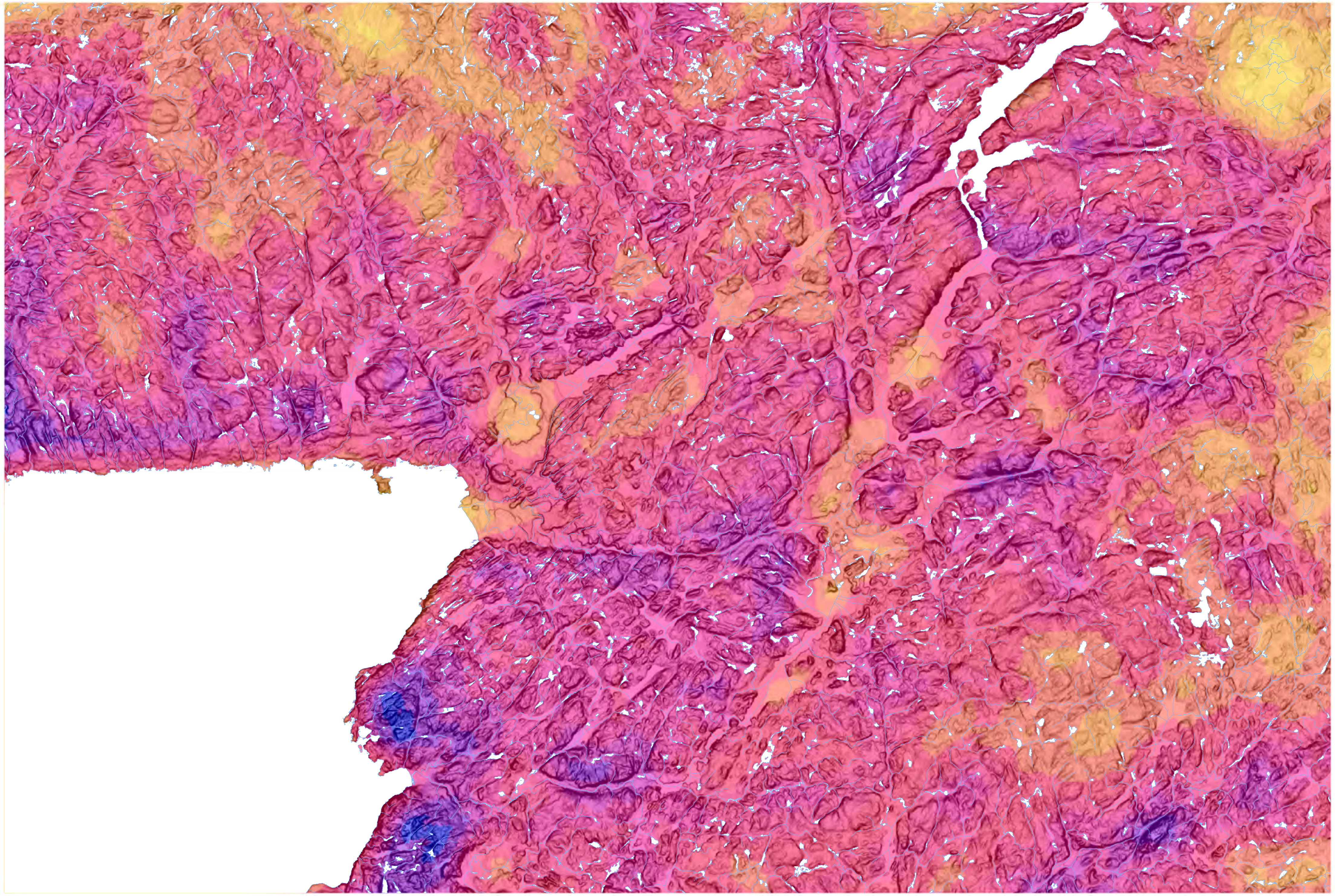

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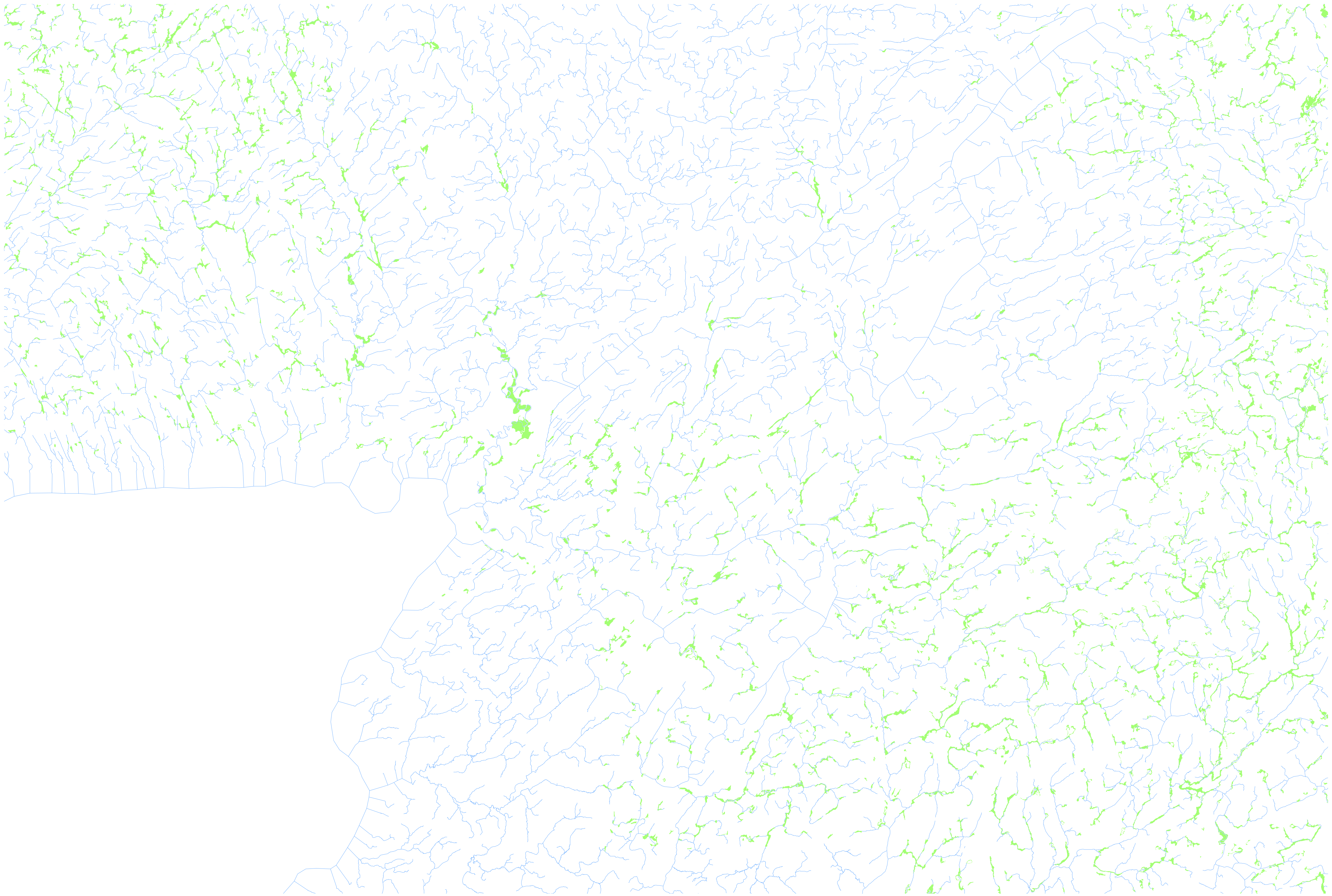

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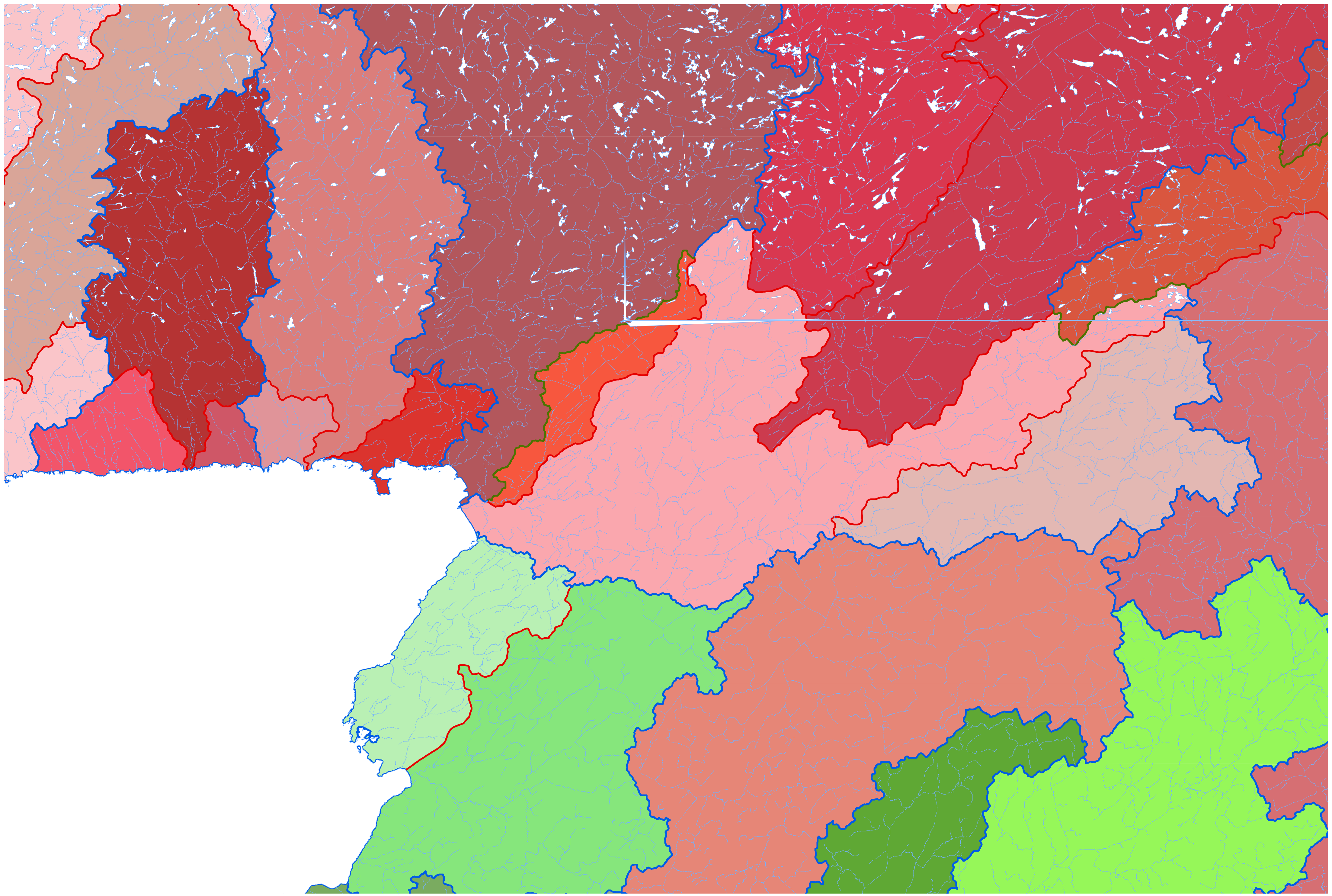

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