NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation

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

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

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT

LINEAMENT INTERPRETATION

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Prepared for:

G.W. Schneider, M.Sc., P.Geo.
Golder Associates Ltd.
6925 Century Avenue, Suite 100
Mississauga, Ontario
Canada L5N 7K2

Nuclear Waste Management Organization (NWMO)
22 St. Clair Avenue East 6th Floor
Toronto, Ontario
Canada M4T 2S3

Prepared by:

Jason Cosford, Ph.D., P.Geo.
L.A. Penner, M.Sc., P.Eng., P.Geo.
J.D. Mollard and Associates (2010) Limited
810 Avord Tower, 2002 Victoria Avenue
Regina, Saskatchewan, Canada S4P 0R7

EXECUTIVE SUMMARY

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

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

This report presents the findings of a lineament interpretation completed as part of the geoscientific desktop preliminary assessment of the area of the four communities (Golder, 2014). The lineament study focussed on identifying surficial and geophysical lineaments and their attributes using publicly-available digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the area of the four communities in northern Ontario. The assessment of interpreted lineaments in the context of identifying general areas that are potentially suitable for hosting a repository is provided in the geoscientific desktop preliminary assessment report (Golder, 2014).

The lineament investigation interprets the location and orientation of potential bedrock structural features (e.g., individual fractures or fracture zones) within the context of the local and regional geological setting. The approach undertaken in this desktop lineament investigation is based on the following:

- Lineaments were interpreted from multiple, readily-available datasets (aeromagnetic, CDED and SPOT);

- Lineament interpretations were made by documented specialist observers and using a standardized workflow;
- Lineament interpretations were analyzed based on an evaluation of the quality and limitations of the available datasets;
- Interpreted lineaments were separated into three categories (ductile, brittle, dyke) based on their character expressed in the aeromagnetic data;
- Lineament interpretations were analyzed using reproducibility tests, particularly the coincidence of lineaments extracted by different observers, coincidence of lineaments extracted from different datasets, relative ages and/or documentation in literature; and
- Final classification of the lineament interpretation was done based on length and reproducibility.

The distribution of lineaments in the area of the four communities reflects the bedrock structure, resolution of the datasets used, and surficial cover. Surface lineament density, as demonstrated in this study, is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures. Lineament density was observed to be highest in the northern part of the area of the four communities where the thickness and extent of surficial cover is relatively low. Lineament density is also influenced by the resolution of the datasets as demonstrated by the comparison of aeromagnetic lineament density interpreted from high and low resolution surveys. On the basis of the structural history of the area of the four communities, a framework was also developed to constrain the relative age relationships of the interpreted lineaments.

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1 INTRODUCTION

In November and December 2012, the City of Elliot Lake, the Town of Blind River, the Township of The North Shore, and the Town of Spanish expressed interest in continuing to learn more about the Nuclear Waste Management Organization's (NWMO) nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the area of the four communities for safely hosting a deep geological repository (Step 3).

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

This report presents the findings of a lineament investigation study completed as part of the geoscientific desktop preliminary assessment of the area of the four communities (Golder, 2014). The lineament study focussed on identifying surficial and geophysical lineaments and their attributes using publicly-available digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the area of the four communities in northern Ontario. The assessment of interpreted lineaments in the context of identifying general areas that are potentially suitable for hosting a repository is provided in the geoscientific desktop preliminary assessment report (Golder, 2014).

1.1 SCOPE OF WORK

The scope of work for this study includes the completion of a lineament interpretation of remotely-sensed datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the area of the four communities (approximately 14,450 km^2), in northern Ontario (Figure 1). The lineament investigation interprets the location and orientation of potential bedrock structural features (e.g., individual fractures or fracture zones) and helps to evaluate their relative timing relationships within the context of the local and regional geological setting. For the purpose of this report, a lineament is defined as, ‘an extensive linear or arcuate geologic or topographic feature’. The approach undertaken in this desktop lineament investigation is based on the following:

- Lineaments were mapped from multiple, readily-available datasets that include satellite imagery (Système Pour l’Observation de la Terre; SPOT), digital elevation models (Canadian Digital Elevation Data; CDED), and aeromagnetic geophysical survey data;
- Lineament interpretations from each source data type were made by two documented specialist observers for each dataset (e.g., geologist, geophysicist). Ductile lineaments were interpreted from the aeromagnetic geophysical survey dataset by an automated picking routine with confirmation by a single documented specialist observer;
- Lineaments were analyzed based on an evaluation of the quality and limitations of the available datasets, age relationships, reproducibility tests, particularly the coincidence of lineaments extracted by different observers, coincidence of lineaments extracted from different datasets, and/or documentation in literature; and
- Classification was done to indicate the significance of lineaments based on length and reproducibility.

These elements address the issues of subjectivity and reproducibility normally associated with lineament investigations and their incorporation into the methodology increases the confidence in the resulting lineament interpretation.

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

- **Ductile lineaments:** Features which were interpreted as being associated with the internal fabric of the rock units (including sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation) were classified as ductile lineaments. This category also includes recognizable penetrative shear zone fabric.

- **Brittle lineaments:** Features interpreted as fractures (joints or joint sets, faults or fault zones, and veins or vein sets), including those that offset the continuity of the ductile fabric described above, were classified as brittle lineaments. This category also includes brittle-ductile shear zones, and brittle partings interpreted to represent discontinuous re-activation parallel to the ductile fabric. At the desktop stage of the investigation, this category also includes features of unknown affinity. This category does not include interpreted dykes, which are classified separately (described below).

- **Dyke lineaments:** For this preliminary desktop interpretation, any features which were interpreted, on the basis of their distinct character, e.g., scale and composition of fracture in-fill, orientation, geophysical signature and topographic expression, were classified as dykes. Dyke interpretation is largely made using the aeromagnetic dataset, and is often combined with pre-existing knowledge of the bedrock geology of the area of the four communities.

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

1.2 Qualifications of the Interpretation Team

The project team employed in the lineament interpretation component of the Phase 1 Geoscientific Desktop Preliminary Assessment of Potential Suitability Study consists of qualified experts from J.D. Mollard and Associates (2010) Limited, Regina (JDMA), Golder Associates Ltd., Mississauga, and Paterson, Grant and Watson, Toronto (PGW). JDMA coordinated the lineament study with the support of PGW who conducted the lineament interpretation on the geophysical data.

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

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

Dr. Jason Cosford, Ph.D., P.Geo. has contributed to a wide range of terrain analysis studies conducted by JDMA, including routing studies (road, rail, pipeline, and transmission line), groundwater exploration, granular resource mapping, and environmental sensitivity analyses. Dr. Cosford, Mr. Penner and Dr. Jack Mollard were responsible for shallow groundwater studies for the Weyburn CO_2 sequestration research project. Dr. Cosford provided interpretation of the surficial lineaments and coordinated the evaluation of lineament attributes, and oversaw the preparation of integrated lineament datasets.

Shayne MacDonald, B.Sc., is an experienced GIS technician and remote sensing specialist. He provided GIS and image processing support for these studies and assisted with developing integrated lineament datasets under the direction of Dr. Cosford.

Jessica O`Donnell, M.Sc., is an experienced GIS technician and remote sensing specialist. She provided GIS and image processing support for these studies and assisted with developing integrated lineament datasets under the direction of Dr. Cosford.

Charles Mitz, M.Eng., P.Geo. is a Senior Engineering Geologist with Golder who has a broad background in geoscience including extensive experience in geotechnical engineering, waste management and hydrogeology in both fractured rock and porous media. He has 20 years of experience in the consulting field, including the management of a number of high profile and multidisciplinary projects. Recently he has worked on the development of the generic geoscientific site selection process and has been involved in the initial geoscientific screening studies for a number of potential sites in the Canadian Shield crystalline rock environment in northern Ontario. Mr. Mitz holds a Bachelor's Degree in Geological Science from Queen's University and a Master's Degree in Civil Engineering from the University of Western Ontario. In this study, Mr. Mitz was the second interpreter of the surficial lineaments.

Stephen Reford, B.A.Sc., P.Eng. is a senior consulting geophysicist and Vice-President of PGW. Mr. Reford has more than 30 years of experience in project management, acquisition and interpretation of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data throughout and gamma-ray spectrometer surveys for clients throughout Canada and around the world. Projects include management of the geophysical component of Operation Treasure Hunt for the Ontario Ministry of Northern Development and Mines as well as a similar role for the Far North Geoscience Mapping Initiative (2006-2009). Mr. Reford has served as a consultant to the International Atomic Energy Agency (IAEA) in gamma-ray spectrometry and is co-author of two books on radioelement mapping. Mr. Reford coordinated the interpretation of geophysical data, and was the lead interpreter of the geophysical lineaments.

Dr. Hernan Ugalde, Ph.D., P.Geo. – is a senior consulting geophysicist for PGW. Dr. Ugalde has 19 years of experience in project management, acquisition, modelling and interpretation of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data for clients throughout Canada and around the world. For PGW, he has worked 7 years full-time and 8 years part-time (while earning his Ph.D., conducting post-doctoral research and lecturing). Projects include a lead role in interpretation and training for a nationwide program in Nigeria and exploration for precious and base metals throughout Latin America. Dr. Ugalde was the second interpreter of the geophysical lineaments.

1.3 REPORT ORGANIZATION

Section 2.0 describes the geological setting of the area of the four communities, which includes subsections on physical geography, bedrock geology, geological and structural history, Quaternary geology, and land use. Section 3.0 provides information on the source data and explains the methodology used to identify and assess lineaments. Section 4.0 presents the findings of the lineament interpretation with a description of lineaments by each dataset and a description and classification of integrated lineaments. Section 5.0 offers a discussion of the findings, specifically the lineament density, reproducibility and coincidence, lineament length, fault and lineament relationships, and relative age relationships. Section 6.0 is a summary of the report.

This report draws upon information from the Phase 1 geoscientific assessment report prepared by Golder (2014), as well as supporting reports on terrain analysis (JDMA, 2014) and geophysics (PGW, 2014).

2 SUMMARY OF PHYSICAL GEOGRAPHY AND GEOLOGY

A detailed discussion of the geological setting of the area of the four communities is provided in Golder (2014). The following sections on physical geography, bedrock geology, geological and structural history, Quaternary geology, and land use, present information from Golder (2014), JDMA (2014) and PGW (2014), where applicable, in order to provide the necessary context for discussion of the results of this lineament assessment (Section 5.0). The regional and local bedrock geology of the area of the four communities is shown on Figures 2 and 3, respectively.

2.1 PHYSICAL GEOGRAPHY

A detailed discussion of the physical geography of the area of the four communities is provided in a separate terrain analysis report (JDMA, 2014) and the following is a summary of that information. The area of the four communities exhibits topographic and drainage features that are characteristic of the Canadian Shield. The topography in this area is largely bedrock-controlled, with bedrock hills and ridges, and structurally controlled valleys acting as the main landscape elements. As a result, topography can reveal much about the bedrock structure and distribution of overburden deposits.

Overall, the northern part of the area of the four communities is a highland and the southern part is a lowland. The narrow lowland along this part of the north shore of Lake Huron is characterized by wave-washed bedrock knolls interspersed with local pockets of glaciolacustrine sediments. The elevation gradient from north to south is from 612 to 176 m, with this elevation drop occurring over a distance of approximate 90 km. The highest point in the area of the four communities is within the highlands north of the Aubinadong River, in the northwest corner of the area. The lowest point is defined by the surface of Lake Huron, which has a chart datum of 176.0 m.

The areas mapped as bedrock within the area of the four communities amount to 76% of the area not covered by Lake Huron (Figure 4). Within these areas, drift deposits are thinnest on the bedrock hills and ridges scattered throughout the landscape, and local drift deposits too small to map explicitly at the scale of 1:100,000 exist within depressions. JDMA (2014) mapped bedrock outcrop using Landsat MSS imagery, and found a greater amount of exposed bedrock in the southern part of the area of the four communities, particularly in the area between Highway 546 and Highway 108. Some of the outcrops within the lowland along the north shore of Lake Huron are expected to represent areas where the overburden deposits were eroded by wave erosion during glacial and postglacial high stands of the Lake Huron basin, leaving the bedrock exposed. The total extent of bedrock outcrops suggested by the Landsat MSS interpretation is about 8% of the portion of the area of the four communities not covered by Lake Huron.

The area of the four communities contains a large number of lakes of various sizes, twenty-four of which are larger than 10 km^2 and ten of which are larger than 20 km^2, with 21% (3,049 km^2) of the area occupied by water bodies, 11% of which is represented by Lake Huron (JDMA, 2014). Waterbodies cover 11.5% of the portion of the area of the four communities not covered by Lake Huron. The large lakes are sufficiently large to conceal geological structures up to about 5 km in length, and clusters of small lakes can conceal structures, especially when the lakes are located in areas covered by overburden.

2.2 BEDROCK GEOLOGY

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

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

The area of the four communities, situated on the north shore of Lake Huron, is underlain by early Proterozoic rocks of the Southern Province and Archean rocks of the westernmost portion of the Abitibi Subprovince of the Superior Province of the Canadian Shield. The Abitibi Subprovince is bounded to the west by the Kapuskasing structural zone (KSZ) and Wawa Subprovince and to the north by the Opatica Subprovince. The southern boundary of the Abitibi

Subprovince is overlain by metasedimentary and metavolcanic rocks of the Huronian Supergroup of the Southern Province. The Southern Province is bounded to the southeast by the Proterozoic Grenville Province. Numerous mafic dyke swarms and mapped faults transect the bedrock in the area of the four communities. Figures 2 and 3 show the regional and local-scale geology for the area of the four communities and the surrounding area.

The Abitibi Subprovince is exposed in the northern half and much of the eastern side of the area of the four communities (Figures 2 and 3). The Abitibi Subprovince is a granite-greenstone-gneiss terrane that was developed between 2.8 and 2.6 billion years ago (Thurston, 1991). It is composed of low metamorphic grade volcanic rocks and granitoid plutonic and gneiss-dominated domains, the latter of which are predominant in the area of the four communities and are represented by the Ramsey-Algoma granitoid complex (e.g., Jackson and Fyon, 1991). The Ramsey-Algoma granitoid complex is a large heterogeneous group of granitic bodies that intruded the older metavolcanic and subordinate metasedimentary rocks of the Whiskey Lake and Benny Lake greenstone belts. Several smaller intrusive bodies are distributed throughout the area of the four communities, including the Cutler pluton, the Seabrook Lake intrusion, the Parisien Lake syenite, and the East Bull Lake intrusive suite, among others (Figure 3).

The Huronian Supergroup underlies the southern portion of the area of the four communities (Figure 2 and 3) and consists of a group of metasedimentary rocks (stratigraphically youngest) and lesser (stratigraphically oldest) metavolcanic rocks ranging in age from 2.5 to 2.2 billion years old. The Southern Province also includes the Sudbury Igneous Complex (ca. 1.85 billion years old) located to the east of the area of the four communities, and the metasedimentary and metavolcanic rocks of the Animikie and Sibley Groups that are exposed further to the west, beyond the assessment area, towards Thunder Bay.

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

2.2.1 WHISKEY LAKE GREENSTONE BELT

The Whiskey Lake greenstone belt (Figure 3) consists of Archean metavolcanic and subordinated metasedimentary rocks that form an arcuate, easterly-striking, 10 km by 30 km, synclinal greenstone belt (Rogers, 1992). The greenstone belt has been subdivided into the Whiskey Lake greenstone belt for the portion south of the Folson Lake fault and a northern component named the Ompa greenstone belt (Easton, 2010) for the portion north of the Folson Lake fault. In the interest of simplicity and consistency with earlier nomenclature, the name Whiskey Lake refers to both components in this assessment. Radiometric ($^{207}Pb/^{206}Pb$) dating from greenstone rocks in the Joubin Township area, located 15 km west of the East Bull Lake intrusion, yielded ages of ca. 2.686 and 2.725 billion years, for upper and lower metavolcanic sequences (Easton, 2010; Easton and Heaman, 2011), while a similar age of 2.689 billion years was obtained from felsic metavolcanic rock of the northern portion of the greenstone belt (Easton, 2010). Drill holes in the Whiskey Lake greenstone belt in the vicinity of Folson Lake (AFRI # 41J08NW0001) indicate a thickness of at least 400 m for the greenstone rocks.

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

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

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

2.2.2 BENNY LAKE GREENSTONE BELT

The Benny Lake greenstone belt (Figure 3) consists of Archean metavolcanic and metasedimentary rocks that form an east-striking 40 km long by 5 km wide greenstone belt that extends from the Geneva Lake area to the Mink Lake area, some 70 km northeast of the City of Elliot Lake. The greenstone belt extends approximately 10 km into the area of the four communities to its mapped termination south of Mink Lake. Card and Innes (1981) described the central part of the belt as consisting of intercalated mafic flows and pyroclastic rocks with intermediate tuffs and tuff-breccia with some volcanogenic metasedimentary rocks including tuffaceous greywake and siltstone, chert, and iron formation. The stratigraphic sequence in this part of the belt comprises cyclic repetitions of mafic, intermediate, and felsic metavolcanics, plus sulphide-bearing tuffs and tuffaceous metasedimentary rocks that commonly lie along contact zones between the metavolcanic units. Outliers of the Huronian Supergroup have also been mapped in the area south of the greenstone belt.

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

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

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

2.2.3 RAMSEY-ALGOMA GRANITOID COMPLEX

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

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

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

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

- Synvolcanic diorite and hornblende tonalite intrusions ranging in age from ca. 2.740 to 2.696 billion years old;
- A transitional suite of tonalite and quartz monzonite intrusions ranging from ca. 2.695 to 2.686 billion years old;

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

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

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

2.2.4 SEABROOK LAKE INTRUSION

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

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

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

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

2.2.5 Parisien Lake syenite

The Parisien Lake syenite is a late Archean, 2.665 billion year old (Krogh et al., 1984), elliptical intrusive stock located about 15 km east of the City of Elliot Lake, adjacent to the East Bull Lake intrusion. It measures approximately 13.5 km east-west and 3.3 km at its widest point north-south. The intrusion is composed of medium- to coarse-grained, pink, equigranular monzodiorite, monzonite and syenite (Rogers, 1992). Predominant minerals are K-feldspar phenocrysts, with interstitial amphibole, biotite, sphene, and magnetite, with a distinctive, locally developed K-feldspar alignment (McCrank et al., 1989). The Parisien Lake syenite is shown on Figure 3 as a diorite-monzonite-granodiorite suite. There is no readily available information on the thickness of this intrusion.

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

2.2.6 East Bull Lake intrusive suite

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

The elliptical East Bull Lake pluton, about 15 km east of the City of Elliot Lake, has surface dimensions of at least 13.5 km east to west, and a maximum north-south extent of 3.5 km (Figure 3). It is about 780 m thick in its central part (McCrank et al., 1989). The East Bull Lake pluton has a U-Pb isotopic age of 2.480 billion years old (Krogh et al., 1984), and it is divided into several large composite rock units distinguishable by variations in mineral composition, texture, and style of internal layering (McCrank et al., 1982; James et al., 1985; Ejeckam et al., 1985). Within the composite units, mineralogical grading produced layers that grade from gabbro to leucogabbro, rhythmic layers that grade upwards from clinopyroxenite and gabbro, to anorthosite layers and thin, centimetre-sized laminations of clinopyroxenite within gabbroic rock (McCrank et al., 1989).

The main mass of the Agnew Lake intrusion is located about 35 km east of the City of Elliot Lake. It is similar in age and size to the East Bull Lake intrusion, with an estimated U-Pb isotopic age of approximately 2.491 billion years old (Krogh et al., 1984), a thickness of 1 to 2.1 km, and an area of 50 km^2 (Vogel et al., 1998). The primary axis of the Agnew Lake intrusion is east-west, similar to the East Bull Lake intrusion, and is thought to reflect the orientation of the rift structure that permitted magma intrusion (Easton et al., 2004), and would have shaped the Agnew Lake and the East Bull Lake intrusions originally into funnel-like bodies (Vogel et al., 1998). The Agnew Lake intrusion is linked to the East Bull Lake intrusive suite on its northwest side by the Streich dyke, a 200 to 300 m wide gabbronoritic body with a strike length of approximately 10 km (not shown on Figure 3). The Agnew Lake intrusion is a product of four major magma pulses that produced an internal layered distribution of gabbronorite, olivine gabbronorite and leucogabbronorite in the intrusive body, each ranging in thickness from a few tens of metres to hundreds of metres. The Camp Eleven fault bisects the intrusion and exhibits 600 m of dextral displacement of this internal layering (Vogel et al., 1998). The Agnew Lake intrusion was wholly emplaced in granitoid rocks of the Algoma plutonic domain, while the top of this intrusion corresponds to a major disconformity separating the Agnew Lake intrusion from the Huronian Supergroup (Vogel et al., 1998). Also, potentially related to the East Bull Lake suite is the Tennyson sill (Prevec, 1993), an approximately 650 m thick body of medium-grained gabbro north of Massey. The Tennyson sill intruded Archean granodiorite, but is crosscut by Matachewan dykes. Easton (2010) interpreted the Tennyson sill to be a primitive phase of the East Bull Lake intrusive suite.

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

2.2.7 Cutler pluton

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

2.2.8 Huronian Supergroup

The Huronian Supergroup (Figures 2 and 3) is a stratigraphic sequence that extends for about 450 km from the east shore of Lake Superior to northwest Quebec, with varying thickness of up to 12 km southwest of Sudbury, thinning northward against rocks of the Ramsey-Algoma granitoid complex (Bennett et al., 1991). The Huronian Supergroup surrounds the City of Elliot Lake and overlies rocks of both the Whiskey Lake greenstone belt and the Ramsey-Algoma granitoid complex over large areas. Deposition of the thick Huronian stratigraphic package in a rift setting started approximately 2.497 billion years ago (Rainbird et al., 2006), influenced by Archean tectonic activity and possibly an early Proterozoic extension event, and was later succeeded by a passive-margin setting (Bennett et al., 1991; Young et al., 2001). Deposition ceased sometime before 2.219 billion years ago (Corfu and Andrews, 1986).

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

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

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

2.2.9 MAFIC DYKES

Mafic dykes and intrusions of diabase and gabbroic composition are widespread in and around the area of the four communities (Figure 3). Although the similar composition and texture of these intrusions has hampered the determination of their age and character, most of the studies carried out in the area of the four communities have historically assigned the mafic intrusions and dykes either to the Matachewan or Nipissing suites. More recent studies (Osmani, 1991; Phinney and Halls, 2001) indicate the presence of at least four distinct generations of mafic dyke emplacement: Matachewan swarm, Nipissing intrusions, Biscotasing swarm, Sudbury swarm, North Channel swarm, and younger unclassified dykes (in addition to the local occurrence of highly deformed unclassified mafic dykes of Archean age). The determination of age relationships is further hampered by the widespread occurrence of composite dykes, resulting from multiple injections of magma into the same fracture system (Easton, 2009). Finally, Easton (2010) noted that south of approximately 46°42′N, the Matachewan swarm diabase dykes lose their magnetic character, making their identification based on aeromagnetic response problematic.

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

2.2.9.1 Matachewan dykes

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

2.2.9.2 Nipissing intrusions

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

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

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

2.2.9.3 Biscotasing dykes

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

2.2.9.4 Sudbury dykes

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

2.2.9.5 North Channel dykes

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

2.2.9.6 Younger dykes

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

2.2.10 Faults

Mapped structures in the area of the four communities include large-scale folds, several mafic dyke swarms of different age and orientation, and a mosaic of brittle faults (Figures 2 and 3). Their complex present day geometrical arrangement is attributed to the protracted history of tectonic events that has overprinted the area, as described in Section 2.3. At the broader regional scale, additional prominent structures include the Sudbury Igneous Complex, the Kapuskasing structural zone and the Grenville Front tectonic zone (Figure 2). The following paragraphs provide additional details on these structural features.

During the Penokean Orogeny and earlier deformational periods, both the Archean basement and Huronian Supergroup were affected by different degrees of folding, deformation and faulting. The synformal structure of the Whiskey Lake greenstone belt and its belt-parallel foliation is evidence of early structural overprinting related to the Archean amalgamation of the Superior Province. The development of the Quirke Lake syncline, Chiblow anticline and Flack Lake syncline (Figure 3) occurred between approximately 2.219 and 1.8 billion years ago in response to northward compression that included tectonic events attributed to the Penokean Orogeny (e.g., Zolnai et al., 1984; Easton, 2013). The regional scale folding is also evident in the map pattern of the gneissic tonalite suite of the Ramsey-Algoma granitoid complex wrapping around a massive granodioritic to granitic core (e.g., Figure 3).

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

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

The regional scale arcuate east-trending Flack Lake fault (Figure 3) extends for about 150 km and transects both the Huronian Supergroup rocks and the Ramsey-Algoma granitoid complex. The Flack Lake fault is interpreted as a north-directed listric thrust that reactivated an earlier normal fault. Its movement history may be related to post-Nipissing and Penokean events (Bennett et al., 1991).

The Murray fault (referred to by some in the literature as the Murray fault zone) is a major east-trending structure that can be traced a few hundred kilometres from Sault Ste. Marie to Sudbury (Robertson, 1967). Within the area of the four communities, the Murray fault parallels the shoreline of Lake Huron (Figure 3) where it is a steeply south-dipping fault zone with approximately 15 to 20 km of reverse sense offset (Zolnai et al., 1984). It records both dextral (Bennett et al., 1991), and sinistral (Abraham, 1953) movement. The Murray fault appears to have been initiated prior to deposition of the Huronian Supergroup, but periodic reactivation occurred synchronous with and after sediment deposition (Reid, 2003; Dyer, 2010). As discussed in Section 2.3, the most recent movement of the Murray fault was during the Grenville Orogeny (Robertson, 1970; Card, 1978; McCrank et al., 1989; Piercy, 2006). North of the fault, the Huronian Supergroup deposits are largely fluvial and accumulated to depths of about 5 km, while south of the fault the deposits are dominated by turbidites that accumulated to depths of 15 to 20 km as reflected by their higher metamorphic grade (Bennett et al., 1991). North of the Murray fault, the Huronian Supergroup is considered largely unmetamorphosed, ranging from sub-greenschist to lower greenschist (Bennett et al., 1991). South of the Murray fault, metamorphism increases to middle greenschist and upward to amphibolite facies (Bennett et al., 1991; Jackson, 2001).

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

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

2.2.11 METAMORPHISM

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

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

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

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

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

2.3 GEOLOGICAL AND STRUCTURAL HISTORY

The geological and structural history of the area of the four communities spans almost 3 billion years and includes both Archean and Proterozoic orogenic events, periods of intense felsic and mafic intrusive activity, and complex brittle deformation. The geological history is moderately well understood in the south where the Huronian Supergroup is exposed, but is less well constrained for the underlying Archean Ramsey-Algoma granitoid complex further to the north and east. The geologic and structural history is discussed below and summarized in Table 1. The discussion integrates the results from studies undertaken mainly within and proximal to the Huronian Supergroup, augmented by studies within the Swayze area (van Breemen et al., 2006), approximately 120 km north of Elliot Lake, to present an integrated geological and structural history for the area of the four communities.

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

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

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

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

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

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

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

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

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

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

Table 1 Summary of the geological and structural history of the area of the four communities.

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

Approximate Time Period (billion years ago)	**Geological Event**
	(continuation of D_6). Post-0.54 billion years ago: sedimentation, erosion, ingression and regression of sea water, shallow sea, glaciations. Exhumation of peneplain.

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

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

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

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

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

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

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

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

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

2.4 QUATERNARY GEOLOGY

Information on Quaternary geology in the area of the four communities is described in detail in the terrain report (JDMA, 2014) and is summarized here. The Quaternary geology of the area of the four communities is dominated at surface by different types of glacial deposits that accumulated with the progressive retreat of the ice sheet during the end of the Wisconsinan glaciation. This period of glaciation began approximately 115,000 years ago and peaked about 21,000 years ago, at which time the glacial ice front extended south of Ontario into what is now Ohio and Indiana (Barnett, 1992).

The area of the four communities is dominated by exposed bedrock or bedrock having only a thin mantle of unconsolidated sediments. Quaternary deposits are predominantly located in bedrock-controlled valleys. Figure 4 illustrates the extent and type of Quaternary deposits in the area of the four communities. Overburden deposits within this area were also mapped as part of the Northern Ontario Engineering Terrain Study (NOEGTS), a program undertaken between 1977 and 1981 (Gartner, 1978a,b,c; 1980 a,b; Roed and Hallet, 1979a,b,c,d; 1980a,b; VanDine, 1979a,b,c,d; 1980a,b,c,d; Gartner et al., 1981). These studies divided the landscape into a set of distinct terrain units within which the engineering characteristics are broadly predictable. Major landforms mapped by the NOEGTS program are shown on Figure 4.

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

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

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

The northward retreat of the ice sheet in the area of the four communities started approximately 12,000 years ago between the Onaway Advance (11,800 years ago) and the Marquette Advance (10,000 years ago). Ice retreat took place as Lake Algonquin spread northward, leaving a series of shorelines during isostatic uplift and opening of the sequence of outlets near North Bay, Ontario. The high water level associated with Lake Algonquin has been mapped between 309 and 312 m above present day sea level (Cowan, 1976; 1985). Lower strand sequences are interpreted as recessional strands representing falling Lake Algonquin water levels as the retreating Laurentide ice sheet exposed a series of outlets south of North Bay. These recessional beaches are believed to have formed between about 10,400 and 10,000 years ago, and some strands may actually represent single storm events (Cowan and Bennett, 1998). After the opening of a very low-level outlet at North Bay after 10,000 years ago, water levels in the Huron-Michigan basin dropped to more than 100 m below present levels, creating two smaller water bodies: Lake Stanley in the main Huron basin and Lake Hough in Georgian Bay (Eschman and Karrow, 1985).

Over time, isostatic uplift continued to raise the North Bay outlet, and by about 7,500 years ago, the Huron-Michigan and Superior basins became confluent again. The St. Marys River thus became the St. Marys Strait connecting the three upper Great Lakes. Ongoing uplift closed the North Bay outlet around 5,500 years ago, restoring high-level outlets at Chicago and Port Huron and initiating the Nipissing phase in the upper Great Lakes. The Nipissing transgression is marked by buried wood and peat 7,300 to 5,900 years old and by the development of a prominent shoreline above the present lake level.

Information on the thickness of Quaternary deposits in the area of the four communities was largely derived from a small number of water well records for rural residential properties, a small number of water well records along the highways, and from diamond drill holes. A more detailed accounting of recorded depths to bedrock in the area of the four communities is provided by JDMA (2014). Diamond drill hole records and water well records in the area show overburden thickness to be between 0 and 137 m.

2.5 LAND USE

The main land use within the area of the four communities is forestry. Other land use activities include agriculture, commercial fishing, trapping and recreation. There are a number of linear infrastructure corridors present within the area, including roads, railways, pipelines and electrical transmission lines. These features do not negatively impact the interpretation of bedrock lineaments. There are numerous active gravel pits in the area, as well as an active building stone quarry. There are currently no active mines in the area of the four communities.

3 METHODOLOGY

3.1 SOURCE DATA DESCRIPTIONS

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

CDED (Figure 5) and SPOT (Figure 6) datasets were used to identify surficial lineaments expressed in the topography, drainage, and vegetation. The resolution of the CDED and SPOT datasets was consistent across the area of the four communities and provided sufficient detail to allow for the identification of surficial lineaments as short as a few hundred metres in length. The higher resolution of the SPOT imagery allowed for finer structures to be identified that were not resolved by the CDED data; but, the CDED data often revealed subtle trends masked by the surficial cover captured in the SPOT imagery. The geophysical dataset included low resolution coverage across the entire the area of the four communities as well as smaller regions of increased resolution within the area (Figure 7). In all cases, the best resolution data available was used for the lineament interpretation. The aeromagnetic data proved useful to interpret bedrock structure beneath areas of extensive surficial cover. Table 2 provides a summary of the source datasets used for the lineament interpretation.

3.1.1 SURFICIAL DATA

CDED (Canadian Digital Elevation Data)

Canadian Digital Elevation Data, 1:50,000 scale, 0.75 arc second (20 m) elevation models (GeoBase, 2011a) served as important data sources for analyzing and interpreting the terrain in the area of the four communities. The digital elevation model (DEM) used for this study, shown as a slope raster in Figure 5, was constructed by Natural Resources Canada (NRCan) using data assembled through the Water Resources Information Program (WRIP) of the Ontario Ministry of Natural Resources (MNR). The source data were 1:20,000 scale topographic map data generated through the Ontario Base Mapping (OBM) program, which was a major photogrammetric program conducted across Ontario between about 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. It was determined that the resolution of the CDED dataset was sufficient to undertake the lineament interpretation.

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 (Figure 5; JDMA, 2014). Table 3 lists the tiles used in the final mosaic.

Hillshaded representations of the CDED elevation data were built using illuminated azimuths of 045º and 315º and solar incidence angles of 45º from the horizon. 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. Figure 5 shows the calculated slope from the CDED elevation data for the area of the four communities. The hillshade and slope rasters were most useful for mapping lineaments.

SPOT (Système Pour l'Observation de la Terre) Imagery

SPOT multispectral (20 m resolution) and panchromatic (10 m resolution) orthoimagery (the latter is shown on Figure 6), were used for identifying surficial lineaments and exposed bedrock within the area of the four communities (GeoBase, 2011b). SPOT multispectral data consist of several bands, each recording reflected radiation within a particular spectral range, and each having a radiometry of 8-bits (or a value ranging from 0 to 255). Fourteen SPOT images (or 'scenes') provided complete coverage for the area of the four communities (Table 4). The scenes are from the SPOT 4 and 5 satellites, with acquisition dates from 2006 and 2007. Ten of the images were captured during the summer (July or August), two in the spring (May) and two in the fall (September). SPOT 5 images were acquired using the High Resolution Geometric (HRG) sensor. Each image covers a ground area of 60 km by 60 km.

Table 2 Summary of source information for the lineament interpretation.

Dataset	Product	Source	Resolution	Coverage	Acquired	Additional Comments
CDED	Canadian Digital Elevation Data (CDED); 1:50,000	Geobase	20 m	Entire area	1978 - 1995	Hillshade and slope rasters used for mapping
Satellite Imagery	Spot 4/5; Orthoimage, multispectral/ panchromatic	Geobase	10 m (panchromatic) 20 m (multispectral)	Entire area	2006, 2007	Panchromatic mosaic used for mapping
Geophysics	East Bull Lake (RA-7) Fixed wing vertical gradiometer magnetic, VLF	GSC	300m/ 150m 0°	East central over the East Bull Lake and nearby intrusions	1981	Higher resolution over intrusions
	Ontario #4 Fixed wing magnetic	GSC	402m/ 305m 0°	West central	1956	Moderate resolution dataset
	Ontario #13 Fixed wing magnetic	GSC	805m/ 305m 0°	Northeast	1960	Lowest resolution dataset
	Ontario #16 Fixed wing magnetic	GSC	805m/ 305m 0°	East	1959	Lowest resolution dataset
	Ontario #17 Fixed wing magnetic	GSC	805m /305m 0°	Most of area of the four communities	1963	Lowest resolution dataset
	GDS1017 Benny Helicopter magnetic, FDEM, VLF	OGS	200m /30m 0°	East central over Benny greenstone belt	1990	4-frequency Aerodat system, radar navigation, higher resolution over Benny greenstone belt
	GDS1236 Elliot Lake-River aux Sables Helicopter magnetic, TDEM	OGS	100m E, 50m W 67m mag 47m TDEM 0°	South central over Whiskey Lake greenstone belt	2008	VTEM system, higher resolution over Whiskey Lake greenstone belt
	AFRI: 20000850 Fixed wing horizontal gradiometer magnetic, radiometric, VLF	North American Gem	100m/ 70m 0°	Northwest	2008	
	AFRI: 20003244	Canada Enerco	200m/ 73m	North of Elliott Lake	2007	MEGATEM system

Dataset	Product	Source	Resolution	Coverage	Acquired	Additional Comments
	Fixed wing magnetic, TDEM		55°			
	AFRI: 20004445 Fixed wing horizontal gradiometer magnetic, radiometric, VLF	Delta Uranium	100m/ 70m 0°	North central	2006	
	AFRI: 200005757-1 to -3 Helicopter magnetic, TDEM	Carina Energy	100m/ 47m 0°	West central over the Huronian Supergroup	2007	AeroTEM II system
Geophysics	AFRI: 20005762 Helicopter magnetic, radiometric	Carina Energy	150m/ 30m 0°	West central over the Huronian Supergroup	2007	
	AFRI: 20006243 Fixed wing horizontal gradiometer magnetic, radiometric, VLF	North American Gem	100m/ 70m 0°	Northwest	2008	
	AFRI: 20006734 Helicopter magnetic, radiometric, VLF	Hawk Uranium	100m/ 30m 0°	North central	2007	
	AFRI: 41I12SW2002 Helicopter vertical gradiometer magnetic, FDEM	Mustang Minerals	100m/ 45m 0°	Southeast over the East Bull Lake and nearby intrusions	2000	Dighem V system

Table 3 List of 1:50,000 scale CDED tiles used for the lineament interpretation.

NTS Tiles:	Ground resolution (m)
41H/13	20
41G/13-16	20
41I/04-05,12-13	20
41J/01-16	20
41O/01-04	20
41P/04	20

Table 4 List of SPOT 4 and 5 multispectral images acquired.

Scene ID	Satellite	Date of image
S4_08223_4702_20070917	SPOT 4	September 17, 2007
S4_08109_4634_20070923	SPOT 4	September 23, 2007
S5_08119_4605_20070515	SPOT 5	May 15, 2007
S5_08141_4702_20070520	SPOT 5	May 20, 2007
S5_08152_4634_20070816	SPOT 5	August 16, 2007
S5_08203_4605_20070816	SPOT 5	August 16, 2007
S5_08234_4634_20070805	SPOT 5	August 05, 2007
S5_08246_4605_20070805	SPOT 5	August 05, 2007
S5_08306_4702_20060811	SPOT 5	August 11, 2006
S5_08318_4634_20060811	SPOT 5	August 11, 2006
S5_08331_4605_20060811	SPOT 5	August 11, 2006
S5_08347_4702_20070721	SPOT 5	July 21, 2007
S5_08402_4634_20060811	SPOT 5	August 11, 2006
S5_08414_4605_20060811	SPOT 5	August 11, 2006

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 UTM projection referenced to the North American Datum 1983 (NAD83). A comparison of lake shorelines in the SPOT imagery with those delineated in the MNR waterbody file suggests that the georeference is generally accurate to within 20 to 40 m or better. It was determined that the resolution of the SPOT dataset was sufficient to undertake the lineament interpretation. The scenes were processed to create a single panchromatic mosaic (Figure 6; JDMA, 2014). An automated contrast matching technique was applied to the images which minimizes sharp variances in pixel intensity, giving the single image a cohesive appearance. The images were extended beyond the defined boundaries of the area of the four communities to allow for the mapping of continuous lineaments extending beyond the area of the four communities.

3.1.2 GEOPHYSICAL DATA

The geophysical dataset incorporates aeromagnetic, gravity and radiometric data available across the entire area of the four communities. The coarse resolution of the gravity and radiometric data were determined to be insufficient to interpret lineaments and so only aeromagnetic data was used for this lineament interpretation. Table 2 provides a summary of the resolution and acquisition parameters for each aeromagnetic dataset used. The magnetic data located within the area of the four communities were processed using several common geophysical techniques in order to enhance the magnetic response to assist with the interpretation of geophysical lineaments. The enhanced magnetic grids used in the lineament interpretation include the total magnetic field reduced to pole, its first and second vertical derivatives, and its tilt angle. These enhanced grids were processed and imaged using the Geosoft Oasis montaj software package. Acquisition parameters, processing methods and enhanced grids associated with the geophysical datasets used in the lineament interpretation are discussed in detail in PGW (2014). Three additional magnetic grids using a combination of gradient and amplitude equalization filters were prepared using the Encom (Pitney Bowes) Profile Analyst software package in order to highlight the edges of magnetic sources. The combination of all of the enhanced magnetic grids provide much improved resolution of subtle magnetic fabrics and boundaries in areas that appear featureless in the total magnetic field.

Figure 7 shows a compilation of the total field (reduced to pole) of the merged magnetic datasets in the area of the four communities. The quality of geophysical data varied significantly across the area of the four communities, as a function of the flight line spacing, the flying height and the age of the survey. The integrity of the higher quality data was maintained throughout and the poorest resolution data was only used where higher resolution data was unavailable. It was determined that overall the quality of the data was sufficient to perform the lineament interpretation at the scale of the area of the four communities.

The majority of the area of the four communities is covered by low-resolution aeromagnetic data published by the Geological Survey of Canada (GSC) and downloaded from their Geoscience Data Repository for Geophysical and Geochemical Data. This data was acquired at a flight line spacing of 805 m (402 m for one survey in the west central part of the area of the four communities) and a sensor height at 305 m.

Three higher resolution magnetic/electromagnetic surveys, one published by the GSC and two published by the Ontario Geological Survey (OGS), were available for use in the lineament interpretation (Table 2). These include the East Bull Lake (RA-7) survey that covers the East Bull Lake and Parisien Lake intrusions in the east central part of the area of the four communities with a flight line spacing of 300 m and a sensor height of 150 m, the Benny Lake greenstone belt survey that covers the Benny Lake greenstone belt across the eastern boundary of the area of the four communities with a flight line spacing of 100 m or 50 m and a sensor height of 30 m, and the Elliot Lake-River aux Sables survey that covers the Whiskey Lake greenstone belt in the south central part of the area of the four communities with a flight line spacing of 200 m and sensor height of 67 m (Figure 7).

Eight additional datasets were retrieved as maps extracted from assessment file reports downloaded from the Ontario Geological Survey's AFRI repository accesses through its Geology Ontario web portal (Table 2). The surveys acquired in 2000 and from 2006 to 2008 were undertaken for various mining companies, mainly involved in exploration for uranium or nickel-PGE. The surveys were chosen based on the quality of magnetic images available in the reports and their locations within the area of the four communities (Figure 7). The images retrieved from the assessment files are presented in the geophysical study by PGW (2014). The eight surveys were acquired with a flight line spacing range of 100 to 200 m and a sensor height range of 30 to 63 m.

The reader should be aware that the higher resolution surveys incorporated in the magnetic images, as well as those extracted from the assessment files, provide greatly improved definition of the magnetic lineaments, especially dykes, compared to the remainder of the area of the four communities where only the lower resolution GSC surveys, dating from the 1956-1963 period, are available. This locally biases the lineament density calculations and presentations but does provide a truer sense of the lineaments present in parts of the area of the four communities.

3.2 LINEAMENT INTERPRETATION WORKFLOW

Lineaments were interpreted using a workflow designed to address issues of subjectivity and reproducibility that are inherent to any lineament interpretation. The workflow follows a set of detailed guidelines using publicly available surficial (CDED, SPOT) and geophysical (aeromagnetic) datasets as described above. The interpretation guidelines involved three steps:

1. Identification of lineaments by two interpreters for each dataset (CDED, SPOT, MAG) and assignment of certainty level (1, 2 or 3);

2. Integration of lineament interpretations by dataset (Figures 8, 9, 10) and first determination of reproducibility (RA_1); and
3. Integration of lineament interpretations for all three datasets (Figures 12 and 13) and second determination of reproducibility (RA_2).

Ductile geophysical lineaments, including all interpreted features, which conform to the penetrative rock fabric in the area of the four communities, such as foliation traces and litho-structural contacts, were picked using the aeromagnetic geophysical survey data by an automated picking routine with confirmation by a single documented specialist observer (Figure 11).

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

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

3.2.1 Step 1: Lineament identification and certainty level

The first step of the lineament interpretation was to have each individual interpreter independently produce GIS lineament maps, and detailed attribute tables, for each of the three datasets. This action resulted in the production of two interpretations for each of the CDED, SPOT, and aeromagnetic datasets and a total of six individual GIS layer-based interpretations. Each interpreter assigned a certainty/uncertainty descriptor (attribute field ‘Certain’ = 1-low, 2-medium or 3-high) to each feature in their interpretation based on their judgment concerning the clarity of the lineament within the dataset. Where a surface lineament could be clearly seen on exposed bedrock, it was assigned a certainty value of 3. Where a lineament represented a bedrock feature that was inferred from linear features, such as orientation of lakes or streams or linear trends in texture, it was assigned a certainty value of either 1 or 2. For geophysical lineaments, a certainty value of 3 was assigned when a clear magnetic susceptibility contrast could be discerned and a certainty value of either 1 or 2 was assigned when the signal was discontinuous or more diffuse in nature. The certainty classification for all three datasets ultimately came down to expert judgment and experience of the interpreter.

Table 5 Summary of attribute table fields populated for the lineament interpretation.

	Attribute	Brief Description
1	Rev_ID	Reviewer initials
2	Feat_ID	Feature identifier
3	Data_typ	Dataset used (CDED, SPOT, Geophys)
4	Feat_typ	Type of feature used to identify each lineament (i.e., dyke, fault, etc if known)
5	Name	Name of feature (if known)
6	Certain	Certainty value (1-low, 2-medium or 3-high)
7	Length*	Length of feature is the sum of individual lengths of mapped polylines (not end to end) and is expressed in kilometres
8	Width**	Width of feature; This assessment is categorized into 5 bin classes: A. < 100 m B. 100 – 250 m C. 250 – 500 m D. 500 – 1,000 m E. > 1,000 m
9	Azimuth	Vector average direction of all line segments forming the lineament (1 – 180°)
10	Buffer_RA_1	Buffer zone width for first reproducibility assessment
11	RA_1	Feature value (1 or 2) based on first reproducibility assessment
12	Buffer_RA_2	Buffer zone width for second reproducibility assessment
13	RA_2	Feature value (1, 2 or 3) based on second reproducibility assessment (i.e., coincidence)
14	Geophys	Feature identified in geophysical dataset (Yes or No)
15	CDED	Feature identified in CDED dataset (Yes or No)
16	SPOT	Feature identified in SPOT dataset (Yes or No)
17	F_Width	Final interpretation of the width of feature
18	Rel_age	Relative age of feature, in accord with regional structural history
19	Notes	Comment field for additional relevant information on a feature

* The length of each interpreted feature is calculated based on the sum of all segment lengths that make up that lineament.

**The width of each interpreted feature is determined by expert judgement and utilization of a GIS-based measurement tool. Width determination takes into account the nature of the feature as assigned in the Feature type (Feat_typ) attribute.

The geophysical dataset also allowed the interpreter to assess the feature type of the lineament. Dyke lineaments were characterized as linear traces in which the magnetic signal of the feature were higher than the surrounding bedrock, whereas the brittle geophysical lineaments were interpreted as linear features with magnetic signals lower than the surrounding bedrock. The ductile lineaments were traced as curvi-linear features using the geophysical data representing the internal fabric of the rock units. These lineaments were initially identified using an automated picking routine, and the accuracy was confirmed by a single documented specialist observer.

It is understood that some of the lineament attributes (e.g., width and relative age) will be further refined as more detailed information becomes available in subsequent stages of characterization should the community be selected by the NWMO and remain interested in advancing in the site selection process.

3.2.2 Step 2: Reproducibility assessment 1 (RA_1)

The two individual GIS lineament maps from each dataset were then integrated to provide a single interpretation for the CDED (Figure 8), SPOT (Figure 9) and aeromagnetic (Figure 10) data that included the results of the first stage reproducibility assessment (RA_1). Reproducibility is judged based on the coincidence, or lack thereof, of interpreted lineaments within an assigned buffer zone. For example, if a lineament was identified by both interpreters within an overlapping buffer zone, then it was deemed coincident and assigned a reproducibility value of two (RA_1 = 2). An initial buffer zone width (Buffer_RA_1) of 200 m was selected to evaluate coincidence. For many of the lineaments, coincidence could be demonstrated with a smaller buffer width, and in these cases a buffer width of either 100 m or 50 m, depending on the maximum offset, was entered in the attribute field. Where a lineament was identified by only one of the interpreters, it received a buffer zone width of zero (Buffer_RA1 = 0) and a reproducibility value of one (RA_1 = 1) in the attribute table.

Where coincident interpreted lineaments were identified, the one line that appeared to best represent the surficial or geophysical expression of the feature (based on the judgment of the integrator) was retained and assigned attributes. In some instances, where deemed appropriate, either an existing line was edited or a new line was drawn as part of the merging process to best capture the expression of the lineament. The decision of whether to retain or edit an existing line, or to draw a new line, was based largely on expert judgment that followed these guidelines: 1) where one continuous lineament was drawn by one interpreter, but as individual, spaced or disconnected segments by the other, a single continuous lineament was carried forward with a reproducibility value of two (RA_1 = 2) provided that the continuous lineament was deemed a better representation of the feature; and 2) where two interpreted lineaments were coincident over less than three-quarters of the total length of the longest lineament, the longest lineament was segmented and each portion was attributed with RA_1 values accordingly. The segments are carried forward into the final mapped interpretation as individual lineaments. Otherwise, if the two lineaments were coincident for more than three-quarters of the length of the longer lineament, they were considered coincident and assigned a reproducibility value of two (RA_1 = 2).

3.2.3 STEP 3: REPRODUCIBILITY ASSESSMENT 2 (RA_2)

In step 3, the three dataset-specific interpretations were integrated into a single map following a similar reproducibility assessment (RA_2) procedure. In this second assessment, reproducibility was based on the coincidence, or lack thereof, of interpreted lineaments between different individual datasets within an assigned buffer zone (Buffer_RA_2). Coincident lineaments were assigned a Buffer_RA_2 value of 200 m, 100 m, or 50 m, depending on the maximum distance between individual lineaments. Where coincident lineaments were identified, one of the existing lines was selected or edited to represent that feature; and, where appropriate, a new line was drawn that best captured the merger of individual lineaments, in a process similar to the integration of RA_1 lineaments. The merged lineaments were then assigned a reproducibility value (RA_2) of two or three, depending on whether the feature was identified in any two or all three of the assessed datasets. Whether two or more lineaments exhibited full or partial RA_2 coincidence was determined by the interpreter using a similar process as described for RA_1 in Section 3.2.2. That is, for full coincidence of two or more lineaments, a single integrated feature, attributed accordingly, is carried forward into the final mapped interpretation. Otherwise, a lineament is segmented and attributed according to the partial coincidence of overlapping lineaments, and the partial segments are carried forward into the final mapped interpretation as individual lineaments. Where two segments share a common end node, the combined length is used to for the length values to capture the total length of the feature. If a lineament was identified in only one dataset, and thus not a coincident lineament, it received a reproducibility value of one (RA_2 = 1) in the attribute table. The dataset within which each feature has been identified is indicated in the appropriate attribute table field (Geophys, CDED, SPOT).

4 FINDINGS

4.1 DESCRIPTION OF LINEAMENTS BY DATASET

4.1.1 SURFICIAL DATASETS (CDED AND SPOT)

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

A total of 2,494 lineaments comprise the dataset of merged lineaments identified by the two interpreters from the CDED digital elevation data (Figure 8). These lineaments range in length from 803 m to 94.5 km, with a geometric mean length of 4.99 km and a median length of 4.35 km. The most notable feature of the CDED lineament orientations when plotted on a rose diagram weighted by length are the dominant west-northwest and north-northwest trends (Figure 8 inset). There is also a notable east-west trend. It is also evident that no dominant trend emerges among the lineaments oriented toward the northeast with a large spread of data across the entire northeast quadrant (Figure 8 insert). A total of 2,415 of the CDED lineaments (97%) were assigned a certainty value of 3. Certainty values of 2 and 1 were assigned to 76 (3%) and 3 (0.001%) of the CDED lineaments, respectively. The RA_1 reproducibility assessment shows coincidence between the two pickers for 740 of the CDED lineaments (30%, RA_1 = 2) and a lack of coincidence for 1,754 of the CDED lineaments (70%, RA_1 = 1).

The SPOT lineament dataset compiled from the merger of lineaments identified by the two interpreters yielded a total of 7,509 lineaments (Figure 9). The length of the SPOT lineaments ranges from 900 m to 139.8 km, with a geometric mean length of 2.2 km and a median length of 1.8 km. When the azimuths of the lineaments are plotted on a rose diagram weighted by length (Figure 9 inset), there appear to be dominant orientations of west-northwest, north-northwest and east to east-northeast amongst an otherwise broad spread of data. Among the lineaments oriented to the northwest, the orientations are largely diffuse with weak trends at 275º, 310º and 345º, matching the trends seen in the CDED data. Lineaments oriented to the east-northeast show a diffuse distribution, with the strongest trend at around 075º. Eighty three percent (83%) of the SPOT lineaments, a total of 6,262, were assigned a certainty value of 3. Certainty values of 2 and 1 were assigned to 1,245 (17%) and 2 (0.03%) of the SPOT lineaments, respectively. The reproducibility assessment shows coincidence for 2,168 (29%) of the SPOT lineaments (RA_1 = 2), and a lack of coincidence for 5,341 (71%) of the SPOT lineaments (RA_1 = 1). The number of lineaments identified by a single interpreter (RA_1 = 1) was comparable for each of the SPOT interpreters.

Orientation data for the SPOT and CDED lineaments exhibit similar broad distribution patterns and also exhibit comparable (weak) dominant orientations of west-northwest, north-northwest and east-northeast.

4.1.2 GEOPHYSICAL DATA

The airborne geophysical data interpretation was able to distinguish between features that could be interpreted as brittle, ductile or dyke lineaments (Figures 10 and 11). Aeromagnetic features interpreted to reflect ductile lineaments have been mapped separately and are shown on Figure 11. Such features are useful in identifying the stratigraphy and ductile structure within the greenstone belts. In this report, the ductile lineaments are shown to provide context to our understanding of the tectonic history of the area of the four communities, but were not included in the statistical analysis undertaken with the dataset. Therefore the following discussion relates only to those lineaments interpreted as brittle or dyke lineaments.

A total of 2,146 lineaments comprise the dataset of merged lineaments identified by the two interpreters from the geophysical data (Figure 10). Of these geophysical lineaments, 460 are interpreted as brittle lineaments, while 1,686 are interpreted as dykes (Figure 10). Among the geophysical features interpreted as brittle lineaments, most (390) were unclassified with respect to relative displacement, but a subset of both dextral (46) and sinistral (24) lineaments with fault offsets were interpreted. The length of the brittle lineaments ranged from approximately 200 m to 144.3 km, with a geometric mean length of 4.2 km and a median length of 4.3 km. Azimuth data, weighted by length, for the brittle lineaments exhibit several strong trends, particularly to the north-northeast and east. The orientation data also exhibit a notable difference between the northeast quadrant, where there are multiple strong trends, and the west-northwest, where there is a single strong trend at about 300º (Figure 10 inset). Sinistral faults show distinct orientations to the north, northwest, and northeast. Dextral faults exhibit similar orientations, but also include trends to the west-northwest and east-northeast.

Geophysical lineaments also include a total of 1,686 features interpreted as dykes, belonging to the Biscotasing, Matachewan, North Channel, and Sudbury dyke suites (Figure 10). The length of these dyke lineaments ranged from approximately 200 m to 48.7 km, with a geometric mean length of 2.9 km and a median length of 3.1 km. Sharp trends allow that each dyke suite can be distinguished by orientation. Biscotasing dykes (n = 266) are oriented strongly toward the east-northeast. These dykes are clustered mostly in the felsic gneiss. Matachewan dykes (n = 396) trend dominantly toward the north-northwest. The distribution of these dykes appears to cluster in the northwest and northeast quarters of the area of the four communities. North Channel dykes (n = 346) exhibit a strong east-west orientation and appear mostly in the area underlain by, and south of, the Huronian Supergroup. Sudbury dikes (n = 678) trend strongly to the northwest and are distributed throughout the entire area of the four communities (Figure 10).

The geophysical lineaments in the area of the four communities that are interpreted as dykes generally have a higher certainty (certainty values of 2 or 3) than those interpreted as brittle lineaments (certainty values of 1 for the lower resolution data or 2 for the higher resolution data). The accuracy of their location within the lower resolution data is on the order of ± 500 m whereas it is ± 100 m or less within the higher resolution data. The transition from lower to higher resolution data shows that a single lineament at low resolution may reflect two or three subparallel lineaments at higher resolution, especially amongst the dykes. The reproducibility assessment identified coincidence for 8 faults (1.7%) (RA_1 = 2) and a lack of coincidence for 452 of the interpreted faults (98%) (RA_1 = 1). Low resolution of the data over almost the entire area makes picking faults difficult as breaks and offsets are not clearly defined. The reproducibility assessment identified coincidence for 884 of the interpreted dykes (52%) (RA_1 = 2) and a lack of coincidence for 802 of the interpreted dykes (48%) (RA_1 = 1).

4.2 DESCRIPTION AND CLASSIFICATION OF INTEGRATED LINEAMENT COINCIDENCE (RA_2)

The integrated lineament dataset produced by determining the coincidence of all lineaments interpreted from the CDED data, SPOT imagery, and geophysical data is presented on Figures 12 and 13. Figure 12 displays the lineament classification based on the coincidence values determined by Reproducibility Assessment 2 (RA_2). Figure 13 displays the lineament classification based on length of interpreted lineaments. The merged lineaments were classified by length using four length bins: >10 km, 5-10 km, 1-5 km and <1 km. These length bins were defined based on an analysis of the lineament length frequency distributions for the area of the four communities.

The merged lineament dataset contains a total of 9,351 lineaments. The merged lineaments range in length from 109 m to 144.3 km. The geometric mean length of these lineaments is 2.5 km and the median length is 2.3 km. Lineaments in the >10 km and 5-10 km length bins represent 7% and 14% of the merged lineaments, respectively, while lineaments in the 1-5 km and <1 km length bins represent 71% and 8% of the merged lineaments, respectively.

Orientation data for the merged lineament dataset (inset of Figures 12 and 13) exhibit a fairly uniform distribution of trends with dominant orientations of west-northwest, north-northwest and east to east-northeast amongst an otherwise broad spread of data. There is a relative paucity of lineaments oriented north-south. It should be noted that the rose diagrams on Figures 12 and 13 are weighted by lineament length, and thus, these orientations are influenced by longer lineaments. In addition, the total dataset is very similar in distribution to the SPOT dataset, reflecting the influence of the large number of SPOT lineaments (n = 7,509).

Results from the reproducibility (coincidence) assessment 2 (RA_2) for this dataset show 257 lineaments (3%) were identified and coincident on all three datasets (RA_2 = 3), and 1,883 lineaments (20%) were coincident with a lineament from one other dataset (RA_2 = 2). A total of 7,211 lineaments (77%) lacked a coincident lineament from the other datasets (RA_2 = 1). There is greater coincidence between surficial lineaments (interpreted from digital elevation data and satellite imagery) than between the geophysical lineaments and either of the surficial datasets. Of the geophysical dataset, about 13% (59 out of 460) of the faults were coincident with a mapped surficial lineament, and 24% of the dykes were coincident with a mapped surficial lineament (406 out of 1,686).

4.3 DESCRIPTION OF LINEAMENTS BY MAJOR GEOLOGICAL UNIT

The bedrock geology of the area of the four communities, as described in Section 2.2, consists mostly of massive granite and gneissic tonalite, with relatively thin lenses of greenstone belts, and overlying supracrustal rocks (Figures 3 and 14). The following discussion provides a description of the lineaments interpreted in the units that are considered potentially suitable for a geological repository. The Ramsey-Algoma granitoid complex has been subdivided into northern and southern domains for the purpose of this description.

The northern part of the Ramsey-Algoma granitoid complex (Unit 15 on Figure 14) consists of massive granodiorite to diorite that covers approximately 1,350 km^2 in the northwest corner of the area of the four communities. Most of the area is exposed bedrock or thin drift over bedrock that offers well-expressed bedrock lineaments, resulting in relatively high lineament density. Surficial cover partially obscures bedrock structures along the northern boundary of the area of the four communities (OGS, 2005). Lineaments interpreted on the northern portion of the Ramsey-Algoma granitoid complex total 1,125 with orientations, weighted by length, trending strongly toward the northwest to north-northwest and north-northeast to northeast (rose diagram A on Figure 14). Matachewan and Sudbury dykes contribute to the northwest-trending lineaments, while Biscotasing dykes contribute to the northeast-trending lineaments. Few North Channel dykes (trending east-west) are interpreted to have intruded the area.

The Ramsey-Algoma granitoid complex (southern part) consists of massive granodiorite to granite from which a total of 3,163 lineaments were mapped. This part of the granitoid complex spans approximately 4,150 km^2 of the area of the four communities across a region that mostly exhibits exposed bedrock or thin drift over bedrock. Given these conditions, bedrock features are well-expressed and lineament density is relatively high. Azimuth data, weighted by length, for lineaments from the southern part of the Ramsey-Algoma granitoid complex exhibit a dominant northwesterly trend and a diffuse northeast to east trend (rose diagram B on Figure 14). While each of the four dyke suites identified in the area of the four communities are evident in the dataset for the southern portion of the Ramsey-Algoma granitoid complex, the Sudbury dykes are most pervasive and contribute to the strong northwest trend in the orientation data.

The area of the four communities features an extensive (2,950 km^2) gneissic tonalite suite (Unit 11 on Figure 14) that, at the surface, separates the Ramsey-Algoma granitoid complex from the Huronian Supergroup. A total of 2,781 lineaments were mapped from the gneissic tonalite and lineament density is relatively high. Bedrock structures are well-expressed because of extensive bedrock exposure and thin drift cover. Surficial cover is increased mostly along the northern boundary of the area of the four communities between White Owl Lake and Ramsey Lake, and in the area south of the Huronian Supergroup. Rose diagram C on Figure 14, weighted by length, for lineament azimuths from the gneissic tonalite shows a dominant trend to the west-northwest, a secondary east-trending peak, and a generally diffuse pattern in other orientations. Each of the four dyke suites identified in the area of the four communities intrude the gneissic tonalite, but the Matachewan and Sudbury dykes are the most pervasive swarms in this unit.

5 DISCUSSION

The following sections are provided to discuss the results of the lineament interpretation in terms of lineament density, reproducibility and coincidence, lineament length, the relationship between mapped faults and interpreted lineaments, and the relative age relationships of the interpreted lineaments.

5.1 LINEAMENT DENSITY

Lineament density, which refers to the length of lineaments per unit area, varies across the area of the four communities (Figures 12 and 13), primarily as a result of geophysical data resolution (Figure 10), and the extent and thickness of overburden cover (Figure 4). Lineament density was calculated using the line density method describe in ESRI ArcGIS software, which determines the length of lineament within a moving circular window (km/km^2). A radius of 1.25 km was used for the moving circular window, based on the repository footprint size and a 50 m cell size. In general, lineament density is quite high across the entire area of the four communities, ranging between 0 and 4 km/km^2.

An understanding of the distribution and thickness of overburden cover within the area of the four communities is essential for interpreting the results of the lineament interpretation, particularly for interpreting information on length and density of surficial lineaments. With limited surficial cover, bedrock topography dominates the landscape and bedrock lineaments such as fractures are well expressed. This understanding is consistent with the observation of a high density of surface lineaments is seen in the northwestern and eastern portions of the area of the four communities where there are extensive areas of bedrock that is either exposed or thinly covered by surficial material. In contrast, local areas of thick drift cover such as valleys and other topographic depressions obscure bedrock features resulting in low lineament density. This understanding is consistent with the observation that the lowest surface lineament densities are found in the southwestern portion of the area where there is a combination of larger lakes and thicker and more extensive drift deposits, particularly ground moraine (Figure 4). Surficial cover also blankets the bedrock along the northern margin of the area of the four communities (OGS, 2005).

The interpretation of geophysical lineaments, on the other hand, is less affected by surficial cover. The variability of the density of geophysical lineaments in the area of the four communities is influenced instead by the resolution of the available magnetic data (Figure 10), more than the presence or absence of overburden cover. Density of geophysical lineaments is also controlled to a large extent by the distribution of dykes across the area of the four communities. For example, a lower geophysical lineament density in the southeastern corner of the area coincides with an area where fewer Matachewan dykes were interpreted from the geophysical data, in contract to a high density of geophysical lineaments in the northwestern corner where numerous Matachewan dykes were interpreted.

An assessment of lineament density by geologic unit shows that lineament density appears highest in the massive granodiorite to granite intrusions and the gneissic tonalite (Figures 12 and 13).

5.2 Reproducibility and Coincidence

Reproducibility values assigned to the lineaments provide a measure of the significance of the bedrock structures expressed in the different datasets. The approach used to assign reproducibility values involved checking whether lineament interpretations from different interpreters (RA_1), and from different datasets (RA_2), were coincident within a specified buffer zone radius. Reproducibility and coincidence values are discussed in detail in Sections 4.1 and 4.2.

The findings from the reproducibility assessment RA_1 indicate that approximately 30% of surficial lineaments were identified by both interpreters (see Figures 8 and 9). Importantly, longer lineaments with higher certainty values were identified more often by both interpreters. The reproducibility assessment of the geophysical lineaments identified as faults shows that just 2% were identified by both interpreters (Figure 10), while the reproducibility assessment of the geophysical lineaments identified as dykes shows that 52% were identified by both interpreters. As with the surficial lineaments, longer geophysical lineaments with higher certainty values were also recognized more often by both interpreters (RA_1=2).

Coincidence between features identified in the various datasets was evaluated for the second Reproducibility Assessment (RA_2). As would be expected, the surficial lineaments interpreted from CDED and SPOT show the highest coincidence at 23%. This is in part explained by the fact that lineaments interpreted from the satellite imagery and the digital elevation data represent surficial expressions of the same bedrock feature. For example, a lineament drawn along a stream channel shown on the satellite imagery is expected to be coincident with a lineament that captures the trend of the associated topographic valley expressed in the digital elevation data. Of the geophysical lineaments, about 20% were coincident with interpreted surficial lineaments. This lower coincidence between surficial and geophysical lineaments is not unexpected, and may be the result of various factors, such as: surficial features may not extend to great depth; structural features may not possess a magnetic susceptibility contrast with the host rock; surface expressions of lineaments may be masked by the presence of overburden; and/or the geometry of the feature (e.g. dipping versus vertical). All these may be further constrained by the resolution of the datasets. Regardless of the degree of coincidence, prominent lineament orientations appeared across all datasets, indicating that each interpreter identified similar lineament trends (see insets on Figures 8, 9 and 10).

Where surficial cover is thicker and more extensive, it appears that the coincidence of interpreted lineaments tended to be lower than in areas of well-exposed bedrock. This observation applies not only to coincidence between surficial lineaments, but also between surficial and geophysical lineaments. For example, along the study area boundary in the southwestern corner of the area of the four communities, where there is more extensive surficial cover, fewer lineaments are coincident than in the area to the northwest where there is extensive bedrock exposure (see Section 4.2).

Variable coincidence between surface and geophysical lineaments also reflects differing source data resolutions. For instance, where there is high resolution aeromagnetic data available, numerous lineaments were identified that were not identified in the surficial datasets.

For these reasons it is necessary to objectively analyze the results of the RA_2 assessment with the understanding that RA_2 = 1 does not necessarily imply a low degree of confidence that the specified lineament represents a true geological feature (i.e. a fracture). The true nature of the interpreted features will need to be investigated further during subsequent stages of the site evaluation process, if the community is selected by the NWMO, and remains interested in continuing with the site selection process.

5.3 Lineament Length

There is no information available on the depth extent into the bedrock of the lineaments interpreted for the area of the four communities. In the absence of available information, the interpreted length can be used as a proxy for the depth extent of the identified structures. A preliminary assumption may be that the longer interpreted lineaments may extend to greater depths than the shorter interpreted lineaments.

As discussed in Section 4.2, longer interpreted lineaments generally have higher certainty and reproducibility values. Although the existence of interpreted lineaments would need to be confirmed through field observations, certainty and reproducibility values provide a preliminary indication that the longer features identified are related to bedrock structures.

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

5.4 FAULT AND LINEAMENT RELATIONSHIPS

The known mapped faults in the area of the four communities include the east-west trending Murray fault and the largely northeast trending Flack Lake fault, as well as northwest trending Spanish American, Pecors Lake, Folson Lake and Webwood faults. Several unnamed mapped faults, trending mostly west to northwest, transect the Huronian Supergroup. Another set of unnamed mapped faults, trending northwest to north, occur in the northeast corner of the area of the four communities. Based on the compilation of interpreted lineaments, there appears to be a close relationship with known mapped faults. All of the named mapped faults are represented by interpreted lineaments. Even most of the smaller unnamed mapped faults correspond closely to the interpreted lineaments. The geophysical lineaments interpreted as sinistral faults do not match with the mapped faults, but some of these correspond to surficial lineaments. Several dextral faults do show a close match with unnamed mapped faults over Chiblow Lake and Matinenda Lake (Figure 11). Nearly all of the mapped faults correspond to a brittle lineament interpreted from the geophysics, and those that do not, with rare exceptions, correspond to a surficial lineament.

5.5 RELATIVE AGE RELATIONSHIPS

The chronology structural history of the area of the four communities, outlined in Section 2.4, provides a framework that may aid in constraining the relative age relationships of the interpreted bedrock lineaments. In brief summary, six main regionally distinguishable deformation episodes

(D_1-D_6) are inferred to have overprinted the bedrock geological units of the area of the four communities. Kenoran orogenesis is associated with D_1-D_2 deformation. D_1 deformation produced folds and an east-trending foliation in the greenstone belts between ca. 2.72 and 2.70 billion years ago. No lineaments were assigned to this early deformational episode. Development of northeast, east-northeast, northwest and west-northwest striking faults, including the Murray and Flack Lake faults occurred between ca 2.651 and 2.497 billion years ago, during D_2. Lineaments associated with the Murray and Flack Lake faults are the oldest identified in the area of the four communities. Despite an interpreted early age of formation, the Flack Lake fault appears to offset a Sudbury dyke, suggesting reactivation more recently than 1.2 billion years ago.

Rifting during D_3 reactivated northwest, west-northwest, and east striking faults and induced emplacement of the Matachewan dykes ca 2.475 to 2.455 billion years ago. Deformation associated with the Blezardian Orogeny (D_4) initiated development of the east-west trending Quirke syncline and Chiblow anticline (Riller et al., 1999), followed by emplacement of ca. 2.1 to 2.2 billion years ago Nipissing diabase intrusions and the ca. 2.17 to 2.15 billion year old Biscotasing dyke swarm.

Penokean orogenesis corresponds to the D_5 deformational episode that includes enhancement and further development of folds and thrusts in the Huronian Supergroup and re-activation of basement faults. Many of the brittle surficial lineaments (i.e. those that do not correspond to dykes) may be attributed to this deformational episode, with the understanding that they may also represent re-activated pre-D_5 structures. Emplacement of the Sudbury dykes followed at ca. 1.238 billion years ago. Because the Sudbury dykes post-date D_5 deformation and pre-date D_6 deformation, the relative age of these lineaments was designated D_{5+}.

The most recent episode of deformation (D_6) includes the Grenville Orogeny, development of the Midcontinent rift, and the formation of a peneplain. The overprint of the Grenville Orogeny in the area of the four communities is unclear, but this episode may have reactivated existing structures produced during D_5. It is significant to note that the Cutler pluton, emplaced ca. 1.7 billion years ago, is cut by brittle fractures of various orientations, demonstrating that many of the surficial lineaments formed or were re-activated during D_6.

It is difficult at the desktop stage of the preliminary assessment of potential suitability to assign temporal relationships with any degree of confidence to the identified surficial lineaments, though it is reasonable to suggest that most brittle features were either formed or reactivated during the most recent episodes of deformation (D_5-D_6). These lineaments may have been subsequently reactivated by stresses associated with more recent orogenies, isostatic adjustment to erosion of a peneplain, and recent glaciations. In addition, the low resolution of the available geophysical data, although sufficient to recognize four differently oriented generations of dyke swarms, is insufficient as a means of indicating any systematic fracture cross-cutting relationships above and beyond what can be determined from the surficial data sets. Apparent offsets of some segment of the north-east-trending dykes may be due to the en echelon nature of their emplacement.

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6 SUMMARY

This report documents the source data, workflow and results from a lineament interpretation of publicly-available digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the area of the four communities in northern Ontario. The lineament analysis provides an interpretation of the location and orientation of possible individual fractures or fracture zones and helps to evaluate their relative timing relationships within the context of the regional geological setting. The three-step process involved a workflow that was designed to address the issues of subjectivity and reproducibility.

The distribution of lineaments in the area of the four communities reflects the bedrock structure, resolution of the datasets used, and surficial cover. Surface lineament density, as demonstrated in this study, is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures. Lineament density was observed to be highest in the north-central part of the area of the four communities where there is higher topography and where the thickness and extent of surficial cover is relatively low.

In terms of reproducibility, longer interpreted lineaments generally have higher certainty and reproducibility values. Comparison between the various datasets (RA_2), indicates that the highest level of coincidence is between surficial lineaments interpreted from CDED and SPOT. This is, in part, explained by the fact that lineaments interpreted from the satellite imagery and the digital elevation data represent surficial expressions of the same bedrock feature. The lower coincidence between surficial and geophysical lineaments may be the result of various factors: surficial features may not extend to great depth; structural features may not possess a magnetic susceptibility contrast with the host rock; surface expressions of lineaments may be masked by the presence of overburden; and the geometry of the feature (e.g. dipping versus vertical). These factors are further constrained by the differing resolution of the various datasets.

The orientations observed for the combined set of lineaments from all sources (except ductile geophysical lineaments) exhibit prominent trends to the east-northeast, to the west-northwest and oriented east-west. Although in general there is an otherwise broad distribution of orientations, there is a relative absence of north-trending lineaments.

At the desktop stage of the preliminary assessment of potential suitability, it is difficult to assign temporal relationships to the identified surficial lineaments. However, most brittle features likely formed, or were reactivated, during the most recent episodes of deformation (D_5-D_6). Geophysical data allowed for identification of several dyke swarms of known age that provide additional constraints on the relative age relationships of the mapped lineaments in the area of the four communities.

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REPORT SIGNATURE PAGE

J.D. Mollard and Associates (2010) Limited

Jason Cosford, Ph.D., P.Geo

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

FIGURES

LEGEND

- Urban municipality
- Municipal boundary
- Communities of Elliot Lake, Blind River, The North Shore and Spanish
- Main road
- Railway
- Utility line
- Waterbody
- Watercourse
- Forest Reserve
- Conservation Reserve
- Provincial Park
- First Nations

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

NORTH

5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE

The area of the four communities

DESIGN	DVZ	25 JUN 2012	FIGURE 1	REVISION 4
GIS	DSM	25 JUN 2014		UTM ZONE 17
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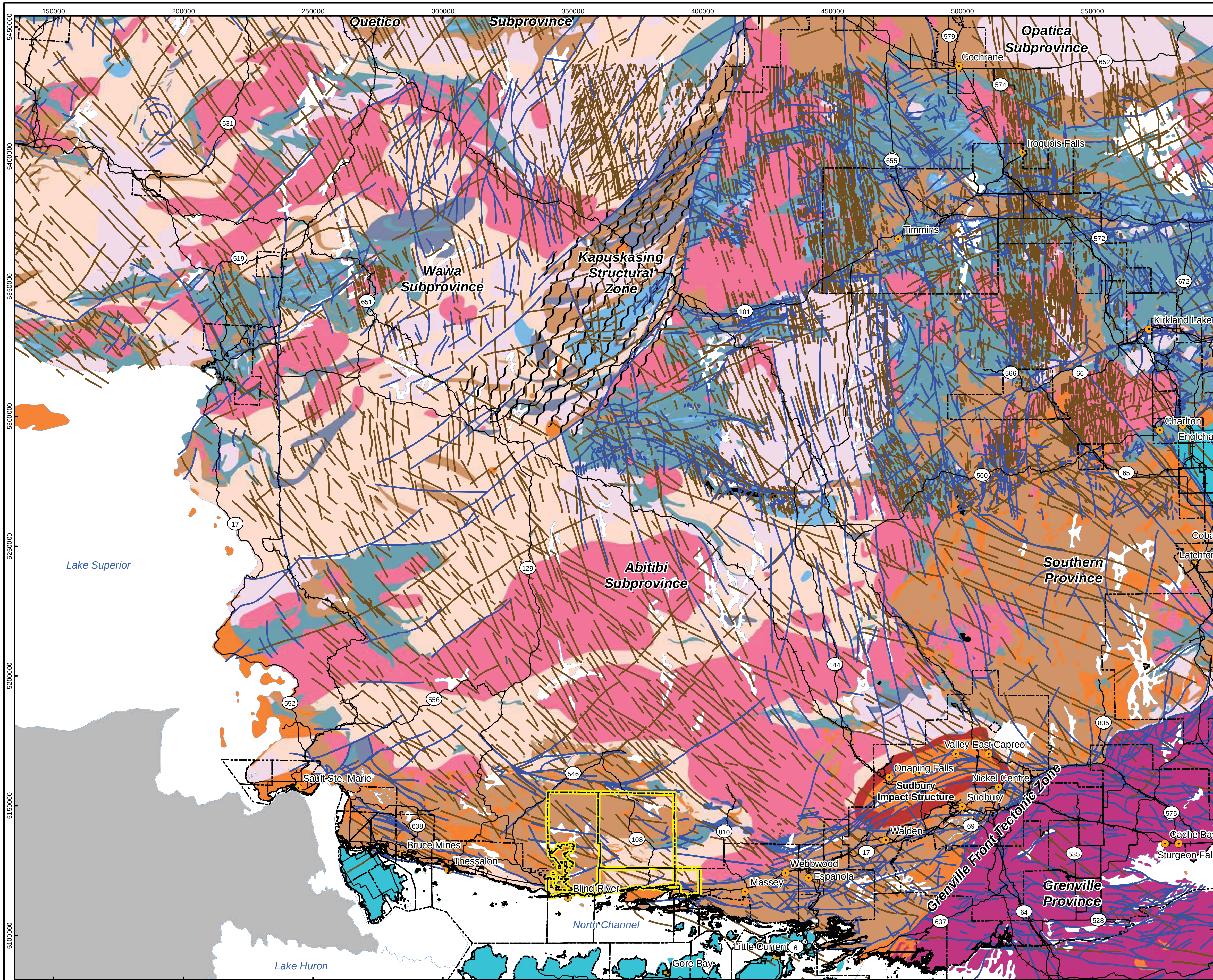
REVIEW	GS	25 JUN 2014		1:550,000



LEGEND

- Municipal boundary
- Communities of Elliot Lake, Blind River, The North Shore and Spanish
- Community
- Main Road
- Railway
- Mapped fault
- Mapped dyke
- Kapuskasing Structural Zone
- Iron formation
- Waterbody

Bedrock geology

Phanerozoic

- Various Paleozoic sedimentary rock units (56, 55, 54)

Protoerozoic

- Various units of the Grenville Province (51, 43, 42, 41, 40, 39)

Southern Province

- Various units of the Southern Province (38, 37, 36, 35, 34, 32, 31, 30, 28, 27, 23, 22)
- Sudbury Igneous Complex (29)
- Huronian Supergroup (21, 20, 19, 18)
- Mafic-ultramafic intrusive rocks and mafic dykes (17)

Archean

Superior Province (Abitibi Subprovince)

- Archean granitoid suites (16, 14, 13, 12)
- Massive granodiorite to granite (15)
- Gneissic tonalite suite (11)
- Mafic and ultramafic rocks (10)
- Metasedimentary (9, 7)
- Migmatized supracrustal rocks (8)
- Metavolcanic rocks (6, 5, 4, 2)

Data sources:
Bedrock: MRD126 Bedrock geology
Road: Selected from MNR road segment
Waterbody: LIO OHN Waterbody

NORTH

20 km

J D MOLLARD

PROJECT: PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE AND SPANISH, ONTARIO

TITLE: Regional tectonic setting of the area of the four communities

DESIGN	DVZ	25 JUN 2012	FIGURE 2	REVISION 4
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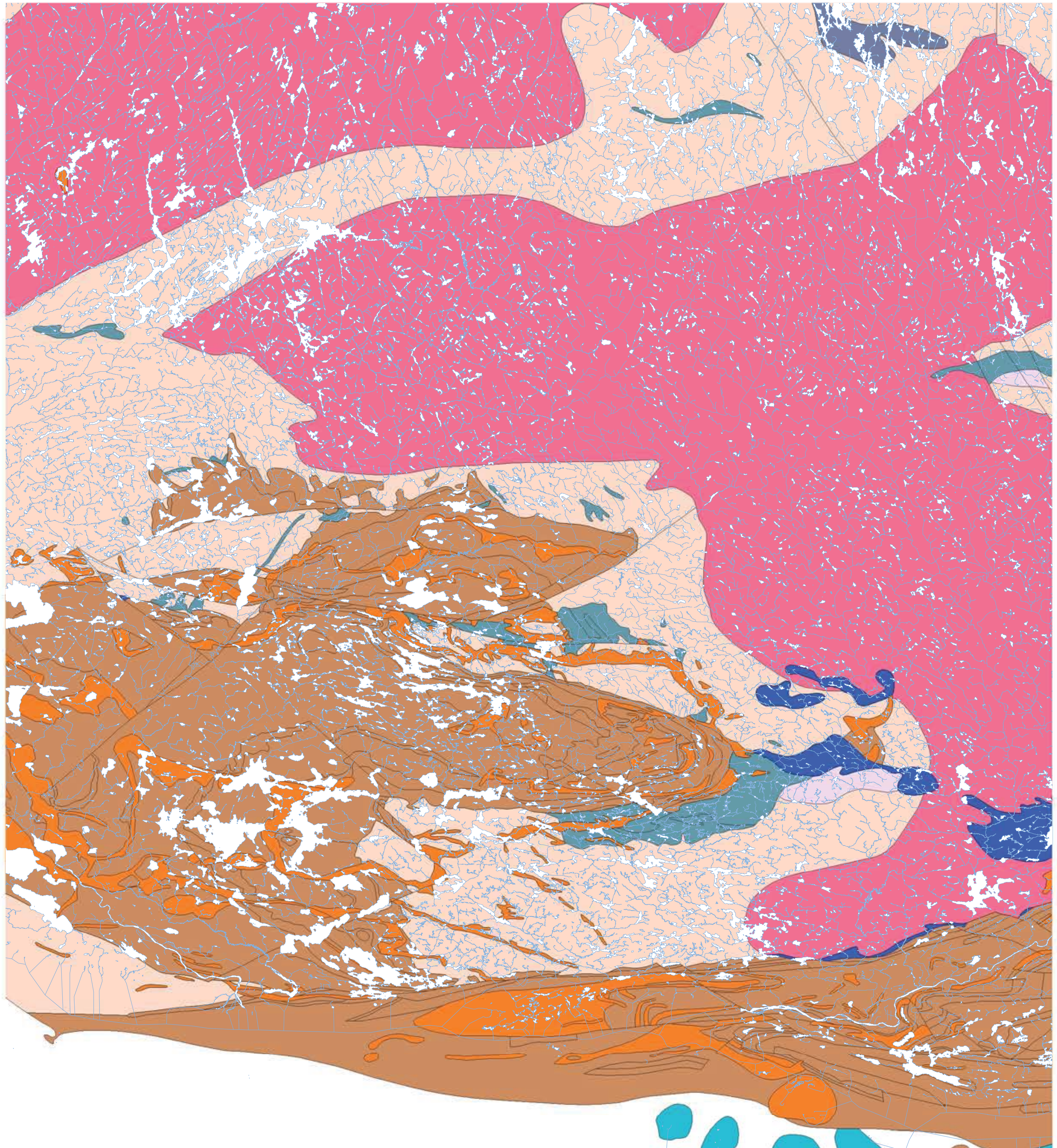

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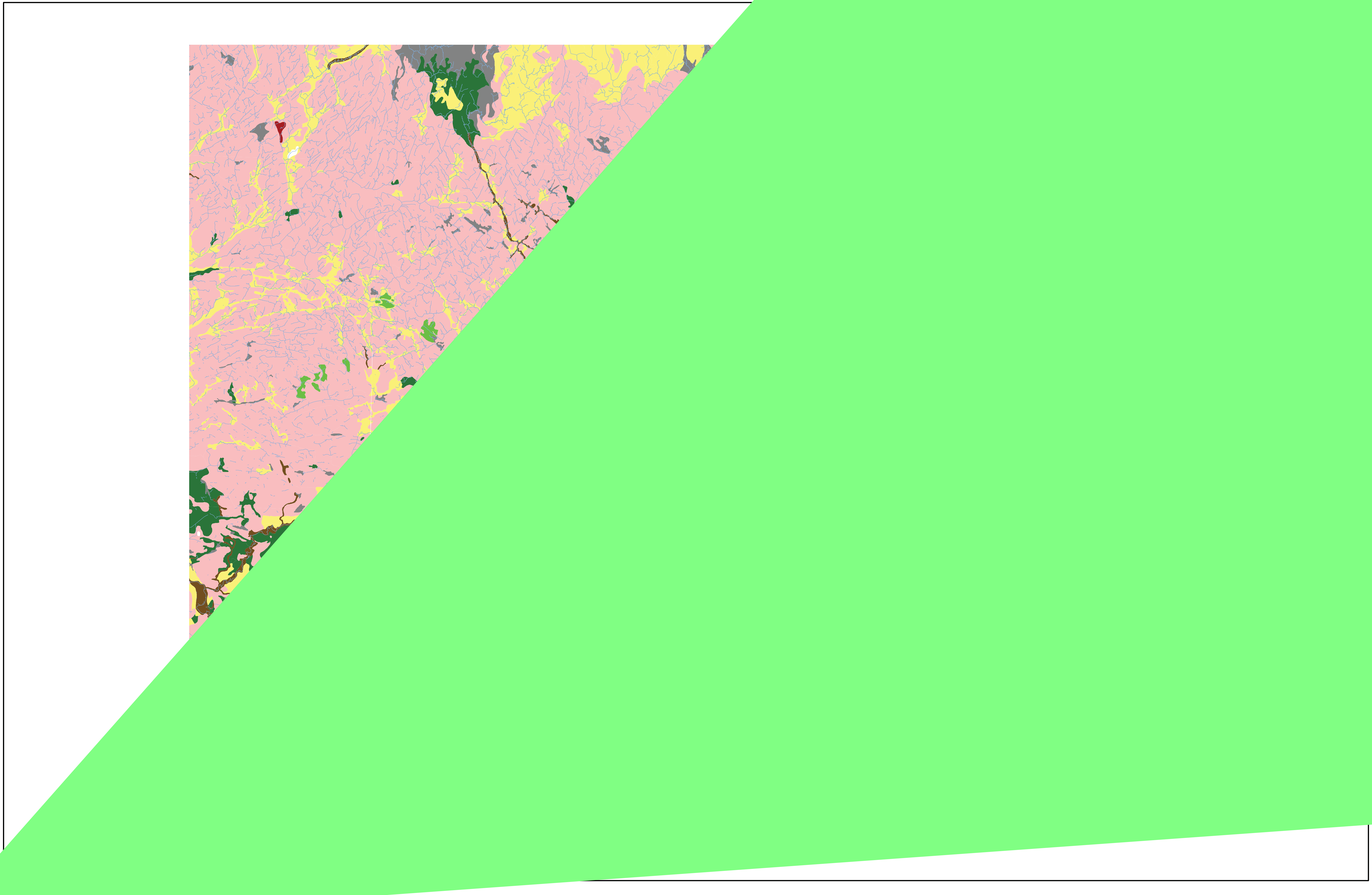

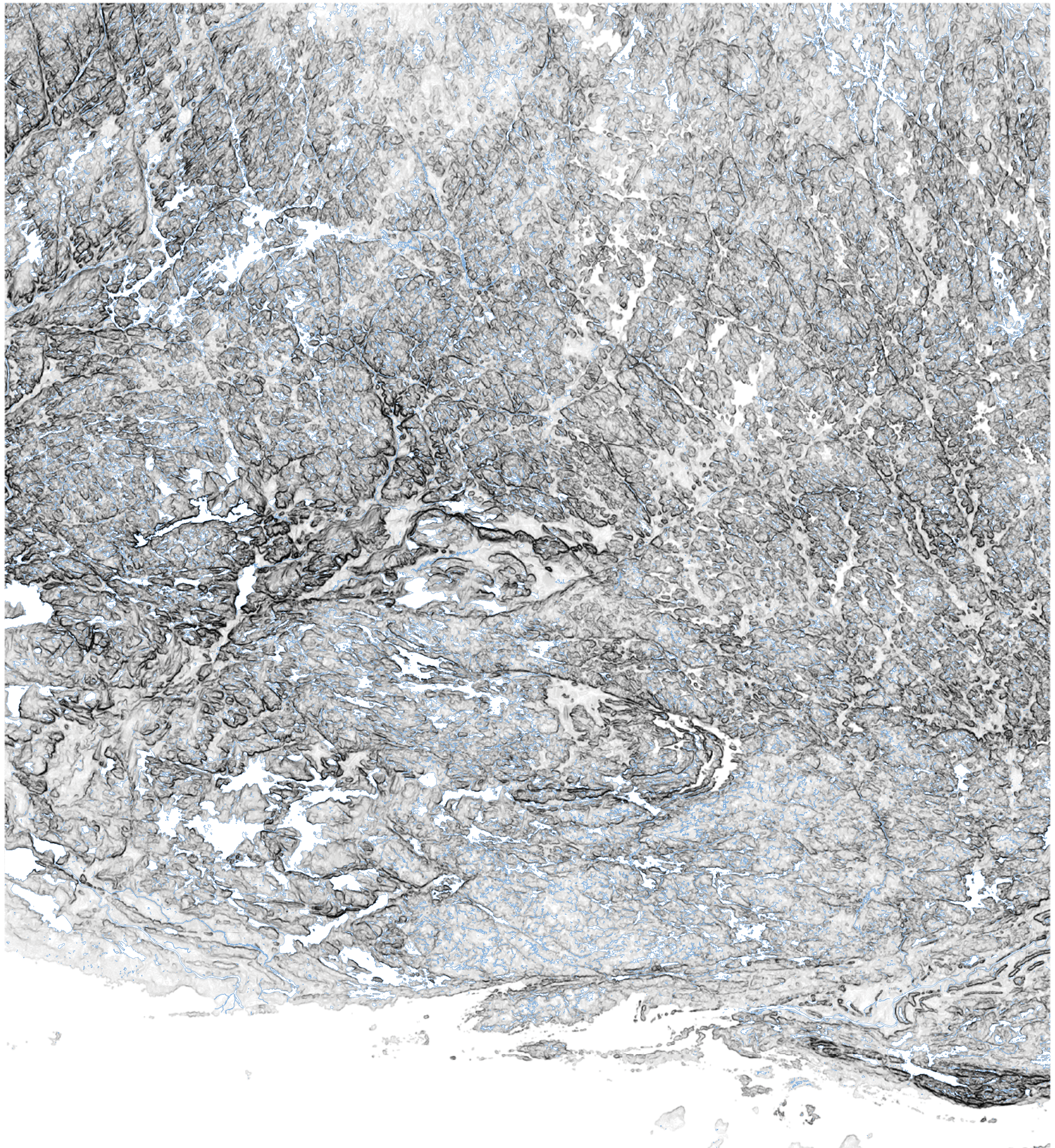

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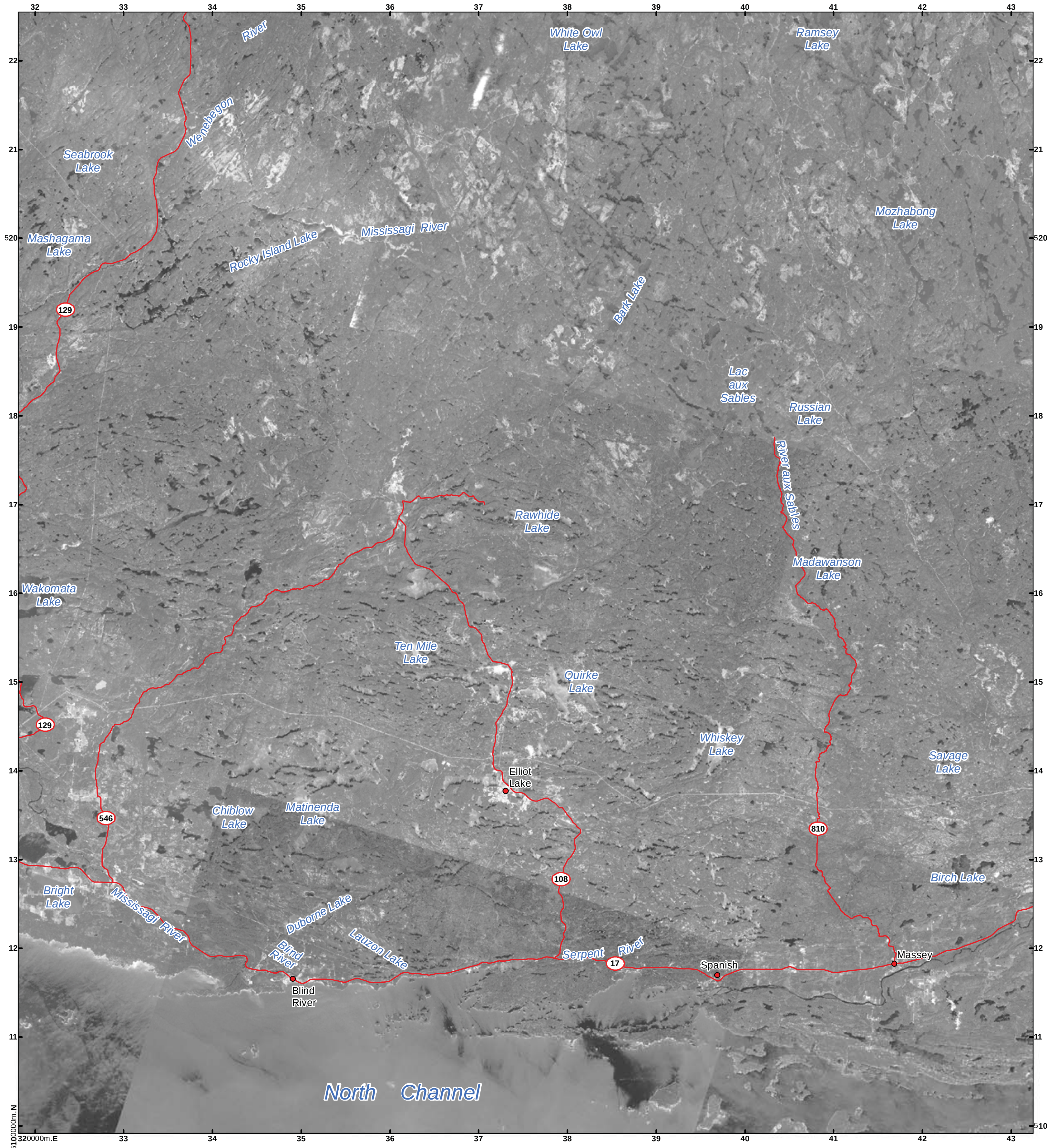

LEGEND

- Urban municipality
- Main road

Data sources:
SPOT: Geobase
Road: Selected from MNR road segment

NORTH
5 km

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PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE
SPOT satellite data

DESIGN	DVZ	02 MAY 2013	FIGURE 6	REVISION 4
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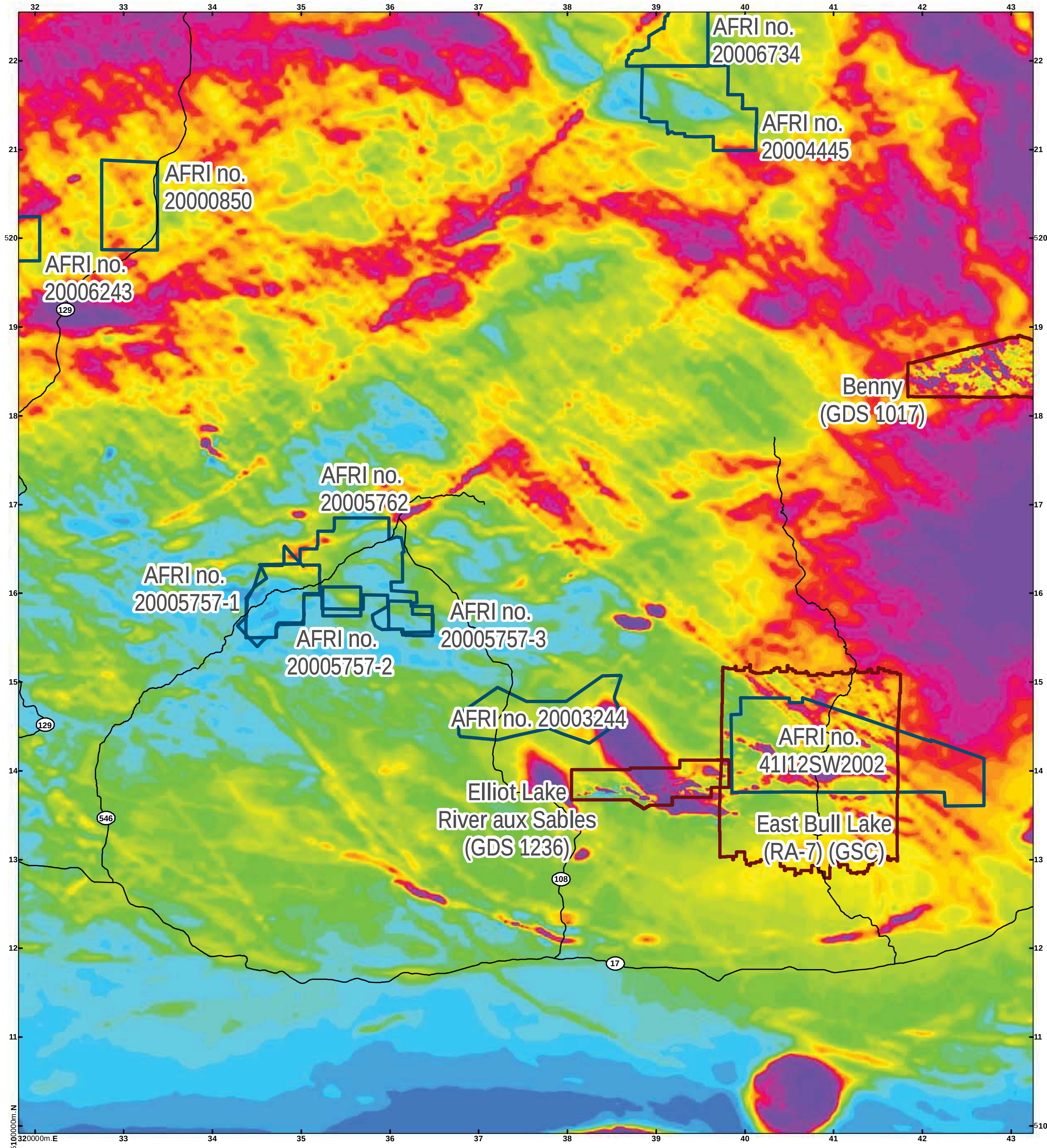
REVIEW	GS	25 JUN 2014		1:550,000



LEGEND

- Main road
- High resolution geophysical survey outline
- Industry geophysical survey outline

RTP (nT)

- 551 to 3,009
- 371 to 550
- 281 to 370
- 231 to 280
- 181 to 230
- 161 to 180
- 141 to 160
- 121 to 140
- 111 to 120
- 91 to 110
- 81 to 90
- 61 to 80
- 41 to 60
- 31 to 40
- 24 to 30
- 11 to 23
- 1 to 10
- -19 to 0
- -39 to -20
- -59 to -40
- -69 to -60
- -89 to -70
- -109 to -90
- -129 to -110
- -149 to -130
- -179 to -150
- -229 to -180
- -299 to -230
- -522 to -300

Data sources:
Hi-resolution Magnetics: OGS GDS1017, GDS1236
Regional Magnetics: GSC nationwide compilation
Road: Selected from MNR road segment

NORTH

5 km

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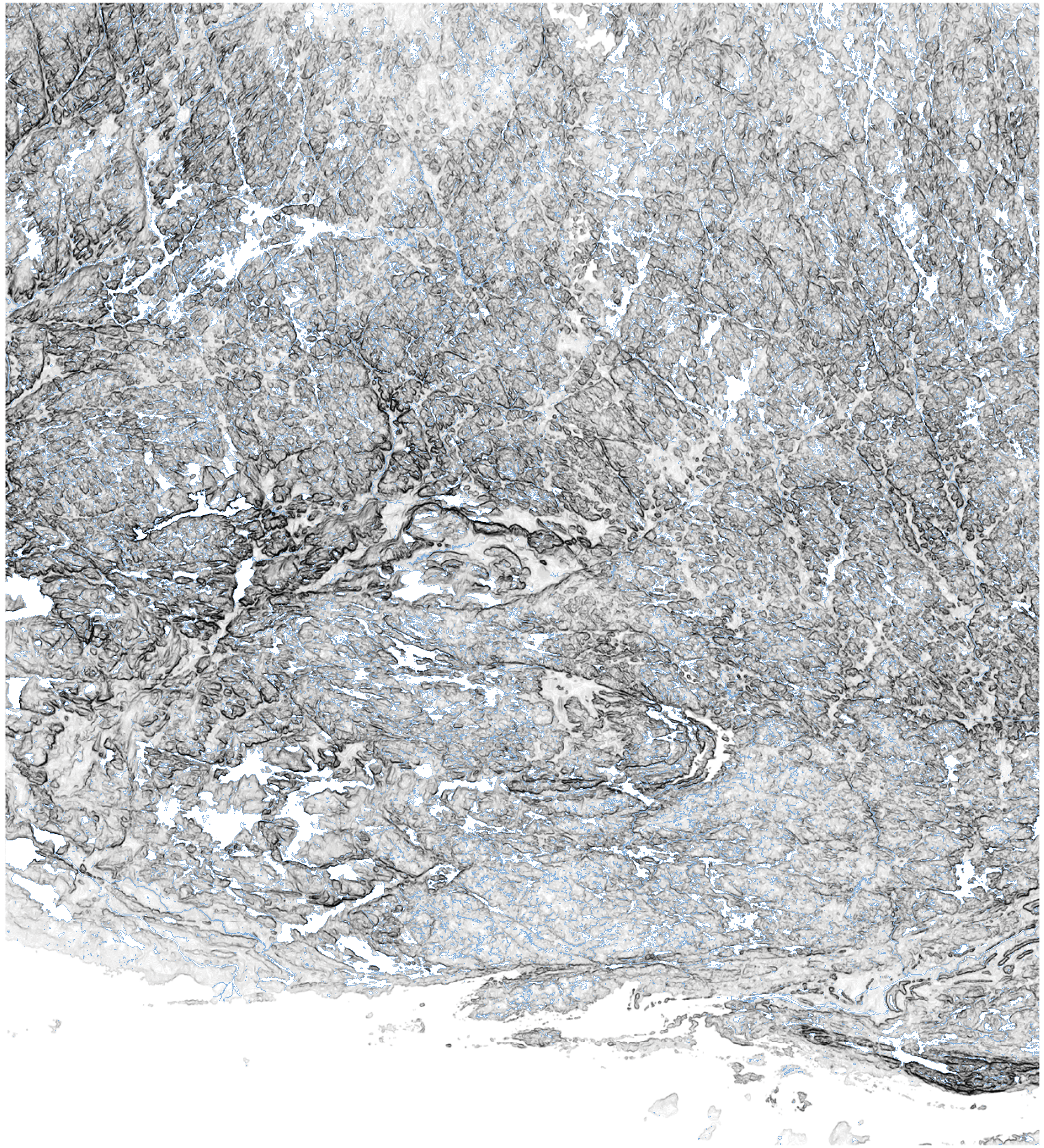
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE
Aeromagnetic data: Pole reduced magnetic field

DESIGN	DVZ	02 MAY 2013	FIGURE 7	REVISION 4
GIS	DSM	25 JUN 2014		UTM ZONE 17
CHECK	JIC	25 JUN 2014		NAD 1983
REVIEW	GS	25 JUN 2014		1:550,000



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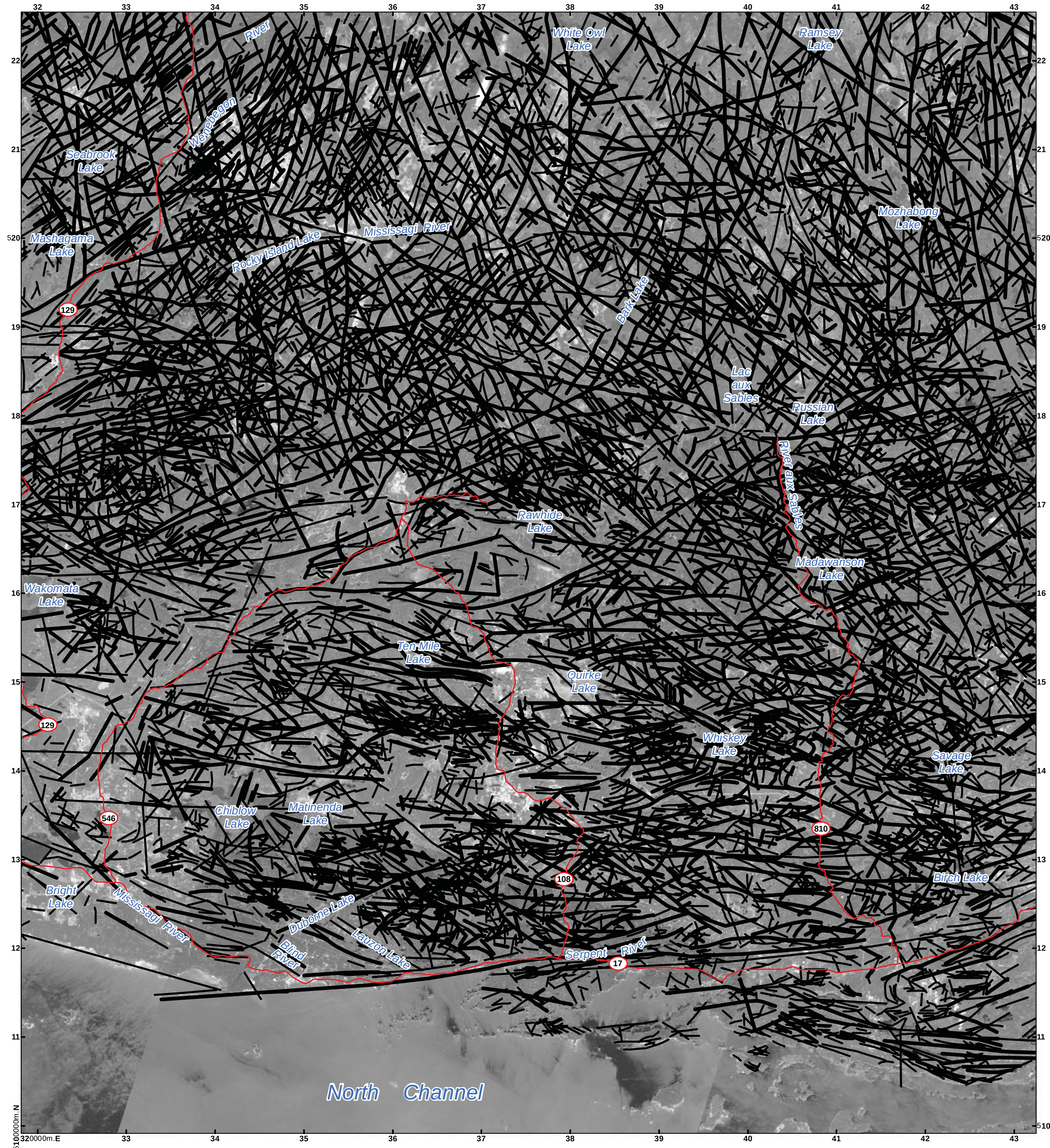


LEGEND

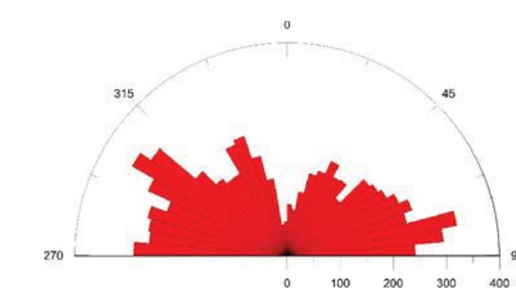
Main road

SPOT lineament RA_1

1

2

SPOT Data - Length Weighted Frequency Rose Plot



N = 7,509

Data sources:
SPOT panchromatic: geobase.ca (10m ground resolution)
Road: Selected from MNR road segment

NORTH

5 km

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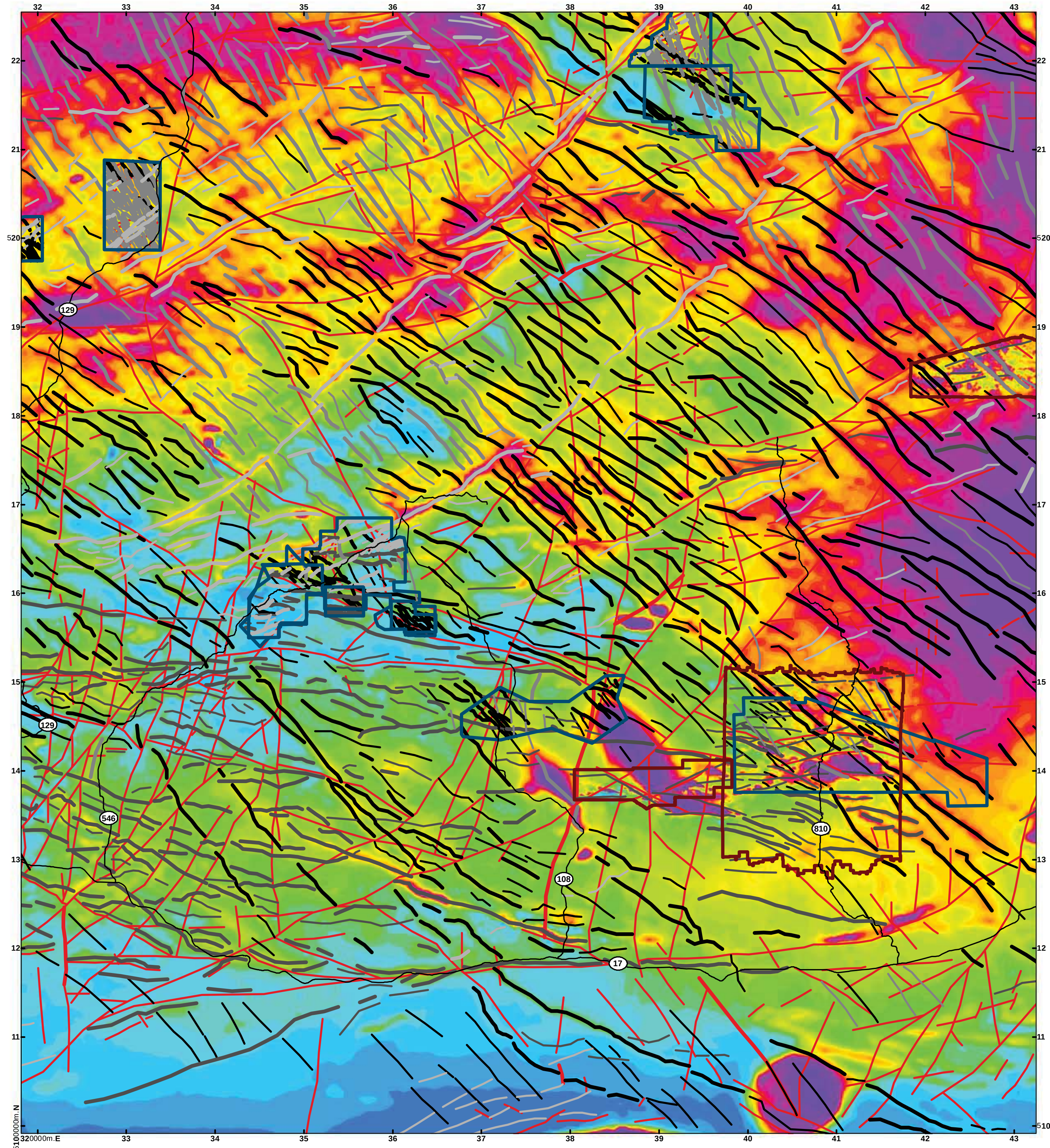
PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE

SPOT reproducibility assessment (RA_1)

DESIGN	DVZ	02 MAY 2013	FIGURE 9	REVISION 4
GIS	DSM	25 JUN 2014		UTM ZONE 17
CHECK	JIC	25 JUN 2014		NAD 1983
REVIEW	GS	25 JUN 2014		1:550,000



LEGEND

- Main road
- High resolution geophysical survey outline
- Industry geophysical survey outline

Fault RA_1

- 1
- 2

RTP (nT)

- 551 to 3,009
- 371 to 550
- 281 to 370
- 231 to 280
- 181 to 230
- 161 to 180
- 141 to 160
- 121 to 140
- 111 to 120
- 91 to 110
- 81 to 90
- 61 to 80
- 41 to 60
- 31 to 40
- 24 to 30
- 11 to 23
- 1 to 10
- -19 to 0
- -39 to -20
- -59 to -40
- -69 to -60
- -89 to -70
- -109 to -90
- -129 to -110
- -149 to -130
- -179 to -150
- -229 to -180
- -299 to -230
- -522 to -300

Bisotasing mafic dyke RA_1

- 1
- 2

Metachewan mafic dyke RA_1

- 1
- 2

North Channel mafic dyke RA_1

- 1
- 2

Sudbury mafic dyke RA_1

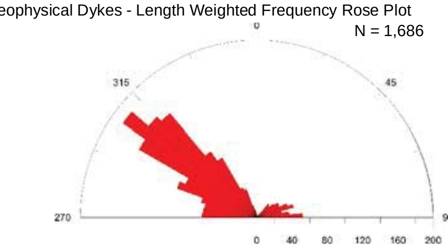
- 1
- 2

Fault RA_1

- 1
- 2

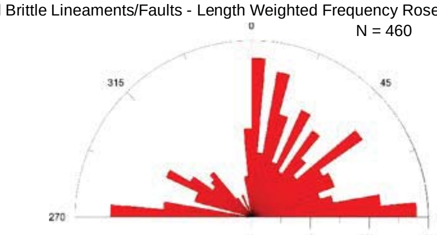
Geophysical Dykes - Length Weighted Frequency Rose Plot

N = 1,686



Geophysical Brittle Lineaments/Faults - Length Weighted Frequency Rose Plot

N = 460



Data sources:
Hi-resolution Magnetics: OGS GDS1017, GDS1236
Regional Magnetics: GSC nationwide compilation
Road: Selected from MNR road segment

NORTH

5 km

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PROJECT: PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, COMMUNITIES OF ELLIOT LAKE, BLIND RIVER, THE NORTH SHORE, AND SPANISH, ONTARIO

TITLE: Aeromagnetic reproducibility assessment (RA_1)

DESIGN	DVZ	02 MAY 2013	FIGURE 10	REVISION 4
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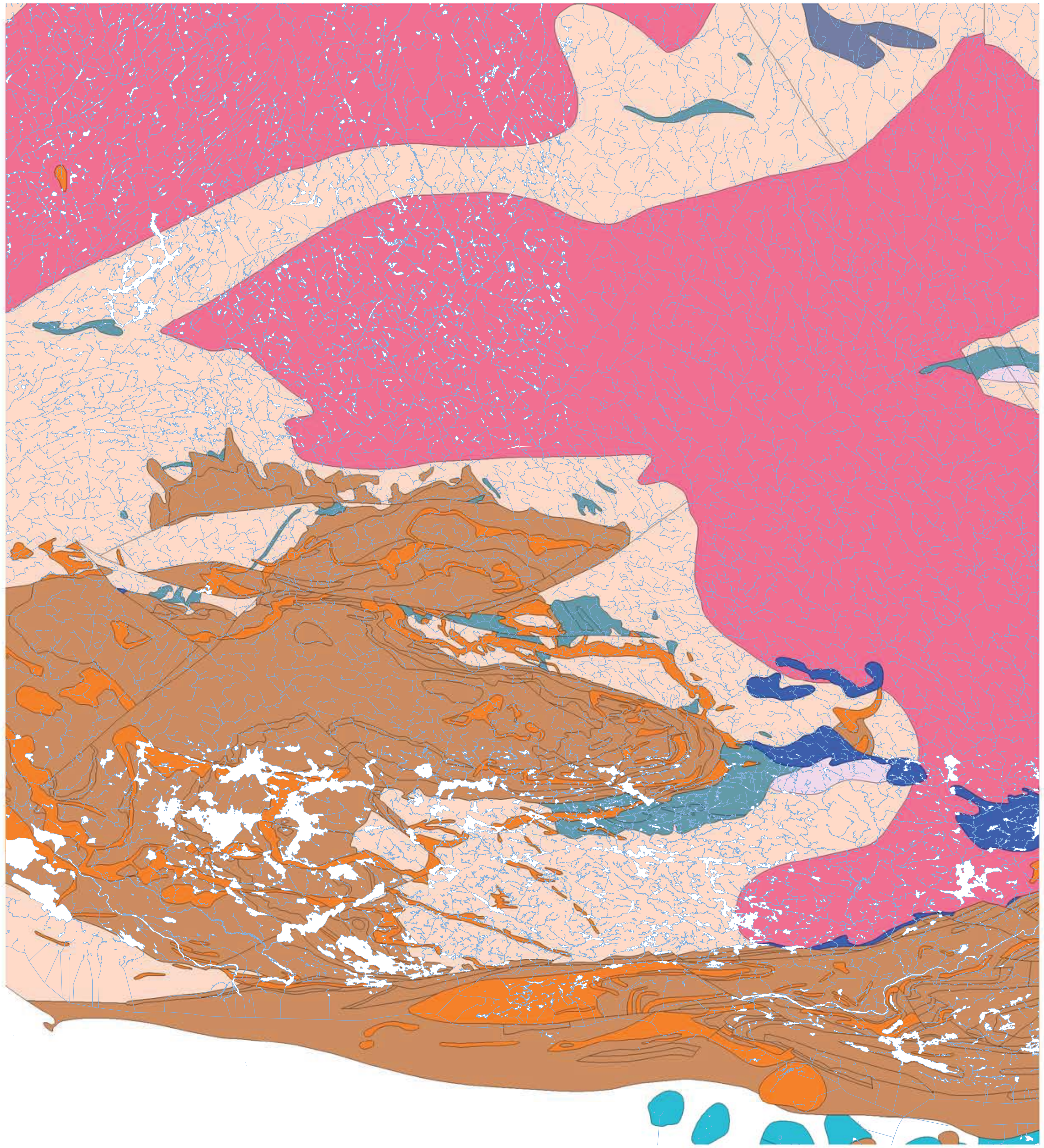
CHECK	JIC	25 JUN 2014		NAD 1983
REVIEW	GS	25 JUN 2014		1:550,000



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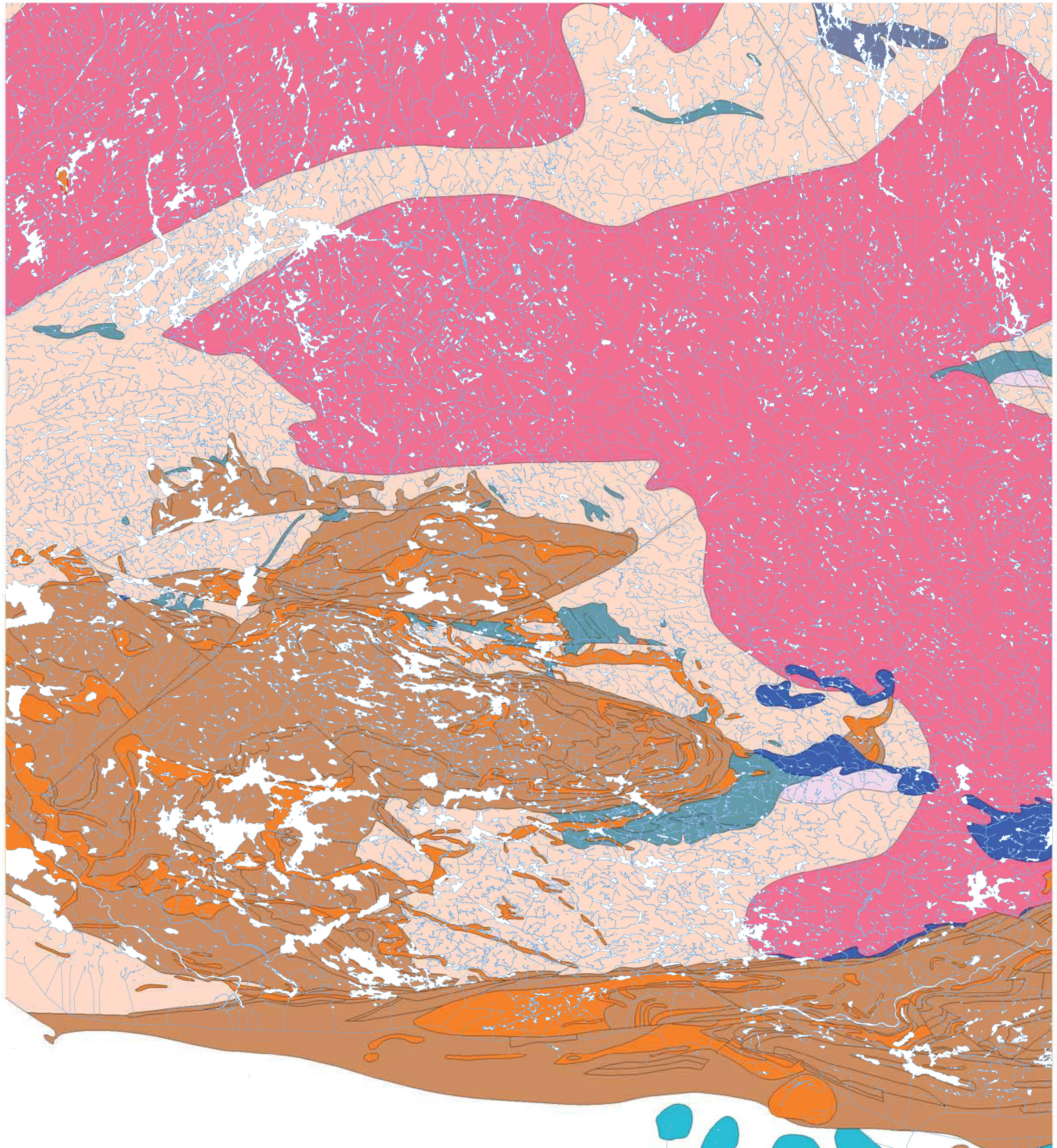

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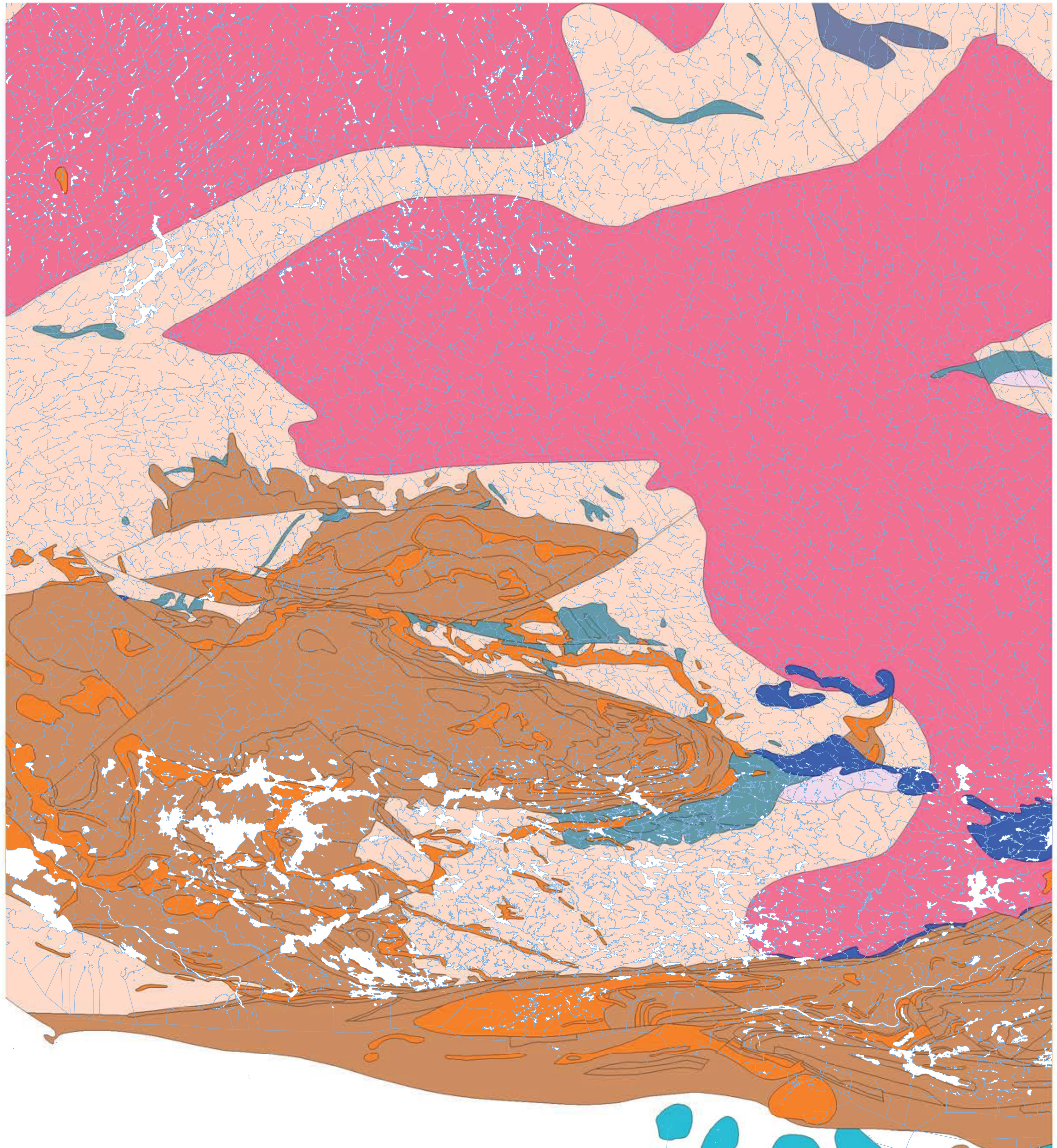

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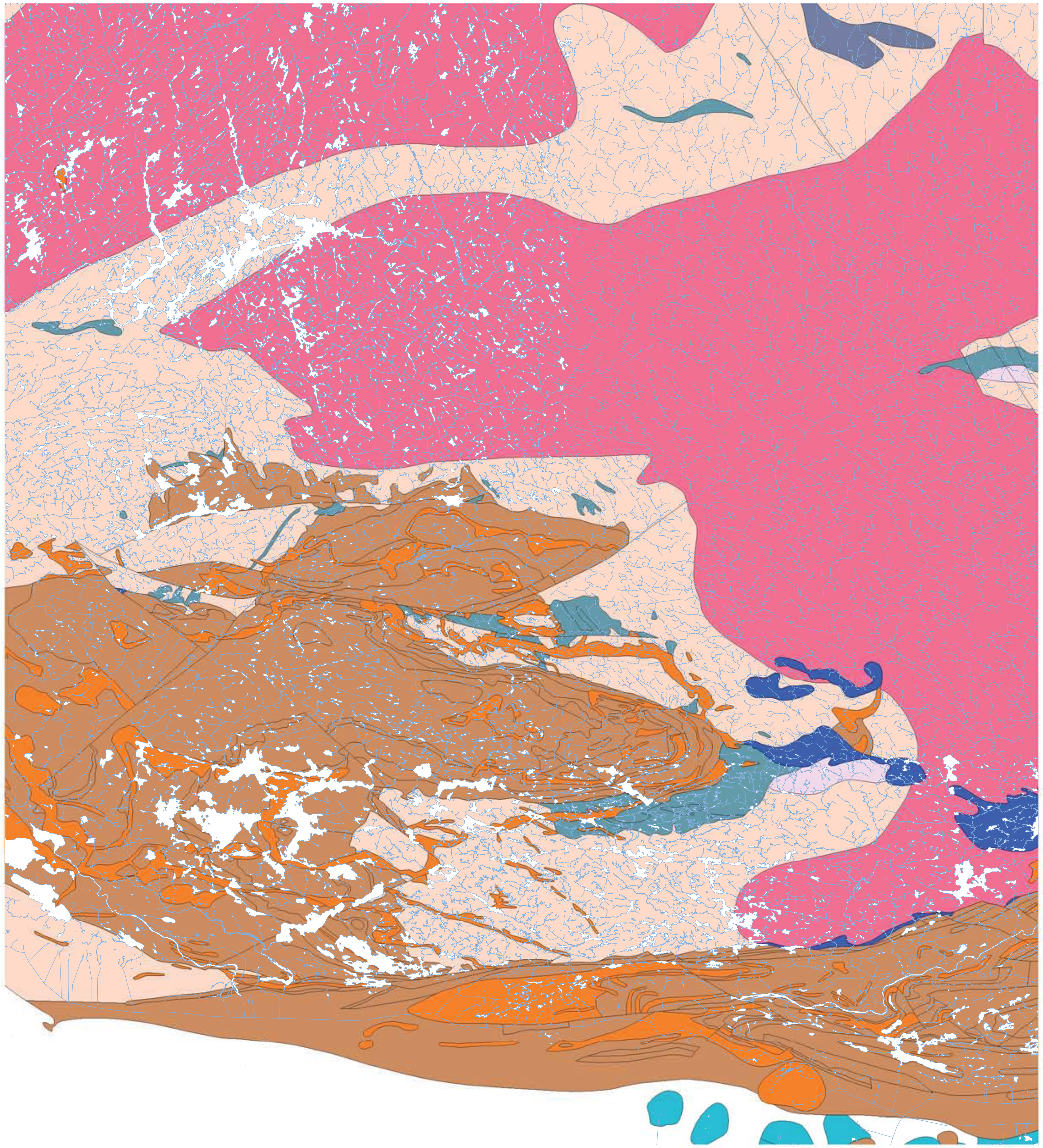

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