NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation

TOWNSHIP OF NIPIGON, ONTARIO

APM-REP-06144-0070

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PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT

LINEAMENT INTERPRETATION

TOWNSHIP OF NIPIGON, ONTARIO

NWMO REPORT NUMBER:
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EXECUTIVE SUMMARY

In May 2013, the Township of Nipigon, Ontario expressed interest in continuing to learn more about the Nuclear Waste Management Organization's (NWMO) nine-step site selection process, and requested that a preliminary assessment be conducted to assess potential suitability of the Nipigon area for safely hosting a deep geological repository (Step 3). This request followed the successful completion of an initial screening conducted during Step 2 of the site selection process.

The preliminary assessment is a multidisciplinary 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, 2014). The objective of the geoscientific desktop preliminary assessment was to determine whether the Nipigon area and its periphery, referred to as the "Nipigon area", contain general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

This report presents the findings of a lineament investigation completed as part of the geoscientific desktop preliminary assessment of the Nipigon area (Golder, 2014). The lineament assessment 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 Nipigon area in northern Ontario. The assessment of interpreted lineaments in the context of identifying general areas that have the potential to meet NWMO's geoscientific site evaluation factors is provided in the desktop preliminary geoscientific 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, SPOT and LandSAT);
- 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 Nipigon area generally reflects the bedrock structure, noting that lineament density is influenced by the extent of surficial cover and the variable resolution of the geophysical data. Surficial lineament density was observed to be highest in the eastern and western parts of the Nipigon area, where bedrock terrain is dominant and the percentage of overburden cover is the lowest. The western third of the Nipigon area, where high resolution geophysical data is available, is characterized by a moderate density of geophysical lineaments with orientations that approximate those seen in the surficial lineaments. In the eastern part of the Nipigon area, where only low resolution geophysical data is available, geophysical lineament density is low and the lineaments are arguably too few to make reliable statistical inferences about orientation trends. Based on the structural history of the Nipigon area, a framework was also developed to constrain the relative age relationships of the interpreted lineaments.

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1 INTRODUCTION

In May 2013, the Township of Nipigon 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 Nipigon area for safely hosting a deep geological repository (Step 3).

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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 Nipigon area (approximately 1,360 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 geophysical 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 is described in more detail below in the context of its 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 dyke lineaments. Dyke interpretation is largely made using the aeromagnetic dataset, and is often combined with pre-existing knowledge of the bedrock geology of the Nipigon area.

The desktop interpretation of remotely-sensed datasets necessarily includes a component of uncertainty as a result of data quality, scale of the Nipigon area, expert judgement, and to a certain extent, the quality of the pre-existing knowledge of the bedrock geology of the Nipigon area. Therefore the ductile, brittle or dyke categorization of each identified feature, as described herein, is preliminary.

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 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 assessment with the support of PGW who conducted the lineament interpretation on the geophysical data.

Following is a brief description of the qualifications 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 surficial 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.

Edna Mueller-Markham, M.Sc., P.Geo. is a senior consulting geophysicist at PGW for the past 16 years. Ms. Mueller-Markham has experience in project management, processing and interpretation of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data for clients throughout Canada and around the world. Projects include management and quality assurance/quality control of geophysical surveys for the Ontario Ministry of Northern Development and Mines as well as a similar role for the Far North Geoscience Mapping Initiative. Ms. Mueller-Markham contributed to the processing of the geophysical data and was the lead interpreter of the geophysical 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 second interpreter of the geophysical lineaments.

1.3 REPORT ORGANIZATION

Section 2.0 describes the geological setting of the Nipigon area, 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.

The primary source for all of the background information presented herein is the main report written by Golder (2014). This report also draws upon information from the 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 Nipigon area is provided in Golder (2014). The following sections on physical geography, bedrock geology, 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 Nipigon area is shown on Figures 2 and 3, respectively.

2.1 PHYSICAL GEOGRAPHY

A detailed discussion of the physical geography of the Nipigon area is provided in a separate terrain analysis report (JDMA, 2014) and the following is a summary of that information. The Nipigon area 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.

The landscape within the Nipigon area ranges in elevation from about 183 m on the surface of Lake Superior to a maximum of 583 m on the highest point of the Kama Hills (Figure 4). Topographic highs generally correspond to bedrock while topographic lows are generally areas of thicker overburden (Figures 3 and 4; JDMA, 2014). Two major topographic lows are present within the Nipigon area (Figure 4). The first is located in the western part of the area and is associated with the Black Sturgeon River and Shillabeer Creek. The second, and much larger topographic low, is centrally located in the Nipigon area and is represented by a broad area of low elevation located between the Nipigon and Jackfish rivers. Between the Black Sturgeon and Nipigon rivers, there is an area of relatively high ground. The zone of highest elevation in the Nipigon area is located east of the Jackfish River and is associated with the Kama Hills and other areas to the north and east.

Approximately half of the Nipigon area was mapped as bedrock terrain during the NOEGTS program (OGS, 2005), with the largest contiguous zone of bedrock terrain located in the eastern half of the area, generally east of the Jackfish River (Figure 4). Areas mapped as bedrock terrain are generally expected to contain a thin mantle of drift, which is less than one metre thick in most places (Gartner et al., 1981) and is generally composed of bouldery sand-rich till (Mollard and

Mollard, 1981a, b). The actual amount of bedrock exposure is generally less than 5% in most areas (JDMA, 2014).

The Nipigon area is characterized by a general paucity of large (≥ 10 km^2) lakes. Lake Superior and Helen Lake are the two waterbodies that cover the largest parts of the Nipigon area (31.6 km^2 and 16.0 km^2, respectively). Aside from these two waterbodies, the rest of the lakes and rivers in the Nipigon area are less than 5 km^2 in size and over 90% are less than 1 km^2 in extent. Waterbodies cover 6.7% (91.4 km^2) of the Nipigon area. The general paucity of large lakes in the Nipigon area and the fact that the largest lakes are generally widely spaced apart from one another results in a condition where lakes generally do not pose a significant obstruction to the identification of major lineaments. One of the largest lakes in the area may outline a major lineament. That is, the north south trending aspect of the linear topographic low filled by Polly Lake, Helen Lake and the Nipigon River south of Helen Lake perhaps could outline the general trend of a significant bedrock structure.

2.2 BEDROCK GEOLOGY

The Nipigon area 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 surrounded by younger Proterozoic rocks.

The Nipigon area is underlain by rocks of the Archean-aged Superior Province which are, in turn, locally overlain by younger strata of the Proterozoic-aged Southern Province (Figure 2). 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 through to Minnesota and the northeastern part of South Dakota. The Superior Province is divided into subprovinces, medium- to large-scale regions that are characterized by similar rock-types, structural style, age, metamorphic grade and mineralization (Figure 2). The Nipigon area is within the Quetico Subprovince of the Superior Province. The Southern Province, which borders the Superior Province to the south from the Sudbury area through to Thunder Bay, comprises younger volcanic and sedimentary rocks of Proterozoic age, deposited over the Archean basement.

The geology of the Nipigon area consists of Mesoproterozoic sedimentary and intrusive rocks, and unconsolidated Quaternary deposits overlying the ca. 2.7 billion year old bedrock of the Canadian Shield. Proterozoic strata are widespread throughout the Nipigon area, but since they invariably overlie rocks of the Quetico Subprovince, the entire Nipigon area may be considered structurally part of the Superior Province. Figure 2 shows the regional bedrock geology and mapped geological faults and dykes of the Nipigon area and surroundings. The Quetico Subprovince is approximately 1,200 km long and bounded on the north by the Wabigoon Subprovince and on the south by the Wawa Subprovince. Subprovince boundaries are steeply dipping and take the form of thrust and/or transcurrent fault contacts (Percival and Williams, 1989); although in many areas the exact point of contact between the subprovinces is not precisely defined. The Quetico Subprovince consists primarily of Archean clastic metasedimentary rocks deposited between ca. 2.698 and 2.688 billion years ago (Percival and Sullivan, 1988). These rocks underwent regional melting and recrystallization (migmatization), and were intruded by 2.70 to 2.65 billion year old granitic rocks (Williams, 1991).

In the southern and western portions of the Nipigon region (Figure 2), the Proterozoic sedimentary rocks of the Sibley and Animikie groups unconformably overlie the Archean metasedimentary rocks of the Quetico Subprovince. The metasedimentary rocks of the Quetico Subprovince and the sedimentary rocks of the Sibley Group in the Nipigon area were intruded by Nipigon diabase sills and dykes related to the failed intracontinental rifting event that occurred approximately 1.115 billion years ago, and by localized ultramafic intrusions, such as the Hele intrusion (Hart, 2005), that occurred approximately 1.115 to 1.105 billion years ago (Heaman and Easton, 2006). Tholeiitic flood basalts of the Osler Group were deposited slightly later than the Nipigon sills (Sutcliffe, 1991) and underlie most of the St. Ignace Island chain to the south and east of the Nipigon area.

The Nipigon area is located on the boundary between the metasedimentary rocks of the Quetico Subprovince of the Superior Province and the sedimentary rocks of the Sibley Group of the Southern Province of the Canadian Shield. The bedrock geology of the Nipigon area is shown on Figure 3. Archean metasedimentary rocks and migmatites of the Quetico Subprovince form the bedrock at surface over the majority of the Nipigon area. These metasedimentary rocks extend beyond the Nipigon area to the north and over an extensive area east of the Black Sturgeon fault zone. To the south and to the west of the Black Sturgeon fault zone, the metasedimentary rocks of the Quetico Subprovince are unconformably overlain by the largely unmetamorphosed, undeformed sedimentary rocks of the Sibley Group. The latter are found to the south of the Township of Nipigon, and northeast along the Lake Superior shoreline.

A number of small granitic intrusive bodies occur in the west of the Nipigon area, east of the Black Sturgeon fault zone (OGS, 2011). These are elongate or lensoid bodies of massive granodiorite to granite. Some of these intrusions are small in width (up to about 1 km wide) and are sub-parallel to the strike of the metasedimentary rocks of the Quetico Subprovince. Other granitic bodies include two irregular intrusions east of the Black Sturgeon River in the area south of Mound Lake, approximately 10 km northwest of the Township of Nipigon. The more southerly of these is an approximately 20 km^2 body of biotite-bearing massive granodiorite to granite bordered on the north by a slightly larger 38 km^2 muscovite-bearing granite intrusion. Both of these granitic bodies are accompanied by distinct magnetic and radiometric geophysical signatures. A separate muscovite granite body outcrops on either side of Helen Lake at Duncan Bay approximately 5 km north of the Township of Nipigon. This unit is approximately 10 km long and 2 km wide, concordant to the gneissic fabric, and lacks a distinct geophysical signature.

In a number of places in the Nipigon area there are localized outcrops of mafic intrusions, diabase sills and dykes, including the Nipigon sill complex, which intrude both Archean metasedimentary rocks and the Mesoproterozoic sedimentary rocks of the Sibley Group. Nipigon sills occur at surface along the southern and western margins of the Nipigon area. Immediately west of the Black Sturgeon fault zone, approximately 1 km southwest of the Township of Nipigon, is the ultramafic Hele intrusion.

The magnetic responses of the metasedimentary rocks and migmatites of the Quetico Subprovince and the sedimentary rocks of the Sibley Group are generally subdued. By contrast, intrusive bodies such as the Archean granites of the Quetico Subprovince and the Hele intrusion show distinct positive magnetic responses. The positive magnetic response over the Hele intrusion shows criss-crossing linear aeromagnetic minima striking approximately 025^o and 100^o, coincident with prominent topographic lineaments. These linear features have been interpreted to be faults (Coates, 1972; Hart, 2005) as have a number of similar lineaments elsewhere in the Nipigon area. The Nipigon sills have a distinctly low magnetic response in comparison to their surrounding host rocks as a result of their magnetization from the time of emplacement.

The main rock types of the Nipigon area are further described in the following subsections.

2.2.1 ARCHEAN METASEDIMENTARY ROCKS

Archean metasedimentary rocks of the Quetico Subprovince (Figure 3) underlie the Nipigon area and constitute the uppermost bedrock unit north of the Township of Nipigon and east of the Black Sturgeon River. Metasedimentary rocks of the Quetico Subprovince also extend beneath the sedimentary rocks of the Sibley Group south of the Township of Nipigon and in the area west of the Black Sturgeon River. Depositional age of the original sediments of the Quetico Subprovince are dated at ca. 2.698 to 2.690 billion years (Percival et al., 2006). Although the thickness of the migmatitic metasedimentary rocks in the Nipigon area is not reported in the literature, a regional thickness of up to 18 km has been interpreted from geophysical studies (White et al., 2003; Percival et al., 2006). A number of lineaments have been mapped as faults in the metasedimentary rocks to the east of the Black Sturgeon fault zone (Hart, 2005). Most of these lineaments follow a north or northwest trend and are spaced about 1.5 to 3 km apart.

Hart (2005) describes the metasedimentary rocks as feldspathic and lithic metawackes, and metasiltstone arranged in beds 3 to 30 cm thick with occasional bands of disseminated andalusite and with a schistosity generally oriented east-northeasterly and usually subparallel to the original bedding (Hart and Magyarosi, 2004). Dip of the foliation/schistosity is variable but generally steep (Hart, 2005).

Rocks of the Quetico Subprovince consist of biotite and/or andalusite schists that are gradually replaced towards the south by amphibolite (Hart, 2005). The schist is composed of fine-grained biotite, plagioclase and quartz, and may be intruded along the schistosity by metre-scale leucocratic dykes of Archean granite (described below). The amphibolite is composed of fine- to medium-grained hornblende, plagioclase and quartz, and shows weakly to moderately well-developed foliation (Hart, 2005).

In the Nipigon area, amphibolite is most often found mixed with leucocratic felsic rocks in the form of irregular interbanded to chaotic mixtures of the two rock types, which Hart (2005) recognized as migmatite. Hart (2005) suggested that migmatites in the Nipigon area could have resulted from the intrusion of felsic granitic intrusive rocks. The complex special arrangement of lithologies displayed in the Nipigon area closely resembles that of an injection complex (Sawyer, 1983), where magma is emplaced in metasedimentary rocks through a myriad of small dykes and veins (Sawyer, 1983; Leitch and Weinberg, 2002). Morfin et al. (2013) report that the migmatites of the Opinaca Subprovince in Quebec display evidence of the repeated injection of magma. Given that the types of rock, rock composition, and age of deposition of rocks of the Opinaca Subprovince are similar to those of the Quetico Subprovince (Morfin et al., 2013), the migmatites of the Quetico Subprovince observed in the Nipigon area could also correspond to an injection complex.

2.2.2 ARCHEAN GRANITES

The metasedimentary migmatites of the Quetico Subprovince in the Nipigon area have been intruded by several irregular shaped granitic bodies, mapped by Hart (2005) as metamorphosed biotite granite within the Township of Nipigon and in the area to the northwest of the Township bordering the Black Sturgeon River canyon. Biotite granite intrusions in the Nipigon area consist of light pinkish grey to light pink granite with less than 10% biotite. These rocks are massive and medium to coarse-grained, with rare, very coarse-grained to pegmatitic sections. Often these granitic intrusions contain xenoliths of the surrounding amphibolites, which are a few metres in diameter. These granitic bodies are in some places cut by pegmatitic dykes.

Muscovite-bearing granitic intrusions are also mapped within the north-central part of the Nipigon area in the form of an approximately 10 km long and 2 km wide body some 5 km north of the Township of Nipigon, and an unnamed, approximately 38 km^2, sub-circular body located south of Mound Lake near the northwest corner of the Nipigon area. The muscovite granite is described as light grey, pinkish grey, to white, massive, and medium to very coarse grained with occasional pegmatitic sections. Xenoliths of metasedimentary and gneissic rocks are present throughout the intrusion, and pegmatitic muscovite granite dykes intrude the granite body and the surrounding gneisses.

Hart (2005) considered the lack of well-developed gneissic textures along with the presence of biotite schist and amphibolite xenoliths in both suites of granitic rocks to be indicative of an intrusive origin, also opening the possibility that both suites may be genetically linked.

2.2.3 SEDIMENTARY ROCKS OF THE SIBLEY GROUP

The Sibley Group is a largely unmetamorphosed, relatively flat-lying sedimentary rock sequence that nonconformably overlies the Archean rocks of the Quetico Subprovince. Rocks of the Sibley Group outcrop along the western margin of the Nipigon area to the west of the Black Sturgeon fault zone, along the southern part of the area along the Lake Superior shoreline, and northward in the area east of the Nipigon River.

The rocks of the Sibley Group in the Nipigon area range from approximately 1.5 to 1.3 billion years in age and have been divided into five formations (Hart, 2005; Rogala et al., 2005), three of which are known to be present in the Nipigon area. According to Rogala et al. (2005), the lowermost unit, the Pass Lake Formation, consists of conglomerates overlain by sandstones; the middle unit, the Rossport Formation, consists of dolomite-siltstone layers on the bottom, stromatolites in the middle and mudstone on the top; and the uppermost unit, the Kama Hill Formation, is composed of shales and siltstones. Younger members of the Sibley Group, the Outan Island and Nipigon Bay formations, have not been mapped within the Township of Nipigon and lands to the north, but these units are known to be present beneath portions of Nipigon Bay (Rogala et al., 2005).

The sedimentary rocks of the Sibley Group in the Nipigon area are estimated to be up to approximately 200 m thick, based on geological mapping by Hart (2005), sparse diamond drill hole information and airborne geophysical data.

2.2.4 THE HELE INTRUSION

The Hele intrusion covers a total area of approximately 40 km^2 and is located to the west of the Black Sturgeon fault zone in the southwest corner of the Nipigon area. The Hele intrusion is underlain by sedimentary rocks of the Sibley Group and has a reported maximum thickness of approximately 130 m (Hart, 2005), based on diamond drill hole information and modelling of available airborne magnetic data.

The Hele intrusion was emplaced about 1.106 billion years ago (Heaman and Easton, 2006), and is composed of altered peridotite interlayered with olivine gabbro and feldspathic peridotite. The peridotite is a highly weathered and serpentinized rock containing numerous, subparallel serpentine and chlorite-rich fractures (Hart, 2005). A few major lineaments, mapped by Hart (2005) as faults, cut across the Hele intrusion in north and east-southeast orientations, the latter with spacings of 1 to 2.5 km.

2.2.5 NIPIGON DIABASE SILL COMPLEX

Nipigon diabase sills are relatively thin, generally flat-lying mafic rocks that intrude and sometimes overlie the other rock types in the Nipigon area. Within the Nipigon area, several small diabase sills occur at surface along a diagonal trend from the northwest corner of the area to the southeast. The outcrops of diabase are typically less than 1 km^2 in size and about 100 m thick (Hart, 2005). Nipigon diabase sills often intrude the older rocks in the area at depth and occur as extensive, relatively flat and thin (less than 50 m thick) intrusive layers (Hart, 2005). Larger Nipigon sill occurrences are mapped north of the Nipigon area.

The sills have been subdivided into several suites including the Logan sills located south of Thunder Bay, Nipigon sills centred on Lake Nipigon, and McIntyre, Inspiration, Jackfish-like and Shillabeer sills. Because the validity of the subdivisions and their nomenclature remains unresolved (Hart, 2005), we have used the term Nipigon sills to encompass all mafic sills in the Nipigon area.

There are no obvious textural or mineralogical differences between the sills; the diabase is commonly medium brown to brownish grey, massive, medium to coarse-grained feldspar and pyroxene with trace olivine and magnetite (Hart and Magyarosi, 2004). Their emplacement is interpreted by Coates (1972), Sutcliffe (1991) and others to be related to the Midcontinent Rift event. The intrusion age of these sill bodies has been constrained to have occurred in the period ca. 1.115 to 1.105 billion years (Heaman et al., 2007).

2.2.6 Mafic dykes

Widely spaced, northwest to northeast-trending diabase dykes intrude the Archean rocks of the Quetico Subprovince in the east part of the Nipigon area (Figure 3). Four such dykes, ranging from 7 to 25 km in length are mapped in the Nipigon area based on the OGS seamless geological coverage of Ontario (OGS, 2011). They are described as 1.180 to 1.130 billion years in age and are not associated with any named dyke swarm. While not recognized within the Nipigon area, northwest trending dykes of the Matachewan dyke swarm (2.475 to 2.45 billion years old) are mapped about 13 km to the northeast of the Nipigon area (e.g., Figure 2).

2.2.7 Faults

There are a number of regional faults within and bordering the Nipigon area. These include the known shear zones and mapped faults that relate to lineaments within the Nipigon area including the northwest trending Black Sturgeon fault zone and the northeast trending Jackpine River fault. The northeast trending Gravel River fault is located just outside the southeast corner of the Nipigon area (Figure 2) and is described further in Golder (2014).

The Black Sturgeon fault zone (Figures 2 and 3) is at least 65 km long and is composed of a series of northwest-trending faults that are coincident with the Black Sturgeon River. The fault zone forms the northeastern border of a graben structure (Hart, 2005). Rock units to the southwest of the fault zone are downthrown by several hundred metres compared to rocks to the northeast, resulting in the widespread preservation of sedimentary rocks of the Sibley Group to the west of the fault zone contrasting with the Archean gneissic rocks that dominate to the east (Hart, 2005).

Similar vertical offsets of between 200 and 300 m are also reported for north-trending faults in the South Armstrong–Gull Bay area on the west shore of Lake Nipigon approximately 50 km north of the Nipigon area (MacDonald, 2004). Within the west-southwest part of the Nipigon area, the Black Sturgeon fault zone is marked by a steep canyon, approximately 1 km wide and 200 m deep, through which the Black Sturgeon River flows. The dip and the width of the fault zone are unknown.

The 45 km long northeast-trending Jackpine River fault (Figures 2 and 3) is located in the eastern part of the Nipigon area. This fault follows the Jackpine River from Kama Bay and extends beyond the Nipigon area to the northeast to its termination near the northern boundary of the Quetico Subprovince. The fault follows a strongly linear topographic feature that crosscuts the younger Proterozoic cover rocks near its southern extension into Nipigon Bay. The fault (and/or its associated splays) has been the subject of sporadic exploration effort targeting gold mineralization. Trenching in the area south of Shark Lake (MDI 42E04SW00005) revealed anastomosing quartz veining and flooding forming a band up to 3 m wide.

Other mapped faults include an unnamed 12 km long fault located to the east of Mound Lake (Figures 2 and 3) and an approximately 27 km long fault that follows the course of the Nipigon River from Cameron Falls along the north border of the Nipigon area to north of Pine Portage (Figure 2). Although not mapped in MRD126 or shown on Figure 3, Coates (1968, 1972) shows a fault running along Frazer Creek from just south of Cameron Falls on the Nipigon River to Elizabeth Lake approximately 12 km to the northwest.

2.2.8 METAMORPHISM

Studies on metamorphism in Precambrian rocks across the Canadian Shield have been summarized in a few publications since the 1970s, including Fraser and Heywood (1978), Kraus and Menard (1997), Menard and Gordon (1997), Berman et al. (2000), Easton (2000a,b) and Berman et al. (2005). The thermochronologic record for major parts of the Canadian Shield is provided 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 (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). The distribution of contrasting grades of metamorphism is a consequence of relative uplift, block rotation and erosion from Neoarchean orogenesis and subsequent local Paleo- and Mesoproterozoic orogenic events and broader epeirogeny during the Neoproterozoic and Phanerozoic.

All rocks in the Quetico Subprovince, except for some of the late-stage granitic intrusions and diabase sills and dykes, were subjected to a complex regional metamorphic history. In the northern Quetico Subprovince, southwest of the Nipigon area in the Atikokan area, M_1 metamorphism is estimated to have occurred between 2.698 and 2.688 billion years ago (Davis et al., 1990). A similar chronology has been proposed in the southern part of the Quetico Subprovince where M_1 is interpreted to have occurred synchronously with D_1 at 2.698 to 2.689 billion years ago (Valli et al., 2004). During D_1, sedimentary rocks of the Quetico Subprovince were structurally stacked and buried up to 20 km deep, reaching upper amphibolite regional metamorphic facies under moderate pressure - moderate temperature conditions in the Jean Lake area (north-northeast of the Nipigon area) (Valli et al., 2004). In the Quetico Subprovince metamorphic grade generally increases progressively southward from greenschist to upper amphibolite facies (Hart, 2005).

Valli et al. (2004) described a second metamorphic event ($M_{2\text{-}3}$) during D_2-D_3, between 2.689 and 2.671 billion years ago, and retrograde, low-pressure, medium-temperature metamorphism associated with D_4 at ca. 2.671 to 2.667 billion years ago. It is possible that this latter event occurred in the Nipigon area, although there is no clear evidence to support it. Rocks of the Sibley Group underwent minor contact metamorphism along the margins of the ultramafic intrusions, such as the Hele intrusion and along the margins of the Nipigon sills. Hornfels textures and skarns usually extend up to 10 m into the sedimentary rocks (Hart, 2005).

2.3 GEOLOGICAL AND STRUCTURAL HISTORY

The geological and structural history of the Nipigon area spans nearly 3 billion years, and consists of Archean rocks of the Quetico Subprovince of the Superior Province unconformably overlain by Proterozoic sedimentary rocks of the Southern Province, both of which are intruded by Proterozoic ultramafic intrusions and diabase sills. The geological and structural history of the Nipigon area is discussed below and summarized in Table 1. The discussion integrates the results from studies undertaken mainly within and proximal to the Nipigon area, augmented by studies elsewhere in the Superior Province.

The oldest rocks in the Nipigon area are gneissic metasedimentary rocks of the Quetico Subprovince. Their precursor sediments are dominantly thick sequences of wackes deposited as turbidites in a laterally extensive marine basin beginning approximately 2.698 billion years ago (Davis et al., 1990). Sedimentation was rapid, in the neighborhood of 10 million years (Davis et al., 1990; Valli et al., 2004), with a likely volcanic sediment source from the northern Wabigoon Subprovince for the northern part of the Quetico belt, whereas the southern part of the belt was likely fed from sources of the Wawa Subprovince to the south of the belt (Sawyer and Robin, 1986; Williams, 1991; Zaleski et al., 1999; Fralick et al., 2006). The depositional setting has been the subject of considerable debate, but an accretionary prism is considered most likely (Percival, 1989; Williams, 1991; Valli et al., 2004; Fralick et al., 2006). Deposition of sediments is believed to have been diachronous throughout the Quetico Subprovince, occurring in the northern part prior to initiation in the south (e.g., Percival, 1989; Davis et al., 1990; Zaleski et al., 1999; Valli et al., 2004; Fralick et al., 2006).

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). The rift setting ultimately evolved into a passive margin setting, allowing development of intracratonic basins in many areas across the Lake Superior region, including deposition of the Huronian Supergroup between ca. 2.497 and 2.10 billion years ago (Corfu and Andrews, 1986; Rainbird et al., 2006) along the north shore of Lake Huron. While it is likely that Huronian strata once covered a much larger area than their present distribution, there is no evidence that this sedimentation took place within the Nipigon area. Though not observed in the Nipigon area, mafic dykes of the ca. 2.475 to 2.45 billion year-old Matachewan swarm extend to within roughly 13 km of the northeast corner of the Nipigon area. In addition, Ernst et al. (2006) used paleomagnetic data to attribute some of the mapped mafic dykes in the Nipigon area to the regionally pervasive ca. 2.121 to 2.101 billion year old Marathon swarm.

There was a tectonic and depositional hiatus of approximately 300 million years after deposition of the Huronian Supergroup, which suggests that the southern margin of the Superior craton was maintained as an elevated passive margin during an extended period of ocean opening and closing until the initiation of the ca. 1.89 to 1.84 billion year Penokean Orogeny (Sims et al., 1989; Schulz and Cannon, 2007).

As a consequence of the Penokean Orogeny, sedimentary rocks of the Animikie Group were deposited nonconformably on the Archean basement in a foreland basin over much of the western portion of the Lake Superior area, ca. 1.875 billion years ago (Fralick et al., 2006). Rocks of the Animikie Group are not known to occur within the Nipigon area, but their presence in the Sibley Peninsula to the southwest of the Nipigon area and along the Lake Superior coast to the southeast suggests that rocks of the Animikie Group likely covered much of the Nipigon area during the Paleoproterozoic Era. The Animikie Group includes the Gunflint Formation and the overlying Rove Formation. Only the Rove Formation has been mapped in the immediate vicinity of the Nipigon area, although the Gunflint Formation is extensively preserved further west toward Thunder Bay. The Rove Formation consists of shale grading upwards to shale interbedded with arkosic wacke. The Rove Formation is approximately 600 m thick in the vicinity of Squaw Bay on the Sibley Peninsula (Geul, 1973). Impact of the Penokean Orogeny and a younger ca. 1.75 billion year Yavapai Orogeny (Piercey, 2006) is known in the Lake Superior area; nevertheless, the possible effects of any of these orogenies are not clear in the Nipigon area.

Following the deposition of the Animikie Group, erosional conditions returned and prevailed within the Nipigon area (Cheadle, 1986), reshaping the Archean paleosurface at the time of deposition of the Sibley Group. Deposition of the sedimentary rocks of the Sibley Group began sometime later than ca. 1.657 billion years ago and continued until approximately 1.3 billion years ago (Hart, 2005). Heaman and Easton (2006) give a maximum age of 1.5 billion years for sedimentation in the Sibley Group. The Sibley Group is a generally unmetamorphosed, relatively flat-lying sedimentary rock sequence that occurs over much of the southern and western margin of the Nipigon area and extends beyond the area to the north, south and west (Figure 3). The Sibley Group unconformably overlies the Rove Formation of the Animikie Group and, more commonly in the Nipigon area, the Archean rocks of the Quetico Subprovince. The preservation of the sedimentary rocks of the Sibley Group to the north of Lake Nipigon suggests an original distribution over a much wider area than at present.

Tectonic activity took place during deposition of the Sibley Group, controlling its deposition with the development of a north-south-oriented half-graben and increasing the basin subsidence (Rogala et al., 2007). The syn-depositional tectonic activity has been ascribed to a sixth deformation period, D_6.

Around ca. 1.15 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. This major rifting event was associated with the deposition of large volumes of volcanic rocks (e.g., the Osler Group at ca. 1.108 billion years) and voluminous emplacement of mafic intrusions, including the areally extensive ca. 1.115 to 1.105 Ga Nipigon sill complex (Heaman and Easton, 2006; Heaman et al., 2007), and the smaller ca. 1.119 to 1.106 billion year old Hele intrusion (Hart, 2005; Heaman and Easton, 2006) located along the west side of the Black Sturgeon River (Figure 3). Nipigon diabase sills are relatively thin generally flat-lying mafic rocks that intrude and sometimes overlie the other rock types in the Nipigon area, and extend far to the north, beyond the north shore of Lake Nipigon. Uplift and erosion of bedrock occurred over a protracted period following the rifting event.

During the Paleozoic Era, commencing in the late Cambrian Period to early Ordovician Period, some of the Nipigon area might have been submerged beneath shallow seas and overlain by flat lying carbonate and shale formations; however, no Paleozoic cover has been recognized in the Nipigon area, either due to depositional hiatus or to its removal by subsequent uplift and erosion. The preservation of Jurassic and Cretaceous-age sedimentary rocks in the James Bay lowlands of Ontario suggests that marine transgression might also have affected the Nipigon area during the Mesozoic, but as with Paleozoic strata any trace of such sediments would have been subsequently removed through erosion. Weathering and erosion of the re-exposed Precambrian surface continued throughout the Cenozoic.

Table 1 Summary of the geological and structural history of the Nipigon area.

Time period (Ga)	Geological event
2.698 to 2.689	Sedimentation within the Quetico Subprovince; initial metamorphic event (M_1). Ca. 2.695 Ga D_1 deformation.
2.689 to 2.671	Main period of deformation ($D_{2\text{-}3}$) and metamorphism ($M_{2\text{-}3}$) of the metasedimentary rocks of the Quetico Subprovince. Characterized by collision between the Quetico accretionary prism and the Wawa-Abitibi terrane.
2.671 to 2.667	D_4 deformation and M_4 greenschist retrograde metamorphism.
<2.667 – 1.7	Supercontinent fragmentation and rifting in Lake Superior area produced voluminous magmatism and development of intracratonic basins. Emplacement of the ca. 2.475 to 2.45 Ga Matachewan dyke swarm. Emplacement of the ca. 2.121 to 2.101 Ga Marathon dyke swarm. Deformation associated with the ca. 1.9 to 1.7 Ga Penokean Orogeny in Lake Superior area; including deposition of the ca. 1.89 Ga Animikie Group. [D_5]
1.5 to 1.339	Deposition of the Sibley Group. [D_6]
1.150 to 1.1	Onset of rifting associated with Midcontinent Rift in the Lake Superior area. [D_7] Emplacement of the ca. 1.119 – 1.106 Ga Hele intrusion. Emplacement of the ca. 1.115 – 1.108 Ga Nipigon diabase sills. Deposition of volcanic rocks of the 1.106 Ga Osler Group.
< ca. 1.1 to present	Gradual erosion of bedrock alternating with deposition and subsequent erosion of strata during marine transgressions in the Paleozoic and Mesozoic, multiple generations of glacial erosion. [D_7]

The structural history in the Nipigon area is complex and poorly understood, owing to the absence of reliable geochronological data for many of the rocks within the area, and multiple lengthy periods of erosion. Recent geological investigations within the Nipigon area and its vicinity conclude that the region has undergone complicated polyphase deformation beginning at the time of sedimentation in the Quetico Subprovince (Valli et al., 2004; Zaleski et al., 1999).

The geological and structural history summarized below integrates the interpretations from throughout, and proximal to, the regional area shown on Figure 2. It is understood that there are potential problems in applying a regional deformation numbering (D_x) system into a local geological history. This summary provides an initial preliminary interpretation for the Nipigon area, which would need to be reviewed through detailed site-specific field studies.

The earliest recognized deformation event (D_1), occurred around 2.695 billion years ago, and was synchronous with on-going sedimentation in the Quetico Subprovince (Valli et al., 2004). D_1 involved folding and thrust imbrication and was accompanied by an upper amphibolite grade metamorphic overprint that occurred in response to the northward subduction of the Wawa Subprovince (Wawa-Abitibi terrane) beneath the Wabigoon Subprovince (Corfu and Stott, 1998; Valli et al., 2004). Subsequent deformation and peak metamorphism (D_2-D_3) occurred approximately 2.689 to 2.671 billion years ago, in a transpressive to compressive system (Sawyer, 1983; Williams et al., 1991), which Valli et al. (2004) divided into two deformation periods extending between 2.689 and 2.684 billion years (D_2) and 2.684 and 2.671 billion years (D_3), respectively. D_2-D_3 developed schistose to gneissic textures in the metasedimentary rocks at, in general, upper amphibolite grade metamorphic conditions, which were sufficient for the metasedimentary rocks to undergo in-situ partial melting in addition to attendant granitic intrusions (Williams, 1991; Hart, 2005). D_2-D_3 is attributed to the final collision – or docking – of the Wawa Subprovince (Wawa-Abitibi Terrane) against the Wabigoon Subprovince (Corfu and Stott, 1998). A subsequent deformation period, D_4, is constrained to have occurred between ca. 2.671 and 2.667 billion years. D_4 involved uplift and exhumation of the metasedimentary rocks of the Quetico Subprovince accompanied by a greenschist facies retrograde metamorphic overprint (Valli et al., 2004).

In addition to these published Archean deformation events, three additional structural events in the Nipigon area have been tentatively defined. D_5 represents a protracted interval of faulting/fracturing events that post-dated Archean deformation but pre-dated the onset of deposition of the sedimentary rocks of the Sibley Group ca. 1.657 billion years ago (Hart, 2005). Though several major dyke swarms were emplaced across the Superior Province during this time interval, the Paleoproterozoic Animikie Group sedimentary sequence is the only clear indicator of activity in the region around the Nipigon area. D_6 includes the faulting/fracturing events that coincided with, and post-dated, deposition of the Mesoproterozoic Sibley Group. Subsequently, rift and post-rift structures associated with development and re-activation of a failed arm of the Midcontinent Rift are included herein as a poorly-constrained D_7 event extending to present. The D_7 structures are interpreted to have controlled emplacement of the Nipigon sills, and likely included the re-activation of most pre-existing structures in the Nipigon area. Post-rift deformation, though possibly important in terms of potential continued re-activation of pre-existing structures, cannot at this stage be confidently distinguished from the rift-related structures. In addition, it is likely that at least some of the D_5 to D_7 faulting was controlled by the re-activation of pre-existing structures in the older bedrock.

2.4 QUATERNARY GEOLOGY

Information on Quaternary geology in the Nipigon area is described in detail in the terrain report (JDMA, 2014) and is summarized here. The Quaternary deposits in the Nipigon area (Figure 4) accumulated during and after the last glacial maximum, known as the Late Wisconsinan glaciation. The Mackenzie and Dog Lake moraines, located to the southwest of the Nipigon area, are thought to have been formed during the Marquette advance about 10,000 years ago (Burwasser, 1977). Ice front fluctuations led to the subsequent deposition of the Eagle-Finlayson, Hartman and Lac Seul moraines, successively from south to north in the area to the west of Nipigon. Within the Nipigon area the most prominent moraine is the Nipigon moraine, which was formed along the west and south side of Lake Nipigon (Zoltai, 1965b) and extends into the northwest and south central portion of the Nipigon area including the settlement area of Nipigon.

A kame terrace on the west margin of the Nipigon valley, west of Helen Lake was formed against the ice margin when the ice sheet partly occupied the valley (Mollard and Mollard, 1981a, b). Outwash sediments consisting of sand and gravel, interpreted to have been deposited in flooded lowlands and valley bottoms in front of the ice sheet (Mollard and Mollard, 1981a, b), are mapped south of Fog Lake and along parts of the Black Sturgeon and Jackpine rivers (Figure 4). Rhythmically bedded silts and clays deposited in glacial Lake Minong are mapped in low-lying parts of the Nipigon area. The thickness of these lake sediments is about 3 m on average and up to a possible maximum of 10 m (Zoltai, 1965a). Glaciolacustrine deltas expected to range in texture from sandy gravel and coarse sand to fine sand and silty sand (Mollard and Mollard, 1981a, b) are mapped locally within the Nipigon area, such as near the mouths of the Nipigon and Jackpine rivers. Raised beach deposits composed of sand, silt, clay and gravel are mapped along the margins of rock ridges and mesas fronting onto Lake Superior.

Information on the thickness of Quaternary deposits in the Nipigon area was largely derived from a small number of water well records for rural residential properties predominantly along the highways, and from diamond drill holes. A more detailed accounting of recorded depths to bedrock in the Nipigon area is provided by JDMA (2014). Diamond drill hole records and water well records in the area show overburden thickness to be up to about 100 m.

2.5 LAND USE

Land use within the Nipigon area includes mostly forestry and linear infrastructure corridors like roads, railways, pipelines and electrical transmission lines. Several active gravel pits are present. These features do not negatively impact the interpretation of bedrock lineaments. There are currently no active mines in the Nipigon area. The Nipigon area is also popular for recreation.

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 Nipigon area. 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 allowed for the identification of surficial lineaments as short as a few hundred metres in length. The CDED and SPOT datasets had unique advantages for characterization of surficial lineaments. The higher resolution of the SPOT imagery allowed for finer structures to be identified that were not resolved by the CDED data, whereas the CDED data often revealed subtle trends masked by the surficial cover in the SPOT imagery. The geophysical dataset for the Nipigon area (Figure 7) consisted of low resolution coverage across the eastern part of the Nipigon area with high resolution data available only for the western third of the area. The higher resolution data allowed greatly improved definition of aeromagnetic lineaments compared to the remainder of the Nipigon area. In all cases, the best resolution data was used for the geophysical lineament interpretation. The aeromagnetic data proved useful to interpret lineaments potentially indicative of bedrock structures, particularly 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 (CDED), 1:50,000 scale, 0.75 arc second (20 m) elevation models (GeoBase, 2011a) served as important data sources for analyzing and interpreting the lineaments in the Nipigon area (Figure 5). The digital elevation model (DEM) used for this assessment, 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 Nipigon area. 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 Nipigon area (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). Two SPOT images (or 'scenes') provided complete coverage for the Nipigon area (Table 4). The scenes are from the SPOT 4 and 5 satellites, with acquisition dates from 2005 (July) and 2008 (August). 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 Nipigon 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 Nipigon area	2005 - 2008	Panchromatic mosaic used for mapping
Geophysics	GSC Regional Magnetic Compilation (Ontario #8)	Geological Survey of Canada	805 m line spacing Sensor height 305 m	Mainly east	1962	Lowest resolution dataset
	Lake Nipigon Embayment (GDS1047)	Ontario Geological Survey	150 m line spacing Sensor height 100 m	West and northwest	2003	High resolution dataset, includes radiometric data
	Nipigon Bay (GDS1226)	Ontario Geological Survey	350 m line spacing Sensor height 39 m	Southeast	1994	Medium resolution, includes Geotem electromagnetic data

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

NTS Tiles:	Ground resolution (m)
42D/13	20
42E/04	20

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

Scene ID	Satellite	Date of image
S4_08843_4857_20080824	SPOT 4	August 24, 2008
S5_08806_4857_20050706	SPOT 5	July 06, 2005

For quality control, Natural Resources Canada (NRCan) provides images that have a maximum of 5% snow and ice cover, 5% cloud cover and a maximum viewing angle of 15°. NRCan orthorectified the SPOT images using three data sources: 1:50,000 scale Canadian Digital Elevation Data (CDED), National Road Network (NRN), and Landsat 7 orthoimagery. The orthoimages are provided in GeoTIFF format, projected using Universal Transverse Mercator

(UTM) projection referenced to the North American Datum 1983 (NAD83). A comparison of lake shorelines in the SPOT imagery with those delineated in the Ministry of Natural Resources (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 Nipigon area to allow for the mapping of continuous lineaments extending beyond the Nipigon area.

3.1.2 GEOPHYSICAL DATA

The geophysical dataset incorporates aeromagnetic, gravity and radiometric data available across the entire Nipigon area, and a small portion of electromagnetic coverage. However, only aeromagnetic data were used for this lineament interpretation. The variable resolution of the other data was insufficient to interpret lineaments. Table 2 provides a summary of the acquisition parameters for each aeromagnetic dataset used. The magnetic data located within the Nipigon area 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 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 Nipigon area. The quality of geophysical data varied significantly from west to east across the Nipigon area, as a function of the flight line spacing, the flying height and the age of the survey (Table 2). The integrity of the higher quality data was maintained throughout and the poorest resolution data were only used where higher resolution data were unavailable. It was determined that overall the quality of the data was sufficient to perform the lineament interpretation at the scale of the Nipigon area.

The majority (roughly 60%) of the Nipigon area to the east 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. These data were acquired at a flight line spacing of 805 m and a sensor height at 305 m.

Two higher resolution surveys, published by the Ontario Geological Survey (OGS), were available for use in the lineament interpretation. These include the Lake Nipigon Embayment survey (OGS, 2004) that covers the western part of the Nipigon area with a flight line spacing of 150 m and a sensor height of 100 m, and the Nipigon Bay survey (OGS, 2003) that extends into the southeast corner of the Nipigon area with a flight line spacing of 350 m and sensor height of 39 m (Figure 7).

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 Nipigon area, 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 5. 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 each associated attribute field is populated for interpreted lineaments 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.

The geophysical dataset also allowed the interpreter to assess the feature type of the lineament. Dyke lineaments were commonly characterized as linear traces in which the magnetic signal of the features were higher than the surrounding bedrock, though a few were interpreted with having a lower magnetic signal than the surrounding bedrock (PGW (2014) Section 5.2.1). Brittle geophysical lineaments were commonly interpreted as linear features along a steep magnetic gradient or less commonly as linear features with magnetic signals lower than the surrounding bedrock. The ductile lineaments, representing the internal fabric of the rock units, were traced as curvilinear features using the geophysical data. 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.

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.

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, was carried forward into the final mapped interpretation. Otherwise, a lineament was segmented and attributed according to the partial coincidence of overlapping lineaments, and the partial segments were carried forward into the final mapped interpretation as individual lineaments. Where two segments share a common end node, the combined length is used for the length value 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 section provides an overview of results of these surface-based interpretations.

A total of 659 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 376 m to 73.7 km, with a geometric mean length of 2.1 km and a median length of 1.9 km. A total of 497 of the CDED lineaments (75%) were assigned a certainty value of 3. Certainty values of 2 and 1 were assigned to 135 (21%) and 27 (4%) of the CDED lineaments, respectively. The RA_1 reproducibility assessment shows coincidence between the two pickers for 310 of the CDED lineaments (47%, RA_1 = 2) and a lack of coincidence for 349 of the CDED lineaments (53%, RA_1 = 1). When plotted on a rose diagram weighted by length, CDED orientations show a dominant trend to the north-northwest (about 340°) with secondary trends to the north (about 005°) and north-northeast (about 025°) and less prominent but consistent trends to the west-northwest (about 295°) and east-northeast (about 060°) (Figure 8 inset).

The SPOT lineament dataset compiled from the merger of lineaments identified by the two interpreters yielded a total of 1,374 lineaments that range in length from 163 m to 163.1 km, with both a geometric mean length and a median length of 1.2 km (Figure 9). Seventy eight percent (78%) of the SPOT lineaments, a total of 1,068, were assigned a certainty value of 3. Certainty values of 2 and 1 were assigned to 285 (21%) and 21 (1%) of the SPOT lineaments, respectively. The reproducibility assessment shows coincidence for 454 (33%) of the SPOT lineaments (RA_1 = 2), and a lack of coincidence for 920 (67%) of the SPOT lineaments (RA_1 = 1). When the azimuths are plotted on a rose diagram weighted by length (Figure 9 inset), several distinct trends appear. The strongest trend appears to the east-northeast (060º). Other main tends include to the northwest (330º), north (two trends at 355º and 005º), and north-northeast (025º). Less prominent, but consistent, trends appear to the east-southeast (about 295°) and west-southwest (about 080°).

Orientation data for the SPOT lineaments appear to be more uniformly distributed than those for the CDED lineaments, with only broadly comparable dominant orientations of west-northwest and east-northeast. Both the surficial datasets show a northerly trend. The more uniform distribution of the SPOT lineament orientations reflects, in part, the higher resolution of this dataset, which allowed for the identification of numerous short subtle lineaments that were not discernible in the lower resolution CDED.

4.1.2 Geophysical data

The airborne geophysical data interpretation was able to distinguish between features that could be interpreted as brittle or dyke (Figure 10) or ductile (Figure 11) lineaments. The ductile features are useful in identifying the distribution of main lithological variations and structure within the metasedimentary rocks of the Nipigon area. In this report, the ductile lineaments are shown to provide context to our understanding of the tectonic history of the Nipigon area, but were not included in the statistical analysis undertaken with the lineament dataset. Therefore the following discussion relates only to those lineaments interpreted as brittle or dyke lineaments.

A total of 269 lineaments comprise the dataset of merged lineaments identified by the two interpreters from the geophysical data (Figure 10). Of these geophysical lineaments, 250 are interpreted as brittle lineaments, while 19 are interpreted as dykes (Figure 10). Among the geophysical lineaments interpreted as brittle, most were unclassified with respect to relative displacement, but both dextral (3) and sinistral (5) movements were identified. The lengths of the brittle lineaments ranged from 358 m to 47.6 km, with a geometric mean length of 3.0 km and a median length of 2.2 km. Orientations of the brittle lineaments, weighted by length and plotted on a rose diagram (Figure 10 inset), exhibit several strong trends, particularly to the east-northeast (065º) and north-south, east-west, and northwest (330º).

Geophysical lineaments interpreted as dykes (19) ranged in length from 570 m to 10.1 km, with a geometric mean length of 3.5 km and a median length of 3.2 km. Orientations of the dyke lineaments include notable trends to the north (010º) north-northeast (025º), east-northeast (065º) and northwest (330º).

Certainty values of 3, 2, and 1 were assigned to 201 (80%), 31 (12%), and 18 (8%) lineaments representing the geophysical brittle lineaments, respectively. The reproducibility assessment (RA_1) of brittle lineaments identified coincidence for 13 lineaments (5%) (RA_1 = 2) and a lack of coincidence for 237 lineaments (92%) (RA_1 = 1). The reproducibility assessment identified coincidence for 5 of the interpreted dykes (26%) (RA_1 = 2) and a lack of coincidence for 14 of the interpreted dykes (74%) (RA_1 = 1). The RA_1 for geophysical lineaments in the Nipigon area is low, due to a number of factors including the generally complex geology that includes sills overprinting magnetic signatures from other geologic units. An additional complicating factor was the very low aeromagnetic resolution across much of the Nipigon area coupled with the fact that one interpreter tended to pick many short lineaments while the other tended to highlight the longer features.

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 geophysics 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, and includes a length-weighted frequency rose diagram as an inset. The merged lineaments were classified by length using four length bins: >10 km, 5-10 km, 1-5 km and <1 km, in order to emphasize the longer features. The merged lineament dataset contains a total of 1,806 lineaments that range in length from 163 m to 167.2 km. The geometric average length of these lineaments is 1.4 km and the median length is 1.4 km. Lineaments in the >10 km and 5-10 km length bins represent 2% and 5% of the merged lineaments, respectively, while lineaments in the 1-5 km and <1 km length bins represent 58% and 35% of the merged lineaments, respectively. Azimuths of the merged lineaments (inset of Figures 12 and 13) exhibit numerous trends that cluster to the north-northwest, north, and northeast. The north-northwest cluster features a dominant trend at about 340º. Lineaments oriented northward follow two main trends at about 355º and 005º. The strongest trend in the data is toward the east-northeast at 060º. 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.

Results from the reproducibility (coincidence) assessment 2 (RA_2) for this dataset show 29 lineaments (1%) were identified and coincident on all three datasets (RA_2 = 3), and 497 lineaments (28%) were coincident with a lineament from one other dataset (RA_2 = 2). A total of 1,280 lineaments (71%) 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 18% (45 out of 250) of the brittle lineaments were coincident with a mapped surficial lineament, and 21% of the dykes (4 out of 19) were coincident with a mapped surficial lineament.

4.3 DESCRIPTION OF LINEAMENTS BY MAJOR GEOLOGICAL UNIT

The bedrock geology of the Nipigon area consists of Archean metasedimentary rocks and granitic intrusions of the Quetico Subprovince (Superior Province), Proterozoic sills and intrusions, and sedimentary rocks of the Sibley Group of the Southern Province (Figure 3). The Archean metasedimentary rocks, which dominate the Nipigon area, covering 807 km^2 at surface, contain a total of 1,298 lineaments. This geological unit exhibits relatively rugged topography with the most extensive bedrock exposure in the Nipigon area, allowing for confident identification of lineaments. Because surficial cover is limited in extent and thickness, there is a high density of interpreted surficial lineaments. Throughout the unit, lineaments exhibit a distinct east-west trend that represents the gneissic foliation. There are also strong trends to the north, northwest, and northeast.

For this discussion, the Archean metasedimentary rocks are separated into two domains defined by the boundary between high- and low-resolution aeromagnetic datasets (Figure 14). Lineaments that cross this boundary were counted twice (once for each side). The western domain, over which there is high-resolution aeromagnetic data, covers an area of about 275 km^2 and includes 459 lineaments that range in total length from 308 m to 73.7 km. Orientation data for these lineaments show prominent trends to the north-northwest, north, and east-northeast (Figure 14). The larger eastern domain, covering 532 km^2, contains 858 lineaments ranging in total length from 170 m to 167.2 km. While the orientation trends noted from the western domain appear in the eastern domain, there are several notable differences; specifically, a dominant trend to the east-northeast (060º) that may be influenced by the proximity to the Gravel River fault located immediately outside the southeastern boundary of the study area. Additionally, trends to the north-northeast (025º) and to the west-northwest (300º) are dominant in the eastern domain.

The Nipigon area features extensive sedimentary rocks of the Sibley Group that cover an area of approximately 235 km^2 from which a total of 278 lineaments were mapped. Sibley Group sediments appear mostly to the west of the Black Sturgeon fault zone and in a smaller area east of Helen Lake. Lineaments interpreted from the Sibley Group exhibit several orientations and appear to extend across the unit boundaries. The most dominant orientation is at 340º, which corresponds to the Black Sturgeon fault zone (Figure 14).

Nipigon sills, often expressed as topographic highs, such as the Kama hills, cover approximately 166 km^2 of the Nipigon area. Lineamentsmapped from the sills (414 in total) appear as distinct traces that extend into adjacent rock units and are often relatively long and unbroken. Orientation data indicate a dominant trend to the north-northwest (Figure 14).

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 refers to the length of lineaments per unit area. Lineament density was calculated using the line density method described in ESRI ArcGIS software, which determines the length of lineaments 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.

Lineament density differs markedly across the Nipigon area, ranging between 0 and 5.5 km/km^2, which reflects differences in lithology and bedrock exposure. The highest surficial lineament densities are observed in the eastern portion of the study area, east of the Jackpine River and in the area east of the Black Sturgeon fault zone to Helen Lake. Both of these areas are underlain by Archean metasedimentary rocks with limited surficial cover that allows for well-expressed bedrock structure. The lowest lineament densities appear closely related to areas of Sibley Group sedimentary rocks and areas covered by surficial deposits. Geophysical lineament density is moderate across the western portion of the Nipigon area reflecting the high resolution coverage in this area. Geophysical coverage is of low resolution across the eastern part of the Nipigon area and this is reflected in a uniformly low density of geophysical lineaments. This locally biases the lineament density calculations and the apparent geophysical lineament density in the high resolution western portion likely provides a truer indication of the geophysical lineament density across the Nipigon area

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 (Figure 12). 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 specific 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 47% of CDED lineaments and 33% of SPOT 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 shows that only 8% of the lineaments were identified by both interpreters (Figure 10). This low reproducibility for geophysical lineaments is thought to be due to the relative complexity of the geology in the Nipigon area. Although reproducibility for geophysical lineaments was relatively low, individual interpreters generally gave their picks a high certainty value (78% Certainty = 3).

The reproducibility of lineament interpretations was further tested by comparing the mapped lineaments picked by two interpreters in this study to the lineament analysis conducted as part of the Lake Nipigon Region Geoscience Initiative, Miscellaneous Release Data - 140 (MRD-140) (Barnett and Shirota, 2004). Although overlapping only with the northwest portion of the Nipigon area, the lineament analysis conducted by Barnett and Shirota (2004) include interpretations from various datasets (air photos, Landsat, CDED, hillshade CDED) that provide an independent test of lineament reproducibility. With rare exceptions, each of the surficial lineaments mapped by Barnett and Shirota (2004) were identified in the corresponding dataset used in this study of the Nipigon area.

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 29%. 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. In contrast, 3% of the geophysical lineaments were coincident with interpreted surficial lineaments. This low coincidence between surficial and geophysical lineaments is not unexpected, and may be the result of various factors, such as: deep structures that are identified in geophysics may not have a surface expression; 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.

Despite the low degree of coincidence, the observed overlap in dominant lineament orientation between all datasets (see insets on Figures 8, 9 and 10) suggests that all datasets are identifying the same regional structures. Among the lineaments with the best reproducibility are those associated with the major fault zones (Black Sturgeon and Jackpine River), as well as the systematic north-trending features across the entire Nipigon area.

Coincidence among lineaments appears to be highest in areas of thin surficial cover and in metasedimentary units and felsic intrusions. The highest coincidence values (RA_2 = 3) are found in the western half of the Nipigon area that lies east of the Black Sturgeon fault zone. Here, north-south trending geophysical lineaments have a surficial expression recorded in the CDED and SPOT datasets. Similar coincidence of surficial lineaments with north-trending geophysical features is also observed in the eastern portion of the Nipigon area despite the low resolution of the aeromagnetic data in this area. The lowest coincidence values occur in areas of thick surficial cover and in the Sibley Group rocks.

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.

5.3 Lineament Length

There is no information available on the depth extent into the bedrock of the lineaments interpreted for the Nipigon area. 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 in the Nipigon area 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 of the higher confidence that the longer features identified are related to bedrock structures.

Figure 13 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 13). Two prominent lineament orientations to the north-northwest (340º) and east-northeast (060º) can be recognized in the length-weighted dataset.

5.4 FAULT AND LINEAMENT RELATIONSHIPS

As discussed in Section 2.2.8, there are a number of mapped structural features in the Nipigon area with established relative age relationships. The named mapped faults (OGS, 2011, MRD126) that relate to lineaments within the Nipigon area include the northwest to north-trending Black Sturgeon fault zone and the northeast trending Jackpine River fault (Figure 2), as well as the Gravel River fault, noting that this fault is located just outside the southeast corner of the Nipigon area. These structures exhibit distinct surficial expressions that were identified on both the CDED and SPOT datasets. In the aeromagnetic data, there are hints of the Jackpine River fault, but the low resolution of the data in this area prevented the interpretation of this feature. For the Black Sturgeon fault zone the aeromagnetic data suggested a broader disturbed zone 1-2.5 km wide, rather than a single brittle fault. The fault zone is characterized by a zoned aeromagnetic response (magnetic low and magnetic high) with a number of aeromagnetic linear features that may reflect zones of ductile shear.

Unnamed mapped faults (Hart, 2005; shown on Figure 3), with few exceptions, coincide with lineaments mapped in the Nipigon Area. Based on the compilation of interpreted lineaments orientations shown in the inset of Figures 12 and 13, the lineament sets identified herein appear to correspond in orientation to these features. Mapped dykes (OGS (2011) MRD126; shown on Figure 2) appear relatively long and continuous, but only a few short and discontinuous sections correspond to the lineaments mapped in the Nipigon area.

The principle neotectonic stress orientation in central North America is generally oriented approximately east-northeasterly (63º ± 28º; Zoback, 1992), although anomalous stress orientations have also been reported in the mid-continent that include a 90º change in azimuth of the maximum compressive stress axis (Brown et al., 1995) and a north-south maximum horizontal compressive stress (Haimson, 1990). Regardless of these local variations, and other potential complicating factors involved in characterizing crustal stresses, including, the effect of shear stress by mantle flow at the base of the lithosphere (Bokelmann, 2002; Bokelmann and Silver, 2002), the degree of coupling between the North American plate and the underlying mantle (Forte et al. 2010), and the influence of the thick lithospheric mantle root under the Canadian Shield, it is useful to attempt a preliminary comparison of the regional east-northeasterly neotectonic stress orientation with the orientation of each lineament set identified herein. The west-northwest lineament set would re-activate in a reverse or strike-slip sense, the NNW to N set would re-activate in a reverse to strike-slip sense, and the NE to ENE set would re-activate in a strike-slip sense, or in tension if the maximum principal stress is vertical.

5.5 RELATIVE AGE RELATIONSHIPS

The main period of metamorphism in the Quetico metasedimentary rocks resulted in folding, and the development of gneissic fabrics that effectively destroyed any pre-existing lineaments. Therefore, it is probable that all brittle fractures visible as surface lineaments within the Nipigon area post-date M_2 at approximately 2.684 to 2.671 Ga. Other stratigraphic age constraints are offered by the Sibley Group sediments at ca. 1.670 to 1.339 Ga and the younger Nipigon sills at ca. 1.113 to 1.110 Ga. Up to four deformation events have been recognized within the Quetico Subprovince (Sawyer, 1983; Williams, 1991; Zaleski et al., 1999) but all of these date to the Archean with the youngest D_4 is represented by small-scale shear zones that cut the earlier formed planar and folded fabrics (Sawyer, 1983). Valli et al. (2004) give an age of 2.671 to 2.667 Ga for D_4.

In addition to these published Archean deformation events, three additional, hypothetical, structural events are identified for the Nipigon area. D_5 represents faulting/fracturing events that post-date Archean deformation but predate the deposition of the Sibley Group metasedimentary rocks ca. 1.657 to 1.450 Ga (Hart, 2005). D_6 includes faulting/fracturing events that crosscut the Sibley Group but do not crosscut the younger ca. 1.113 to 1.111 Ga Nipigon sills (Heaman et al., 2007). Finally, D_7 includes events that postdate the emplacement of the Nipigon sills and their near-contemporaneous mafic intrusions such as the Hele intrusion.

Examination of mapped surface lineaments reveals that the greatest proportion crosscut the youngest rock unit in the area, the Nipigon sills, and hence post-date 1.113 to 1.111 Ga. Few obvious truncations are visible and these are mostly ambiguous. Therefore, all mapped surface lineaments are assigned to the D_5 to D_7 interval with the understanding that they may also represent the reactivation of pre-existing (pre-D_5) structures in the underlying and older bedrock units.

With respect to the three main named faults on the Nipigon area, the Black Sturgeon fault zone clearly cuts and displaces 1.5 Ga Sibley Group sediments and is therefore D_6 or younger. The Gravel River fault offsets Quetico metasedimentary rocks by up to 50 km and so must post-date M_2. The Jackpine River fault and Gravel River fault appear to truncate Sibley Group sediments but in this case the relationship is ambiguous owing to the degree of lateral removal of these strata possibly resulting from the action of glacial melt waters in the Quaternary. A possible southern extension of the Gravel River fault cuts Osler Group volcanics in the St. Ignace archipelago suggesting that movement along this fault post-dates ca. 1.0 Ga and may be assigned to D_7.

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 Nipigon area, 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.

Lineaments were mapped from multiple, readily-available datasets that include digital elevation models (CDED), satellite imagery (SPOT), and geophysical survey data. The total number of lineaments interpreted from these data sources were 659, 1,374, and 269, respectively. The distribution of lineaments in the Nipigon area reflects the bedrock structure, resolution of the datasets used, and surficial cover. Surficial lineament density ranged between 0 and 5.5 km/km^2, reflecting differences in the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures. Lineament density was observed to be highest in the eastern and western parts of the Nipigon area, where thin surficial cover and exposed bedrock revealed numerous fractures in the crystalline rock. The lowest lineament densities were observed in the central part of the Nipigon area where relatively thick surficial deposits cover sedimentary rocks of the Sibley Group. Geophysical lineament density is moderate across the western third of the Nipigon area reflecting the high resolution coverage in this area. Geophysical coverage is of low resolution across the eastern part of the Nipigon area and a uniformly low density of geophysical lineaments was identified there.

Reproducibility (RA_1) and certainty of interpreted lineaments were highest for longer lineaments. These lineaments also have high coincidence values in the comparison of interpreted lineaments among the various datasets (RA_2). Higher coincidence values are observed between surficial lineaments interpreted from the CDED and SPOT datasets than between the surficial and geophysical lineaments. 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: deep structures identified in geophysics may not have a surface expression; 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 main trends in orientation observed for the merged lineaments from all sources include broad trends to the east-northeast, north-northwest, and north. These orientations are also approximately coincident with the orientations of mapped faults and dykes across the Nipigon area.

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REPORT SIGNATURE PAGE

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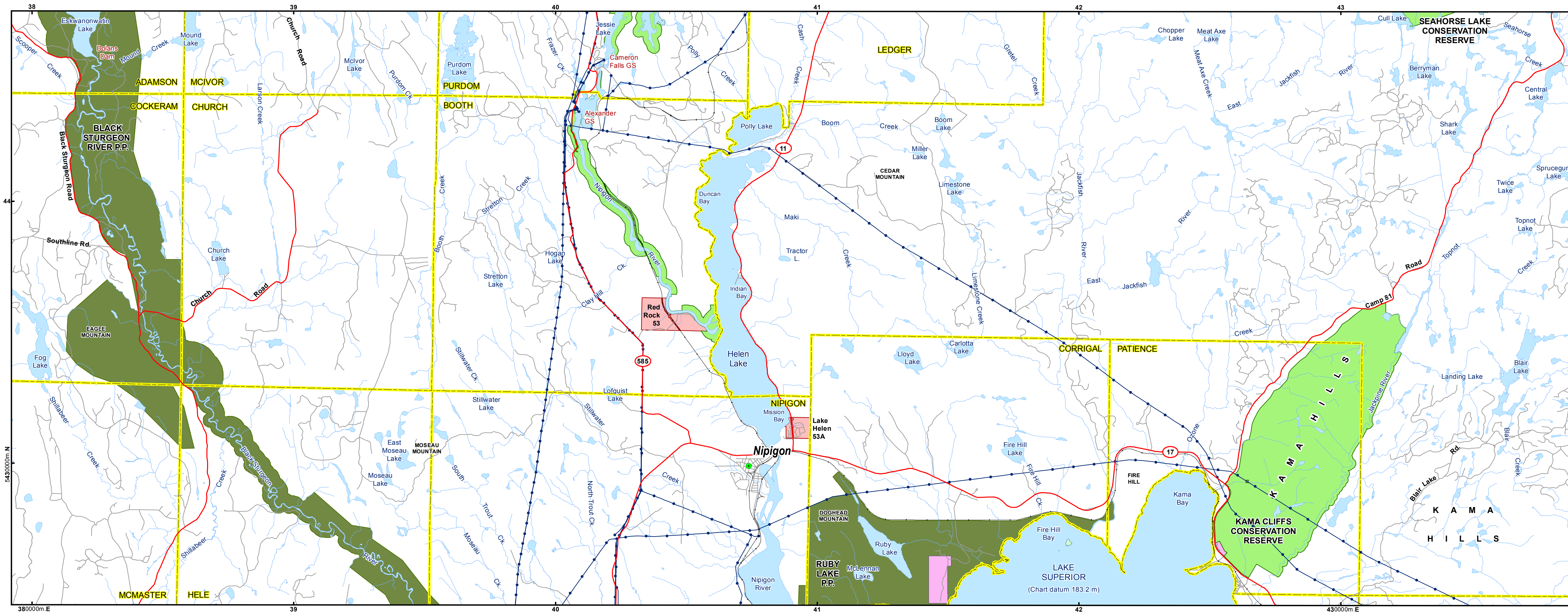
FIGURES



LEGEND

- Nipigon (settlement)
- Rail
- Main road
- Hydro line
- Local road
- Township
- Waterbody
- Watercourse
- Conservation Reserve
- Forest Reserve
- Provincial Park
- Recommended Conservation Reserve
- First Nation reserve

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Parks: LIO CLUPA Land use
Hydro line: Selected from LIO Utility

NORTH

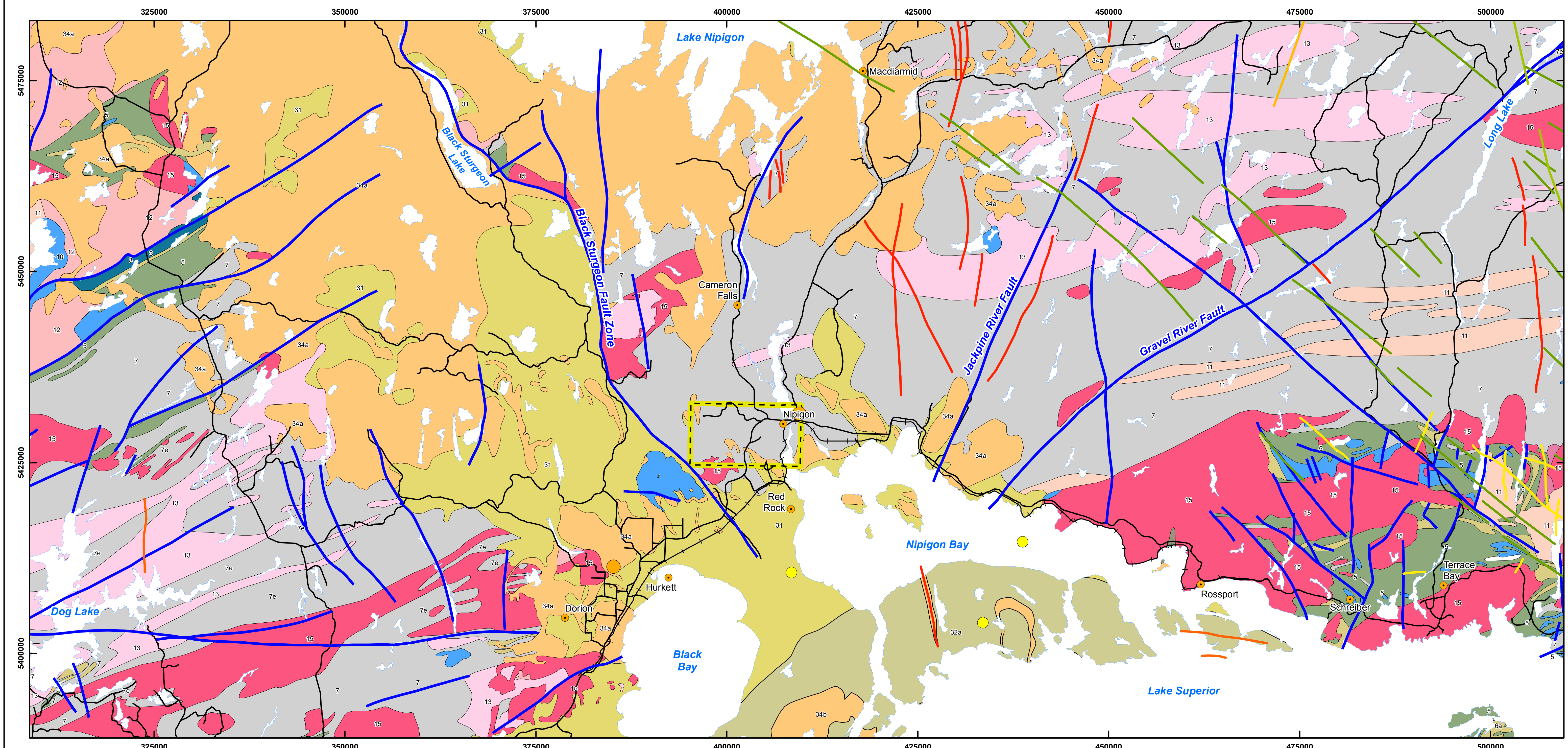
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
Township of Nipigon and surrounding area

DESIGN	DVZ	05 SEP 2013	FIGURE 1	REVISION 3
GIS	DSM	27 FEB 2014		UTM ZONE 16
CHECK	JIC	27 FEB 2014		NAD 1983
REVIEW	GS	27 FEB 2014		1:150,000



LEGEND

Municipal Boundary (Township of Nipigon)
Community
Main Road
Railway
Waterbody
Mapped Fault

Dykes and Sills
- Logan and Nipigon mafic sills
- Mafic sills and dykes
- Marathon, Kapuskasing or Biscotasing mafic dyke
- Matachewan mafic dyke
- Pickle Crow mafic dyke (Molson swarm) normal
- Unsubdivided mafic dyke (Keweenawan age)

Seismic events (Magnitude)
- < 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- > 3.0

Bedrock geology
- 34 Mafic and related intrusive rocks (Keweenawan age)
- 34a Logan and Nipigon sills: diabase sills
- 34b Mafic sills and dykes
- 32 Osler Gp., Maminse Point Fm., Michipicoten Island Fm.
- 32a Basalt and associated conglomerate and arkose
- 31 Sibley Gp.
- 24 Sedimentary rocks (Animikie Group)
- 24a Rove Formation: argillite, shale, wacke, minor volcanic rocks
- 15 Massive granodiorite to granite
- 15a Potassium feldspar megacrystic units
- 14-Diorite-monzodiorite-granodiorite suite
- 13 Muscovite-bearing granitic rock
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
- 7 Metasedimentary rocks (Paragneisses and Migmatites)
- 6 Felsic to intermediate metavolcanic rocks
- 6a Dacitic and Andesitic flows, tuffs and breccias
- 5 Mafic to intermediate metavolcanic rocks
- 3 Mafic metavolcanic and metasedimentary rocks

NORTH

10 km

Data sources:
DEM: 1:50,000 Hillshaded CDED
Seismic events: Earthquakes Canada (1985-2013)
Geology: MRD 126 Bedrock geology
Main road: LIO Ontario road segment
Waterbody: LIO OHN Waterbody

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
Regional tectonic setting of the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 2	REVISION 10
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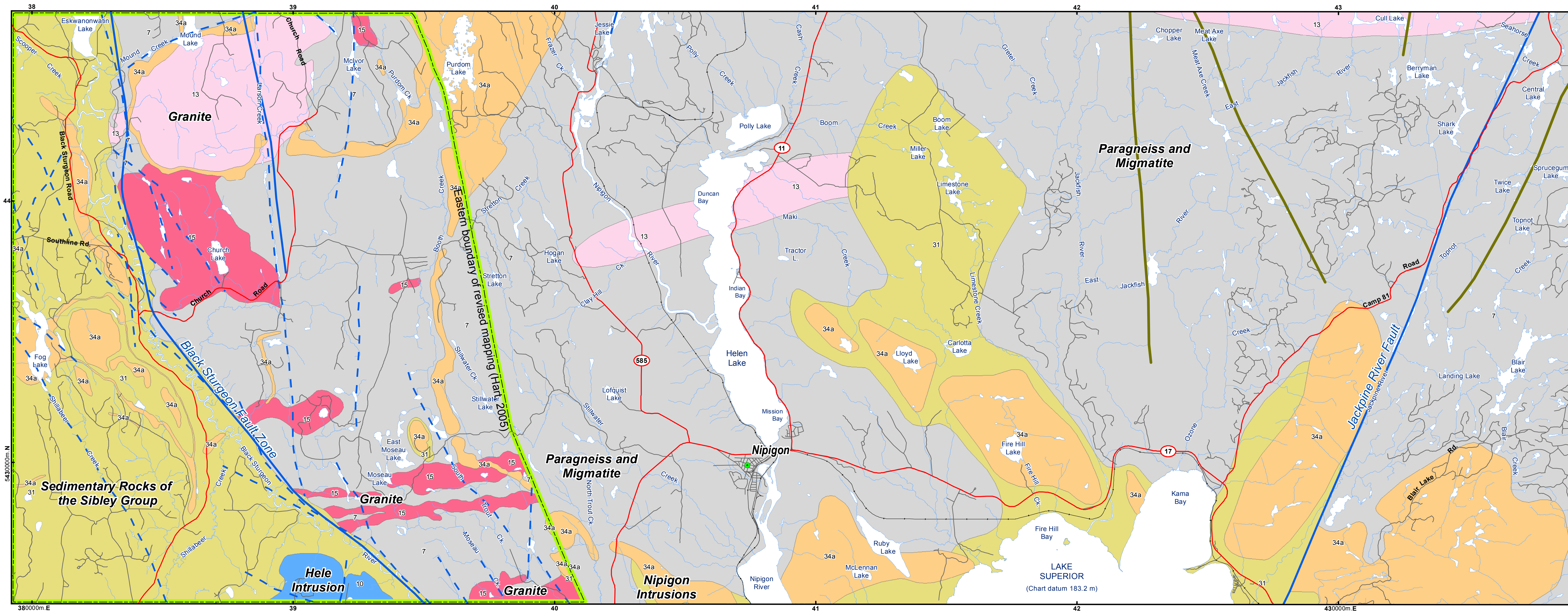
REVIEW	GS	04 JUN 2014		1:500,000



LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Rail
- Mapped fault
- Mapped dyke
- Lineament / fault (Hart, 2005)
- Waterbody
- Watercourse
- Revised mapping (Hart, 2005)

Bedrock geology

- 34 Mafic and related intrusive rocks (Keweenawan age)
- 34a Logan and Nipigon sills: diabase sills
- 31 Sibley Gp.
- 15 Massive granodiorite to granite
- 13 Muscovite-bearing granitic rock
- 10 Mafic and ultramafic rocks
- 7 Metasedimentary rocks (Paragneisses and Migmatites)

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Geology: OGS MRD 126 scale 1:250,000

NORTH

5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
Bedrock geology of the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 3	REVISION 7
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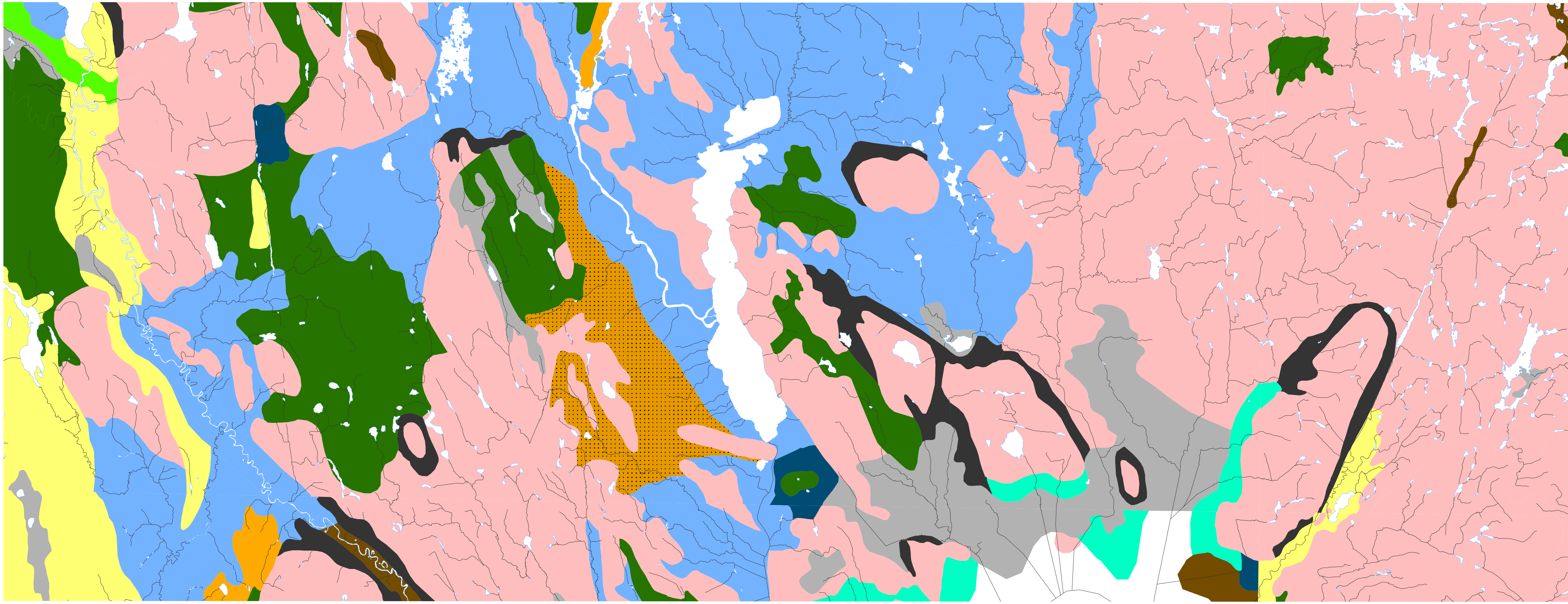
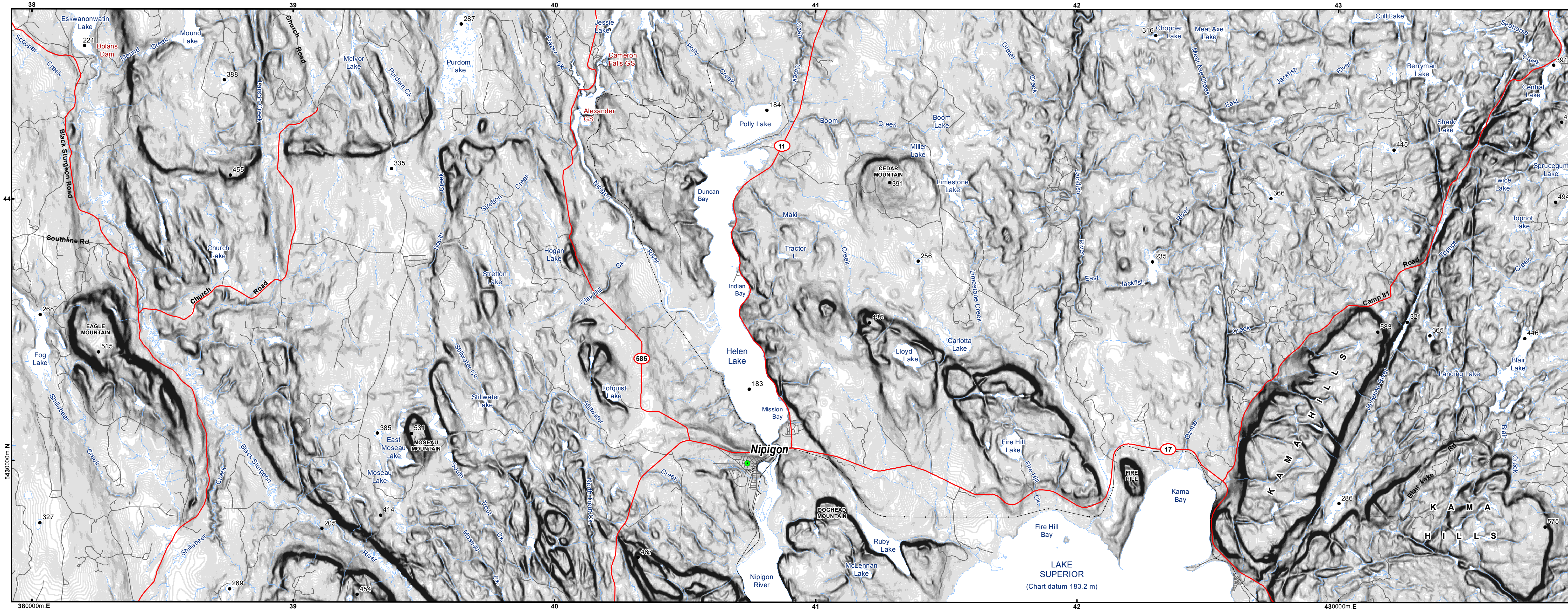
REVIEW	GS	02 JUN 2014		1:150,000





LEGEND

•	Spot height (m)	**Slope (°)**	
●	Nipigon (settlement)		0 - 0.4
	Main road		0.5 - 3.1
	Local road		3.2 - 5.7
	Rail		5.8 - 8.3
	Waterbody		8.4 - 10.9
	Watercourse		11 - 13.6
			13.7 - 16.2
			16.3 - 18.8
			18.9 - 56.4

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Rail: LIO Railway
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
DEM: GeoBase CDED 1:50,000

NORTH

5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
CDED digital elevation data for the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 5	REVISION 3
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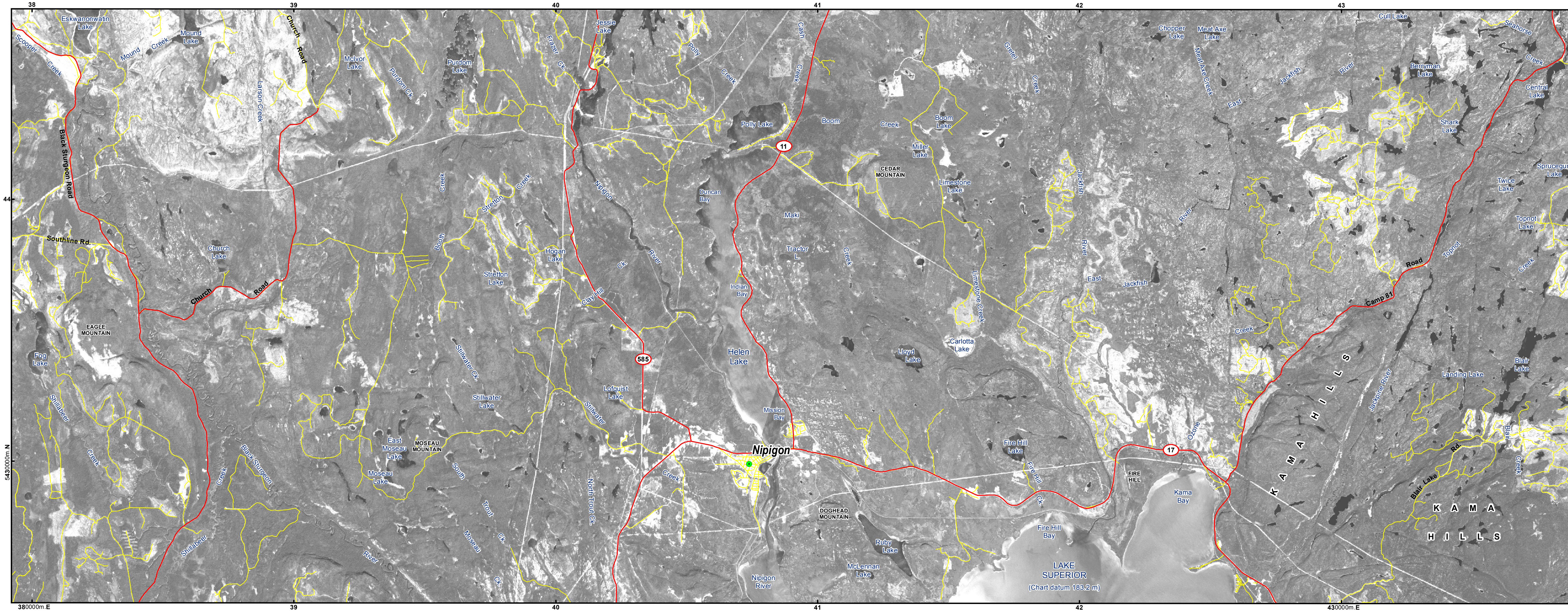
CHECK	JIC	30 MAY 2014		NAD 1983
REVIEW	GS	30 MAY 2014		1:150,000



LEGEND

- Nipigon (settlement)
- Main road
- Local road

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
SPOT: GeoBase (2013b)

NORTH

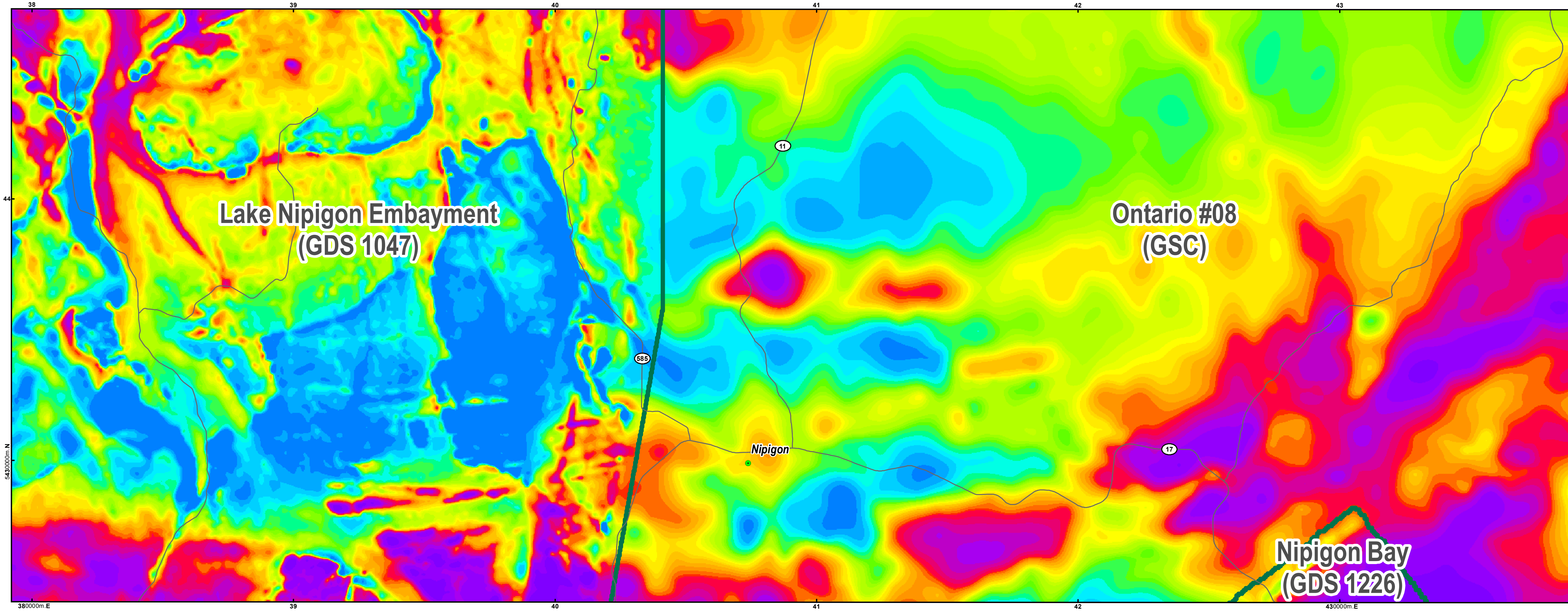
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
SPOT satellite data for the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 6	REVISION 2
GIS	DSM	05 DEC 2013		UTM ZONE 16
CHECK	JIC	05 DEC 2013		NAD 1983
REVIEW	GS	05 DEC 2013		1:150,000



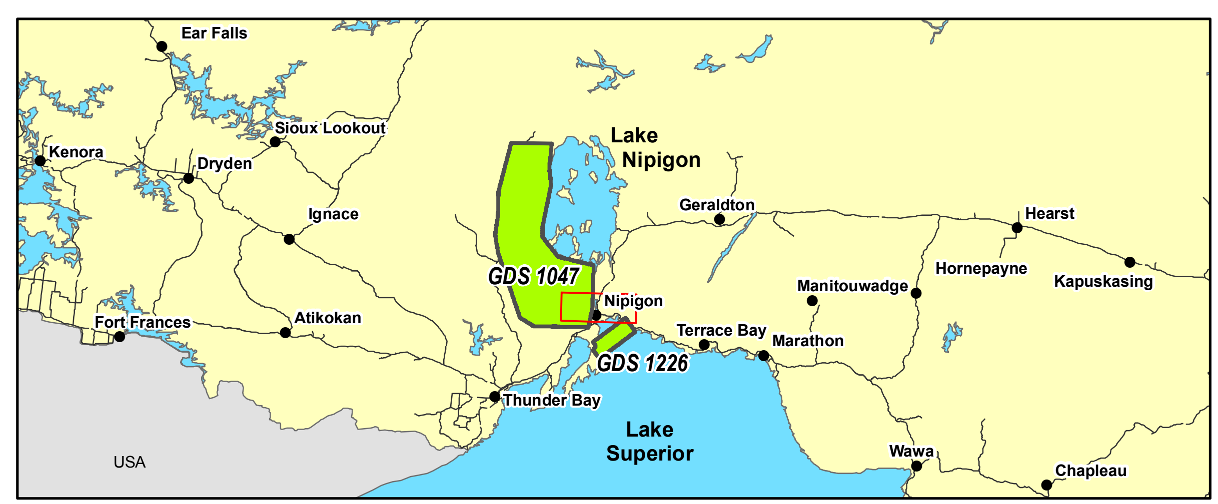
LEGEND

RTP (nT)

- 191 to 1,341
- 111 to 190
- 76 to 110
- 56 to 75
- 36 to 55
- 21 to 35
- 6 to 20
- 1 to 5
- -9 to 0
- -19 to -10
- -29 to -20
- -39 to -30
- -44 to -40
- -54 to -45
- -59 to -55
- -64 to -60
- -69 to -65
- -74 to -70
- -84 to -75
- -89 to -85
- -94 to -90
- -99 to -95
- -109 to -100
- -119 to -110
- -129 to -120
- -139 to -130
- -154 to -140
- -174 to -155
- -1,550 to -175

- Nipigon (settlement)
- Main road
- Nipigon survey outline

Data sources:
Hi-resolution Magnetics: Ontario #8, OGS GDS1047, GDS1226
Regional Magnetics: GSC nationwide compilation
Main road: LIO Ontario road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse



NORTH

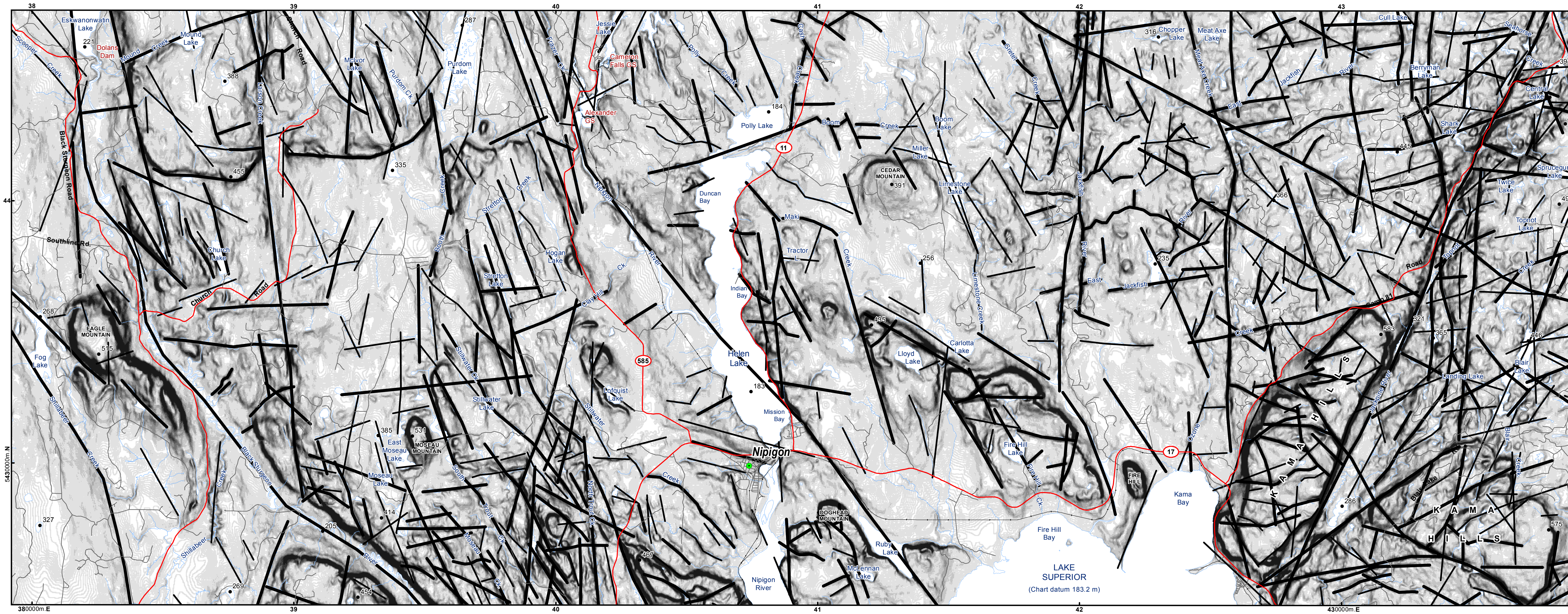
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
Pole reduced magnetic field for the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 7	REVISION 4
GIS	DSM	10 FEB 2014		UTM ZONE 16
CHECK	JIC	10 FEB 2014		NAD 1983
REVIEW	GS	10 FEB 2014		1:150,000



LEGEND

- Spot height (m)
- Nipigon (settlement)
- Main road
- Local road
- Rail

CDED lineament RA_1

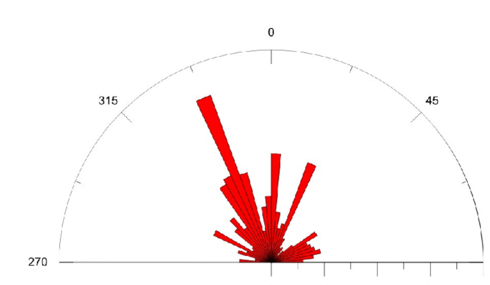
- 1
- 2
- Waterbody
- Watercourse

Slope (°)

- 0 - 0.4
- 0.5 - 3.1
- 3.2 - 5.7
- 5.8 - 8.3
- 8.4 - 10.9
- 11 - 13.6
- 13.7 - 16.2
- 16.3 - 18.8
- 18.9 - 56.4

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Rail: LIO Railway
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
DEM: GeoBase CDED 1:50,000

Nipigon CDED Data - Length Weighted Frequency Rose Plot



N = 659

NORTH

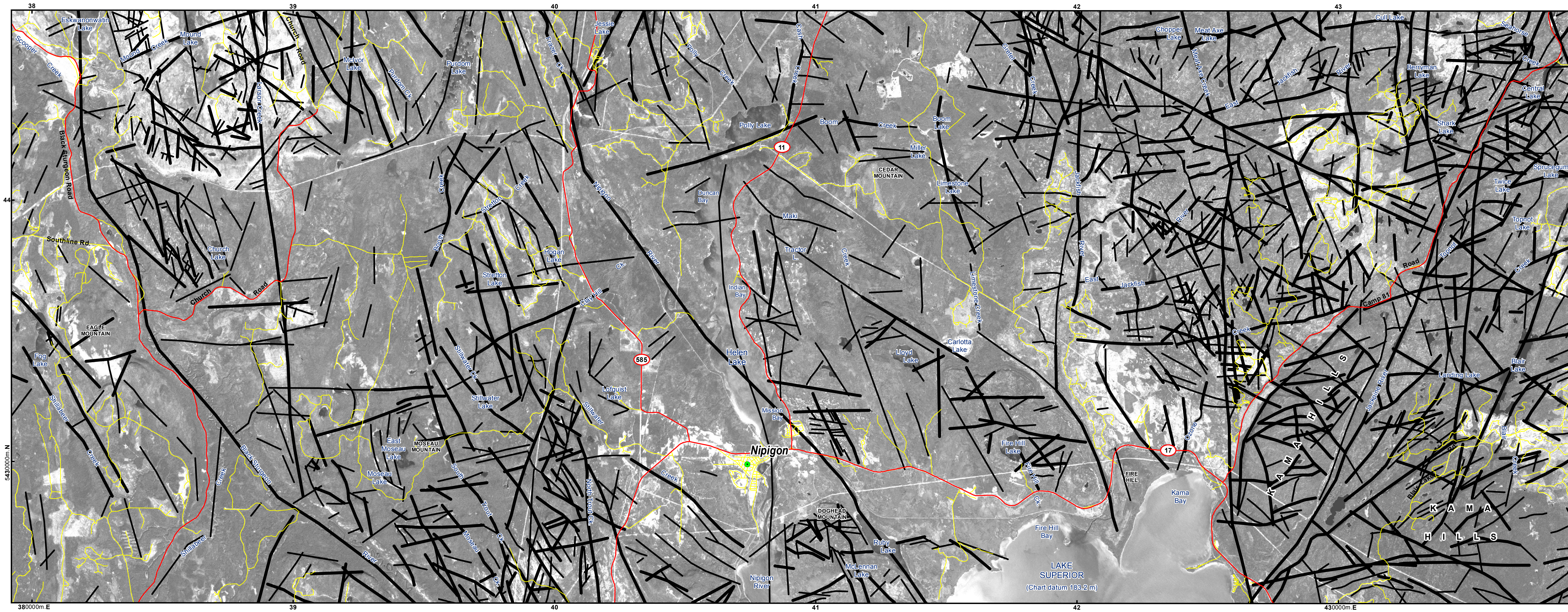
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
CDED reproducibility assessment (RA_1)

DESIGN	DVZ	05 SEP 2013	FIGURE 8	REVISION 2
GIS	DSM	30 MAY 2014		UTM ZONE 16
CHECK	JIC	30 MAY 2014		NAD 1983
REVIEW	GS	30 MAY 2014		1:150,000



LEGEND

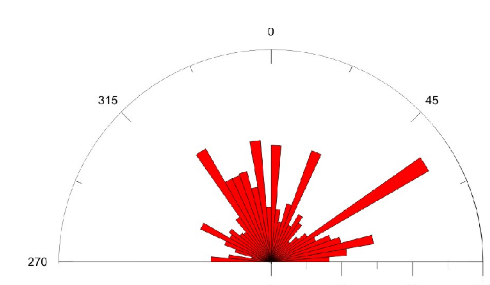
- Nipigon (settlement)
- Main road
- Local road

SPOT lineament RA_1

- 1
- 2

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
SPOT: GeoBase (2013b)

Nipigon SPOT Data - Length Weighted Frequency Rose Plot



N = 1,374

NORTH

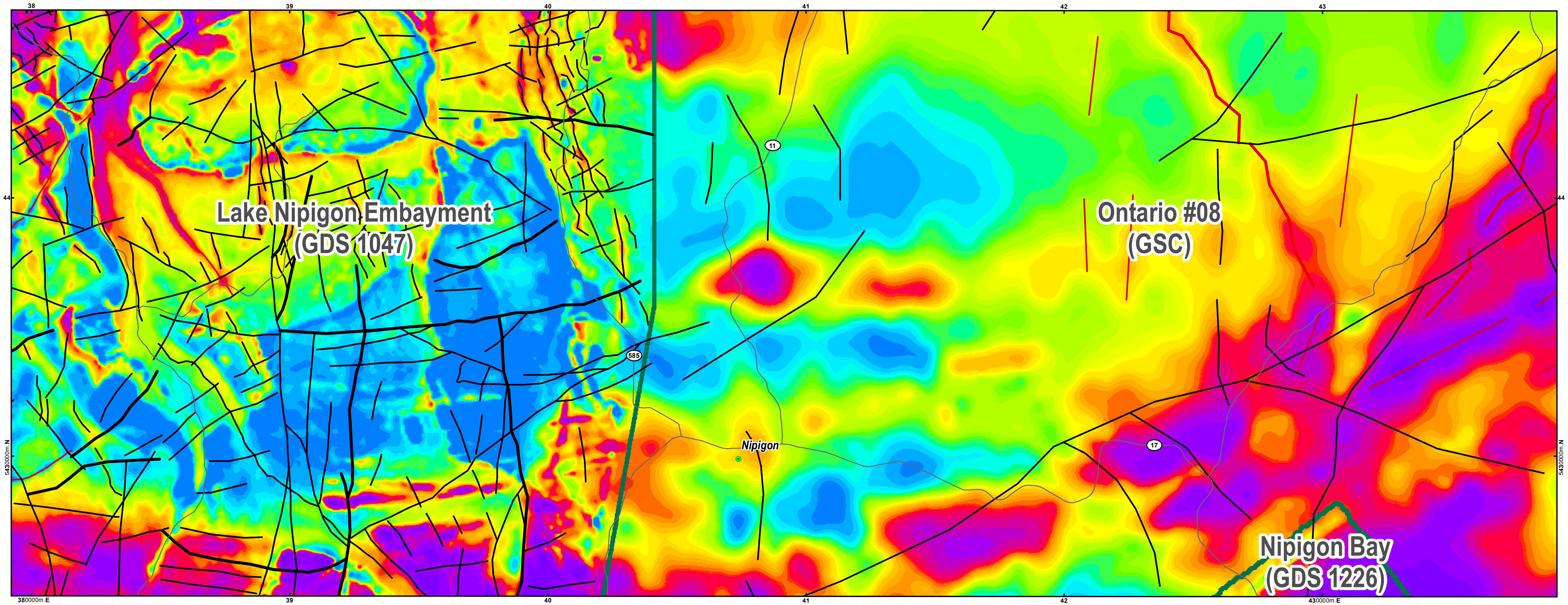
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
SPOT reproducibility assessment (RA_1)

DESIGN	DVZ	05 SEP 2013	FIGURE 9	REVISION 2
GIS	DSM	30 MAY 2014		UTM ZONE 16
CHECK	JIC	30 MAY 2014		NAD 1983
REVIEW	GS	30 MAY 2014		1:150,000



LEGEND

RTP (nT)

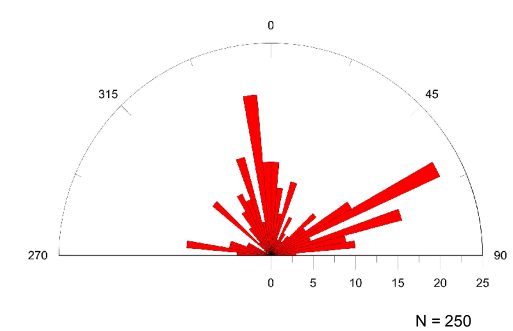
- 191 to 1,341
- 111 to 190
- 76 to 110
- 56 to 75
- 36 to 55
- 21 to 35
- 6 to 20
- 1 to 5
- -9 to 0
- -19 to -10
- -29 to -20
- -39 to -30
- -44 to -40
- -54 to -45
- -59 to -55
- -64 to -60
- -69 to -65
- -74 to -70
- -84 to -75
- -89 to -85
- -94 to -90
- -99 to -95
- -109 to -100
- -119 to -110
- -129 to -120
- -139 to -130
- -154 to -140
- -174 to -155
- -1,550 to -175

Nipigon (settlement)
Main road
Nipigon survey outline

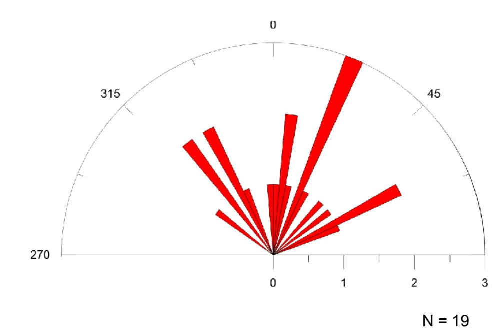
Fault RA_1
1
2

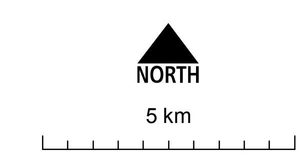
Dyke RA_1
1
2

Nipigon Geophysical Brittle Lineaments - Length Weighted Frequency Rose Plot



Nipigon Geophysical Dykes - Length Weighted Frequency Rose Plot





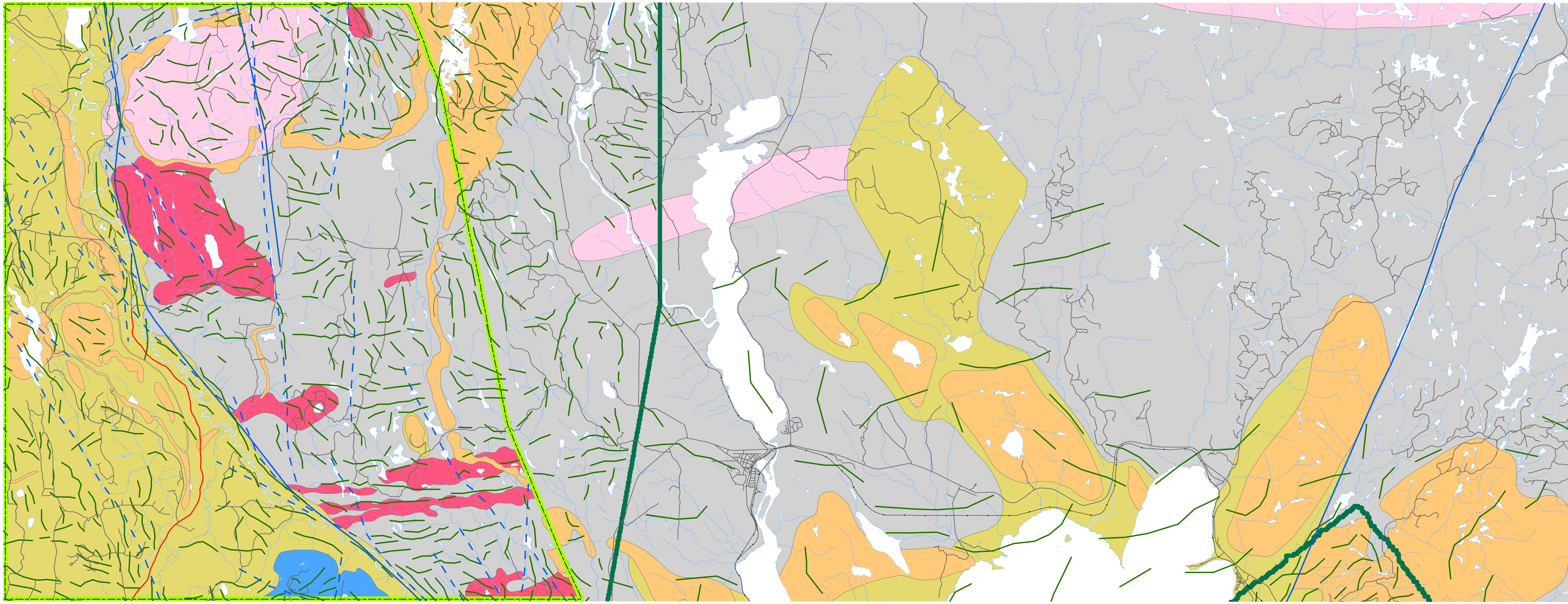
Data sources:
Hi-resolution Magnetics: Ontario #8, OGS GDS1047, GDS1226
Regional Magnetics: GSC nationwide compilation
Main road: LIO Ontario road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse

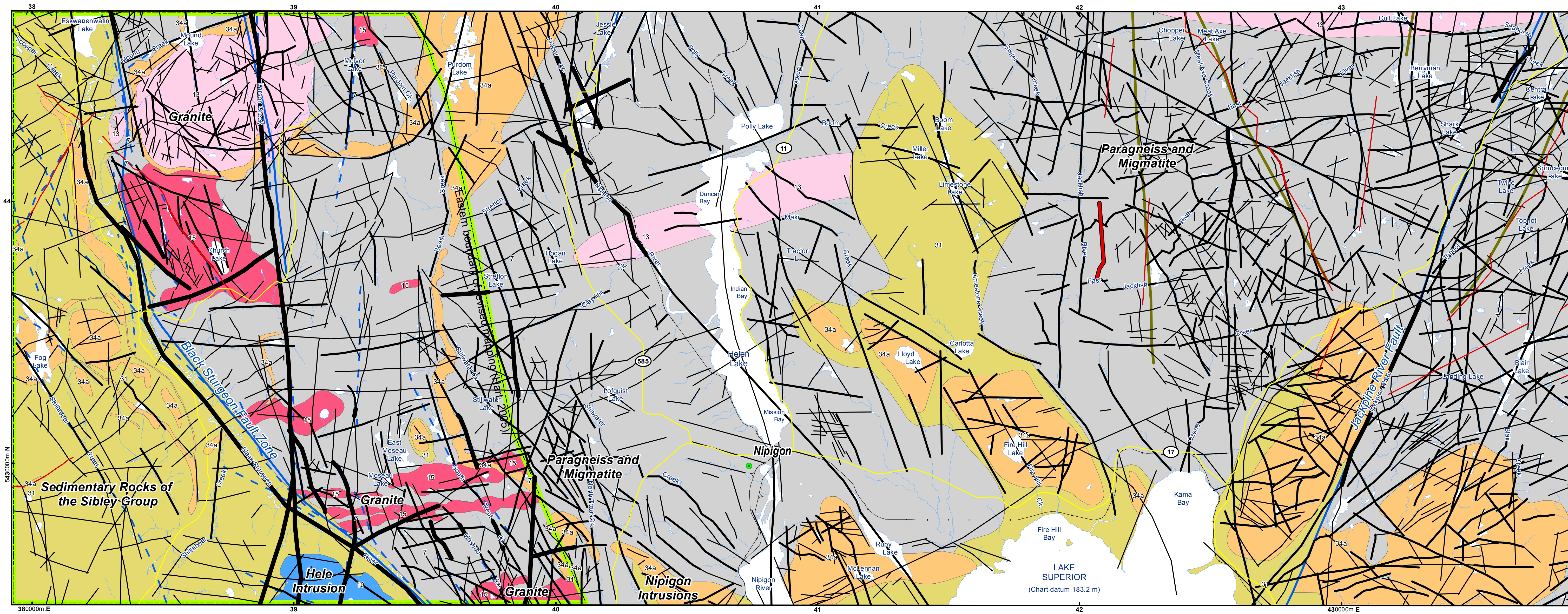
J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
Aeromagnetic reproducibility assessment (RA_1)

DESIGN	DVZ	05 SEP 2013	FIGURE 10	REVISION 5
GIS	DSM	30 MAY 2014		UTM ZONE 16
CHECK	JIC	30 MAY 2014		NAD 1983
REVIEW	GS	30 MAY 2014		1:150,000





LEGEND

- Nipigon (settlement)
- Main road
- Rail

Lineament RA_2

- 1
- 2
- 3

Dykes RA_2

- 1
- 2
- 3

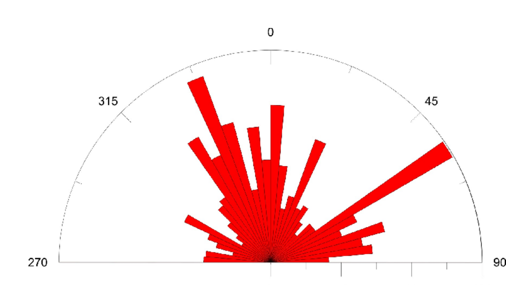
- Mapped dyke
- Mapped fault
- Lineament / fault (Hart, 2005)
- Waterbody
- Watercourse
- Revised mapping (Hart, 2005)

Bedrock geology

- 34 Mafic and related intrusive rocks (Keweenawan age)
- 34a Logan and Nipigon sills: diabase sills
- 31 Sibley Gp.
- 15 Massive granodiorite to granite
- 13 Muscovite-bearing granitic rock
- 10 Mafic and ultramafic rocks
- 7 Metasedimentary rocks (Paragneisses and Migmatites)

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Geology: OGS MRD 126 scale 1:250,000

Nipigon All Data - Length Weighted Frequency Rose Plot



N = 1,806

NORTH

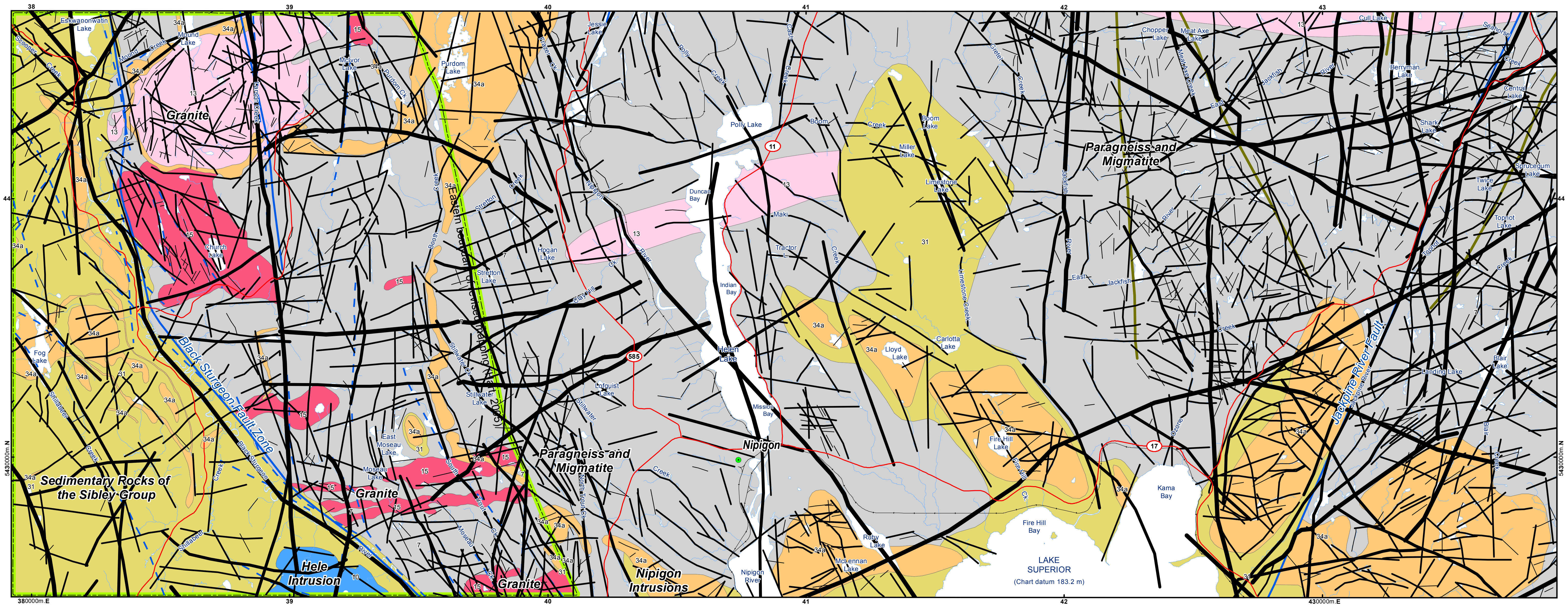
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
Lineament classification by reproducibility assessment (RA_2)

DESIGN	DVZ	05 SEP 2013	FIGURE 12	REVISION 8
GIS	DSM	02 JUN 2014		UTM ZONE 16
CHECK	JIC	02 JUN 2014		NAD 1983
REVIEW	GS	02 JUN 2014		1:150,000



LEGEND

- Nipigon (settlement)
- Main road
- Rail

Lineament RA_2

- 0 - 1 km
- 1 - 5 km
- 5 - 10 km
- 10+ km
- Mapped dyke
- Mapped fault
- Lineament / fault (Hart, 2005)

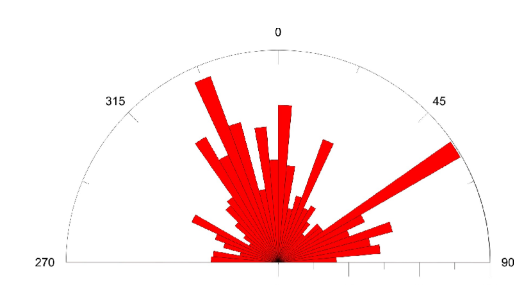
- Revised mapping (Hart, 2005)
- Waterbody
- Watercourse

Bedrock geology

- 34 Mafic and related intrusive rocks (Keweenawan age)
  - 34a Logan and Nipigon sills: diabase sills
- 31 Sibley Gp.
- 15 Massive granodiorite to granite
- 13 Muscovite-bearing granitic rock
- 10 Mafic and ultramafic rocks
- 7 Metasedimentary rocks (Paragneisses and Migmatites)

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Geology: OGS MRD 126 scale 1:250,000

Nipigon All Data - Length Weighted Frequency Rose Plot



N = 1,806

NORTH

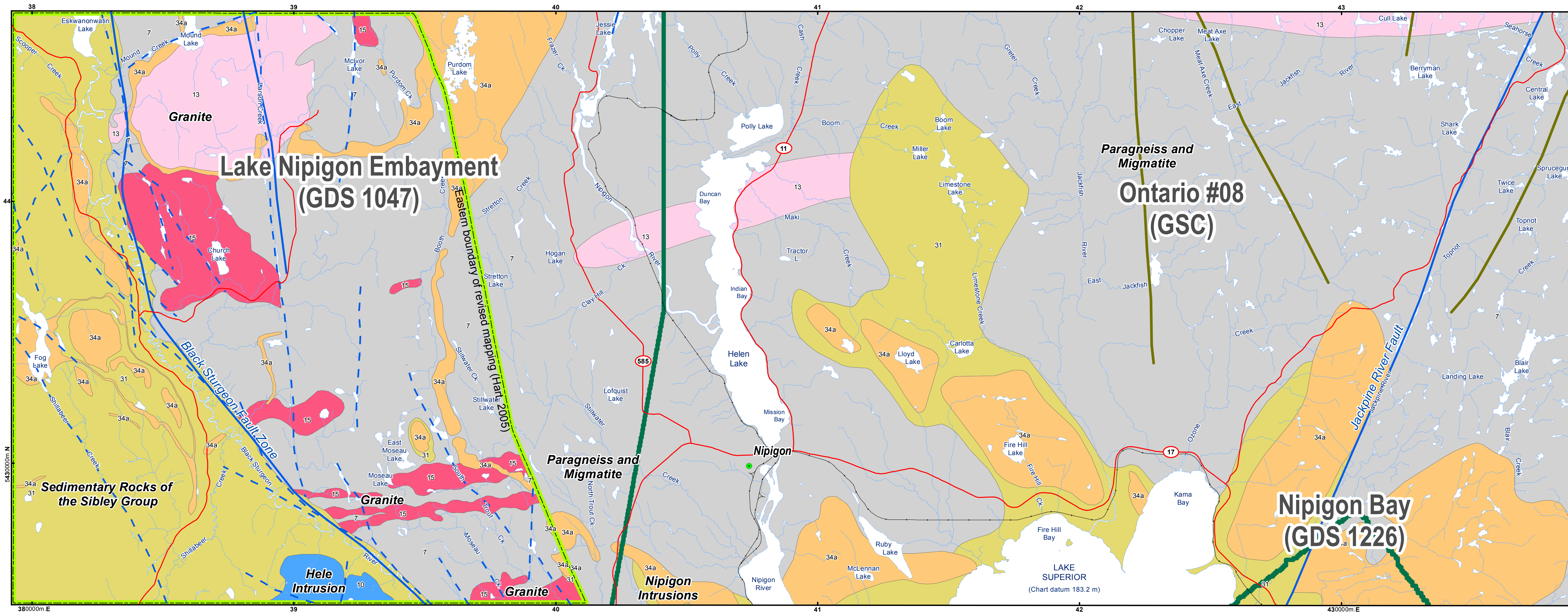
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

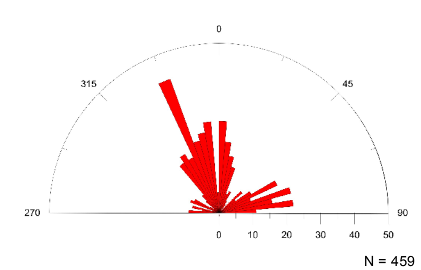
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
Lineament classification by length

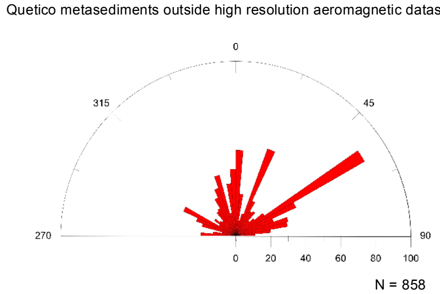
DESIGN	DVZ	05 SEP 2013	FIGURE 13	REVISION 8
GIS	DSM	02 JUN 2014		UTM ZONE 16
CHECK	JIC	02 JUN 2014		NAD 1983
REVIEW	GS	02 JUN 2014		1:150,000



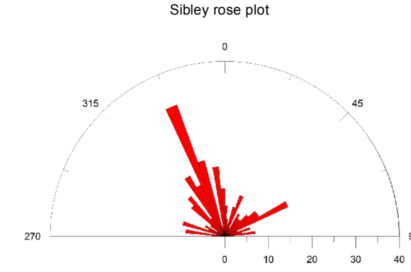
Quetico metasediments within high resolution aeromagnetic dataset



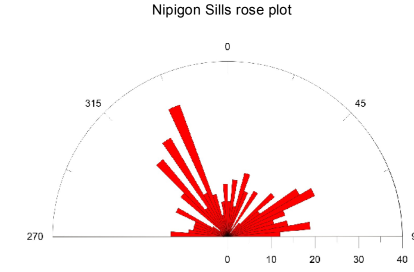
Quetico metasediments outside high resolution aeromagnetic dataset



Sibley rose plot



Nipigon Sills rose plot



NORTH

5 km

LEGEND

- Nipigon (settlement)
- Main road
- Rail
- Mapped dyke
- Mapped fault
- Lineament / fault (Hart, 2005)
- Waterbody
- Watercourse
- Revised mapping (Hart, 2005)
- Nipigon survey outline

Bedrock geology

- 34 Mafic and related intrusive rocks (Keweenawan age)
- 34a Logan and Nipigon sills: diabase sills
- 31 Sibley Gp.
- 15 Massive granodiorite to granite
- 13 Muscovite-bearing granitic rock
- 10 Mafic and ultramafic rocks
- 7 Metasedimentary rocks (Paragneisses and Migmatites)

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Geology: OGS MRD 126 scale 1:250,000

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS

TITLE
Lineament orientations by major geological unit in the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 14	REVISION 10
GIS	DSM	02 JUN 2014		UTM ZONE 16
CHECK	JIC	02 JUN 2014		NAD 1983
REVIEW	GS	02 JUN 2014		1:150,000