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

TOWNSHIP OF NIPIGON, ONTARIO

APM-REP-06144-0068

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PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT

TERRAIN AND REMOTE SENSING STUDY

TOWNSHIP OF NIPIGON, ONTARIO

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EXECUTIVE SUMMARY

In May 2013, the Township of Nipigon, Ontario, expressed interest in learning 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 the 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 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 contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

This report presents the findings of a terrain and remote sensing assessment completed as part of the geoscientific desktop preliminary assessment of the Nipigon area (Golder, 2014). The main information sources relied on are the Canadian Digital Elevation Data (CDED), the SPOT and Landsat satellite imagery, and the maps and reports from the Northern Ontario Engineering Geology Terrain Study (NOEGTS). The study addresses the following seven objectives:

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

The report provides an overview of the bedrock and Quaternary geology within the Nipigon area, including estimates of overburden thickness. Areas expected to contain a thin mantle of drift generally composed of bouldery sand-rich till (mapped as 'bedrock terrain') make up about half of the Nipigon area. Although actual areas of exposed bedrock delineated using SPOT and Landsat imagery cover only about 5% of the Nipigon area, several extensive areas of rock

outcrop are present, the most notable being a large area of metasedimentary rock in the eastern part of the area and a granitic intrusion in the northwest part of the area.

Drainage divides mapped in the provincial quaternary watershed database were confirmed using the CDED surface model. Groundwater flow within drift deposits and in shallow bedrock aquifers is expected to mimic the pattern of surface flow, with groundwater divides generally coinciding with surface drainage divides. Creeks, rivers, lakes and wetlands constitute the main groundwater discharge locations.

The existing network of paved roads provides access to areas underlain by granitic or metasedimentary rocks in the west, central and east parts of the area. However, there remain large blocks of land that are either inaccessible or accessible only by local resource roads of variable quality.

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1 INTRODUCTION

In May 2013, the Township of Nipigon, Ontario, expressed interest in learning 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). The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations (NWMO, 2014).

This report presents the findings of a terrain and remote sensing assessment completed as part of the geoscientific desktop preliminary assessment of the Township of Nipigon and its periphery, referred to as the "Nipigon area" (Golder, 2014). The objective of the geoscientific desktop preliminary assessment was to determine whether the Nipigon area contains general siting areas that that have the potential to meet NWMO's geoscientific site evaluation factors.

1.1 OBJECTIVES

This report presents an analysis of the terrain in the Nipigon area using existing remote sensing and geoscientific information sources. The main information sources relied on in this assessment are maps and reports from the Northern Ontario Engineering Geology Terrain Study, Canadian Digital Elevation Data, and SPOT and Landsat satellite imagery. Additional data sources included the Water Well Information System, the Ontario Drill Hole Database, and the Assessment File Research Imaging database. This study addresses the following seven objectives:

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

The objectives above were carried out for the Nipigon area using the data and methods described in Section 1.3.

1.2 Location

The Nipigon area is approximately 59.9 km by 22.7 km in size, encompassing an area of about 1,359 km^2 (Figure 1). The approximate western, northern, eastern and southern limits of the Nipigon area are (UTM Zone 16, NAD83): 379208, 5447276, 439088, and 5424551 m. The settlement of Nipigon is located on the west shore of the Nipigon River, between Helen Lake and Nipigon Bay.

1.3 Data and methods

This section summarizes the remote sensing and geoscientific data sources used in this assessment, including an evaluation of the quality of the data. The datasets are all publicly available.

1.3.1 NOEGTS

Overburden deposits within the Nipigon area were mapped as part of a program undertaken between 1977 and 1980 entitled the Northern Ontario Engineering Geology Terrain Study (NOEGTS). These studies divided the landscape into a set of distinct terrain units within which the engineering characteristics are broadly predictable. The terrain units were delineated by identifying landforms from black and white air photos at scales ranging from 1:68,800 to 1:50,000. Interpreted terrain units were checked against published and unpublished maps and reports that documented previous field visits and observations. A limited amount of fieldwork was undertaken in 1977 and 1978, which involved observing terrain conditions from roads to corroborate the aerial photo interpretation. The results of the terrain studies were intended to provide a framework for regional planning and a database on which to conduct site studies. In many areas of northern Ontario, including the Nipigon area, maps produced from these programs currently represent the best level of detail available for surficial geology mapping and descriptions of terrain conditions.

The Ontario Geological Survey (OGS) digitized the NOEGTS maps and published the digital data in the form of a miscellaneous release of data (OGS, 2005a). For the current study, a part of the NOEGTS digital map layer was clipped and then transformed from geographic coordinates into Universal Transverse Mercator (UTM) projection (Zone 16).

Four Northern Ontario Engineering Geology Terrain Studies (Gartner, 1979a, b; Mollard and Mollard, 1981a, b) along with four maps at a scale of 1:100,000 (Gartner, 1980a, b; Mollard, 1979a, b) describe the terrain conditions in the Nipigon area. These reports provide background information on the physiography, bedrock geology and Quaternary geology, followed by descriptions of the occurrence and nature of the engineering geology terrain units outlined on the accompanying maps. The terrain reports include estimates of the distribution and thickness of overburden deposits. They also discuss the influence of the terrain conditions on general construction (e.g., location and construction of highways, town sites, waste disposal sites, cottage subdivisions, airfields), aggregate resource potential (e.g., asphalt aggregate, traffic gravel, base course and sub-base for pavement structures) and groundwater resource potential.

In addition to the NOEGTS reports and maps, another important source of information on the surficial geology in this area is the regional investigation of Zoltai (1965a, b). This work involved identifying and mapping surficial deposits using an approach that combined fieldwork with the interpretation of 1:63,000 scale air photographs. All roads were traversed, and numerous airplane flights were used to access remote areas.

Barnett (2004) reported on fieldwork carried out as part of the Lake Nipigon Region Geoscience Initiative (e.g., Dyer and Barnett, 2007; Easton et al., 2007). Barnett (2004) presents preliminary work towards a regional Quaternary geology synthesis for the Nipigon Embayment.

1.3.2 CDED

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

Canadian Digital Elevation Data, 1:50,000 scale, 0.75 arc second (20 m) elevation models (GeoBase, 2013a) served as important data sources for analyzing and interpreting the terrain in the Nipigon area. The digital elevation model (DEM) used for this study was constructed by Natural Resources Canada (NRCan) using data assembled through the Water Resources Information Program (WRIP) of the Ontario Ministry of Natural Resources (MNR). The source data were 1:20,000 scale topographic 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.

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

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

Surface analyses were performed on the digital elevation model to characterize slope and relief. Slope was calculated using the standard grid-based method employed in ArcGIS, which involves fitting a plane to the elevation values of a three by three neighbourhood centred on the processing cell. Slope is defined as the maximum slope of that plane, which can also be thought of as the dip of the plane, and aspect is equivalent to the dip direction. Relief was calculated in two ways. The first was by subtracting the average elevation within a radius from the elevation value in the processing cell. The second was defined as the range in elevation within a circular window, calculated with 2 km and 20 km radii. The second relief calculation represents a high pass filter. The density of steep slopes was calculated as the number of points with a slope of at least 6° within a search radius. Both 250 m and 2 km search radii were used. The threshold of 6° was found to be effective in distinguishing between the rugged bedrock-controlled areas and the areas of gentle slope, often associated with thicker overburden cover.

1.3.3 SPOT

SPOT multispectral orthoimagery at a resolution of 20 m and panchromatic imagery at 10 m resolution were used to identify features such as areas of exposed bedrock (GeoBase, 2013b). SPOT multispectral data consist of several 8-bit bands, each recording reflected radiation within a particular spectral range. SPOT 4 and 5 images were acquired using the HRV and HRG sensors, respectively (Table 1). Each image covers a ground area of 60 km by 60 km.

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

Two SPOT images (or 'scenes') provided complete coverage for the Nipigon area (Table 2). The scenes are from the SPOT 4 and 5 satellites. The images were captured in the summers of 2005 and 2008.

During the course of this assessment, the SPOT imagery were viewed in stereo using the CDED as a surface reference. Stereo viewing provides a much better opportunity to interpret landforms than if the imagery are viewed in two-dimensions.

Table 1 Characteristics of SPOT 4 and 5 multispectral bands.

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

Table 2 List of SPOT 4 and 5 multispectral images acquired.

Scene ID	Satellite	Date of image
S4_08843_4857_20080824	SPOT 4	24 August 2008
s5_08806_4857_20050706	SPOT 5	06 July 2005

To map rock outcrops using the SPOT data, all four multispectral bands were used as inputs in a principal component analysis, generating three components. As it was found that outcrops could be identified as having high values on the second component, this component was reclassified to produce a preliminary outcrop map, which was then edited to remove roads, utility lines, wetlands, clearcuts and any other non-outcrop areas. As the spectral range and relatively high resolution of the SPOT panchromatic imagery allowed outcrops to be identified clearly, the panchromatic imagery provided a useful reference for the editing process. Clearcuts were generally removed from the outcrop map, as in most cases it was difficult to distinguish between outcrops, exposed mineral soil, or other landcover types in clearcuts. Section 5 presents the SPOT imagery, providing reference to maps showing the panchromatic imagery, a false-colour composite image and a derived outcrop map. The false-colour composite image was generated from the three components of the principal component analysis; it provides a visual reference to the many landcover types within the Nipigon area. Section 5.2.1 describes the distribution of exposed bedrock in the area, as observed from SPOT and Landsat imagery.

1.3.4 LANDSAT

Landsat data from July 2001 and May 1988 were used to map rock outcrops in the Nipigon area. The Landsat data provided alternate images of the distribution of exposed bedrock across the Nipigon area. In general, the resulting outcrop maps are similar to the map produced using the SPOT data, but the Landsat data also suggested some differences in the amount of exposed bedrock, particularly in the eastern part of the Nipigon area. As a result, it was worthwhile including results from both SPOT and Landsat imagery. The older imagery predates a major May 1999 wildfire in the northwest corner of the area, which allowed for an assessment of the extent of exposed bedrock in this area prior to the wildfire, thereby assisting with the interpretation of what parts of the burn zone truly are exposed bedrock versus exposed mineral soil or other landcover types.

Cloud-free Landsat 7 coverage for the Nipigon area was acquired from GeoBase (2013c). The sensor onboard the Landsat 7 satellite is the Enhanced Thematic Mapper (ETM). ETM data consist of one panchromatic band with a pixel size of 15 m, six multispectral bands with a pixel size of 30 m, and one thermal infrared band with a pixel size of 60 m (Table 3). The acquisition date of the Landsat image used in this study was July 4th, 2001. To map rock outcrops using the Landsat ETM data, all six multispectral bands were used as input in a principal component analysis, generating three components. As it was found that outcrops could be identified as having high values on the second component, this component was reclassified to produce a preliminary outcrop map, which was then edited to remove roads, utility lines, wetlands, clearcuts and any other non-outcrop areas. Outcrops shown clearly in the SPOT panchromatic imagery were used as a reference dataset to guide the editing process. Section 5 presents the Landsat ETM imagery, including a false-colour composite image and a derived outcrop map.

Table 3 Characteristics of Landsat ETM bands.

Band	Type	Spectral Range (μm)	Resolution (m)
1	Visible	(0.45-0.52)	30
2	Visible	(0.52-0.6)	30
3	Visible	(0.63-0.69)	30
4	Near-Infrared	(0.77-0.9)	30
5	Near-Infrared	(1.55-1.75)	30
6	Thermal	(10.40-12.5)	60
7	Mid-Infrared	(2.08-2.35)	30
8	Panchromatic	(0.52-0.9)	15

Cloud-free Landsat 5 coverage for the Nipigon area was acquired from the NASA Landsat Program (2013). The sensor onboard the Landsat 5 satellite was the Thematic Mapper (TM). Thematic Mapper data consist of six multispectral bands and one thermal band, with pixel sizes of 28.5 m and 120 m, respectively (Table 4). The acquisition date of the Landsat TM data was June 9th, 1988. To map rock outcrops using the Landsat TM data, all six multispectral bands were used as input in a principal component analysis, using the same approach as adopted for the Landsat ETM data. Section 5 presents the Landsat TM imagery, including a false-colour composite image and a derived outcrop map.

Table 4 Characteristics of Landsat TM bands.

Band	Type	Spectral range (μm)	Resolution (m)
1	Visible	(0.45-0.52)	28.5
2	Visible	(0.52-0.6)	28.5
3	Visible	(0.63-0.69)	28.5
4	Near-Infrared	(0.76-0.9)	28.5
5	Near-Infrared	(1.55-1.75)	28.5
6	Thermal	(10.40-12.5)	120
7	Mid-Infrared	(2.08-2.35)	28.5

1.3.5 FRI IMAGERY

Ontario Forest Resource Inventory (FRI) orthoimagery was reviewed during the course of this study. The aerial photography forming the FRI imagery for the Nipigon area was acquired in 2008 and 2010, with 2010 imagery covering all but the westernmost 10 km of the area. The true-colour imagery has a ground resolution of 40 cm, and is delivered in the form of four-band multispectral imagery acquired in the summer during leaf out conditions. For this assessment, the FRI imagery was viewed using an online tool developed by Land Information Ontario (LIO, 2013). The imagery can be quite useful for identifying the condition of access roads and identifying rock outcrops. Although outcrops are shown in detail in the FRI imagery, the SPOT and Landsat imagery provide an excellent site-wide depiction of the extent of rock outcrops across the Nipigon area that is sufficient for this assessment. The detailed mapping of rock outcrops from high-resolution aerial imagery, such as the FRI imagery, is beyond the scope of this assessment. Section 4.1 provides examples of the FRI imagery, illustrating examples of wetlands situated in different terrain settings.

1.3.6 DRILL HOLES AND WATER WELLS

A preliminary review was made of data on overburden thickness obtained from databases compiled by the OGS and the Ontario Ministry of the Environment (MOE). Section 5.1 summarizes the results of the subsurface information reviewed.

Water well records from the MOE Water Well Information System (WWIS) for the Nipigon area were acquired (MOE, 2013). The WWIS contains 147 water well records located within the Nipigon area, completed between 1952 and 2012. Most of the wells are located near the settlement of Nipigon. Of the 147 wells referred to above, 143 wells contain useful hydrogeological information, and 84 well records contain usable information on depth to bedrock.

The Ontario Drill Hole Database was compiled by the OGS from assessment files, with the most recent official release of the database in December 2005 (OGS, 2005b). A preliminary analysis of the database was completed during this study. Assessment files were reviewed to check the borehole locations and depth to bedrock values. Assessment files are stored in the Assessment File Research Imaging (AFRI) database held by the OGS. Some of the assessment files contain descriptions of overburden cover and site accessibility.

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

Within the Nipigon area, the boreholes are found in two locations, near Eagle Mountain in the central-west part of the area (Fog Lake claim group) and on the Jackpine River property in the northeast part of the area (see Section 5.1.1). Additional information on the geology, overburden deposits and accessibility of the two locations mentioned above can be found in assessment files completed by Aubut (1990), Barnes (1979) and Barr (1989). Only eight boreholes are contained within the OGS database for the Nipigon area, with five on the Jackpine River property and three east of Eagle Mountain (see Section 5.1.2).

2 SUMMARY OF GEOLOGY

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

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. 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. 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.

2.1 BEDROCK GEOLOGY

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 2. 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 western part 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.

2.1.1 ARCHEAN METASEDIMENTARY ROCKS

Archean metasedimentary rocks of the Quetico Subprovince (Figure 2) 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) described 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 subparallel to the original bedding. Dip of the foliation/schistosity is variable but generally steep.

Rocks of the Quetico Subprovince consist of biotite and/or andalusite schists that are gradually replaced towards the south by amphibolites (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.

2.1.2 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.

2.1.3 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 but these units are known to be present beneath portions of Nipigon Bay (Rogala et al., 2005).

The sequence of sedimentary rocks of the Sibley Group in the Nipigon area is 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.

2.1.4 The Hele intrusion

The Hele intrusion covers a total area of approximately 40 km^2 and is located 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.

2.1.5 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).

2.1.6 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 2). Four such dykes, ranging from 7 to 25 km in length are mapped in 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.

2.1.7 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 and is described further in Golder (2014).

The Black Sturgeon fault zone (Figure 2) 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 (Figure 2) 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 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, 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.

2.1.8 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_{2-3}) 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).

2.2 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 5. 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 2). 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 2). 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 5 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. 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.

2.3 Quaternary Geology

Continental ice sheets have advanced and retreated across northern parts of North America numerous times during the last 2.4 million years (Shackleton et al., 1990; Peltier, 2002) – a period of geological time known as the Quaternary Period. All unconsolidated deposits in the Nipigon area are attributed to the Wisconsinan stage. The Wisconsinan glaciation began approximately

115,000 years ago and peaked about 21,000 years before present, during the late Wisconsinan glaciation, at which time the glacial ice front extended south of Ontario into Ohio and Indiana (Barnett, 1992). After the ice sheet had reached its maximum extent at about 20,000 years ago, it began retreating northward, interrupted occasionally by readvances. Data on ice flow directions from the literature (Zoltai, 1965a) reveal that glacial ice flowed in a generally westerly to southwesterly direction across the Nipigon area from the Hudson Bay basin.

The northward retreat of the ice sheet in the Nipigon area started approximately 10,500 years ago when the area temporarily became partially ice-free (Dyke et al., 2003). 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. The orientation of the Nipigon moraine indicates that the most recent glacial advance was in a south-southwesterly direction from a glacial centre further to the north-northeast.

Extensive ice-marginal deltas along the Nipigon moraine, observed a short distance northwest of the Nipigon area, indicate that a high-level proglacial lake fronted the glacier during moraine formation (Barnett, 2004), most likely glacial Lake Minong, which occupied the Lake Superior basin. As the ice sheet began its recession northward from the Nipigon moraine, glacial Lake Minong expanded into low-lying, newly deglaciated areas. About 9,500 years ago, glacial Lake Minong had reached its maximum extent, coalescing with the ancestral Lake Nipigon (glacial Lake Kelvin) (Barnett, 1992; Slatterly et al., 2007). Further to the north, drainage was blocked by the residual ice mass remaining over the Hudson Bay basin. This created glacial Lake Agassiz, which covered a maximum area of approximately 1 million km^2 (Bajc et al., 2000) including the majority of lands to the north of the present Lake Nipigon.

Beginning about 9,500 years ago, Lake Agassiz began draining through the Lake Nipigon basin into Lake Superior (Clayton, 1983). At least six outlets from Lake Agassiz via Lake Nipigon to Lake Superior are thought to have been present during deglaciation (Teller and Thorleifson, 1983; Lemoine and Teller, 1995) though it is unlikely that these were active simultaneously. The most prominent of these outlets is the Pijitawabik canyon located north of the Nipigon area. This deeply (>150 m) incised steep-walled valley cuts through Nipigon sills for a distance of about 20 km. The canyon follows a southeasterly trend to a point about 14 km north of the Nipigon area, where it then turns sharply to the southwest at a nearly right-angled bend. The outlet leaves the canyon immediately north of the Nipigon area and in the last 7 km before Helen Lake its path follows relatively low-relief Archean basement. Other outlets of Lake Agassiz include the Black Sturgeon River canyon, the Shillabeer and Cash channels of the Wolf Lake drainage system immediately southwest of the Nipigon area, and the Nipigon River. Drainage of Lake Agassiz through the Lake Nipigon basin into the Lake Superior basin halted at about 9,000 years ago, as indicated by the cessation of glacial clay sedimentation at multiple locations on the floor of Lake Superior (Breckenridge et al., 2004; Hyodo and Longstaffe, 2011).

From about 10,000 to 5,000 years ago, water levels in the Lake Superior basin dropped from about 300 m elevation through several Minong and post-Minong stages to a low level of about 140 m, at the start of the Houghton phase (Farrand and Drexler, 1985). As lake levels dropped, erosion of surficial deposits by river and lake currents resulted in the redistribution of sediment onto adjacent low-lying areas. In some areas within the confines of glacial Lake Minong, erosion around the receding lakeshore was effective at removing overburden deposits from the bedrock surface, producing areas of bare rock (Zoltai, 1965a).

A kame terrace on the west margin of the Nipigon valley, west of Helen Lake, would have 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 3). 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.

As the ice sheet retreated northward, newly deglaciated areas to the south began to rise isostatically, recovering from the weight of the ice sheet. This uplift caused water levels in the Great Lakes to rise (Barnett, 1992). By about 5,000 years ago, differential isostatic uplift in the north and south parts of the Great Lakes basins resulted in high water levels in lakes Superior, Huron and Michigan and Georgian Bay, referred to as the Nipissing Great Lakes (Barnett, 1992).

East of Thunder Bay, these high water levels produced strong shoreline features about 30 m above the present shoreline of Lake Superior (Farrand and Drexler, 1985).

Since the disappearance of the ice sheets and glacial lakes, modern streams have developed alluvial flood plains and organic deposits have accumulated in wet depressions. The largest organic deposits are located adjacent to the north shore of Lake Superior, extending northwest from Fire Hill Bay and Kama Bay.

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. Diamond drill hole records and water well records in the area show overburden thickness to be up to about 100 m.

3 TOPOGRAPHY

Canada is divided into several physiographic regions, each possessing characteristic geological features, and, as a result, more or less distinctive topographic features. The largest of these regions is the Canadian Shield, occupying nearly half of Canada, including all of the Nipigon area. A general sense of the physical features of the Shield, including an accurate impression of the extent of exposed bedrock, can be obtained from the description of Lord (1957, p. 1):

> "… most of the Shield has a relief of less than 200 feet [about 60 m]. Intense glaciation has left scattered rounded rock outcrops and rocky ridges separated by glacial deposits, muskegs, and myriads of lakes of many sizes and shapes, here and there connected by rivers with rapids alternating with stretches of relatively quiet water. Rock exposures probably total less than 10 per cent of the surface."

Topographic analysis in Shield settings can provide useful information about the presence of thick drift deposits, as illustrated by Harrison (1957, p. 21):

> "... local relief is very low and the skyline monotonously even—features that are characteristic of an ancient peneplain and that have been remarked on in hundreds of reports. Recent drilling in some interior areas of the Shield, formerly thought to be flat and featureless, has shown depths of overburden of 400 feet [about 120 m] or more, so that at least some of the peneplained appearance is due to filling in of low spots by glacial debris."

The Nipigon area lies within the Port Arthur hills physiographic region of the Canadian Shield (Bostock, 1970), which consists of ridges and cuestas produced by the underlying sequence of Proterozoic diabase sills and sedimentary rocks, with the flat-lying diabase sills on the hilltops responsible for shielding the underlying weaker rocks from erosion. As is common throughout the Shield, the rocks in this region are deeply incised by fractures and faults (Thurston, 1992).

This section provides topographic information based on CDED. Section 4.3 describes drainage patterns associated with the topography. Section 3.2.1 presents topographic maps used to discuss the extent of thin drift deposits and exposed bedrock across the Nipigon area.

3.1 Elevation

The landscape within the Nipigon area (Figure 4) ranges in elevation from about 183 m on the shore of Lake Superior to a maximum of 583 m at the highest point of the Kama Hills (Figure 4). The lower elevation limit in the Nipigon area is represented by a dynamic feature. That is, although the surface of Lake Superior is represented by a chart datum of 183.2 m, its elevation during the period 1918 to 2012 fluctuated between 183.01 m (in 2007) to 183.86 m (in 1952) (Canadian Hydrographic Service, 2013). The highest point in the area, identified using the digital elevation model, is a point on the northern margin of the Kama Hills, where a fire tower is depicted in the 1:50,000 scale National Topographic Service map 42 E/4. The elevation at this point is 583 m according to both data sources.

The map of elevation (Figure 4) allows for the delineation of the major topographic features in the area. Two major topographic lows are present within the Nipigon area. 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. As stated above, the highest elevations in the Nipigon area are located east of the Jackfish River and are associated with the Kama Hills and other areas to the north and east.

Farrand (1960) studied the succession of glacial lakes that occupied the Lake Superior basin as it became free of ice. The Minong Stage formed the highest lake to occupy the entire Lake Superior basin. It formed three beaches, the highest of which can be found at an elevation of 290 m in this area. This elevation is plotted as an important reference line on Figure 3 and Figure 4, as most of the glaciolacustrine clay plains in the area are located below it, much of the exposed bedrock is located in proximity to it, and it defines the western and eastern highlands in the Nipigon area.

3.2 Relief

Relief is a metric that can be defined in different ways, and the calculated value of relief depends on the horizontal dimension considered. The total relief in the Nipigon area is approximately 400 m, which places an upper limit on the relief in local zones. Relief was calculated in two ways. The first was by subtracting the average elevation within a radius from the elevation value in the processing cell (termed departure), providing an indication of the degree to which a point is expressed negatively or positively. This calculation was used to delineate broad highlands and lowlands (Section 3.2.1), and local hills and depressions (Section 3.2.2). The second was defined as the range in elevation within a circular window, providing an indication of the maximum relief or roughness within the window. This calculation was used to delineate areas of low relief, which are typically associated with thicker more extensive drift deposits filling lows in the bedrock topography (Section 3.2.3).

3.2.1 HIGHLANDS AND LOWLANDS

A map of departures from the average elevation within a 20 km radius (Figure 5) can define further the highlands and lowlands in the area, including further definition of the highlands between the Black Sturgeon and Nipigon rivers (western highland) and east of the Jackfish River (eastern highland). The inset map provided on Figure 5 shows the areas that are either negatively or positively expressed at this scale of calculation. This map shows that the main break in the eastern highland is the north-northeast trending lineament formed by the Jackpine River. The main break in the western highland is a north trending lineament extending along Larson Creek. The highlands and lowlands shown on Figure 5 (inset) are included on maps presented in Section 5, as, respectively, they represent the first-order recharge and discharge areas of the regional shallow groundwater flow system (see Section 6).

3.2.2 HILLS AND DEPRESSIONS

A map of departures from the average elevation within a 2 km radius (Figure 6) can define local topographic highs, some of which are associated with mesas and escarpments capped by diabase sills (Figure 2). Figure 6 shows hills in shades of red, whereas depressions are shown in shades of blue. The mesas, or ‘table-top mountains’, in this area typically contain cliffs around parts of their margins, with the lower portion formed of Sibley Group sediments and the upper portion formed of Nipigon diabase (Barnes, 1979). The diabase forms a resistive cap that shelters the underlying rocks from erosion. Some of the more impressive hills are named, such as Eagle, Mosseau, Doghead and Fire Hill mountains. Hills in this area extend as much as 150 to 300 m above the nearby terrain (e.g., profiles A and C, Figure 4).

Many of the positively expressed areas shown on Figure 6 match closely with areas mapped as bedrock terrain on Figure 3. The hills delineated on Figure 6 are generally expected to highlight key locations where thin drift deposits can be found within the much larger areas mapped as bedrock terrain. Rock outcrops are often preferentially located on the tops or sides of hills, although this is only the case for hilltops that are located below about 290 to 300 m elevation. The tops of most mesas rarely display visible indications of bedrock of appreciable size or quantity. This may be the result of drift cover preserved by the high elevation of these surfaces with respect to the maximum elevation of the proglacial lakes that occupied the Lake Superior basin during deglaciation. The inset map on Figure 6 displays the areas that stand at least 10 m higher than average. With only one known possible exception, at the settlement of Nipigon, these hills are expected to be bedrock-controlled, and no surficial deposits in the Nipigon area are known to have sufficient surface relief to have been included into this selection of hills. These hills are expected to be areas of relatively thin drift. They also represent potential recharge areas associated with local shallow groundwater flow systems.

Depressions shown in shades of blue on Figure 6 generally coincide with bedrock-controlled lineaments, or with valleys cut into thick and extensive surficial deposits by creeks and rivers. Many of the depressions contain wetlands, lakes and streams. These depressions are generally expected to represent local groundwater discharge zones. However, in some instances, particularly at higher elevations, it is possible that local depressions represent recharge zones for groundwater flow systems of intermediate scale, whereby discharge occurs in depressions at lower elevations. In describing surface water flow along rivers and creeks, Section 4.3 provides examples of the widths and depths of valleys in this area. Topographic profiles also illustrate some of these features (B and C, Figure 4; D, Figure 5; H and I, Figure 6).

3.2.3 Low relief areas

A map showing the range in elevation within a 250 m radius (Figure 7) illustrates the distribution of high and low relief zones within the Nipigon area, providing an indication of the roughness of the terrain. The upper limit of relief calculated at this scale is about 260 m.

Several large areas, mostly characterized by less than 20 m of relief, are highlighted on Figure 7 and are numbered on the inset map. The lack of relief in these areas is in most cases expected to be associated with thick and extensive drift deposits filling lows in the bedrock topography, and these low relief areas are used to facilitate a discussion in Section 4.1 on areas of poor drainage. Most of the low relief areas shown on Figure 7 correspond with overburden deposits delineated on Figure 3. For example, the flat areas south and west of the Black Sturgeon River (Nos. 3, 4) are depicted on Figure 3 as being covered by ground moraine, outwash or glaciolacustrine deposits. The large low relief area bounded in the north between Larson and Booth creeks (No. 9) is shown on Figure 3 as an extensive area underlain by morainal and glaciolacustrine deposits. One of the largest zones of low relief in the Nipigon area, extending north and south of Cedar Mountain and north of Polly Lake (Nos. 17-19), is mapped on Figure 3 as the largest glaciolacustrine plain in the area. Parts of low relief areas 20 and 21, which extend inland from Kama and Fire Hill bays, are depicted on Figure 3 as the area's largest organic deposits. The general absence of large low relief zones on the eastern highland is expected to correspond with an absence of extensive overburden deposits (Figure 3).

3.3 SLOPE

The distribution of slope within the Nipigon area is highly skewed towards values less than about 10°, with values below this cutoff representing about 89% of the data. Only about 23% of the area is represented by a slope value of 6° or more. Part of the reason for this is the presence of lakes represented in the digital elevation model as flat areas, but the flatness of the area is not restricted to the lakes. Even the rugged bedrock terrain is made up of areas of gentle slope interrupted only at the margins of knobs, ridges and trenches. The tops of rock ridges, mesas and other bedrock-controlled hills generally display gentler slopes than what is represented around their flanks.

3.3.1 TERRAIN ROUGHNESS

The main and inset maps of Figure 8 show the densities of slopes equal to or greater than 6° using search radii of 250 m and 2 km, respectively. This map shows in detail where relatively level surfaces can be found within otherwise rugged terrain, and it compliments the relief map shown on Figure 7 in characterizing the roughness of the terrain. This slope density calculation is used in Section 8 to illustrate the range of accessibility conditions present in several areas of extensive rock outcrop in the Nipigon area.

Rarely are the mesas and other hills in this area steep on all sides (Figure 8). In the central part of the Nipigon area, the largest mesas are steeper on their north sides, for example, Doghead and Cedar mountains and the mesas at Lloyd and Fire Hill lakes. This is probably due to the dip of the Sibley strata, although no structure measurements are recorded on any bedrock maps for this part of the Nipigon area. It is probable that glacial erosion has influenced the shape of these landforms as well.

3.3.2 SURFACE LINEAMENT MASKING

Areas of steep slope form the margins of many of the rugged bedrock-controlled landforms in the Nipigon area, such as rock ridges, mesas and linear depressions supporting creeks and rivers. As steep slopes on the surface of the Precambrian Shield are often associated with irregularities in the bedrock topography, with some exceptions (e.g., end moraines, creek valleys cut into drift deposits), zones displaying a high density of steep slopes can be an approximate indicator of a general absence of extensive thick overburden deposits. Many of the extensive areas lacking steep slopes are relatively flat due to the presence of drift filling lows in the bedrock topography. A map showing the density of steep (≥ 6°) slopes within a 2 km radius was prepared (Figure 8 inset) to indicate the broad areas where the thickness of overburden might be relatively low and, conversely, where the surficial deposits could be thicker. The slope density map suggests an alternative, but largely consistent, image of the areas of extensive thick drift as compared with the image suggested by the areas of low relief shown on Figure 7.

As the presence of thick drift can obscure the surface expression of lineaments, areas of low slope density may coincide with areas of lower surface lineament density. This is due to masking of the surface expression of lineaments by drift. The areas of low slope density shown on the Figure 8 inset are areas where SPOT and CDED could be less reliable in identifying the presence or absence of a lineament. These are the areas where the lineament interpreter is blinded to some extent by the presence of thick overburden. The use of low slope density as an indicator of low confidence in identifying the presence or absence of a surface lineament also accounts for the areas covered by lakes, as the lakes are represented as flat surfaces in the digital elevation model.

As thick drift can hinder bedrock-mapping activities, which can result in less confidence in the geologic model developed for the area, it is useful to map out the areas of thick and thin drift in detail. However, areas of low slope density or low relief are not always associated with thicker drift deposits. There are zones within the Nipigon area where wave erosion during high glacial and postglacial stands of the Lake Superior basin has stripped the drift deposits from low-relief bedrock surfaces. These areas of exposed bedrock are generally located within proximity of or below the 290 m elevation contour, which was the highest lake level to occupy the entire Lake Superior basin (Farrand, 1960).

4 DRAINAGE

Surface water drainage and the distribution of waterbodies and wetlands are important factors to consider in the preliminary assessment. Surface water flow is a useful indicator of groundwater flow at shallow depth. The distribution of lakes and wetlands influences the accessibility and amenability of a site to construction. Section 4.1 describes the size, distribution and depth of lakes, and the distribution of wetlands in the area. Section 4.2 outlines the existing watershed file and the drainage analysis conducted. Section 4.3 describes the pattern of surface water flow formed by the rivers and creeks.

4.1 WATERBODIES AND WETLANDS

Waterbodies cover 6.7% (91.4 km^2) of the Nipigon area though few exceed 10 km^2 in area (Table 6) (Figure 9). Aside from Lake Superior, Helen Lake is the largest waterbody in the Nipigon area (16.0 km^2). The rest of the lakes and rivers in the area are less than 5 km^2 in size and over 90% are less than 1 km^2 in extent. The general paucity of large lakes and the fact that the largest lakes are generally widely spaced results in a condition where lakes generally do not pose a significant obstruction to the identification of major lineaments. In fact, one of the largest lakes in the area could actually outline a major lineament. That is, the north south trend of the linear topographic low filled by Polly Lake, Helen Lake and the Nipigon River south of Helen Lake could outline the general trend of a significant bedrock structure.

The MNR completed depth surveys of various lakes in northern Ontario in the 1970s. Eskwanonwatin Lake, located in the northwest corner of the Nipigon area (Figure 9), is the only lake in the area with such a survey. The survey indicates a maximum depth of 9.1 m, but this depth was partly a function of the timber crib dam (Dolan’s Dam) at the outlet of the lake, and this structure burnt in a wildfire in May 1999 (MNR, 2012). The Nipigon River between the Alexander Generating Station and Helen Lake is at most 15 m deep (OPG, 2005). Depth data for the Nipigon River south of Helen Lake and for Lake Superior were obtained from a nautical chart (Canadian Hydrographic Service, 2002). The portion of Lake Superior within the Nipigon area reaches its greatest depth of 19.5 m south of Kama Bay. However, the greatest depth of any waterbody known in the area occurs along the Nipigon River near the southern boundary of the Nipigon area, where a sounding of 17 fathoms (about 31 m) is reported on the nautical chart.

Wetlands depicted on Figure 9 are from the Wetland Unit map file produced by the Ministry of Natural Resources. Larger, relatively extensive wetlands can be found locally, such as around Carlotta Lake and west of McLennan Lake. The larger wetlands with more rounded aspects are generally associated with flat topography, sometimes associated with extensive, poorly drained overburden deposits. For example, Figure 9 (inset B) shows the extensive wetland on the north side of Carlotta Lake, which extends into the flat, unconfined terrain to the north. Smaller, somewhat elongate wetlands are often confined within bedrock-controlled linear depressions. For instance, Figure 9 (inset A) shows wetlands confined within the bedrock controlled valley of South Trout Creek. No extensive wetlands (>1.0 km^2) are mapped in the area. All of the wetlands and wetland complexes shown on Figure 9 are smaller than 1.0 km^2 in extent, and mapped wetlands cover only 1.5% of the Nipigon area or 1.6% of the portion of the area not covered by Lake Superior, Lake Helen and the portion of the Nipigon River downstream of Lake Helen. However, a better appreciation for the distribution of large areas of wet, swampy ground can be obtained from the areas delineated as organic terrain on Figure 3, and to some extent from the low relief areas shown on Figure 7, both of which are plotted on Figure 9. Outside of these large low-relief areas, the roughness of the topography is expected to promote surface runoff and thereby result in better drainage and fewer swampy areas.

Table 6 Largest lakes in the Nipigon area.

Name	Type	Area (km^2)	Perimeter (km)
Mound Lake	Lake	1.0	5.9
Eskwanonwatin Lake	Lake	1.3	6.1
Ruby Lake	Lake	1.4	7.3
Nipigon River[1]	River	1.5	28.6
Blair Lake	Lake	1.6	18.3
Black Sturgeon River[2]	River	1.6	83.7
Fog Lake	Lake	1.7	12.0
Jessie Lake	Lake	1.7	24.7
Polly Lake	Lake	2.4	7.4
Purdom Lake	Lake	2.5	25.8
Nipigon River[3]	River	4.2	21.2
Helen Lake	Lake	16.0	33.7
Lake Superior	Lake	31.6	39.6

Metrics obtained from LIO OHN Waterbody file
Metrics refer to portion of waterbody within the Nipigon area
[1]Nipigon River between Jessie Lake and Helen Lake
[2]Black Sturgeon River downstream of Eskwanonwatin Lake
[3]Nipigon River downstream of Helen Lake

4.2 WATERSHEDS

A watershed, also known as a catchment, basin or drainage area, includes all of the land drained by a watercourse and its tributaries. A drainage basin analysis was conducted to confirm and, where possible, partition the most detailed available mapping of watersheds by the MNR. The delineation of drainage divides can be useful for determining surface water flow directions and contributing to an initial understanding of the shallow groundwater flow system.

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

The movement of water over the landscape was modelled using the watershed analysis function in the program TNTmips, with the CDED elevation model as the surface model. The CDED digital elevation model used for this analysis was created by NRCan using the same provincial data on which the Provincial DEM was constructed. As a result, the DEM used here is comparable with that used by the MNR to construct the quaternary watersheds.

The procedure followed in the drainage analysis was to confirm the boundaries in the quaternary watershed file and then subdivide the quaternary watersheds where possible. Note that the quaternary watersheds do not represent the smallest catchments that can be delineated in most areas, as local ridges and highland complexes are present, which serve to further control surface flow directions within each watershed.

The result of the drainage analysis is a single set of lines and polygons, representing a merged watershed file (Figure 10). One of the inset maps on Figure 10 illustrates the tertiary watersheds in the Nipigon area. As there is virtually no limit to the number of times that a watershed can be subdivided, the minimum size of basin was limited to maintain a consistent scale of delineation. Where modelled drainage divides matched well with the quaternary watershed boundaries, the procedure was to accept the existing quaternary watershed boundary. Newly delineated drainage divides were then used to subdivide the quaternary watersheds. Each portion of the catchment boundary was specified as being modelled both in this study and by the MNR or in this study only. Effort was made to ensure that the newly delineated drainage divides honoured the existing watercourse map file, such that drainage divides do not cross watercourses.

4.3 SURFACE FLOW

Surface water flow through the Nipigon area is contained within the Great Lakes – St. Lawrence watershed directed entirely toward Lake Superior, with drainage primarily accomplished by the Black Sturgeon, Nipigon, Jackfish and Jackpine rivers and their tributaries. Three tertiary watersheds are present within the area: the Black Sturgeon, Nipigon and Jackpine watersheds (Figure 10 inset). The following subsections describe surface water flow along the rivers and creeks in the area. Figure 10 provides a useful reference for many of the descriptions below, and other figures are referred to as appropriate.

4.3.1 BLACK STURGEON WATERSHED

The Black Sturgeon River is the seventh largest tributary to Lake Superior, with a mean annual flow of 19 m^3/s (Swainson, 2001). The total drainage area of the Black Sturgeon watershed, based on the MNR tertiary watershed file, is 5,507 km^2. The river is approximately 100 km long, extending from Black Sturgeon Lake south to Black Bay, on Lake Superior. The portion of the river extending through the Nipigon area is about 28 km long, dropping 21 m from the north to the south boundaries of the area. Throughout this reach, the river meanders across the wide floor of a drift-filled valley, which is the surface expression of the Black Sturgeon fault zone (Coates, 1972). Eroding channel margins are common, as are tiny oxbow lakes. Typical channel widths are 15 to 30 m. Between Eskwanonwatin Lake and Black Bay, there are seventeen sets of rapids (Sakamoto, 2006), several of which are upstream from Larson Creek. Downstream of Shillabeer Creek, the river is contained within an impressive, steep-walled valley, 150 to 250 m high and 1.0 to 1.5 km wide (profile D, Figure 5). The river is protected within the Black Sturgeon River Provincial Park over much of its length. Within the Nipigon area, Shillabeer Creek and Larson Creek are the main tributaries. Others include Scooper Creek, Mound Creek, and Moseau Creek.

4.3.2 NIPIGON WATERSHED

The Nipigon River extends for a length of about 50 km from Lake Nipigon (Figure 10, inset A) to Nipigon Bay on Lake Superior. It represents the largest tributary to Lake Superior, both in Canada and the United States, with a mean annual flow of 365 m^3/s (OPG, 2005). The total drainage area of the Nipigon watershed, based on the MNR tertiary watershed file, is 25,230 km^2. However, the total area drained through the watershed increases by 13,578 km^2 once the drainage area of the Ogoki Diversion (north of Lake Nipigon) is considered (OPG, 2005). The Nipigon River drops about 44 m from the north to the south boundaries of the Nipigon area as it extends from Jessie Lake through Helen Lake, and then into Lake Superior. The Cameron Falls and Alexander generating stations modify flows on the Nipigon River in this area. Within the Nipigon area, the Nipigon River is marked by its relatively wide channels and by its expansive lake sections (as compared with other rivers in the area). From Alexander Generating Station to Helen Lake, the river is nearly straight, its maximum depth is about 15 m, and its channel widths range from 85 to 190 m (OPG, 2005). Here, the present-day river channel is set within a much larger valley, about 3 km wide (profile B, Figure 4), which represents the Nipigon spillway, and was partly responsible for draining a glacial lake occupying the Lake Nipigon basin (Lake Kelvin) about 9,000 years ago (Zoltai, 1965a). The present-day channel is entrenched about 20 m into a glaciolacustrine plain for the first 6 km below the Alexander Generating Station, typically about 300 m wide, with bank heights decreasing along the lower part of the reach, where Taylor (1897) observed low banks formed of horizontally laminated silts and clays. Where the river spills into Helen Lake, there is a delta, which is reportedly composed dominantly of sand and silt (Taylor, 1897). The largest tributaries to the Nipigon River in this area are Frazer, Booth, Cash and Stillwater creeks.

4.3.3 JACKPINE WATERSHED

Multiple rivers and creeks, some not situated in the Nipigon area, drain the Jackpine watershed, including the Cypress, Dead, Gravel, Jackfish and Jackpine rivers and Ozone Creek. The later three are the three streams dominantly responsible for draining the portion of the watershed within the Nipigon area. The Jackpine watershed has a drainage area of 2,260 km^2, based on the MNR tertiary watershed file, and it includes St. Ignace Island, which is south of the Nipigon area. The watershed within and outside of the Nipigon area is marked by a remarkable scarcity of overburden deposits (Figure 3; OGS, 2005a).

The Jackfish River drains a large part of the eastern half of the Nipigon area. Overall, it follows a structurally controlled north-south course from the north boundary of the Nipigon area to Fire Hill Bay, on Lake Superior. The river can be divided into upper and lower reaches by the junction of the East Jackfish River. The upper reach marks a transitional zone between the drift-covered plain to the west and the thinly drift covered terrain to the east. The terrain along the upper reach is mixed, with most of the main branch eroding into a clay plain from which isolated bedrock hills protrude. Below Limestone Creek, the river extends along the base of a prominent escarpment. The land immediately east of the lower reach is particularly flat and poorly drained. The main tributaries to the Jackfish River in this area are the East Jackfish River and Gretel and Limestone creeks.

Gretel Creek drains part of the glaciolacustrine plain west of the Jackfish River. The abundant wetlands along the outer branches of the creek indicate stagnant drainage conditions over the low-lying plain. A short distance north of the Nipigon area, near where the Jackfish River enters the area, is Hanson Lake and Hanson Creek. Frape et al. (1984a) studied the hydrogeology and geochemistry of mineral licks in the Hanson Lake area and found that groundwater was upwelling through glaciolacustrine silts and clays 2 to 10 m thick deposited on an undulating bedrock surface. They reported typical hydraulic conductivities of 3.0×10^{-7} cm/s for the silts and clays. The low hydraulic conductivities of the silts and clays deposited in this area are responsible for the wet, swampy drainage conditions.

Limestone Creek drains a large part of the clay plain south of Cedar Mountain (Figure 6). It also drains Lloyd Lake, Carlotta Lake, Limestone Lake and the nearby hills. Stagnant drainage is common on the plain around Limestone Creek, particularly around Carlotta Lake (Figure 9). Carlotta Lake is a peculiar water feature. It is evidently quite shallow. Its shallowness is due to the flat terrain on which it is situated. Given the typical characteristics of and widespread occurrence of mineral springs in the region (Chamberlin et al., 1977; Fraser and Reardon, 1980), its position at the base of an escarpment formed partly of Sibley Group rocks (Figure 2) makes it a plausible discharge zone for a local groundwater flow system associated with the Pass Lake Formation (Franklin et al., 1980) or other possible aquifers in the group.

Ozone Creek drains an important part of the thinly drift-covered eastern highland east of the Jackfish River. The creek drains part of the mesa above Camp 81 Road and a large, thinly drift-covered area north of the road. Drainage is good throughout the basin, except along the lowest 3 km before Kama Bay, where it extends through a poorly drained clay plain with extensive organic deposits. The middle reach of the Ozone Creek basin contains a vast number of rock outcrops, with a particular concentration on the 4 km by 5 km surface shown on Figure 12 (insets). Along the north and west edges of this surface, the creek flows through linear trenches typically 15 to 25 m deep and 200 wide, with a maximum depth of about 40 m. Profile H (Figure 6) illustrates the surface expression of the western trench and the main part of this surface.

The Jackpine River extends along an impressive north-northeast trending trench formed on the Jackpine Fault zone. The only portion of the river not contained within this linear topographic depression is in the northeast corner of the Nipigon area, where the river passes through Central Lake. The portion of the river within the Nipigon area is about 27.5 km long, with a vertical drop of 208 m across this reach (Figure 4). As a result, its gradient across the Nipigon area is much steeper than that of the Nipigon and Black Sturgeon rivers to the west. The trench it follows is typically 80 to 100 m deep and 400 to 500 m wide in some of the most linear and symmetrical sections. Profile I (Figure 6) shows the scale of the linear depression formed over the Jackpine Fault zone near Shark Lake. Within the Nipigon area, Seahorse, Topnot and Blair creeks are some of its named tributaries.

5 TERRAIN CHARACTERISTICS

Surface lineaments are either difficult or impossible to detect in areas of thick and extensive overburden deposits, as thick drift deposits are able to mask the surface expression of lineaments. In these areas, the lineament interpreter is "blinded" to some extent by the presence of thick overburden. An understanding of the distribution and thickness of overburden is, thus, essential for interpreting the distribution of lineaments mapped from satellite imagery and topographic data (JDMA, 2014), particularly with respect to lineament length and density. In areas of sporadic drift deposits, the drift can conceal minor lineaments, producing low apparent lineament density, and it can censor the lengths of major structures. In areas of thick and extensive overburden, major structures could exist that would be undetected from SPOT and CDED. Furthermore, areas of thin drift that also contain abundant bedrock exposure are more readily amenable to site characterization, as such locations would enable further investigation of the potentially suitable bedrock formations through outcrop mapping of bedrock structures and preliminary rock mass characterization. As a result, a detailed understanding of the type and distribution of thick and extensive overburden deposits across the Nipigon area is important, as is the distribution of exposed bedrock.

This section provides information on overburden deposits based on descriptions of the deposits mapped through the Northern Ontario Engineering Geology Terrain Study (Figure 3) and on other available data. Section 5.1 presents a preliminary review of water well and drillhole data on overburden thickness. Details on the expected composition, distribution and thickness of surficial deposits within the terrain units shown on Figure 3 are presented in Section 5.2. The extent of exposed bedrock was mapped using SPOT (Figure 11, Figure 12), Landsat ETM (Figure 13) and Landsat TM (Figure 14) imagery, and the derived outcrop maps are overlain onto topographic maps, generated using CDED, on Figure 15, Figure 16 and Figure 17, respectively. The latter three maps are used in Section 5.2.1 to facilitate a discussion on the extent of exposed bedrock.

Note that for many surficial deposit types, the surface deposit overlies other overburden deposits. As a result, the estimated thickness for a particular deposit does not necessarily represent total overburden thickness. It is also important to note that only limited water well or borehole data are available to characterize drift thickness in this area. It is extremely unlikely that the available subsurface data have captured true maximum drift thickness. Overburden deposits more than 120 m thick have been observed elsewhere on the Canadian Shield (Harrison, 1957).

5.1 DRILL HOLE AND WATER WELL DATA

Data on overburden thickness from water well records collected by the Ministry of the Environment (MOE, 2013) and from diamond drill holes compiled by the Ontario Geological Survey (OGS, 2005b) were reviewed to supplement the information on surficial deposits compiled from the literature (Section 5.2). The locations of these wells and drill holes are shown in Figure 3.

5.1.1 WATER WELL INFORMATION SYSTEM

Water well records from the MOE Water Well Information System (WWIS) for the Nipigon area were acquired (Section 1.3.6). There are 84 water well records with data on depth to bedrock in the Nipigon area, 79 of which are located within the Township of Nipigon. The depth to bedrock in the 84 wells ranges from zero to 82.3 m with an average of 29.3 m.

The terrain around the settlement of Nipigon is characterized by a low-relief plain with two ridges that rise 20 to 40 m above the plain. The ridges are shown on Figure 3 as two west-northwest trending areas of bedrock terrain within a drift-covered area. The morphology of these ridges can be seen on Figure 6, with profile F (Figure 5) also illustrating their shape. For reasons outlined below, it is suspected that the northern ridge actually represents a surficial deposit, not a rock ridge. Several wells are located along the southern flank of this ridge, and all of them indicate drift deposits 20 to 50 m thick. Aggregate pits exist along the axis and northern flank of the ridge. Discussion with the owner of one of the pits on this ridge indicated that the pit is producing mainly sand, that the sand overlies clay, and that bedrock has not been encountered (James Nichols, personal communication 2013). No rock outcrops or rock cuts have been identified on this ridge in satellite or aerial imagery. Lawson (1893) described a landform on the west bank of the Nipigon River, at the railroad bridge, which extended at least 60 m above the level of the river, and which he interpreted as a great bar that once separated the early-postglacial equivalents of Helen Lake and Lake Superior. Lawson (1893) also described seven wave-cut terraces etched into the ridge, whereas others have described three (McCann, 1997). Taylor (1897) indicated that this ridge is composed of soft clay, sand and silt with gravels above. Zoltai (1965b) also interpreted this ridge as a surficial landform, but rather than a bar, he interpreted it as an end moraine modified by lake action. If this ridge is composed of surficial materials, not bedrock, then it illustrates the uncertainty in terrain coverage resulting from the preliminary nature of the available surficial mapping, which has identified this area as a rock ridge.

Nevertheless, the three thickest drift deposits intersected by water wells in the Nipigon area range from 51.8 to 82.3 m thick and these wells are located within the low areas between the ridges, near or within the settlement of Nipigon. This is consistent with our expectation that the thickest drift deposits will be located generally in the low-lying areas and depressions.

5.1.2 Ontario Drill Hole Database

Diamond drill holes recorded in the OGS drill hole database occur in two locations within the Nipigon area. Although there are only a small number of drill holes, these data nevertheless provide some information on overburden deposits within the area.

The Jackpine River property, in the northeast part of the Nipigon area (Figure 3), contains five boreholes located in an area mapped as bedrock terrain with depth to bedrock reported in the boreholes ranging from zero to seven metres. One of the holes was drilled in 1971, with the four other holes drilled in the early 1990s. No information on overburden composition was reported in the drill logs. These boreholes provide what are expected to be typical values for overburden thickness within the areas mapped as bedrock terrain on Figure 3.

The Fog Lake claim group is located near the west margin of the Nipigon area, near Eagle Mountain. Three boreholes are reported east of Eagle Mountain within the Black Sturgeon valley, drilled in 1980 by Uranerz Exploration & Mining Limited. No information on the composition of the overburden deposits intersected was reported. The two boreholes located closer to Eagle Mountain report lower drift thickness values of about 7 m, whereas the hole located further within the valley intersected an overburden deposit 28.6 m thick. These boreholes further support our expectation that drift deposits are typically thickest within low-lying areas and thinner along the flanks and crests of hills and ridges.

5.2 NOEGTS Terrain Units

5.2.1 Bedrock Terrain

Approximately half of the Nipigon area was mapped as bedrock terrain during the NOEGTS program, with the largest contiguous zone of bedrock terrain located in the eastern half of the area, generally east of the Jackfish River (Figure 3). 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, 1981b). However, as illustrated from the water well data (Section 5.1.1), drift deposits within areas mapped as bedrock terrain can be much thicker locally, with deposits 30 to 50 m thick observed in an area mapped as bedrock terrain near the settlement of Nipigon. This illustrates the need to interpret the thickness of overburden deposits and the amount of exposed bedrock in the areas mapped as bedrock terrain with caution.

The extensive areas not delineated through NOEGTS as bedrock terrain are identified in Section 3.2 to coincide, in general, with large areas of low relief. The lack of relief in these areas is in most cases expected to be associated with thick and extensive drift deposits filling lows in the bedrock topography, resulting in low confidence in identifying major structures using SPOT and CDED in these areas. The network of major bedrock structures displayed throughout the thinly drift covered parts of the Nipigon area is almost surely to exist beneath the overburden.

Figure 15, Figure 16 and Figure 17 present maps showing the areas of exposed bedrock mapped from SPOT, Landsat ETM and Landsat TM data, respectively. The areas of exposed bedrock delineated on these maps are plotted on a morphological map showing positively expressed bedrock-controlled landforms such as hills, ridges and mesas. In addition, the morphological component of the map subdivides the Nipigon area into highlands and lowlands based on whether the relief calculation made using a 20 km search radius is positive or negative (Figure 5). As can be seen on these figures, slopes at least 15° in magnitude form the margins of many of the most impressive, positively expressed, landforms in the area. Slopes of this magnitude are generally indicative of the presence of cliffs. The combined area of exposed bedrock mapped from the SPOT and Landsat images was plotted on the insets of Figure 2 and Figure 3.

It is important to note that the areas delineated as bedrock terrain on Figure 3 do not represent areas of widespread exposed bedrock. The reader should interpret the bedrock terrain mapped during the NOEGTS campaign as general areas where thin drift deposits are expected, and where local small areas of exposed bedrock could be relatively common. ‘Bedrock terrain’ is mapped over 52.4% of the portion of the Nipigon area not covered by a waterbody of any size, or over 52.1% of the portion of the area not covered by Lake Superior. In contrast, only 4.6, 4.3 and 4.0% of the Nipigon area is mapped as ‘exposed bedrock’ from the SPOT, Landsat ETM and Landsat TM data, respectively. These estimates of the extent of exposed bedrock are consistent with what Lord (1957) indicated was common on the Canadian Shield, namely less than 10%.

The satellite mapping of bedrock outcrops revealed an absence of exposed bedrock within several of the areas mapped as bedrock terrain (Figure 3), and of particular note in this regard are the mesas. Relatively few outcrops were identified on the tops of mesas. The few outcrops were generally limited in extent and were widely scattered. For example, using the 40 cm FRI imagery no outcrops were found on the top of Moseau Mountain. Most of these hilltops are at higher elevations than the highest glacial and postglacial stages of the Lake Superior basin (about 290 m). As a result, any drift cover has not been eroded by wave action. The distribution of rock outcrops on Doghead Mountain is revealing in this regard. Outcrops are generally only found on portions of the mountain that are below 290 m elevation. The burn zone of a September 2006 forest fire on the west edge of Eagle Mountain, at 450 to 500 m elevation, as viewed using the FRI imagery, provided an opportunity to gain insight into the possible outcrop distribution that could be found beneath the forest canopy on many of the mesas. It was found that the outcrops were small and scattered between larger drift-covered areas. It is interpreted that a drift veneer on the mesas provides sufficient soil conditions to support a forest, which then renders the small outcrops difficult to identify using satellite or aerial imagery.

A comparison of the hills shown on Figure 15 with the areas of bedrock terrain shown on the Figure 15 inset illustrates that many of the areas mapped as bedrock terrain coincide with hills. Several of the hills delineated on Figure 15, particularly the ones displaying steep slopes around their margins, represent mesas, such as Eagle Mountain and the Kama Hills, which are capped by diabase sills (Figure 2). Others represent hills formed in granitic or metasedimentary rocks. The hills and ridges delineated on Figure 15, in almost all cases, are bedrock-controlled and represent areas where overburden deposits are expected to be relatively thin as compared with the surrounding low-lying areas. Except for the ridge on the north side of the settlement of Nipigon, the Nipigon area contains no known positively expressed surficial deposits, such as eskers or end moraines, that are of sufficient size and prominence to be included within the selection of hills shown on these figures.

The insets provided on Figure 15, Figure 16 and Figure 17 illustrate that most of the exposed bedrock occurs in areas mapped as bedrock terrain by the NOEGTS program. These insets also show the areas delineated by Zoltai (1965a) as bare rock eroded by lake action, which represent areas where overburden deposits were stripped from the bedrock surface by shore erosion during glacial and postglacial high stands of the Lake Superior basin. These areas of bare rock generally outline the best areas of exposed bedrock delineated from the three different satellite images.

Within bedrock terrain, bearing capacities are usually excellent, blasting is required for excavations, earth borrow is scarce, groundwater resources are unpredictable, and trafficability is poor (Gartner et al., 1981).

Several belts of exposed bedrock have been identified in the Nipigon area and are described below. Section 8 provides a discussion of the accessibility of these outcrop belts.

5.2.1.1 NIP10 burn zone

A May 1999 wildfire entitled Nipigon fire #10 or NIP10 (Scarratt, 2001) has produced one of the most extensive zones of exposed bedrock in the Nipigon area. The Figure 13 inset shows a detailed view of the NIP10 burn zone, with outcrops appearing in white on the panchromatic inset image. The burn zone is located in the northwest corner of the Nipigon area (see insets on Figure 15 and Figure 16). The August 2008 SPOT image (Figure 12 and Figure 15) covering the western half of the Nipigon area and the July 2001 Landsat ETM image (Figure 13 and Figure 16) illustrate the extent of exposed bedrock present in this area after the occurrence of the wildfire. The June 1988 Landsat TM image (Figure 14 and Figure 17) illustrates the exposed bedrock within this area prior to the wildfire, which is considerably less than that shown in the post-fire imagery. The main areas of exposed bedrock within the NIP10 burn zone are distributed on topographic highs in a belt up to 4 km wide centred on Larson Creek and in another belt centred on the south and west margins of the granitic intrusion, where escarpments capped by diabase sills are found (Figure 2). The internal portion of the muscovite granite intrusion, south of Mound Lake, is represented by a low relief surface (No. 7, Figure 7 inset) displaying a relative scarcity of exposed bedrock. The pattern of exposed bedrock described above is broadly similar to that portrayed on the bedrock map of Coates (1971).

The portion of the NIP10 wildfire within the Nipigon area is mainly located over the circular muscovite granite intrusion rimmed by diabase (Figure 2). As a result, the metasedimentary rocks to the east, around McIvor Lake, are not as well exposed.

5.2.1.2 West of Church Lake

Abundant exposed bedrock can be found on a north-northwest trending bedrock-controlled topographic high west of Church Lake (Figure 15 to Figure 17). The area is 1.5 km wide and 4 km long, and Figure 2 indicates that it is underlain by intrusive rocks ranging from granodiorite to granite. It rises about 150 m above the Black Sturgeon River.

5.2.1.3 North and South Trout creeks

A considerable amount of exposed bedrock can be found near the southern margin of the Nipigon area within an east-west trending belt 3 km wide and 5 km long located west of Highway 17 (Figure 15 to Figure 17). Zoltai (1965b) mapped this area as a belt of bare rock (Figure 15 inset), and he interpreted that the drift deposits had been stripped from the bedrock surface by wave action as lake levels fell following deglaciation. The belt broadly follows the 290 m elevation contour (Figure 3 inset), the maximum elevation of the Lake Minong stage observed near the settlement of Nipigon (Farrand, 1960). Rock types included within this belt consist of granitic and metasedimentary rocks as well as diabase sills. Sibley Group rocks are exposed in cliffs on the sides of distinct hills. South Trout Creek and North Trout Creek and their tributaries extend along linear valleys and other structurally controlled lows in this area, with most of the exposed bedrock occurring on isolated rock knobs rising above wet, swampy lows. One of the larger depressions in the bedrock is a north trending feature, 50 m wide, supporting a pond surrounded by wetlands (inset A, Figure 9). The high density of steep slopes observed in this area (Figure 8) testifies to the ruggedness of the terrain.

5.2.1.4 East bank of Helen Lake

Exposed bedrock can be found on many of the local topographic highs within a 2 km-wide belt extending above the east bank of Helen Lake, between Mission Bay and Indian Bay (Figure 15 to Figure 17), an area underlain by metasedimentary rocks (Figure 2). Zoltai (1965b) mapped a similar belt of bare rock extending along the east bank of Helen Lake (Figure 15 inset). The most extensive area of rock outcrop within this belt is a north-northwest trending ridge 1 km wide and 3 km long above Mission Bay (Figure 11 inset). Highway 17 extends along the southern margin of this low-relief upland. Highway 11 passes within a few hundred metres of its northwest tip. A prominent north-northwest trending linear escarpment that connects Helen and Ruby lakes represents the southwest edge of this flat-topped ridge. The escarpment is higher to the north-northwest, with a height of about 40 m at Highway 17 and a maximum height above Helen Lake of about 100 m. The distribution of rock outcrops on this ridge reveals a distinct fabric of swampy linear depressions associated with bedrock structures.

5.2.1.5 Eastern highland

Rock outcrops can be found throughout the thinly drift-covered eastern highland east of the Jackfish River, almost exclusively in areas underlain by metasedimentary rocks (Figure 15 to Figure 17). Noteworthy clusters of rock outcrops are found along the middle reaches of the East Jackfish River and Ozone Creek. The most extensive area of exposed bedrock on the eastern highland is a 3 km-wide, 14 km-long, north trending belt located north and slightly east of Kama Bay. Zoltai (1965b) identified the same north trending belt of bare rock as an area where drift deposits were stripped through wave erosion along the shores of glacial and postglacial lakes (Figure 15 inset). The belt broadly follows the 290 m elevation contour (Figure 3 inset), the maximum elevation of the Lake Minong stage of the Lake Superior basin observed near the settlement of Nipigon (Farrand, 1960). Rock outcrops are also present in other locations underlain by metasedimentary rocks at higher elevations within the eastern highland. The widespread occurrence of rock outcrops on the eastern highland is indicative of a general lack of thick and extensive overburden deposits. Few rock outcrops were identified on the tops of the Kama Hills.

As noted above, rock outcrops are found in abundance on the eastern highland east of the Jackfish River. However, thicker overburden deposits in some areas east of the Jackfish River result in a relative lack of rock outcrops. The main area underlain by extensive overburden deposits east of the Jackfish River is located immediately north of Kama Bay (Figure 3; No. 21, Figure 7 inset). Here, outcrops are restricted to isolated rock knobs protruding from the surrounding, flat, swampy plain. Much of this generally drift-covered zone is delineated as organic terrain on Figure 3. Another area where thicker, more extensive drift deposits can be found is along the East Jackfish River within a broad, east-west trending topographic low that extends from near the mouth of Meat Axe Creek to Berryman Lake. This flat-floored, wet and swampy trough is about 1.0 to 1.5 km wide, roughly 8 km long and is bound to the north and south by discontinuous lines of rock knobs and escarpments. The lowest 5 to 8 km of the Jackpine River extends through an area of extensive overburden deposits, mapped as outwash on Figure 3.

5.2.2 Morainal terrain

On Figure 3, areas where the till is generally thick enough to mask any topographic irregularities associated with the bedrock topography are mapped as ground moraine (Mollard and Mollard, 1981b). The term ground moraine refers to an extensive deposit of till forming an undulating to rolling plain. The thickness of till within the areas mapped as ground moraine is expected to range from less than one metre to many tens of metres (Mollard and Mollard, 1981b).

End moraines mark former static positions of the glacier margin during deglaciation. The Nipigon moraine is the only major end moraine mapped in the Nipigon area, situated in the northwest corner of the area (Figure 3). The moraine formed along the margin of an ice lobe situated in the Nipigon basin (Barnett, 2004). It is composed primarily of thick sand and gravel deposits. Extensive ice-marginal deltas along the moraine indicate that a high-level proglacial lake fronted the glacier during moraine formation (Barnett, 2004). As proglacial lake levels dropped, erosion of the moraine by river and lake currents resulted in the redistribution of sand and gravel onto adjacent low-lying areas (Barnett, 2004). Similarly, Zoltai (1965a) described this moraine as remarkably flat on top locally, and on his map (Zoltai, 1965b) it is classified as a moraine modified by wave action.

Within the Nipigon area, the Nipigon moraine trends west-northwest and extends through the Black Sturgeon valley (Figure 3), where a channel cut through the moraine contains the Black Sturgeon River. The Black Sturgeon Road extends along the Nipigon moraine for a considerable distance northwest of the Nipigon area. Estimates of the thickness of the moraine using topographic data are somewhat problematic due to the complex geometry of the landform in relation to the surrounding terrain, but some indications are that it is at least 10 m thick. The SPOT imagery indicates the clear presence of an extension of the moraine onto the highland east of the Black Sturgeon valley. Here, the feature is a sinuous esker-like ridge 100 to 200 m wide that extends for 3 km along a subtle east-southeast trending topographic low. It rises at most 5 m above the adjacent terrain, and locally displays two crests with a central trough. Its elevation ranges from about 380 to 385 m. Zoltai (1965b) mapped this eastern extension of the moraine and indicated that it was not modified by wave erosion. The high elevation of this deposit would have protected it from being modified by erosion or deposition within a high-level proglacial lake.

A possible end moraine not mapped on Figure 3 is the ridge on the north side of the settlement of Nipigon, which Highway 17 extends along for about 3.5 km west of the Nipigon River (Figure 6). The ridge is 20 to 40 m high and about 500 m wide. Zoltai (1965b) mapped this feature as an end moraine modified by lake action. On Figure 3, the feature was mapped as a rock ridge. As discussed in Section 5.1.1, there is a possibility that this ridge is formed of surficial materials, not bedrock.

The till in the Nipigon area is generally sandy with high percentages of stones, boulders and gravel, and little clay (Zoltai, 1965b). Barnett (2004) indicates that the till in this area is commonly stony with a sandy to silty matrix, and that thicker till deposits occur beneath undulating plains or within small boulder-covered ridges. Barnett (2004) described the boulder-covered ridges in this region as discontinuous ridges commonly 3 to 5 m high, with the ridges marking expected minor standstills of the ice margin. Zoltai (1965a) described such ridges as washboard moraines, indicating that they represent linear hills typically 30 m wide at their base, usually less than 6 m high, occurring in groups of 5 to 20, usually separated by less than 150 m. The long axis of the ridge is oriented normal to the latest direction of ice flow. Although washboard moraines have not been mapped in the Nipigon area, it is likely that such features would be identified if a detailed surficial mapping program were undertaken.

5.2.3 GLACIOFLUVIAL TERRAIN

Four different landform types deposited by glacial meltwater are mapped in the Nipigon area (Figure 3): esker, kame, outwash plain, and valley train. Materials forming these landforms generally consist of gravel, sand and silt.

Eskers are characterized by long, narrow sand and gravel ridges, which can include braided, branching, beaded and kettled segments (Mollard and Mollard, 1981b), and their deposition is associated with supraglacial, englacial and subglacial streams. Zoltai (1965a) suggested that the crests of eskers observed in the region extend about 5 to 20 m above the surrounding landscape. Most ridges trend roughly parallel with the last direction of glacial flow. Materials within eskers consist of sandy gravel and gravelly sand complexly layered and often exhibiting collapse structures; pockets and layers of silt and fine sand, boulders and till can also be found within and along the flanks of eskers (Mollard and Mollard, 1981b). There are two main eskers mapped in the Nipigon area (Figure 3). One trends north-northeast extending along the west margin of Jessie Lake, northwest of Helen Lake. The other is located southwest of the Black Sturgeon River near the southern boundary of the Nipigon area. Both features display very little surface relief or definition in general, although the feature on the west bank of Jessie Lake is the better defined feature of the two.

A large area extending north-northwest from the settlement of Nipigon has been mapped as a glaciofluvial kame deposit (Figure 3). Kames are hills, mounds or terraces formed from sediment that accumulated in contact with the ice sheet and were subsequently deposited on the land surface with melting of the ice sheet. The deposit is situated like a terrace, high up on the west margin of the Nipigon valley. Kames in the region vary from mere accumulations of gravel on the margins of bedrock-controlled hills to sizable hills or knolls of sand and gravel (Zoltai, 1965a). Larger steep-sided kames tend to display irregular surfaces and can contain deep kettle hole depressions (Mollard and Mollard, 1981b). Kames are generally composed of complexly interbedded sand and gravel strata exhibiting fold, fault and pinch-out structures (Mollard and Mollard, 1981b). Minor amounts of silt, till and boulders are also expected within kames. Zoltai (1965a) suggested that the largest kames in the region are greater than 1.5 km^2 in extent and rise 15 to 30 m above the surrounding terrain. The kame deposit in the Nipigon area displays no obvious large hills of sand and gravel, like those described in the literature. Best described as a kame terrace, this feature displays an undulating upper surface with a much steeper lower margin. Lofquist Lake and another small lake 2 km to the north have no mapped stream outlets and could represent kettle lakes.

Within the Nipigon area, outwash plain deposits are mapped south of Fog Lake, and valley train outwash deposits are mapped along parts of the Black Sturgeon and Jackpine rivers (Figure 3). Outwash sediments consist of sand and gravel and are interpreted to have been deposited in flooded lowlands and valley bottoms after being transported by meltwater flowing from the front of a glacier (Mollard and Mollard, 1981b). Outwash deposited on top of stagnant glacial ice tends to be highly variable in terms of texture, and the topography can be irregular due to the uneven collapse of sediment as the underlying ice melted. Outwash deposited over proglacial plains or in valleys tends to be less variable. Outwash deposits are good potential sites for groundwater development (Mollard and Mollard, 1981b), and the high permeability of these materials makes them important pathways for groundwater flow.

Larger glaciofluvial deposits have the potential to represent significant regional aggregate or groundwater supplies. The good foundation conditions and abundance of suitable borrow and granular materials make these landforms ideal for transportation routes, building sites, forest management staging areas, and airport locations.

5.2.4 GLACIOLACUSTRINE TERRAIN

Three types of glaciolacustrine deposits are mapped in the Nipigon area: raised beach ridge, glaciolacustrine delta, and glaciolacustrine plain. Glaciolacustrine plains are the most extensive of the three deposit types found in the Nipigon area.

Fine-grained glaciolacustrine deposits are mapped in low-lying parts of the Nipigon area, including north and south of Cedar Mountain, north of Polly Lake and within the Black Sturgeon and Nipigon valleys (Figure 3). These deposits generally occur as rhythmically bedded or massive silts and clays, and form some of the most extensive overburden deposits mapped in the area. Zoltai (1965a) reported that rhythmically bedded silts and clays found near the north shore of Lake Superior tend to occupy valley flats between mesas and between other topographic highs, with the thickness of the lake sediments being about 3 m on average and up to a possible maximum of 10 m. Frape et al. (1984a) augured an array of holes to bedrock through a glaciolacustrine deposit a short distance north of the Nipigon area near the Jackfish River, and found silts and clays 2 to 10 m thick deposited on an undulating bedrock surface. The silts and clays showed average hydraulic conductivities in the order of 3.0×10^{-7} cm/s, which is typical of glaciolacustrine silts and clays (Fetter, 2001). Low-lying silt and clay plains have a high water table and are subject to local flooding during spring runoff and heavy cloudbursts (Mollard and Mollard, 1981b).

Maps presented in the literature (Zoltai, 1965a; Teller and Thorleifson, 1983; Slatterly et al., 2007) indicate that the glaciolacustrine sediments mapped in the Nipigon area were deposited within glacial lakes of the Lake Superior basin. Farrand (1960) studied the succession of glacial lakes that occupied the Lake Superior basin as it became free of ice. The Minong Stage formed the highest lake to occupy the entire Lake Superior basin. It formed three beaches, the highest of which displays an elevation of 289.5 m in the Nipigon area. Farrand (1960) found 13 raised beaches or wave-cut terraces in total. The highest beaches were formed of silts and clays, whereas the lower stages produced beaches of sand and silt. Slatterly et al. (2007) showed that water planes associated with the Minong phase of Lake Superior were confluent with early stages of the glacial lake that occupied the Lake Nipigon basin (Lake Kelvin).

Raised beach deposits are mapped along the margins of rock ridges and mesas fronting onto Lake Superior near Kama Bay and Fire Hill Bay (Figure 3). Mollard and Mollard (1981b) suggest that, in general, the deposits are thin and consist of bouldery, gravelly, and sandy wave- and current-transported materials. The deposits are mapped as narrow bands typically 1 to 1.5 km wide extending along the margins of local topographic highs (Figure 3).

Glaciolacustrine deltas are mapped locally within the Nipigon area, such as near the mouths of the Nipigon and Jackpine rivers (Figure 3). Deltaic deposits occur where spillways delivered sediment into proglacial lakes. Materials in these deltas range from sandy gravel and coarse sand near the delta apex to fine sand and silty sand in the distal portion of the delta (Mollard and Mollard, 1981b). The finer materials in the distal portion of a delta are expected to grade into and interfinger with the fine-grained glaciolacustrine materials deposited on the lake floor. According to the owner of several aggregate pits in the area, the aggregate pits in the deltaic deposit mapped near the mouth of the Nipigon River (Figure 3) contain a relative abundance of gravel as compared with the abundant sand found in pits on the ridge on the north side of Nipigon. Thurber (1995) described the materials encountered above the east bank of the Nipigon River, upstream of Highway 17, as consisting of a great depth of high permeability granular materials with a low permeability silt capping layer over much of the area away from the bank crest.

Immediately north of the Nipigon area, 10 km north of Cedar Mountain, Cash Creek forms a transitional zone between a glaciolacustrine delta to the east and a glaciolacustrine plain to the west (Zoltai, 1965b). Pye (1960) delineated the area west of the creek as a low, flat, swampy area underlain by sand and clay, and he regarded the land to the east as sand terraces. Zoltai (1965a) mentioned the delta east of Cash Creek, situated at the mouth of the Pijitawabik spillway, as an example of a particularly well developed glaciolacustrine delta. According to Zoltai (1965a), deltaic deposits in this region are typically more than 15 m thick and generally consist of stratified coarse-to-medium sand, with gravel and strata of very fine sand or silt present locally. Given the information above, it is possible that the glaciolacustrine materials north of Cedar Mountain grade from silts and clays to silty sands with distance to the north.

Glaciolacustrine plains are often associated with poor drainage and organic terrain. The geotechnical properties of silts and clays are usually poor, with low shear strengths that decrease with depth, poor bearing capacities, and high frost susceptibility (Gartner et al., 1981). These materials can have high moisture contents and can be difficult to handle and compact. Glaciolacustrine deltas are generally good groundwater prospects and can contain sand and gravel aggregates suitable for concrete or asphalt pavement production (Mollard and Mollard, 1981b). The raised beaches in this area were suggested to be generally too thin and narrow to constitute a major source of granular construction material (Mollard and Mollard, 1981a). However, several aggregate pits in the area (Figure 3) are located on the flanks of hills at or slightly below 290 m elevation, which could suggest that these pits are sourcing material from raised beaches.

5.2.5 ORGANIC TERRAIN

All types of peatlands are mapped through the NOEGTS program as organic terrain, with no attempt to distinguish between marsh, swamp, bog, or fen (Gartner et al., 1981). Peatlands are wetlands with massive deposits of peat that are at least 40 cm thick. The organic material is peat and muck (wet fine-grained sediment), and in most organic terrain, stagnant drainage or wet surface conditions are common. The two largest areas of organic terrain mapped on Figure 3 extend inland from Kama and Fire Hill bays on Lake Superior. The wetlands and low relief areas mapped on Figure 9 provide a further indication of the potential areas where organic deposits and poor drainage can be found in the Nipigon area.

Although peat and muck deposits generally occur as thin surficial layers, in places these organic deposits can be several metres thick and the thickness can change drastically over very short distances (Mollard and Mollard, 1981b). The locations of deeper pockets of organic material can be difficult to predict without extensive test drilling (Mollard and Mollard, 1981b). Zoltai (1965a) suggested that the average thickness of the smaller organic deposits in this region is about 3 m.

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

6 GROUNDWATER

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

6.1 SHALLOW GROUNDWATER FLOW

In general, shallow groundwater flow within the Nipigon area is expected to mimic the pattern of surface flow suggested by the watershed map shown on Figure 10. Precipitation and snowmelt will recharge bedrock and surficial aquifers on the two major topographic highs (Figure 4) and on the many local hills and ridges in the area (Figure 6), and groundwater will discharge into topographic lows. As a result, the highlands shown on Figure 15 will be the major recharge zones, and the hills will be minor recharge zones. Water table position is expected to vary with relief, with a deeper water table beneath topographic highs and a shallower water table beneath topographic lows. Fault zones and other weakness zones in the bedrock are typically expressed as linear depressions on the surface. Minor linear depressions in the highlands and on hills will be areas where water collects and could act as recharge zones for intermediate to larger-scale flow systems within the bedrock. Permeable drift deposits in the highlands and on hills could discharge into underlying bedrock aquifers. Relatively deep bedrock aquifers beneath the highlands and hills could recharge surficial aquifers in adjacent low-lying areas. In turn, these low-lying surficial aquifers would tend to discharge into streams, lakes and wetlands.

Recharge through precipitation and snowmelt often occurs in the highlands and on hills, however, permeable surficial deposits exposed at the surface in low-lying areas will also be recharged directly through infiltration of rainwater and snowmelt. The glaciolacustrine delta on the east shore of the Nipigon River, near the Highway 17 crossing (‘Nipigon Bridge’), if granular materials were exposed at the surface, would be an example of such a deposit. However, the granular materials here are draped by a low permeability silt layer, which impedes the rate of vertical infiltration and recharge (Thurber, 1995). In addition, in the Nipigon area in general, the most common surficial materials deposited at low elevations are the glaciolacustrine silts and clays forming extensive plains within the lowlands (Figure 3). The low hydraulic conductivities of these materials restrict the infiltration of rainwater and snowmelt, resulting in swampy conditions and seasonal flooding, particularly in areas of poor drainage. The groundwater conditions near the Nipigon Bridge (Thurber, 1995) consist of a lower water table within the deep granular materials at a level at or slightly above the river level, and a shallower water table perched above the granular materials within the overlying silt materials.

Although it is expected that streams, lakes and wetlands will dominantly represent groundwater discharge areas, in certain cases these surface water features could be responsible for recharging the underlying aquifers. Some lakes situated over permeable surficial deposits in the Nipigon area do not have stream outlets delineated in the 1:20,000 scale mapping of the Ontario Hydrographic Network. For example, Lofquist Lake and another small lake west of Highway 585 have no mapped stream outlets. The streams mapped at lower elevations beneath these lakes are mapped as originating near the lower boundary of the permeable kame deposit on which the lakes are situated, suggesting that they are spring-fed creeks. Lofquist Lake could be what Meyboom (1967) described as a flow-through lake, where groundwater flows in on the upslope side and out on the downslope side of the lake. Two small lakes connected by a wetland on the glaciolacustrine delta northwest of Doghead Mountain have no stream outlets. There are also some small lakes without stream outlets on the mesa at Fire Hill Lake. It is expected that water contained within some lakes and wetlands in the Nipigon area will be released into underlying fractured bedrock aquifers, particularly within structurally controlled depressions, and perhaps more so for high elevation lakes and wetlands.

Mineral rich springs have been identified along the north shore of Lake Superior and around Lake Nipigon (e.g., Fraser and Reardon, 1980). The groundwater discharging at these ‘moose licks’ has generally been inferred to have originated from bedrock aquifers, commonly from the evaporite facies of the Precambrian Sibley Formation (Tanton, 1931), with several of the observed licks occurring at the base of ridges (Chamberlin et al., 1977). Frape et al. (1984a) investigated a mineral lick immediately north of the Nipigon area and cast some doubt on the Sibley Formation as the groundwater source at that location. The array of piezometers implemented in their study confirmed that groundwater was upwelling through glaciolacustrine deposits up to 10 m thick in that area. They found no supporting evidence for the discharge of deep, crystalline rock brine such as found at depth in other parts of the Canadian Shield (e.g., Frape and Fritz, 1987; Frape et al., 1984b).

6.1.1 SURFICIAL AQUIFERS

The most significant shallow aquifers in the Nipigon area are expected to be located in the lowlands and are primarily expected to be associated with thick outwash, kame, end moraine and glaciolacustrine delta deposits. Raised beach and kame terrace deposits could also contain groundwater supplies.

6.1.2 BEDROCK AQUIFERS

The bedrock terrain in the Nipigon area (Figure 3) is generally well drained and this terrain unit is considered to have only poor to fair potential for groundwater supplies (Mollard and Mollard, 1981b). Much of the groundwater in the bedrock is confined to fractures in the upper 45 to 60 m of bedrock, with permeability varying depending on the spacing, depth and aperture of discontinuities (Mollard and Mollard, 1981b). The presence of discrete structures, such as fault zones, dykes, lithological layers, and fracture zones introduces complexity to the groundwater flow systems in bedrock, resulting in potential local departures from the simple topographically controlled flow systems.

The Pass Lake Formation and to a lesser degree the other formations in the Sibley Group have been described as good aquifers (Scott, 1987). These rocks are believed to be associated with groundwater flow systems responsible for mineral-rich springs along the north shore of Lake Superior (Tanton, 1931; Fraser and Reardon, 1980). Some of the springs are located near the base of ridges formed partly of Sibley Group rocks (Chamberlin et al., 1977). It appears plausible that, depending on the orientation and continuity of the Sibley Group strata and the connectivity of the strata with structures such as fracture zones and faults, these rocks could represent important pathways for transmitting groundwater from high elevations within ridges and mesas to the surrounding lowlands.

6.2 DEEP GROUNDWATER FLOW

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

7 NEOTECTONIC FEATURES

Neotectonics refers to recent or ongoing deformation, stress and displacement in the Earth's crust. These processes are related to tectonic forces acting in the North American plate as well as those associated with the numerous glacial cycles that have affected the northern portion of the plate, including all of the Canadian Shield, during the last 2.4 million years (Shackleton et al., 1990; Peltier, 2002).

The movement and interaction of tectonic plates creates horizontal stresses that result in crustal compression. The mean orientation of the current major horizontal principal stress in central North America, based on the World Stress Map (Heidbach et al., 2009), is northeast (063° ± 28°). However, a north-south maximum compressive stress axis appears to dominate in the mid-continental region and anomalous stress orientations have been identified in northwest Ontario (Haimson, 1990; Brown et al., 1995; Martino et al., 1997; Maloney et al., 2006).

Repeated cycles of glaciation and deglaciation throughout the Quaternary have induced stresses by sequentially loading and unloading the Earth's crust. The loads associated with glaciation were sufficient to depress the crust by hundreds of metres. Crustal rebound began once the weight of the ice was removed, and rebound continues to occur today in this area, albeit slowly (Adams and Clague, 1993).

The stresses associated with cycles of glacial loading and unloading, acting along with tectonic stresses, can result in seismic events related to displacements along ancient discontinuities in the bedrock. Holocene reactivation of faults due to either tectonic forces or forces associated with isostatic uplift could, in some cases, result in surface features, such as fault scarps or offset landforms. The magnitude of vertical displacements expected along fault scarps from isostatic rebound would be in the order of metres. To detect features of this size remotely, air photos or other detailed remote sensing data such as high-resolution airborne LiDAR would be required. Consequently, it is not practical to identify this type of feature using the satellite imagery and topographic data available in this study. Identification of such features could, after extensive field studies, lead to the establishment of fault displacements and the dating of fault movements, which would provide useful information on paleoseismic activity in the region.

Other evidence of Holocene seismic activity, whether tectonic or glacially induced, could take the form of deformation within surficial deposits. For example, in the event of a major earthquake, liquefaction-prone sediments (i.e., silts and fine sands) would be expected to liquefy if they were located below the water table at the time of an earthquake. Exposures of Quaternary sediments in gravel pits or along road cuts or river banks would need to be investigated to determine whether liquefaction has occurred. If evidence of liquefaction was found, then it would need to be determined whether it was associated with a seismic event or with some other cause, such as glacial overriding during a late-glacial readvance. A map showing aggregate pits and any sizable sediment exposures along roads or riverbanks would be a useful tool for organizing fieldwork aimed at searching for evidence of liquefaction.

In the Nipigon area, the best prospect for finding liquefaction-prone deposits of silts and fine sands would be in glaciolacustrine deposits that are intermediate between deltaic and deep-water. In addition, silts and fine sands occur in association with the glaciolacustrine silts and clays, particularly in nearshore environments of proglacial lakes (Zoltai, 1965a). The northern part of the area, around Cash Creek and immediately north of the Nipigon area, would be one possible prospect for sands and silts in a glaciolacustrine deposit. Zoltai (1965a) described the delta east of Cash Creek and slightly north of the Nipigon area, which forms the delta at the mouth of the Pijitawabik spillway, as a particularly well developed delta. Pye (1960) has labelled the area west of Cash Creek as a low, flat, swampy area underlain by sand and clay, and he regarded the land to the east as sand terraces. Thus, within Ledger Township, Highway 11 provides access through deep-water and deltaic depositional settings in the north part of the Nipigon area and further north. Aggregate pits and creek bluffs would form the main locations where sediment exposures might be found in this area. Another obvious prospect for liquefaction-prone sediments is near the settlement of Nipigon, where a deltaic deposit has been mapped east of the Nipigon River. Many aggregate pits are situated within the delta and elsewhere along Highway 17 east and west of the Nipigon River. River bluffs downstream of Helen Lake could also be inspected.

8 ACCESSIBILITY CONSTRAINTS

Highways 11 and 17 form branches of the Trans-Canada Highway that connect the Nipigon area to major centres elsewhere in Ontario and Canada. Roads shown on Figure 1 are divided into main roads and local roads. In addition to Highways 11 and 17 shown on Figure 1, additional main roads include, from west to east across the Nipigon area, the Black Sturgeon Road, Church Road, Highway 585 and the Camp 81 Road. The local roads shown in Figure 1 are based on the MNR road segment file. Although the available main roads in the Nipigon area provide a high level of existing access to the west, central and east parts of the area, there remain large blocks of land that are either accessible only by local resource roads of variable quality or are not currently accessible by road.

Using relief maps and other maps (Figure 4 through Figure 8; Figure 15), this report has illustrated the presence of hills, cliffs and escarpments and other high-relief topographic features throughout the Nipigon area that could represent significant access constraints. Road construction can be extremely difficult and costly in areas of highly uneven bedrock topography where the bedrock is near the surface (Mollard and Mollard, 1981b). Extensive drilling and blasting can be required in these areas to maintain good vertical or horizontal road alignments and for the construction of building foundations. Low relief areas were also emphasized on several figures (e.g., Figure 7 and Figure 9) as possible locations of poorly drained, swampy terrain. Poor drainage could also pose access and construction constraints. Stream crossings would need to be considered in the planning of new roads.

The availability of sand and gravel is a vital component of road construction and maintenance. Several aggregate pits are shown on Figure 3. Many more pits are present in the area, as indicated by the satellite imagery. Several of the active pits shown on Figure 3 are located near the flanks of hills and near the 290 m elevation contour, perhaps suggesting that raised beach deposits form good aggregate resources in this area.

To provide an indication of the ruggedness of the topography in the different areas were rock outcrops are concentrated, Figure 18 shows the density of steep (≥ 6°) slopes within a 250 m radius, along with an overlay of outcrops mapped from the Landsat TM imagery and the distribution of local roads. The slope density map is divided into three classes, using 500 and 1,000 points/km^2 as class boundaries. These class boundaries are equivalent to 20% and 40% divisions. That is, a density of 500 points/km^2 indicates that 20% of the ground within the 250 m search radius displays a slope value of at least 6°. Wetlands are also shown on Figure 18, and Section 4.1 and Figure 9 provide more information on wetlands and surface drainage.

The level of accessibility ranges substantially across the Nipigon area, with different access constraints encountered in different areas. Sections 8.1 through 8.5 describe five areas where an abundance of exposed bedrock has been identified using satellite imagery. These areas would be more readily amenable to site characterization, as the exposed bedrock would enable outcrop mapping of bedrock structures and preliminary rock mass characterization. However, the roughness of the topography varies considerably from one area to the next and within each area.

8.1 NIP10 BURN ZONE

Located in the northwest corner of the Nipigon area, the NIP10 burn zone is an area roughly 45 km^2 in extent where muscovite granite in the northwest corner of the Nipigon area is extensively exposed due to a May 1999 wildfire (Figure 15). This is the largest muscovite granite intrusion mapped in the Nipigon area (Figure 2). The area is accessible by the Black Sturgeon Road and Church Road. Logging roads are present on the high ground east and west of Larson Creek (Figure 6), where the largest concentration of rock outcrops was identified (Figure 15 and Figure 16). Figure 18 shows that the roughest terrain is located within a band around Larson Creek and along the escarpment forming the southern and western rims of the granitic intrusion. Although much of the exposed bedrock is concentrated in the rough terrain around Larson Creek, outcrops are found throughout the intrusion (Figure 13 inset), including in local areas of relatively low relief. The other feature of interest in terms of accessibility on this granitic intrusion is the large swamp situated in the flat area south of Mound Lake, in the centre of the intrusion.

8.2 WEST OF CHURCH LAKE

The north-northwest trending local highland immediately west of Church Lake (Figure 6) coincides with the mapped extent of a granitic intrusion (Figure 2). This rocky hill can be accessed by the Black Sturgeon Road and Church Road. Although there are no logging roads extending onto the highland, where the outcrops are found, the Church Road approaches to within a kilometre of the southern tip of the highland. Figure 18 shows that steep slopes are abundant within its margins, but there are relatively flat zones on top of the ridge.

8.3 North and South Trout creeks

In the southern part of the Nipigon area, between the Black Sturgeon River and Highway 17, metasedimentary and granitic rocks are exposed within outcrops on hills surrounding North Trout Creek and its tributaries (Figure 2). The east end of the outcrop belt is within 100 m of Highway 17. A logging road extending west of Highway 17, a couple kilometres south of the Nipigon area along Highway 17, apparently once extended upstream along South Trout Creek, providing access to the central portion of the zone of exposed bedrock. However, this road is likely in very poor condition, as it cannot be identified in the 2010 FRI imagery. Some of the topography in this area displays considerable relief, and the outcrops in this belt occur in areas of steep slope, mainly on the sides of hills (see Figure 9, inset A).

8.4 East bank of Helen Lake

Exposed metasedimentary rock can be found on many of the local topographic highs found within a 2 km-wide belt extending above the east bank of Helen Lake (Figure 18). The most significant area of exposed bedrock is situated above a north-northwest trending escarpment east of Mission Bay. Most of the outcrops on this ridge occur within an area of gentle slope. Profile G (Figure 6) illustrates the low-relief surface expression of this upland. Excellent access is provided to this ridge by Highways 17 and 11. The prominent escarpment here is higher to the north-northwest, with a maximum height above Helen Lake of about 100 m. Further south, where Highway 17 extends through the escarpment, it is about 40 m high. Even with the construction of a large embankment along the lower part of the climb, and rock cuts near the crest, the average road grade throughout the climb appears to be steep. A logging road originating at Highway 17, east of the escarpment, extends north onto the southern edge of the ridge.

8.5 Eastern highland

Exposed bedrock can be found throughout the thinly drift-covered eastern highland east of the Jackfish River (Figure 15 to Figure 17) where metasedimentary rocks are exposed (Figure 2). Noteworthy outcrop concentrations exist within a north trending belt 3 km-wide, 14 km-long, located north and slightly east of Kama Bay. The most accessible areas are those that are closest to the Camp 81 Road. A good example of an area of extensive bedrock exposure is located on the north side of the Camp 81 Road, about 4.5 km north of the Trans-Canada Highway. This area is shown in detail on the insets of Figure 12. It consists of a 4 km by 4 km low-relief surface bounded by linear trenches to the north and west (Figure 6, profile H), along which Ozone Creek flows. There is a 2 km square clearcut on this surface, as shown in the imagery (Figure 12 insets). As a result, a logging road extends onto the centre of the block. Many of the other sites of excellent rock exposure east of the Jackfish River are located further from Camp 81 Road or are in relatively rough terrain.

9 SUMMARY

This report presents an analysis of the terrain in the Nipigon area using available remote sensing and geoscientific information sources. The main information sources relied on in this study are the Canadian Digital Elevation Data (CDED) elevation model, the SPOT and Landsat imagery, and the maps and reports from the Northern Ontario Engineering Geology Terrain Study (NOEGTS). Additional information sources included the Ontario Drill Hole Database, the Water Well Information System, several geospatial files on drainage features and roads obtained from Land Information Ontario, and information on drainage and overburden characteristics from the literature.

Surface lineaments are either difficult or impossible to detect in areas underlain by thick and extensive overburden deposits, where the lineament interpreter is to some extent blinded. An understanding of the distribution and thickness of overburden deposits within the Nipigon area is thus essential for interpreting the distribution of lineaments mapped from SPOT and CDED. Areas of thin drift with an abundance of exposed bedrock are more readily amenable to site characterization activities, as such locations would enable further investigation of the potentially suitable bedrock formations through outcrop mapping of bedrock structures and preliminary rock mass characterization. As a result, the extent of thick and extensive overburden deposits and the distribution of exposed bedrock across the Nipigon area are the focus of several sections in this report (e.g., Sections 5 and 8).

Elevations in the Nipigon area range from about 183 m on the surface of Lake Superior to a maximum of 583 m on a nearby mesa associated with the Kama Hills. Two major topographic lows are present within the Nipigon area. 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 highest elevations in the Nipigon area are found in an area of minimal overburden cover east of the Jackfish River.

A map and descriptions of the surficial deposits in the Nipigon area are presented in this report based on the best available surficial mapping, which is the 1:100,000 scale NOEGTS mapping. Approximately half of the Nipigon area is delineated as bedrock terrain, where drift deposits are generally less than 1 m thick and are dominantly composed of bouldery, sand-rich till. The extensive overburden deposits delineated through NOEGTS are shown to coincide in general with large areas of low relief delineated using CDED. The lack of relief in these areas is in most cases expected to be associated with thick and extensive drift deposits filling lows in the bedrock topography, resulting in lower confidence in identifying major structures using SPOT and CDED in these areas. The largest zone devoid of extensive overburden deposits is located in the eastern third of the Nipigon area. Although the NOEGTS mapping provides a reasonable overall image of the distribution of thick versus thin overburden deposits across the Nipigon area, it does not provide a detailed image of the distribution of exposed bedrock.

Water well data dominantly from within or near the settlement of Nipigon revealed the presence of overburden deposits up to 82 m thick in the immediate area. Drill hole and water well data generally indicated that the thickest overburden deposits were located away from bedrock-controlled topographic highs. Maps of bedrock-controlled topographic highs, where thin overburden deposits are expected, have been presented in this report in several figures (Figure 6 and Figure 15 to Figure 17). Water well data indicated the presence of overburden deposits 30 to 50 m thick in an area mapped as bedrock terrain during the NOEGTS program. This illustrated the need to interpret the thickness of drift deposits and the amount of exposed bedrock in the broad areas mapped as bedrock terrain with caution.

Glaciolacustrine silts and clays form some of the most extensive overburden deposits in the area, with thicknesses of 2 to 10 m being common. Glaciolacustrine deltas are mapped locally in the Nipigon area. Deltaic deposits in this region are typically more than 15 m thick and generally consist of stratified coarse-to-medium sand, with gravel and strata of very fine sand or silt present locally. Many of the creeks in low-lying parts of the Nipigon area, such as Shillabeer, Larson, Cash and Boom creeks, are entrenched 10 to 30 m into drift-covered landscapes, suggesting that the overburden deposits in those areas are probably at least that thick.

Exposed bedrock was mapped using SPOT, Landsat ETM and Landsat TM data. Consistent results were obtained from the three satellite images in terms of the distribution of exposed bedrock. The areas displaying the greatest amount of exposed bedrock identified using satellite imagery matched closely with the areas delineated as areas of bare rock in the regional surficial geology map of Zoltai (1965b). A reasonable match was also found by comparing the areas of bedrock outcrop shown on a bedrock map covering the western half of the Nipigon area (Coates, 1971). Estimates of the amount of exposed bedrock derived from the satellite imagery range between 4.0 and 4.6% of the Nipigon area. The outcrop mapping provided a useful dataset for understanding the distribution of exposed bedrock beyond the generalized image obtained through the delineation of bedrock terrain on the NOEGTS maps.

Five belts where rock outcrops are strongly concentrated are described in Section 5.2.1. The three main areas of extensive rock outcrop in the western half of the Nipigon area are located east of the Black Sturgeon River and are at least partly underlain by granitic rocks, composed either of massive granodiorite to granite or of muscovite-bearing granitic rock. All areas of extensive rock exposure in the eastern half of the Nipigon area are underlain by metasedimentary rocks.

Drainage divides delineated in the provincial quaternary watershed file produced by the Ministry of Natural Resources (MNR) were confirmed using the CDED surface model. JDMA also subdivided the quaternary watersheds and produced an updated watershed file. Drainage within this area is entirely towards Lake Superior via the Black Sturgeon, Nipigon, Jackfish and Jackpine rivers and their tributaries. As a first-order approximation, shallow groundwater flow within bedrock and surficial aquifers in the Nipigon area will be topographically controlled. Thus, regional flow patterns will mimic surface drainage patterns. The major recharge areas will be the two major topographic highs. Minor areas of recharge will occur on local topographic highs. The discharge areas are the lowlands. Sand and gravel deposits associated with outwash, kame, esker, and glaciolacustrine delta deposits will be the most significant surficial aquifers and these deposits are located in the lowlands. Groundwater flow from bedrock and surficial aquifers in the highlands and hills will recharge surficial deposits in the lowlands. Lowland surficial aquifers will then discharge into lakes, rivers and wetlands.

Features indicative of reactivation of ancient bedrock structures due to cycles of glacial loading and unloading or due to tectonics where not identified in the data sets readily available for this desktop assessment. A detailed assessment of fault scarps or offset Quaternary deposits would require air photo interpretation or other detailed remote sensing tools, such as airborne LiDAR. Silt and fine sand deposits prone to liquefaction could record evidence of paleoseismic events. Prospective locations where silts and fine sands could be found were discussed. Fieldwork would be required to inspect sediment exposures in gravel pits, road cuts and riverbanks to identify liquefaction structures.

Highways 11 and 17, and several other main roads in the Nipigon area provide a high level of access to the west, central and east parts of the area, although there remain large blocks of land that are either accessible only by local resource roads of variable quality or are not currently accessible by road.

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REPORT SIGNATURE PAGE

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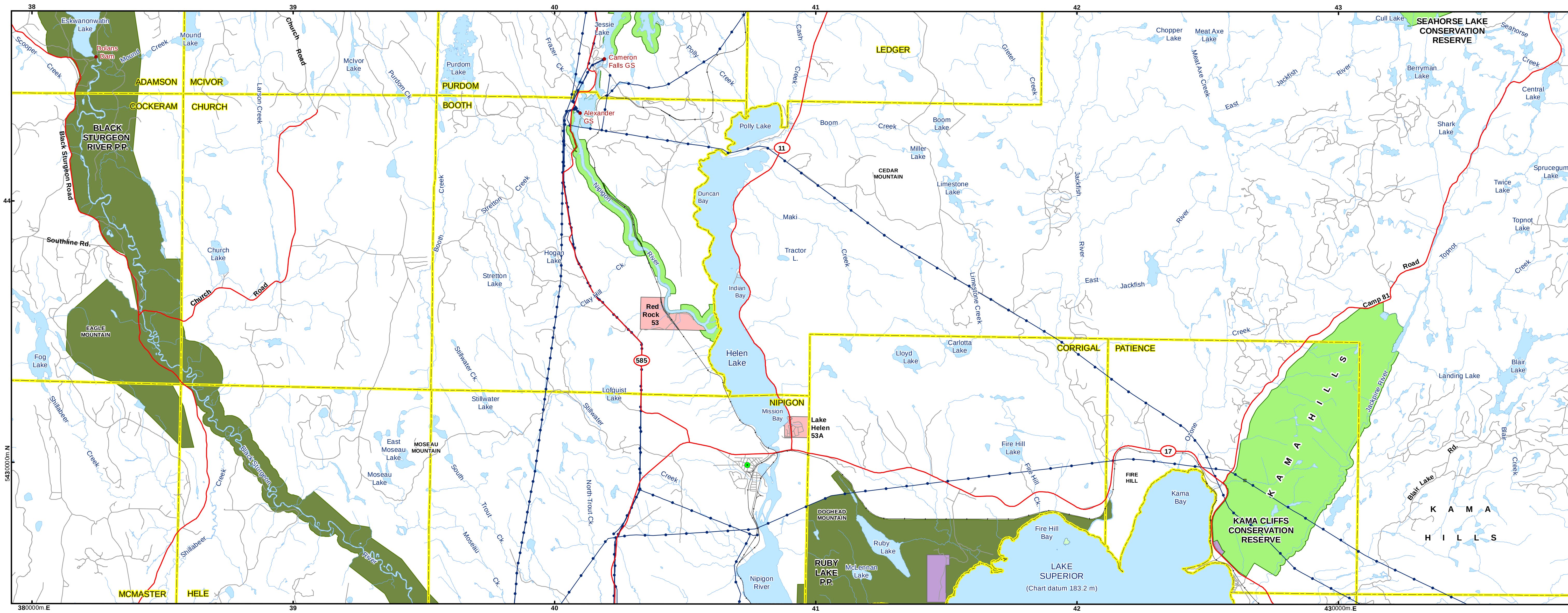
David van Zeyl, M.Sc.

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

FIGURES



LEGEND

- Nipigon (settlement)
- Water control structure
- 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

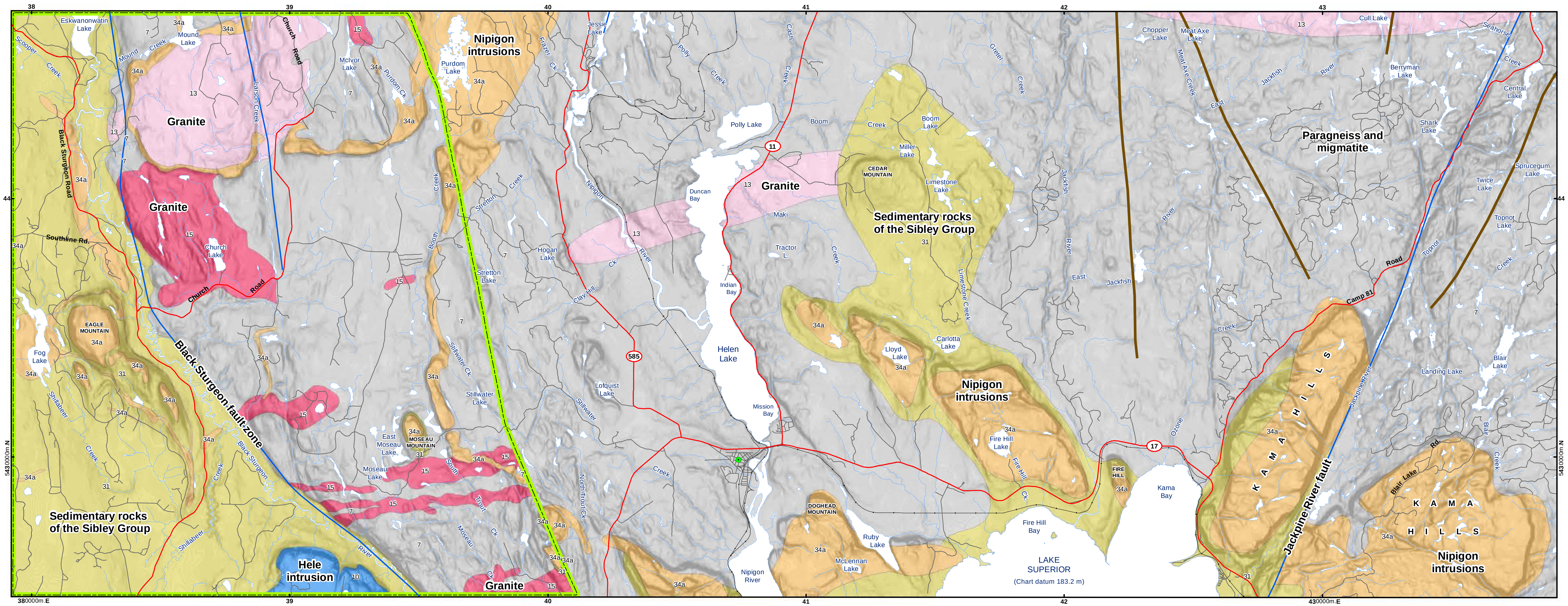
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

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

TITLE
Township of Nipigon and surrounding area

DESIGN	DVZ	05 SEP 2013	FIGURE 1	REVISION 2
GIS	DVZ	27 FEB 2014		UTM ZONE 16
CHECK	LAP	27 FEB 2014		NAD 1983
REVIEW	CWM	27 FEB 2014		1:150,000



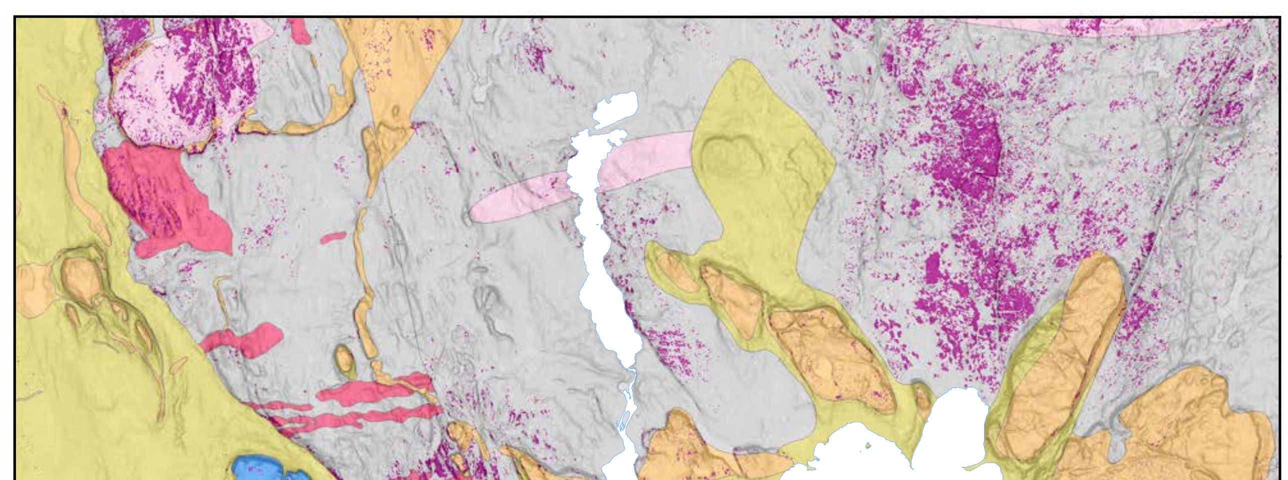
LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Rail
- Waterbody
- Watercourse
- Revised mapping (Hart, 2005)
- Fault
- Dikes

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
DEM: GeoBase CDED 1:50,000



INSET LEGEND

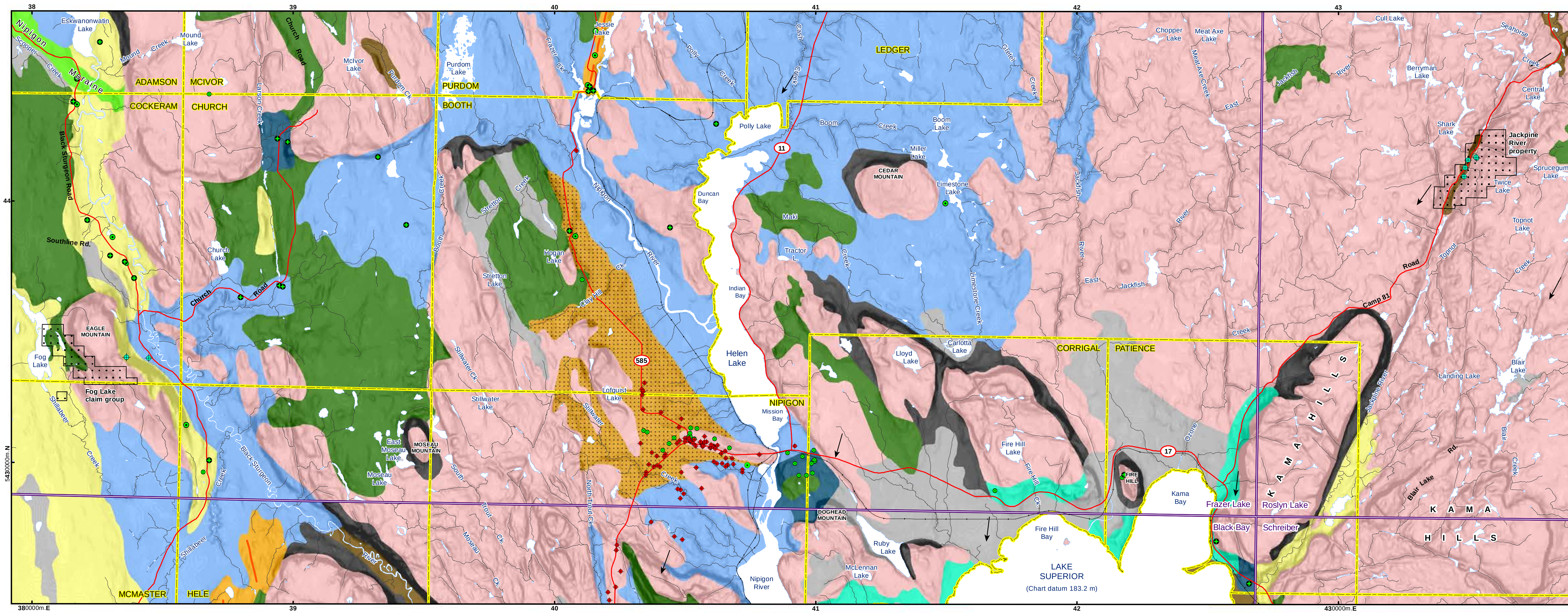
- Waterbody
- Bedrock outcrop

NORTH

5 km

J D MOLLARD

PROJECT	PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO			
TITLE	Bedrock geology of the Nipigon area			
DESIGN	DVZ	05 SEP 2013	FIGURE 2	REVISION 4
GIS	DVZ	30 APR 2014		UTM ZONE 16
CHECK	LAP	30 APR 2014		NAD 1983
REVIEW	CWM	30 APR 2014		1:150,000



LEGEND

Nipigon (settlement)	Ground moraine	Water well (MOE)
Ice flow (Zoltai)	End moraine	Drillhole (OGS)
Main road	Glaciofluvial outwash	Aggregate pit (MNR)
Rail	Glaciofluvial esker	Aggregate pit (JDMA)
AFRI report area	Glaciofluvial kame	Aggregate pit (NOEGTS)
Esker	Glaciolacustrine plain	
NOEGTS index	Glaciolacustrine delta	
Township	Glaciolacustrine beach	
Waterbody	Colluvium	
Watercourse	Alluvial	
	Organic	
	Bedrock	

INSET LEGEND

- 290 m contour
- Below 290 m elev.

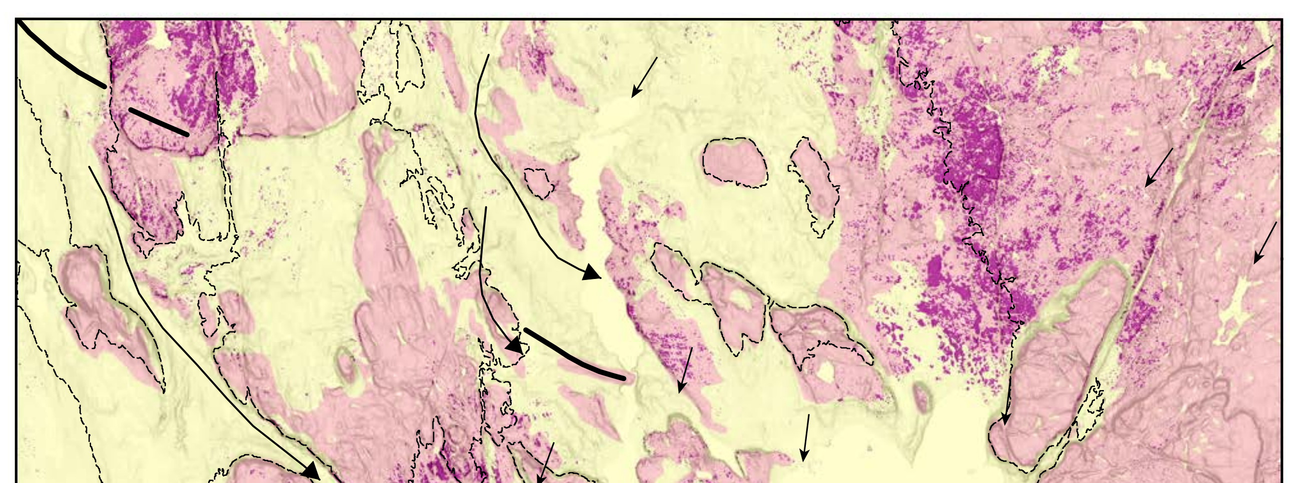
Surficial geology

- Bedrock
- Surficial or water
- Bedrock outcrop

Surficial features (Zoltai, 1965b)

- Meltwater channel
- End moraine
- Ice flow

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 160 scale 1:100,000
Outcrop: Mapped from 3 satellite images



NORTH

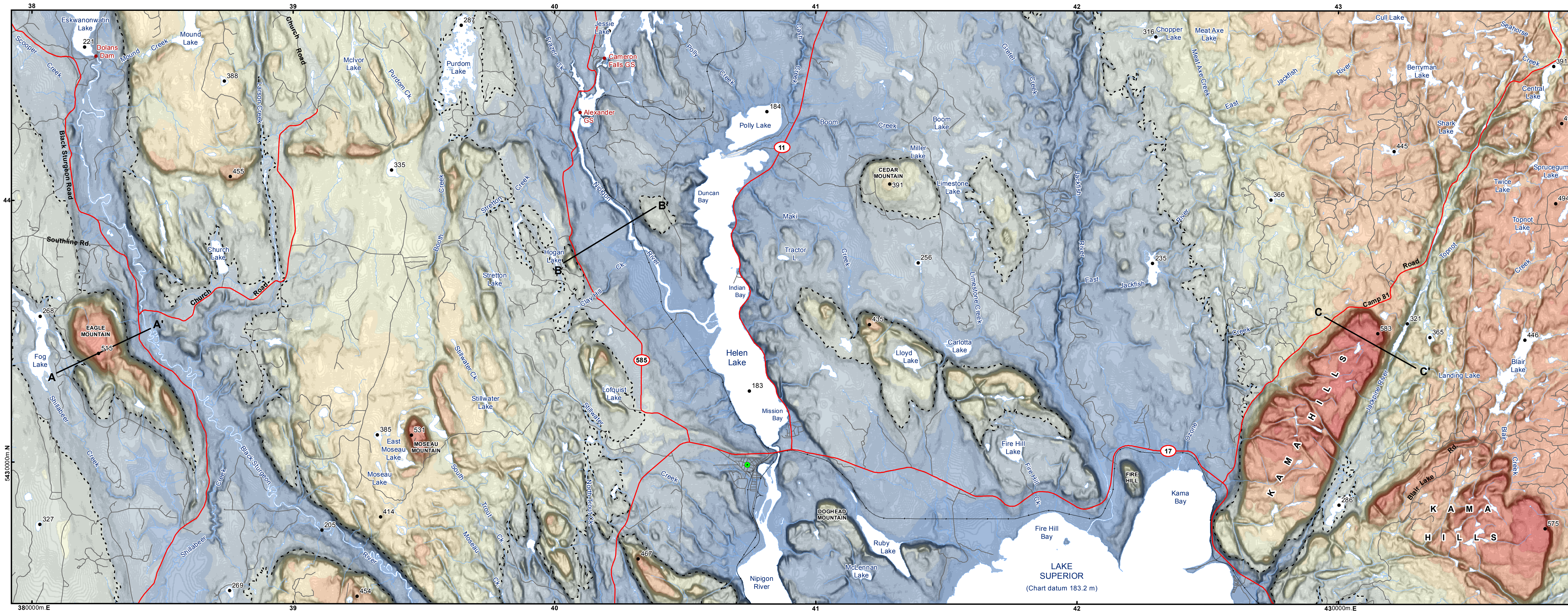
5 km

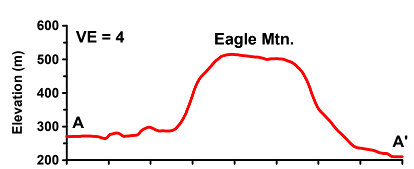
J D MOLLARD AND ASSOCIATES (2010) LIMITED

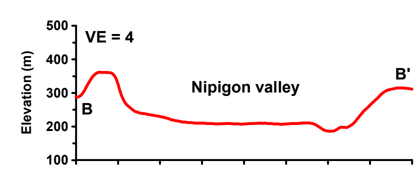
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO

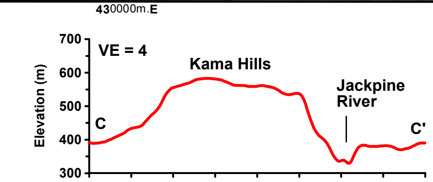
TITLE
Surficial geology of the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 3	REVISION 2
GIS	DVZ	29 MAY 2014		UTM ZONE 16
CHECK	LAP	29 MAY 2014		NAD 1983
REVIEW	CWM	30 MAY 2014		1:150,000









LEGEND

- Water control structure
- Spot height (m)
- Nipigon (settlement)
- Profile
- Main road
- Local road
- Rail
- 290 m contour
- Waterbody
- Watercourse

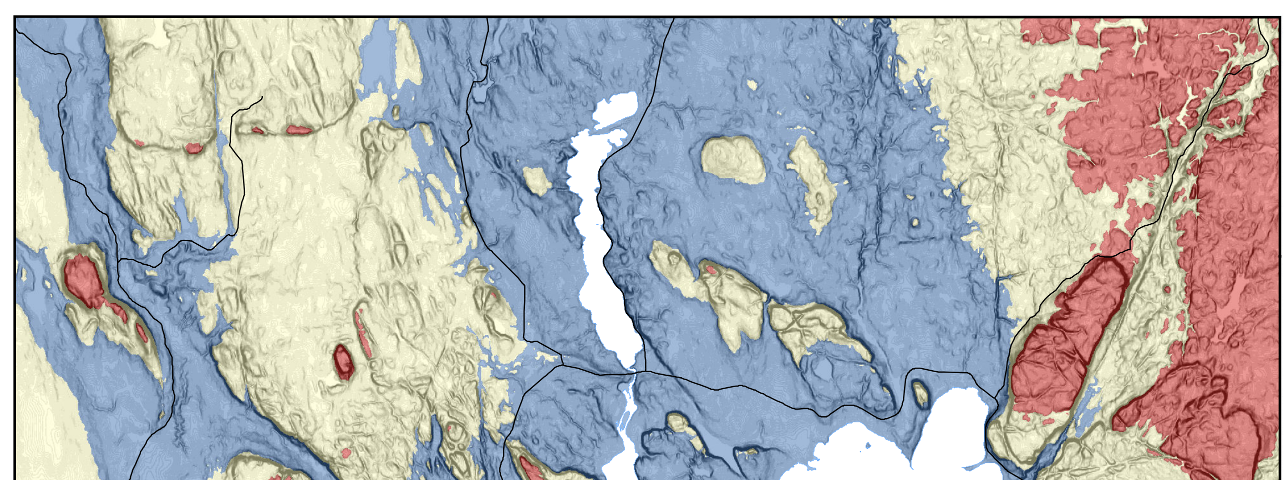
Slope (°)	Elevation (m)
0 - 0.4	183 - 202
0.5 - 3.1	203 - 245
3.2 - 5.7	246 - 288
5.8 - 8.3	289 - 331
8.4 - 10.9	332 - 374
11 - 13.6	375 - 417
13.7 - 16.2	418 - 460
16.3 - 18.8	461 - 503
18.9 - 56.4	504 - 546
	547 - 583

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

INSET LEGEND

Elevation (m)

- 178 - 290
- 290.1 - 425
- 425.1 - 583



NORTH

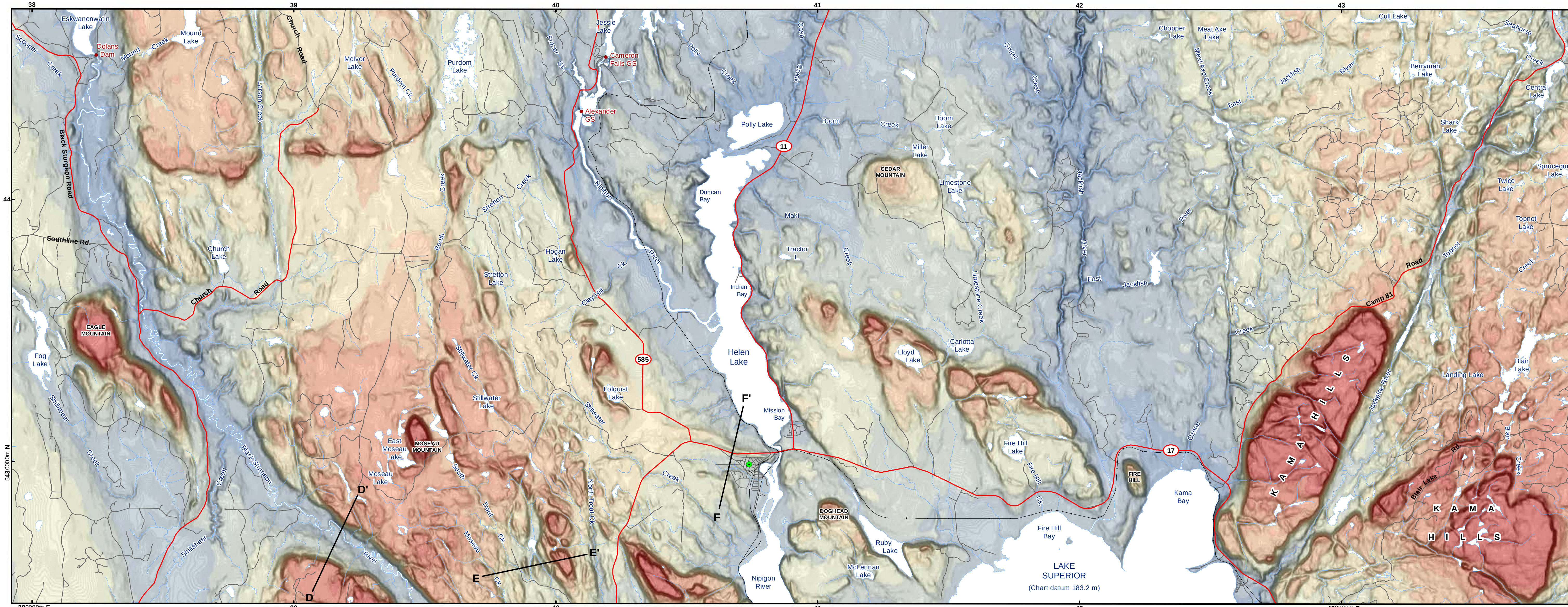
5 km

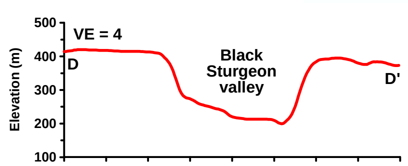
J D MOLLARD AND ASSOCIATES (2010) LIMITED

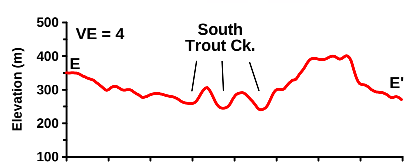
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO

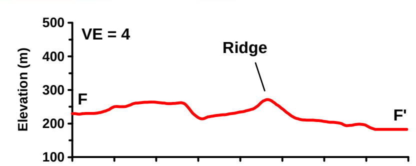
TITLE
Elevation within the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 4	REVISION 2
GIS	DVZ	29 MAY 2014		UTM ZONE 16
CHECK	LAP	29 MAY 2014		NAD 1983
REVIEW	CWM	30 MAY 2014		1:150,000









LEGEND

- Water control structure
- Nipigon (settlement)
- Profile
- Rail
- Main road
- Local road
- 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

Relief (m)

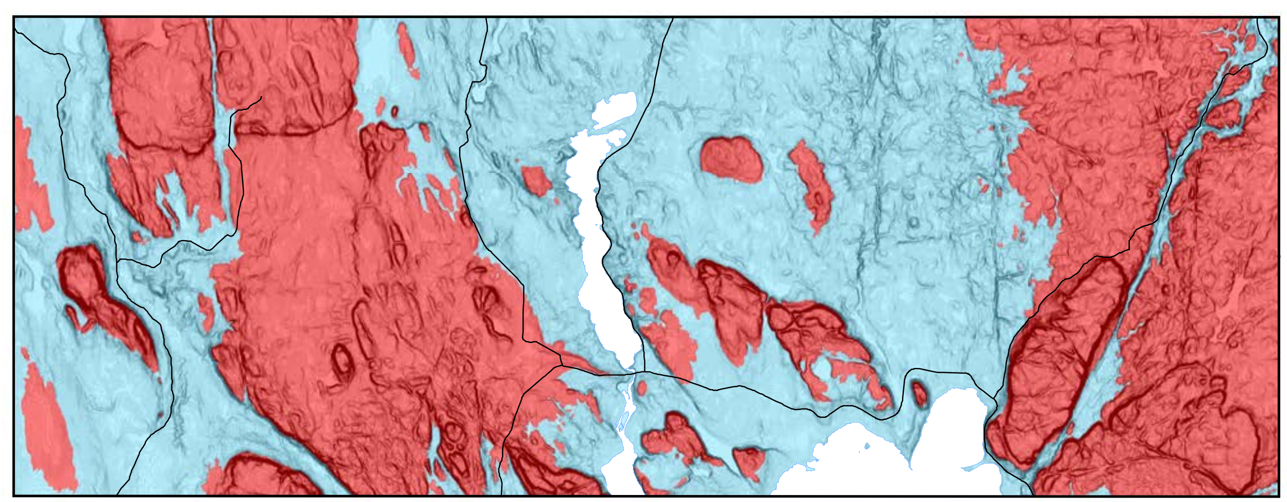
- -121.6 - -117.5
- -117.4 - -82.9
- -82.8 - -48.2
- -48.1 - -13.6
- -13.5 - 21
- 21.1 - 55.7
- 55.8 - 90.3
- 90.4 - 124.9
- 125 - 159.6
- 159.7 - 249.8

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

INSET LEGEND

Relief (m)

- -121.6 - 0
- 0.1 - 249.8



NORTH

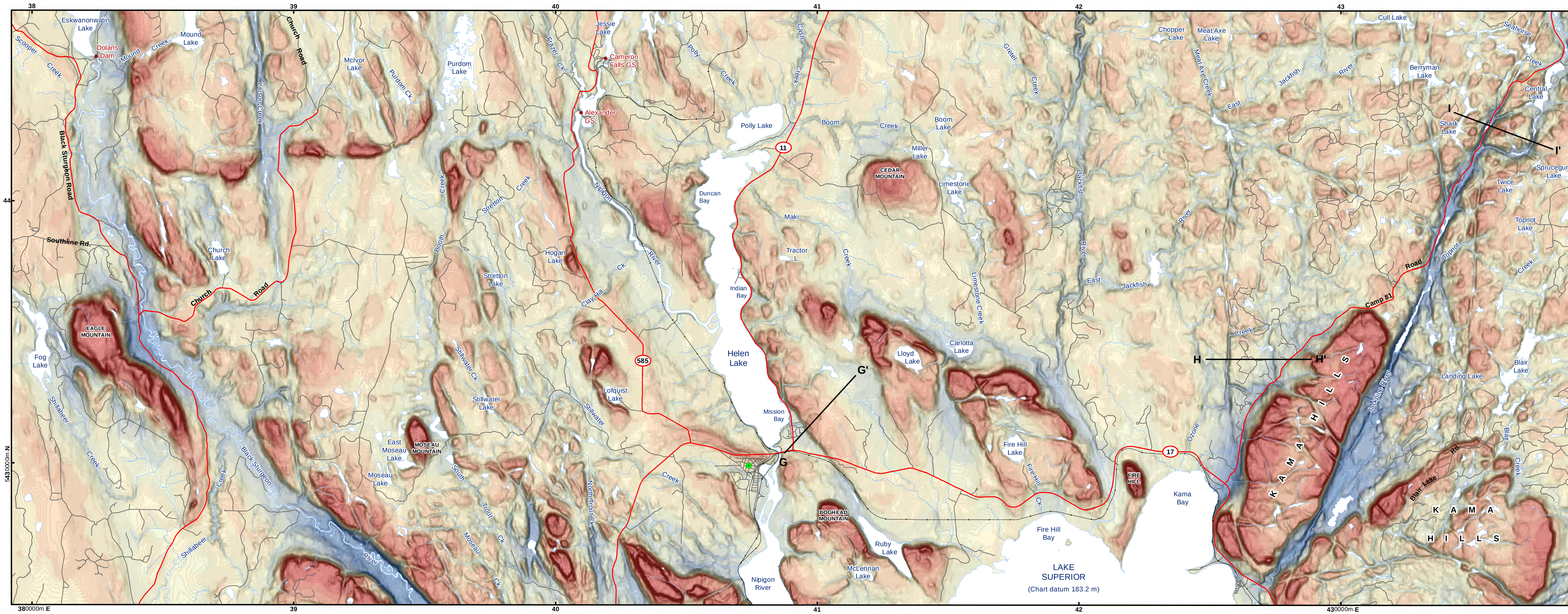
5 km

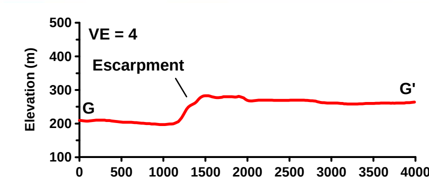
J D MOLLARD AND ASSOCIATES (2010) LIMITED

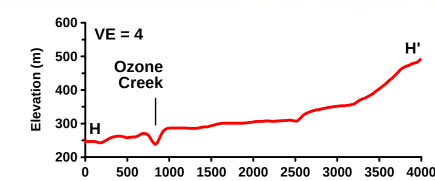
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO

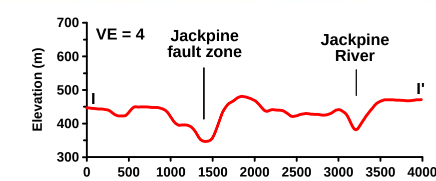
TITLE
Departure in elevation within 20 km radius

DESIGN	DVZ	05 SEP 2013	FIGURE 5	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	14 NOV 2013		1:150,000









LEGEND

- Nipigon (settlement)
- Water control structure
- Profile
- Rail
- Main road
- Local road
- 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

Relief (m)

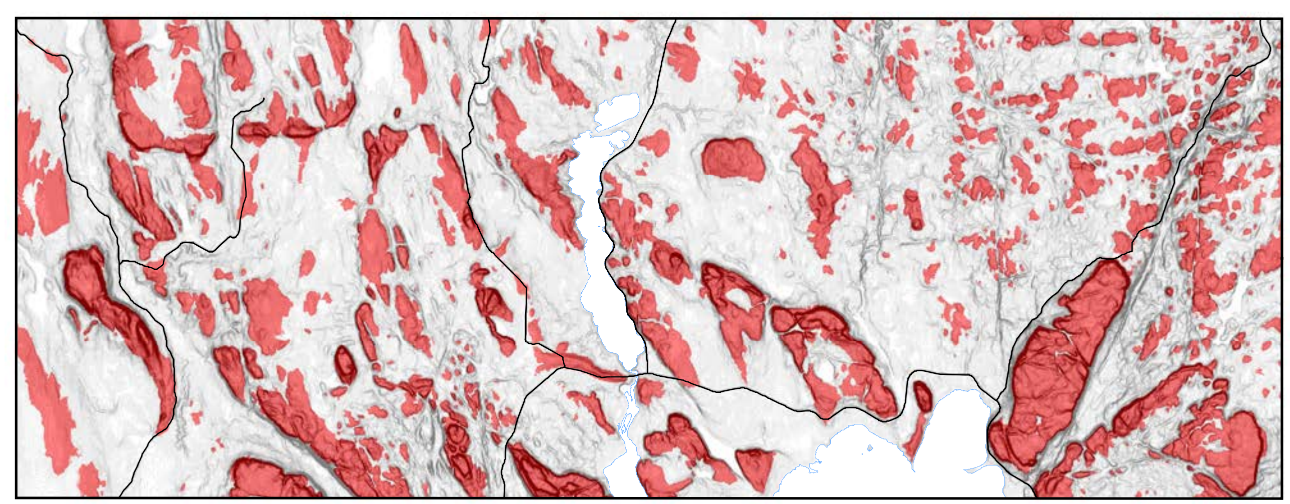
- -131.6 - -78.1
- -78 - -63.9
- -63.8 - -49.8
- -49.7 - -35.7
- -35.6 - -21.5
- -21.4 - -7.4
- -7.3 - 6.7
- 6.8 - 20.9
- 21 - 35
- 35.1 - 49.1
- 49.2 - 63.3
- 63.4 - 181.8

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

INSET LEGEND

Relief (m)

- -131.6 - 10
- 10.1 - 181.8



NORTH

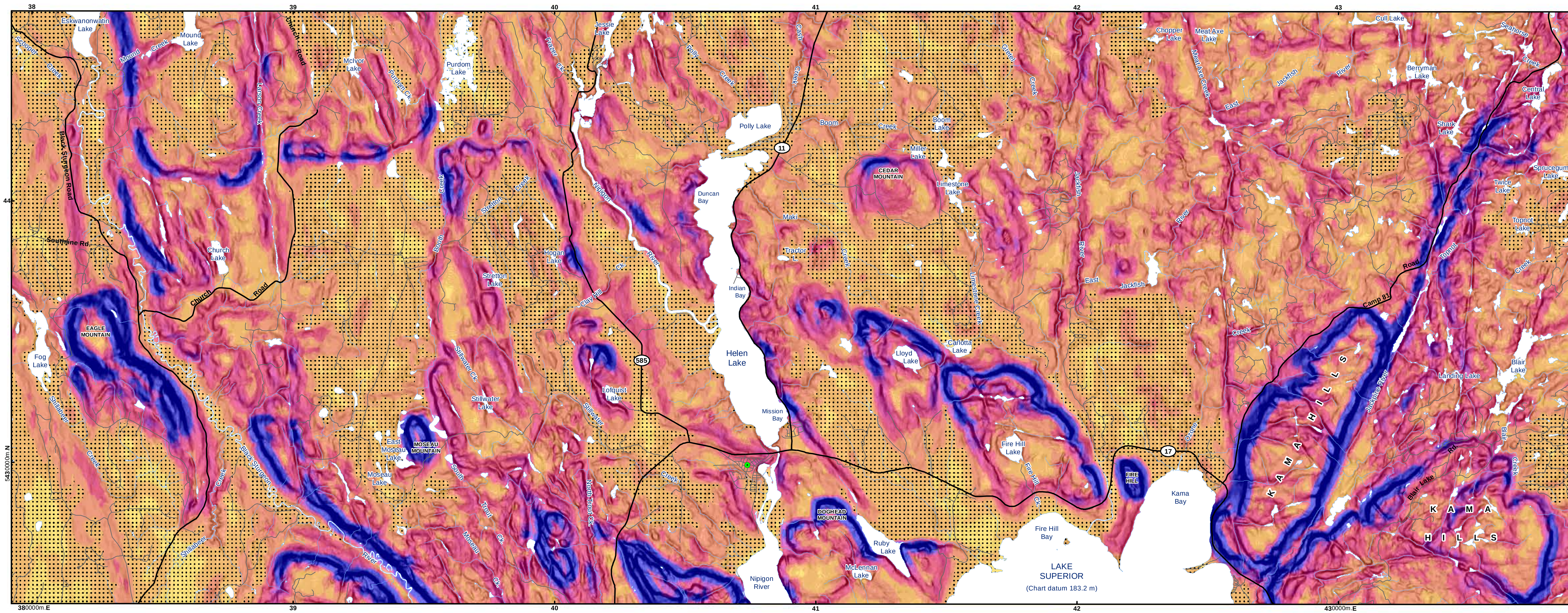
5 km

J D MOLLARD

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

TITLE
Departure in elevation within 2 km radius

DESIGN	DVZ	05 SEP 2013	FIGURE 6	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	14 NOV 2013		1:150,000



LEGEND

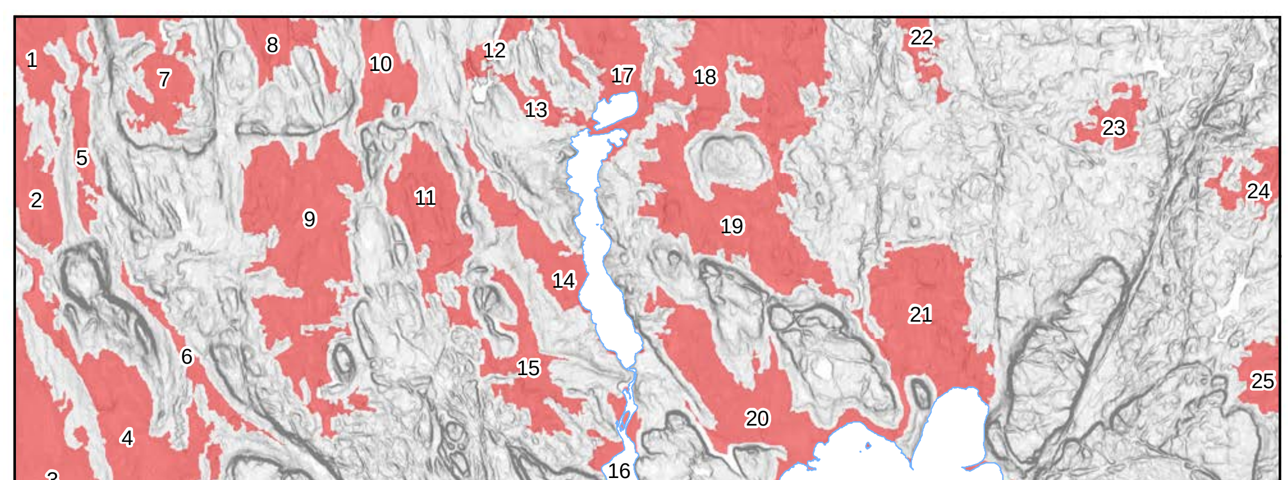
- Nipigon (settlement)
- Main road
- Local road
- Waterbody
- Watercourse
- Low relief area

Slope (°)	Relief (m)
0 - 0.4	0 - 6.3
0.5 - 3.1	6.4 - 20.5
3.2 - 5.7	20.6 - 34.7
5.8 - 8.3	34.8 - 48.9
8.4 - 10.9	49 - 63
11 - 13.6	63.1 - 77.2
13.7 - 16.2	77.3 - 91.4
16.3 - 18.8	91.5 - 263
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

INSET LEGEND

Low relief area



NORTH

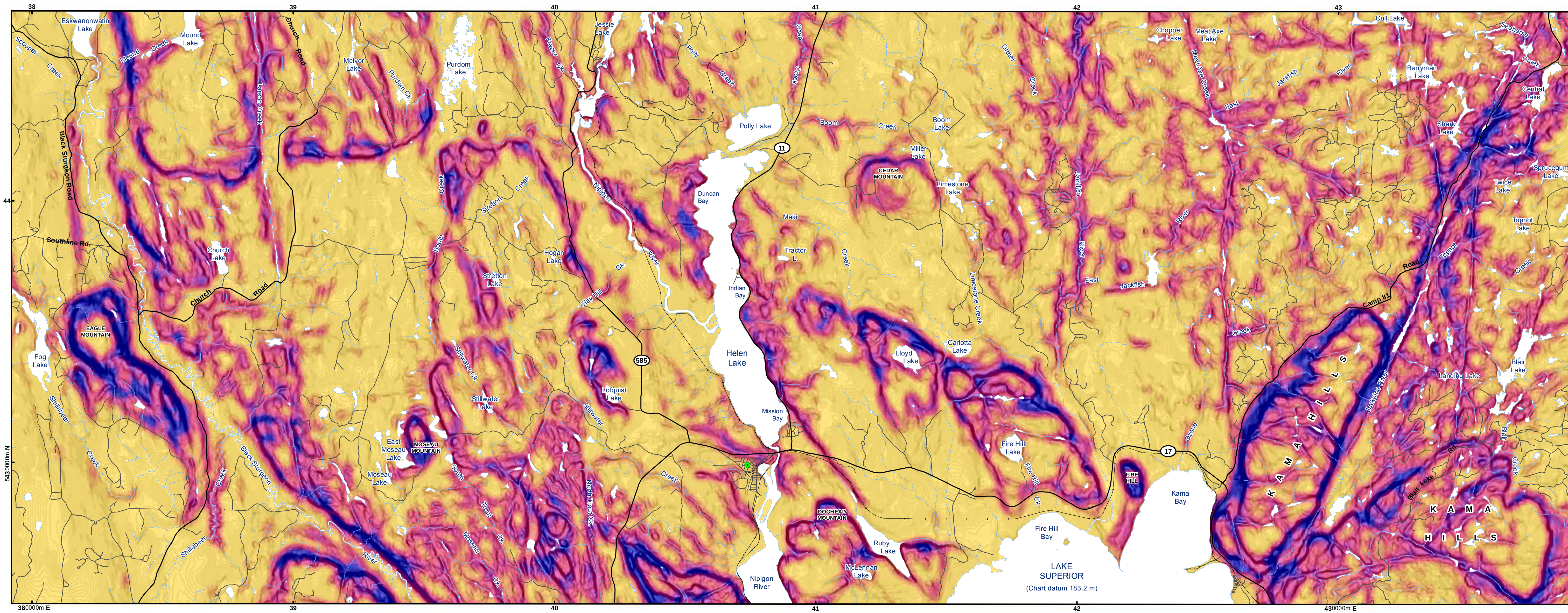
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

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

TITLE
Range in elevation within 250 m radius

DESIGN	DVZ	05 SEP 2013	FIGURE 7	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	14 NOV 2013		1:150,000



LEGEND

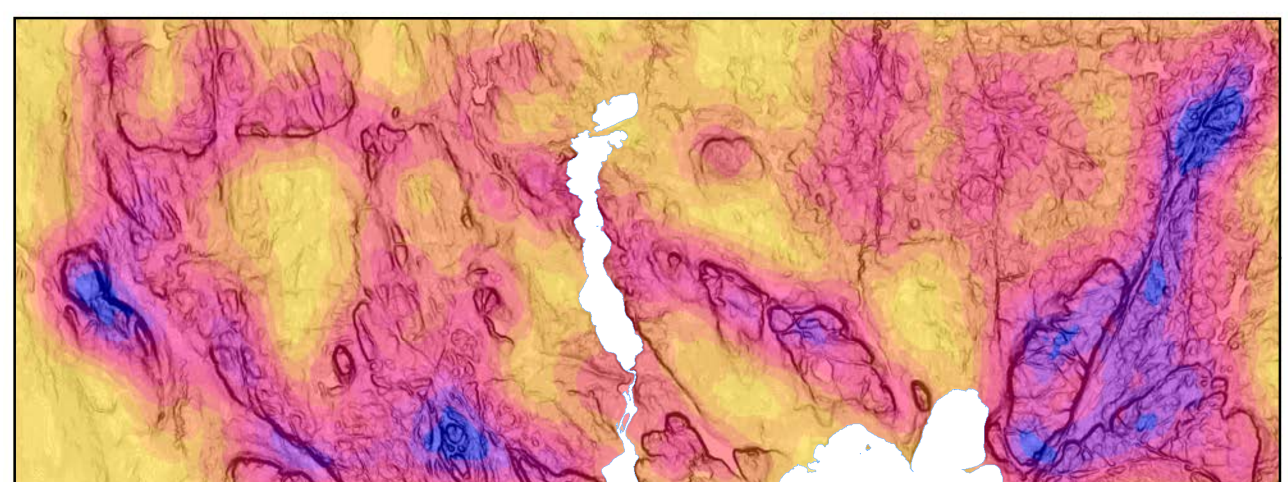
- Nipigon (settlement)
- Main road
- Local road
- Rail
- Waterbody
- Watercourse

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

Slope density (250 m radius)

Points\km^2
0 - 292
293 - 592
593 - 892
893 - 1,192
1,193 - 1,492
1,493 - 1,791
1,792 - 2,091
2,092 - 2,506

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



INSET LEGEND

Slope density (2 km radius)

Points\km^2
0 - 157
158 - 325
326 - 493
494 - 662
663 - 830
831 - 998
999 - 1,166
1,167 - 1,334
1,335 - 1,579

NORTH

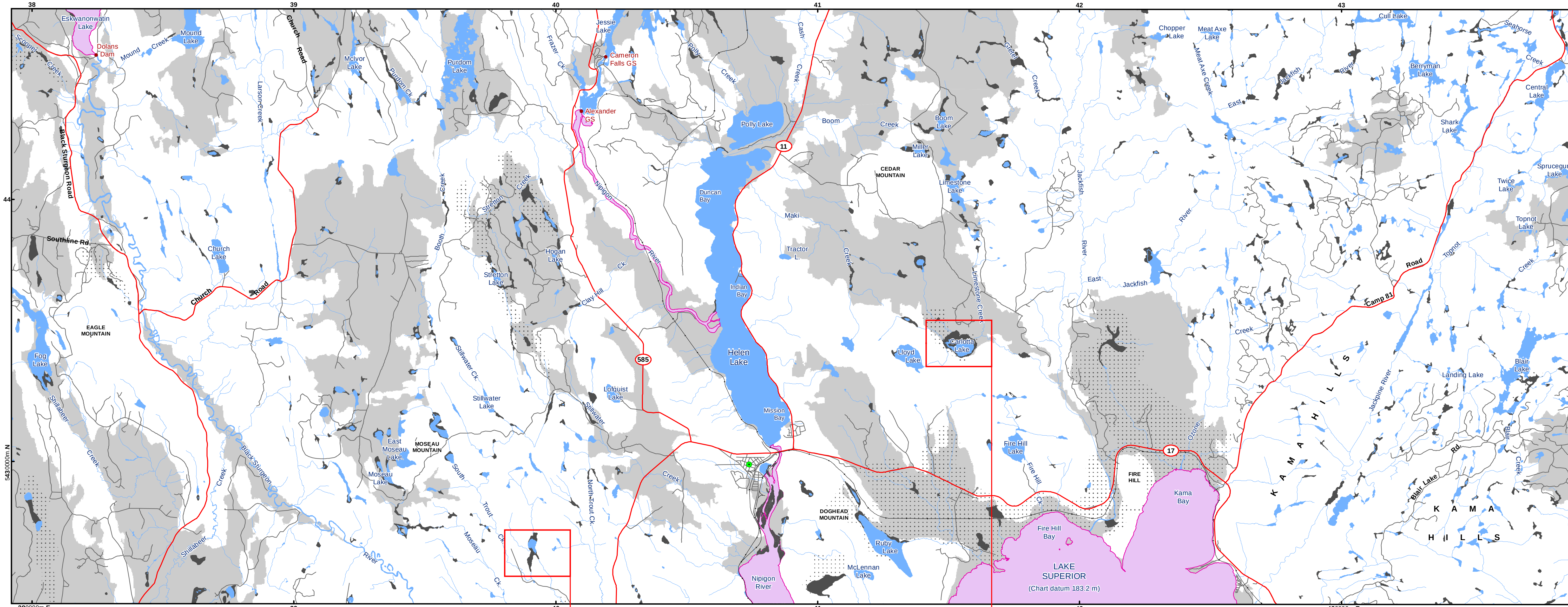
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

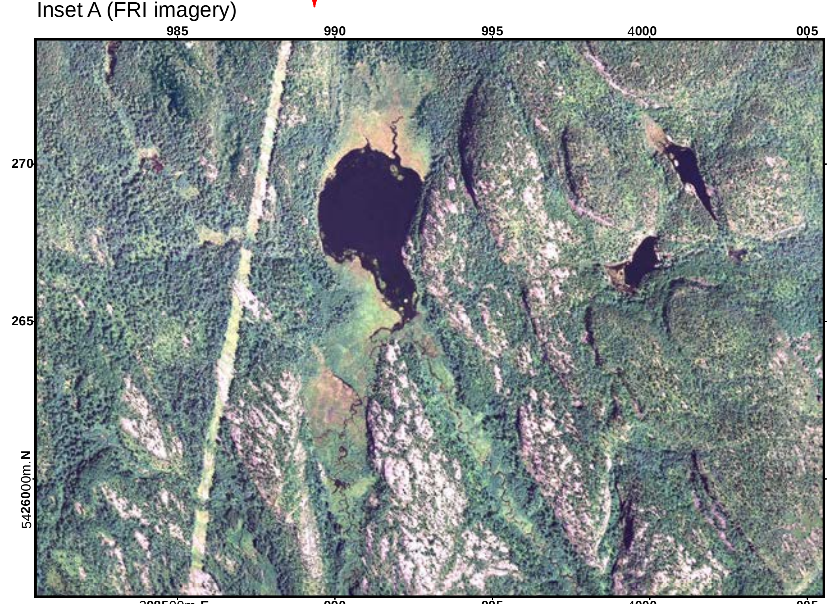
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO

TITLE
Density of steep (≥6°) slopes within 250 m radius

DESIGN	DVZ	05 SEP 2013	FIGURE 8	REVISION 2
GIS	DVZ	16 DEC 2013		UTM ZONE 16
CHECK	LAP	17 DEC 2013		NAD 1983
REVIEW	CWM	17 DEC 2013		1:150,000



Inset A (FRI imagery)



1:24,000

Inset B (FRI imagery)

1:24,000

LEGEND

- Water control structure
- Nipigon (settlement)
- Rail
- Main road
- Local road
- Wetland
- Waterbody (with depth data)
- Waterbody
- Watercourse
- Low relief area

Landform (NOEGTS)

- Organic terrain

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

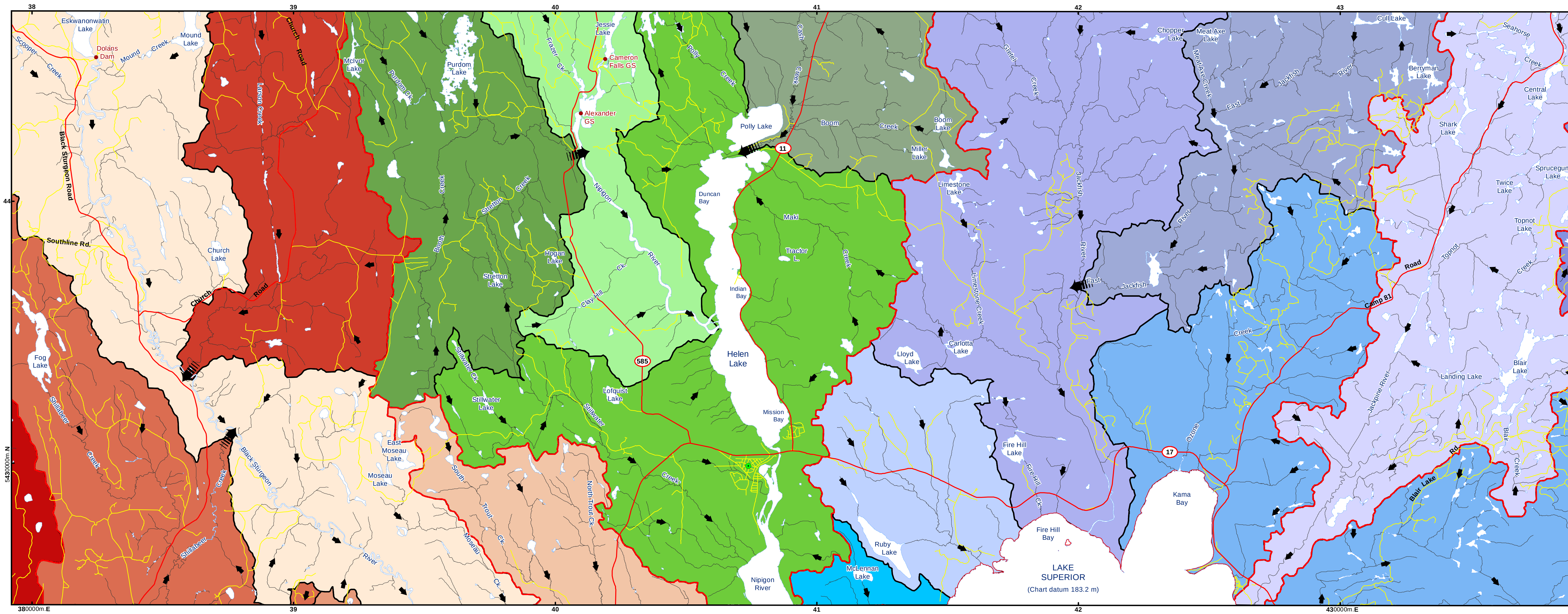
PROJECT

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

TITLE

Surface drainage features in the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 9	REVISION 2
GIS	DVZ	16 DEC 2013		UTM ZONE 16
CHECK	LAP	17 DEC 2013		NAD 1983
REVIEW	CWM	17 DEC 2013		1:150,000



LEGEND

- Nipigon (settlement)
- Water control structure
- Watershed outflow
- Flow
- Main road
- Local road
- Waterbody
- Watercourse

Watershed

- JDMA
- JDMA\MNR

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

INSET LEGEND

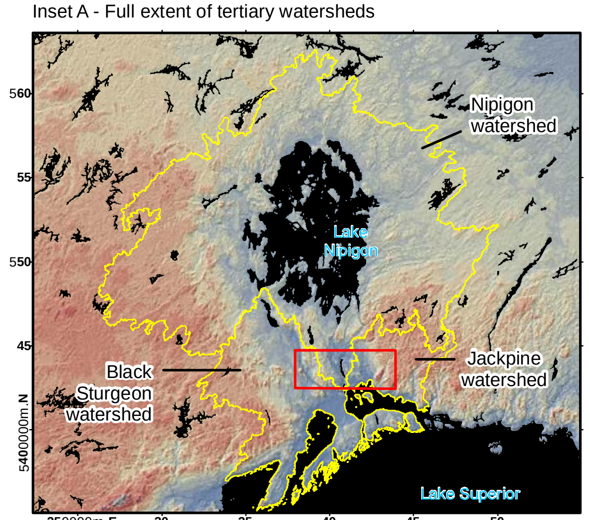
Tertiary watershed

- Black Sturgeon
- Jackpine
- Nipigon

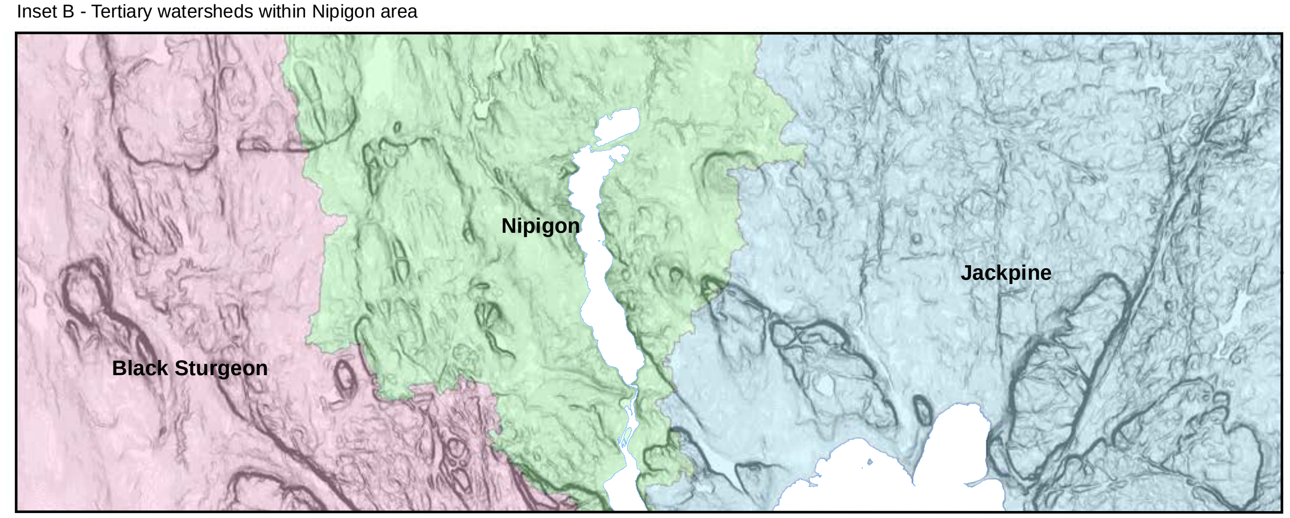
Elevation (m)

- 183 - 231
- 232 - 280
- 281 - 328
- 329 - 377
- 378 - 425
- 426 - 473
- 474 - 522
- 523 - 570

Inset A - Full extent of tertiary watersheds



Inset B - Tertiary watersheds within Nipigon area



NORTH

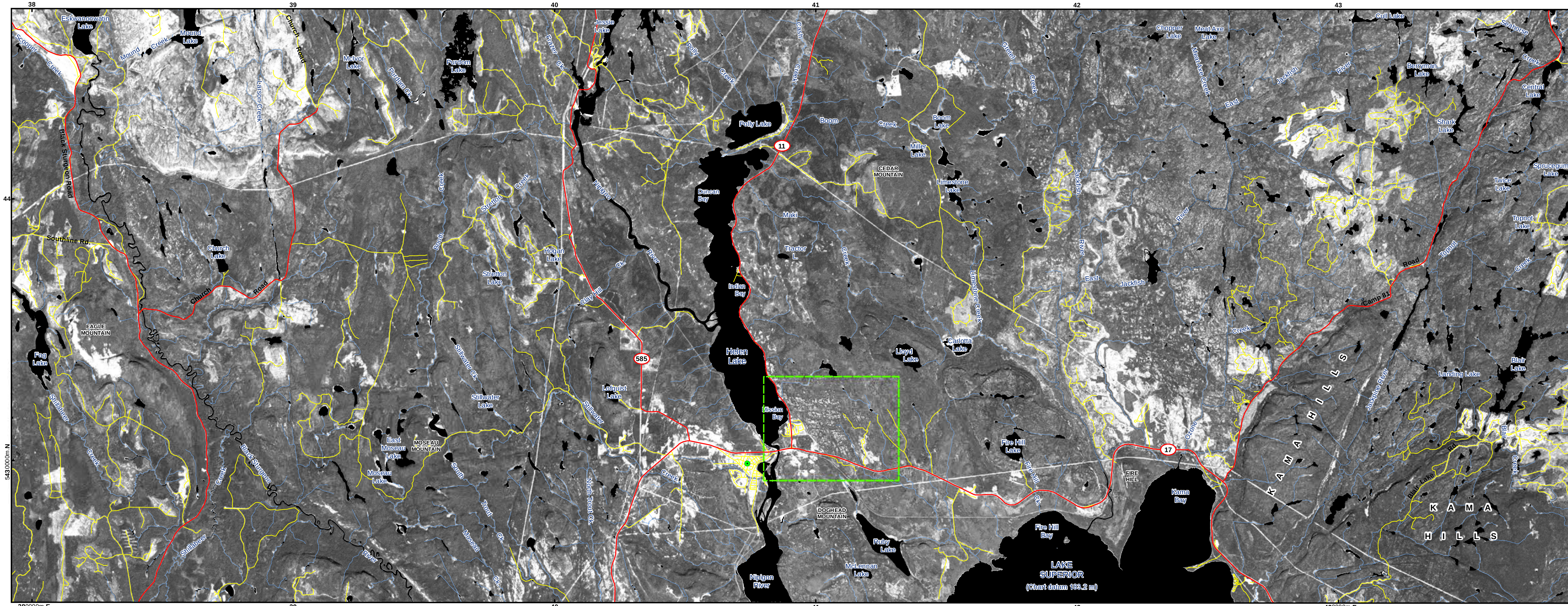
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

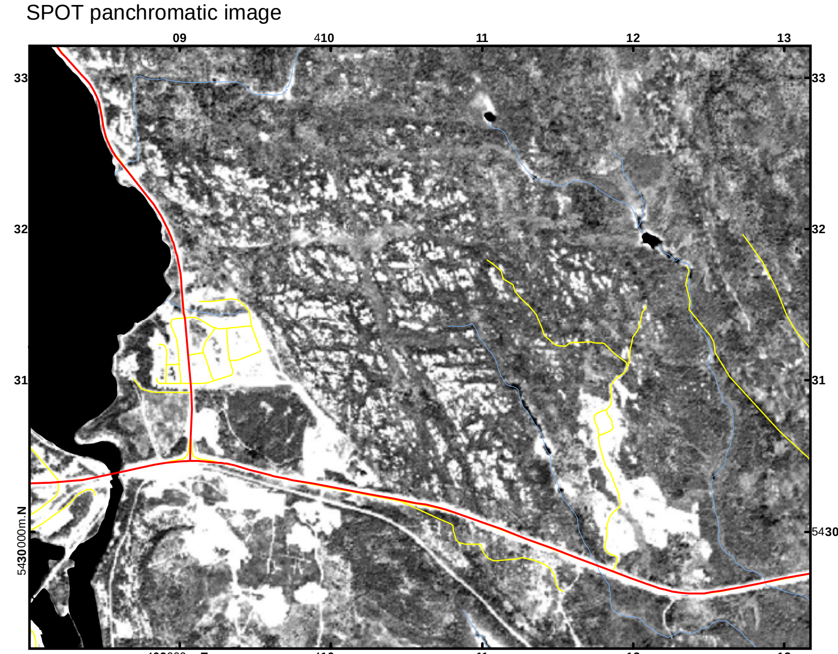
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO

TITLE
Watersheds in the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 10	REVISION 2
GIS	DVZ	29 MAY 2014		UTM ZONE 16
CHECK	LAP	29 MAY 2014		NAD 1983
REVIEW	CWM	30 MAY 2014		1:150,000

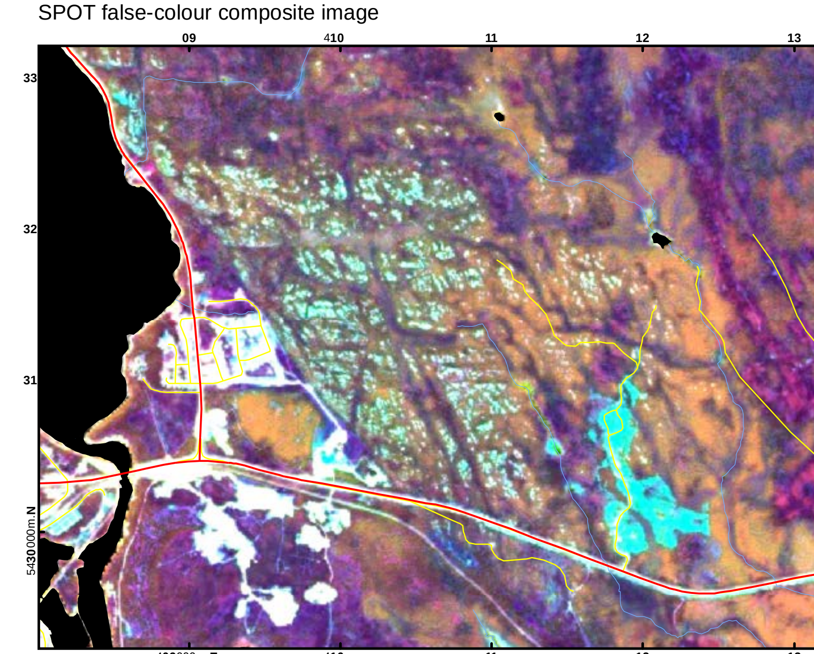


SPOT panchromatic image



1:50,000

SPOT false-colour composite image



1:50,000

LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Watercourse

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

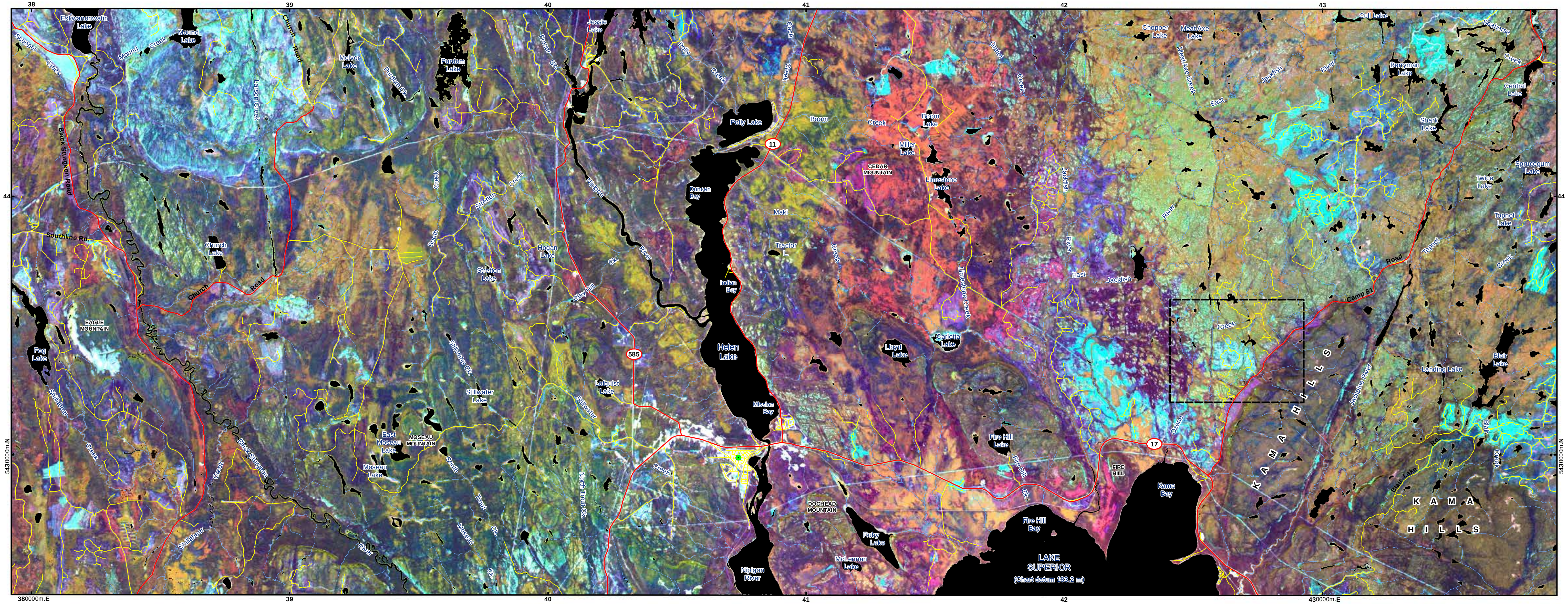
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

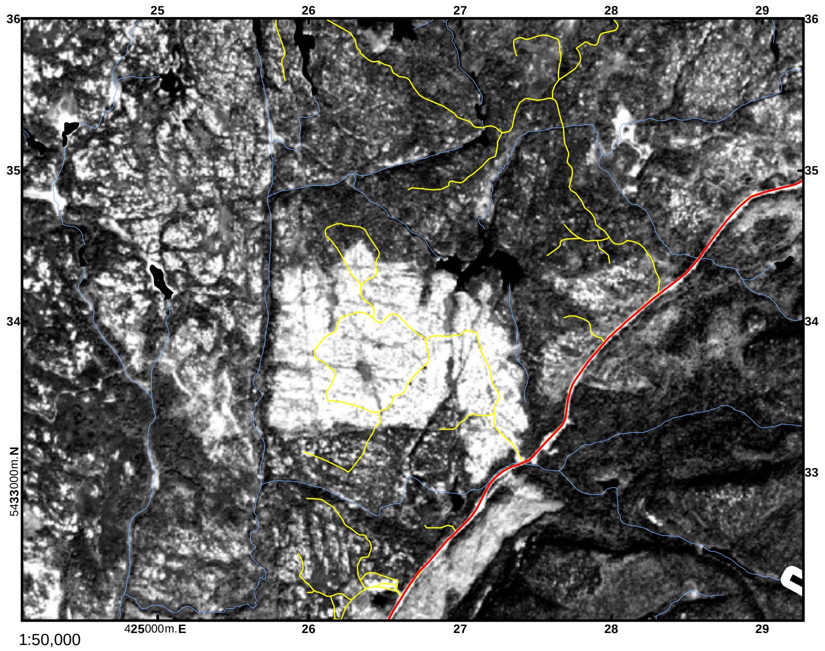
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO

TITLE
SPOT panchromatic imagery

DESIGN	DVZ	05 SEP 2013	FIGURE 11	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	15 NOV 2013		1:150,000

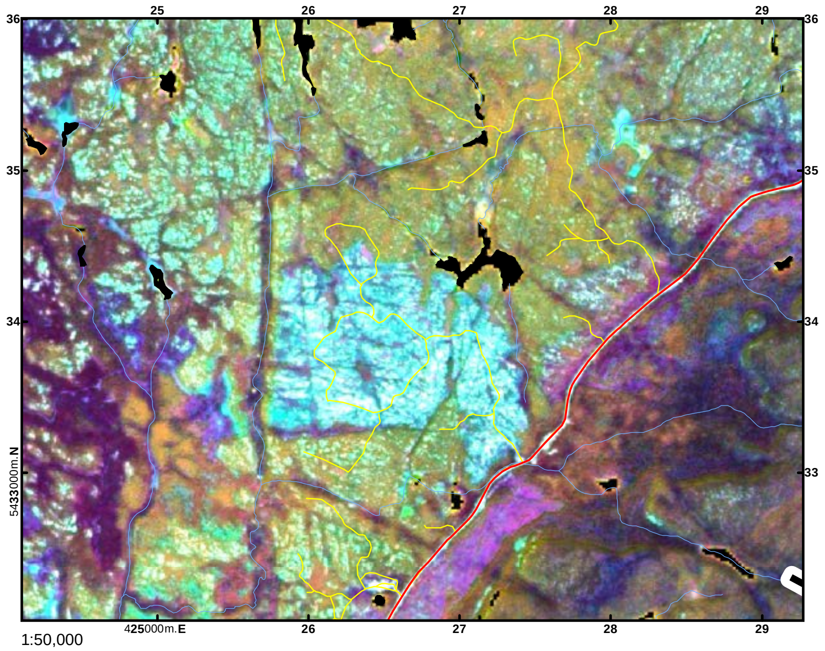


SPOT panchromatic image



1:50,000

SPOT false-colour composite image



1:50,000

LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Watercourse

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

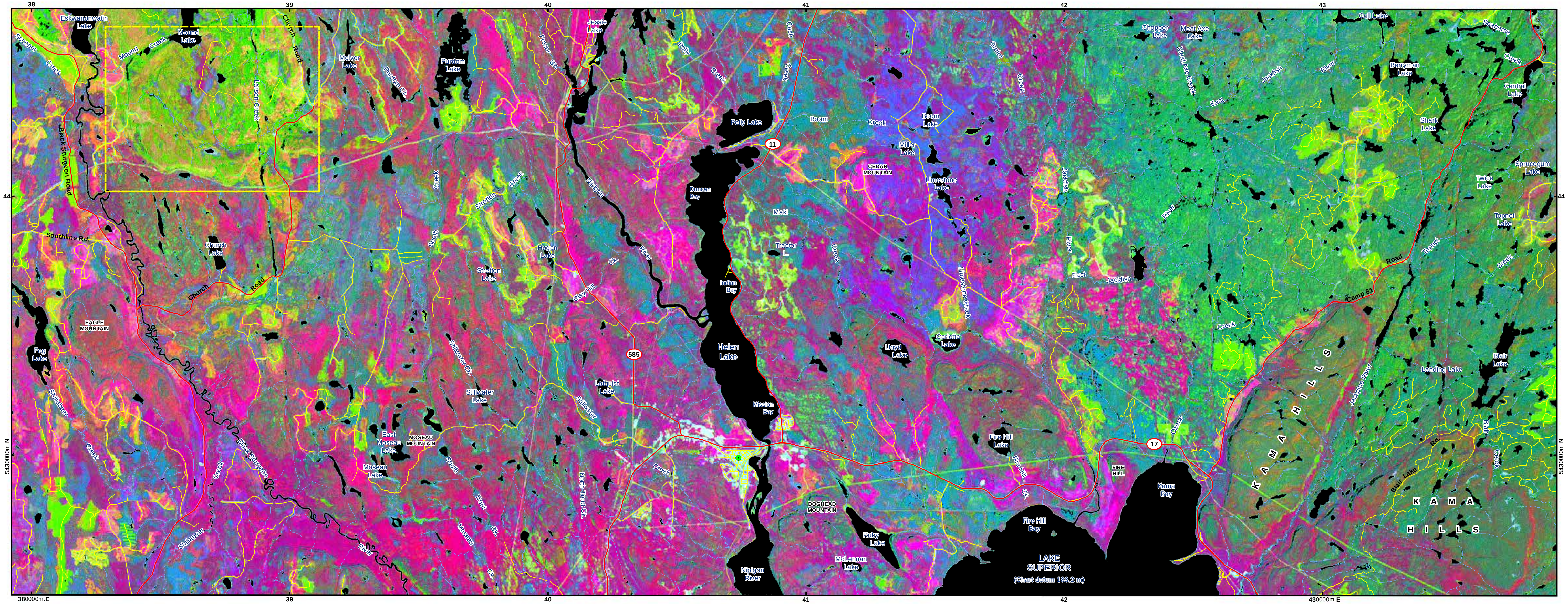
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

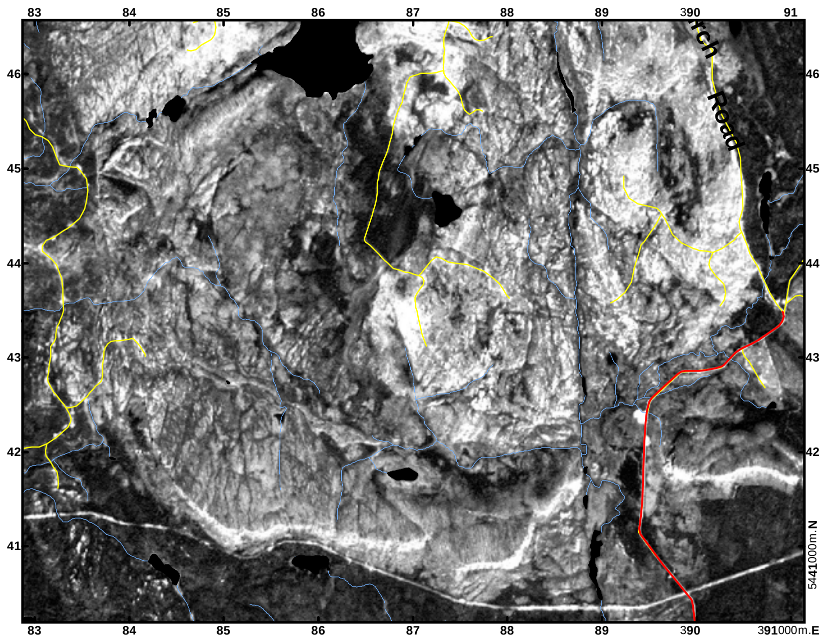
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO

TITLE
SPOT false-colour composite image

DESIGN	DVZ	05 SEP 2013	FIGURE 12	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	15 NOV 2013		1:150,000

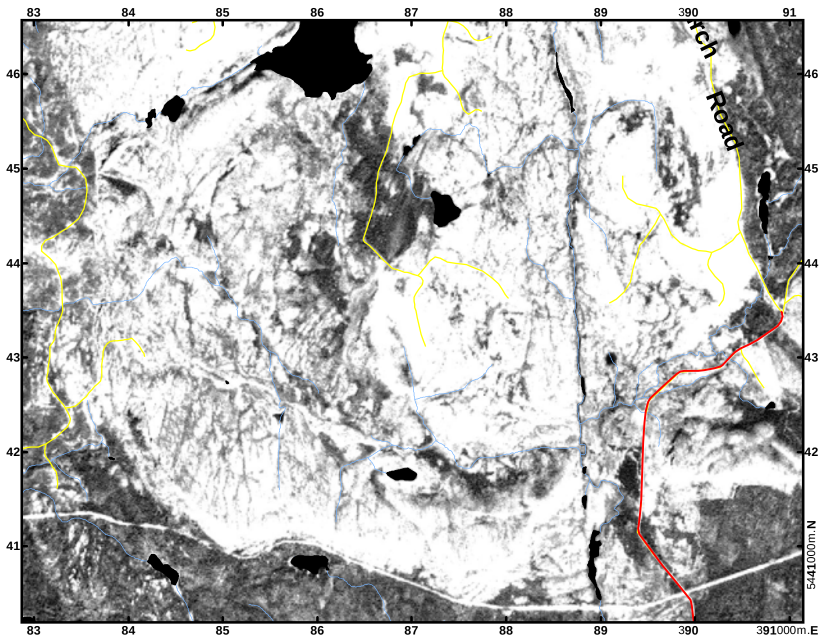


SPOT panchromatic image



1:80,000

Landsat ETM false-colour composite image



1:80,000

LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Watercourse

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)
Landsat: GeoBase (2013c)

NORTH

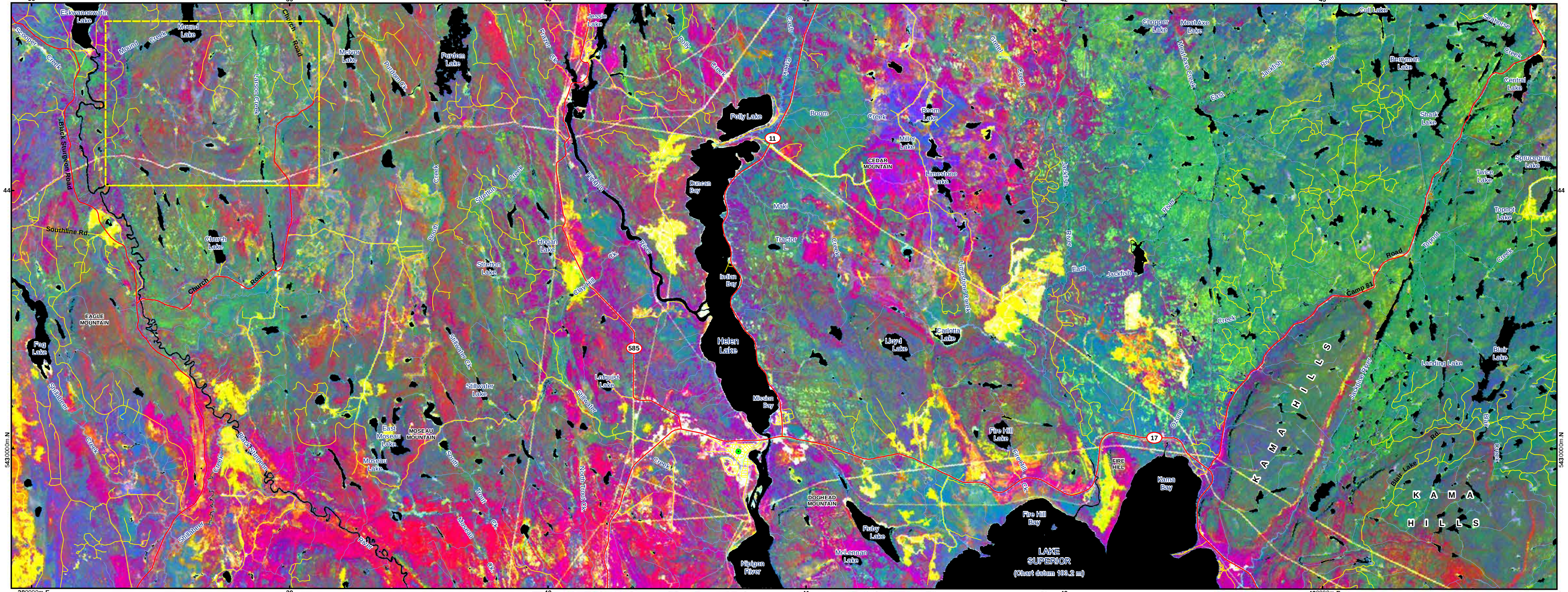
5 km

J D MOLLARD

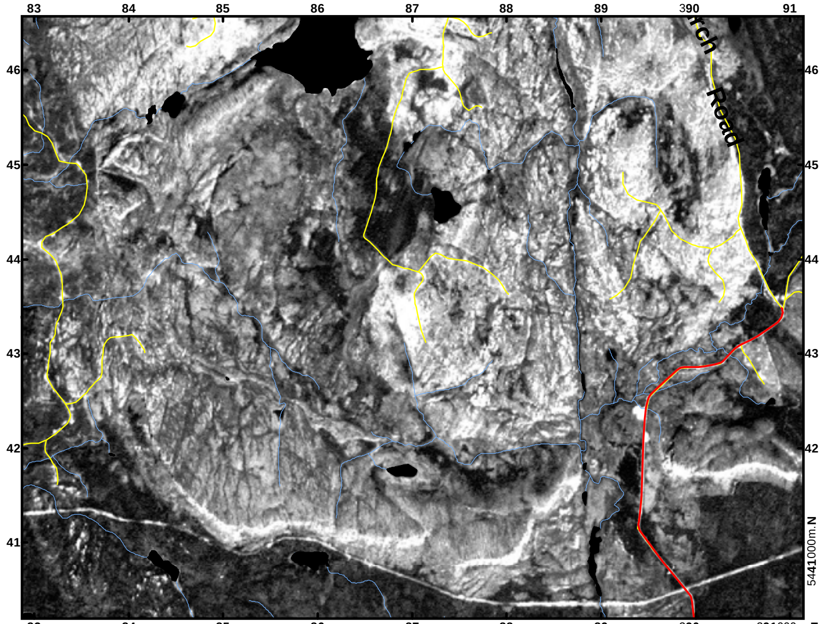
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, NIPIGON AREA, ONTARIO

TITLE
Landsat ETM false-colour composite image

DESIGN	DVZ	05 SEP 2013	FIGURE 13	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	15 NOV 2013		1:150,000

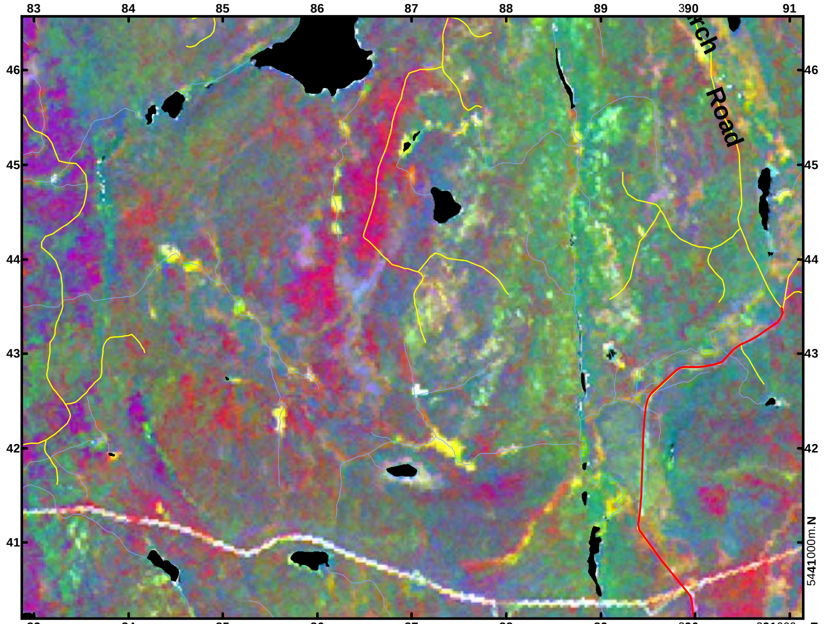


SPOT panchromatic image



1:80,000

Landsat TM false-colour composite image



1:80,000

LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Watercourse

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)
Landsat: NASA Landsat Program (2013)

NORTH

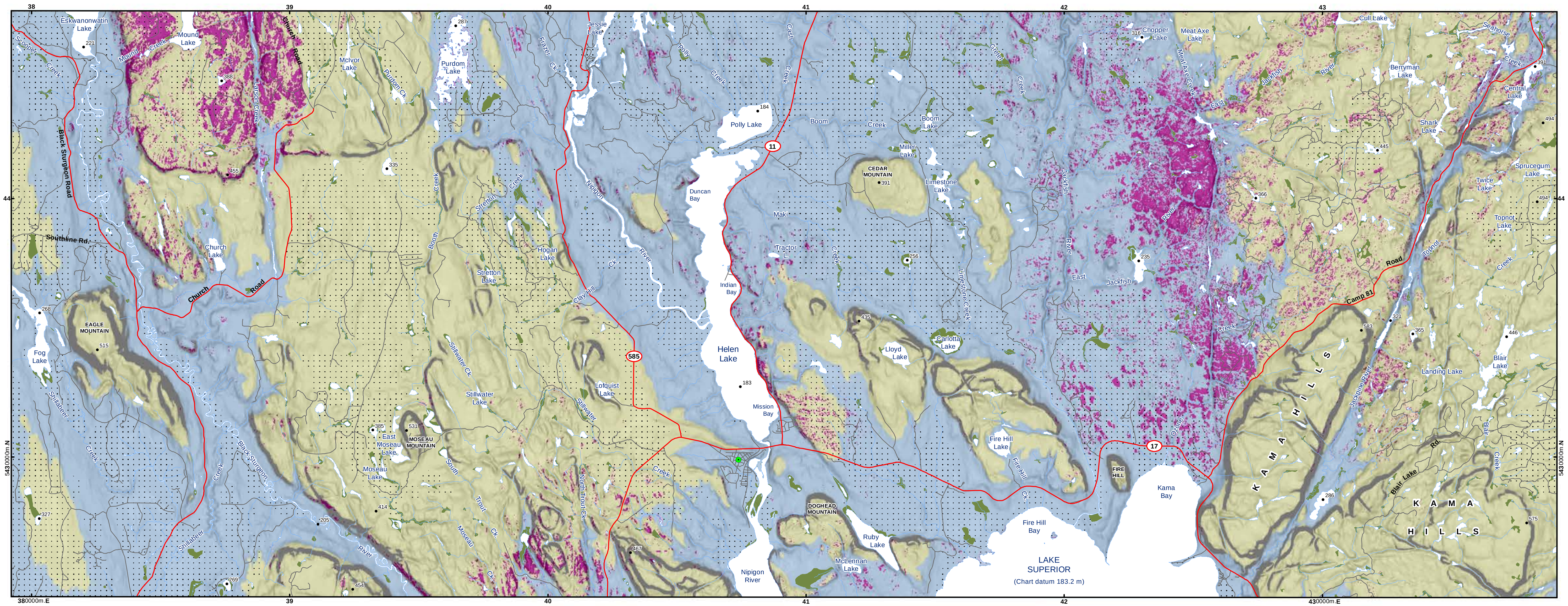
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

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

TITLE
Landsat TM false-colour composite image

DESIGN	DVZ	05 SEP 2013	FIGURE 14	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	15 NOV 2013		1:150,000



LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Spot height (m)
- Hill outline
- Waterbody
- Watercourse
- Wetland
- Low relief area
- Bedrock outcrop

Topography

- Slope 15° or greater
- Hill \ ridge\ mesa
- Lowland
- Highland

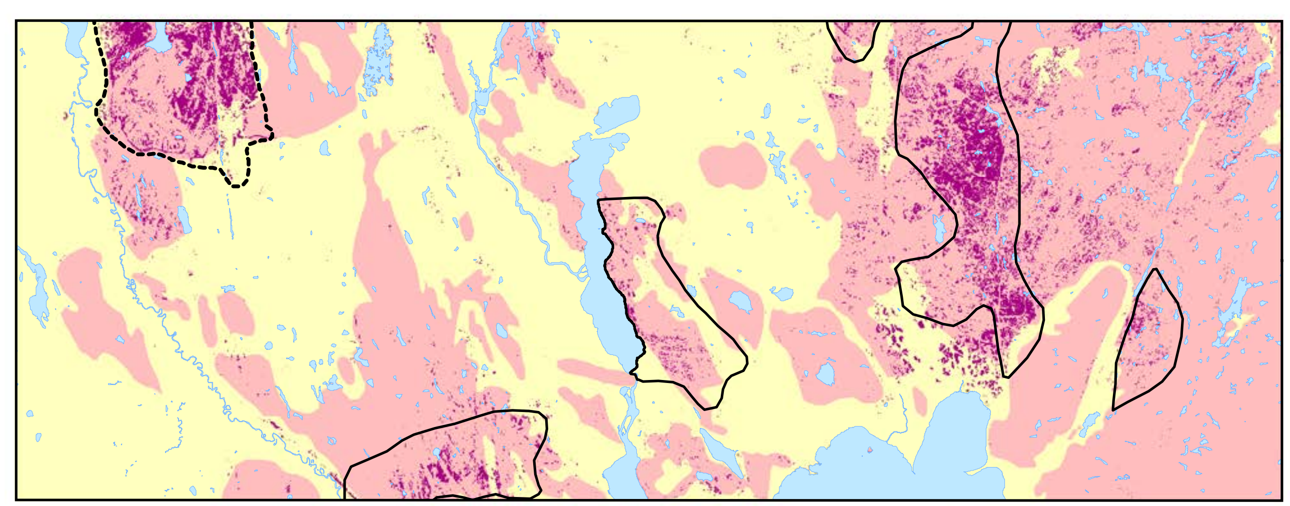
Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Wetland: LIO Wetland Unit
Topography: Derived from CDED

INSET LEGEND

- NIP10 burn zone
- Bare rock (Zoltai, 1965b)
- Bedrock outcrop

Surficial geology

- Bedrock
- Surficial



NORTH

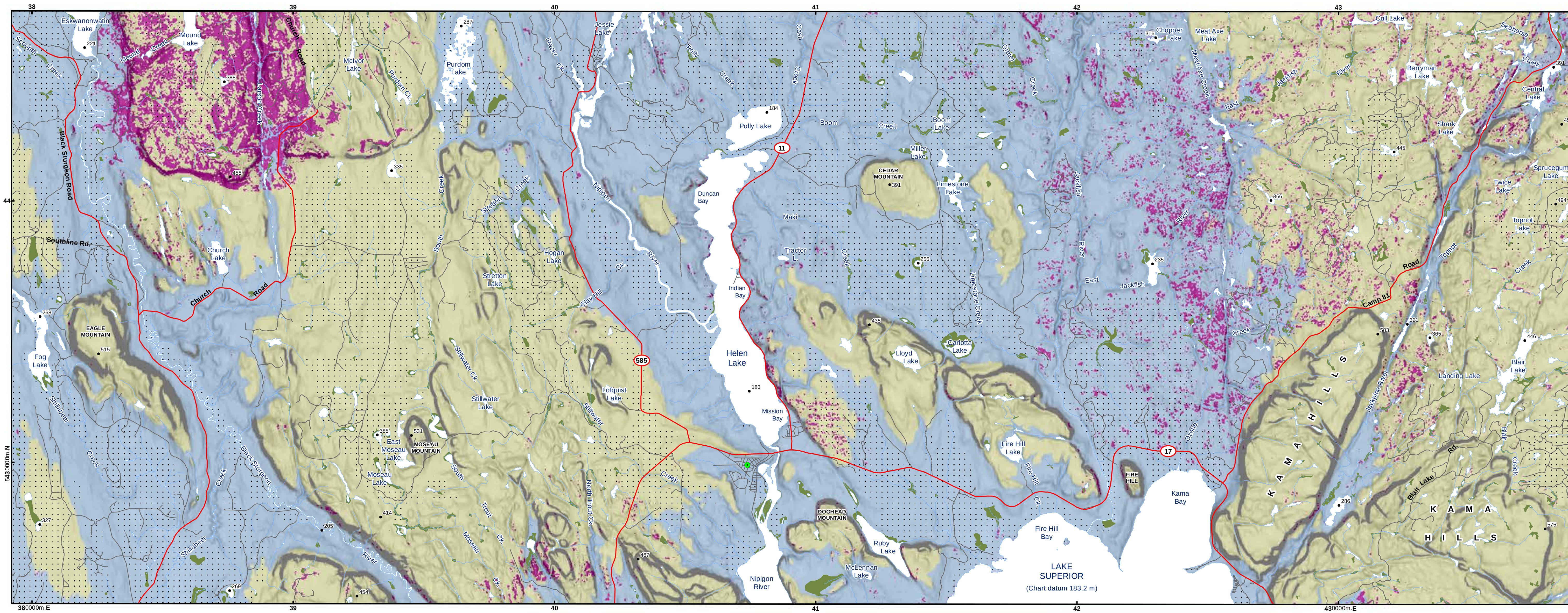
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

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

TITLE
Bedrock outcrops mapped from SPOT imagery

DESIGN	DVZ	05 SEP 2013	FIGURE 15	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	15 NOV 2013		1:150,000



LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Spot height (m)
- Hill outline
- Waterbody
- Watercourse
- Wetland
- Low relief area
- Bedrock outcrop

Topography

- Slope 15° or greater
- Hill \ ridge\ mesa
- Lowland
- Highland

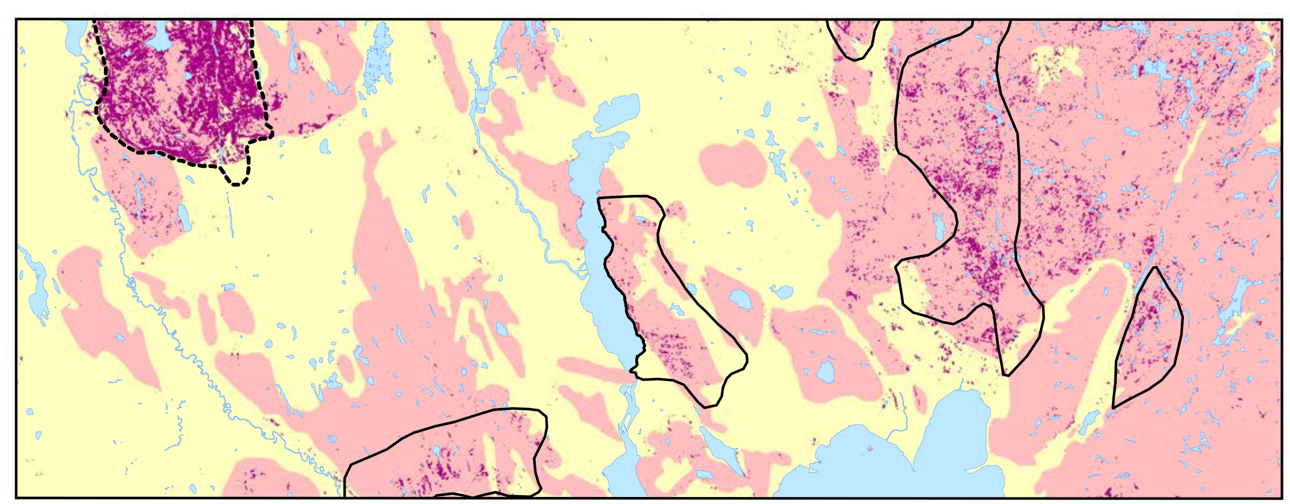
Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Wetland: LIO Wetland Unit
Topography: Derived from CDED

INSET LEGEND

- NIP10 burn zone
- Bare rock (Zoltai, 1965b)
- Bedrock outcrop

Surficial geology

- Bedrock
- Surficial



NORTH

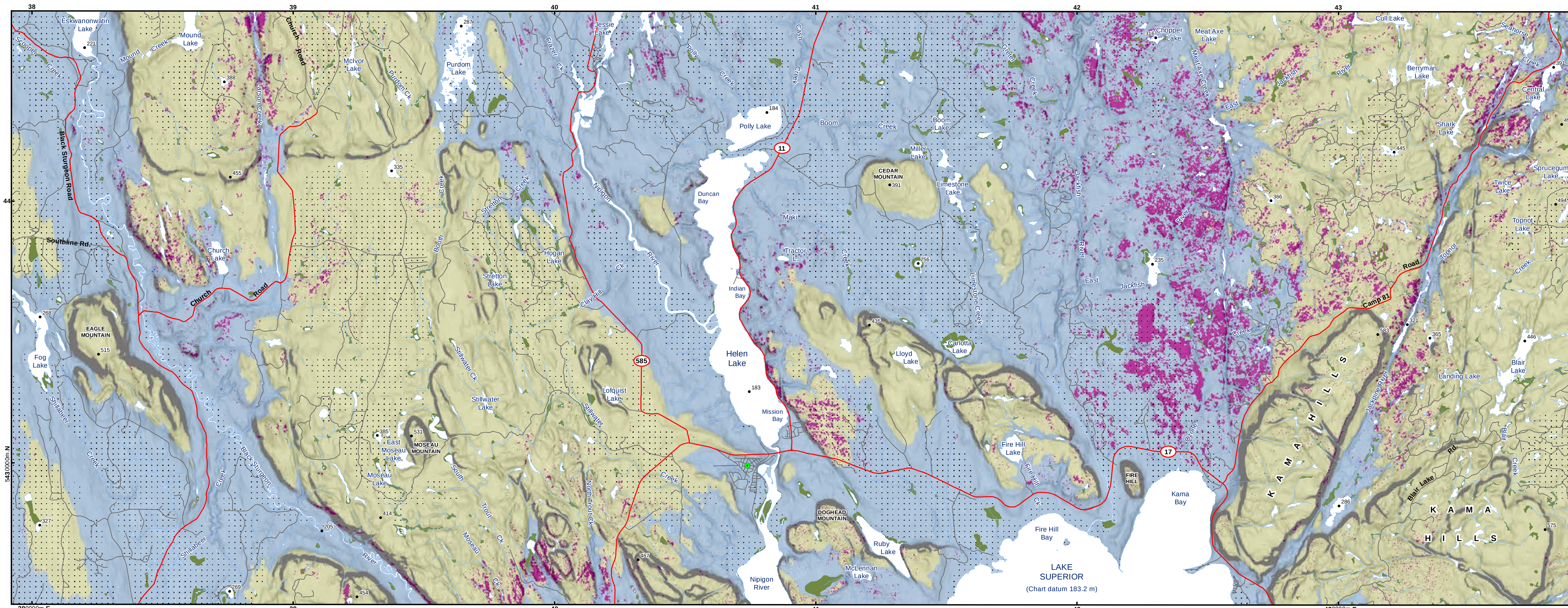
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

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

TITLE
Bedrock outcrops mapped from Landsat ETM imagery

DESIGN	DVZ	05 SEP 2013	FIGURE 16	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	15 NOV 2013		1:150,000



LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Spot height (m)
- Hill outline
- Waterbody
- Watercourse
- Wetland
- Low relief area
- Bedrock outcrop

Topography

- Slope 15° or greater
- Hill \ ridge\ mesa
- Lowland
- Highland

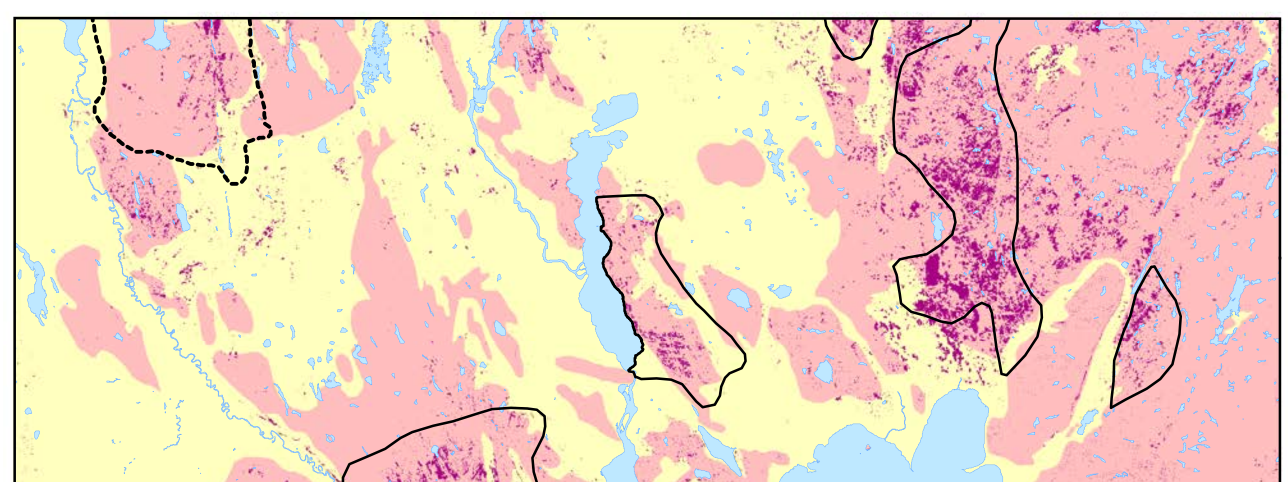
Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Wetland: LIO Wetland Unit
Topography: Derived from CDED

INSET LEGEND

- NIP10 burn zone
- Bedrock outcrop
- Bare rock (Zoltai, 1965b)

Surficial geology

- Bedrock
- Surficial



NORTH

5 km

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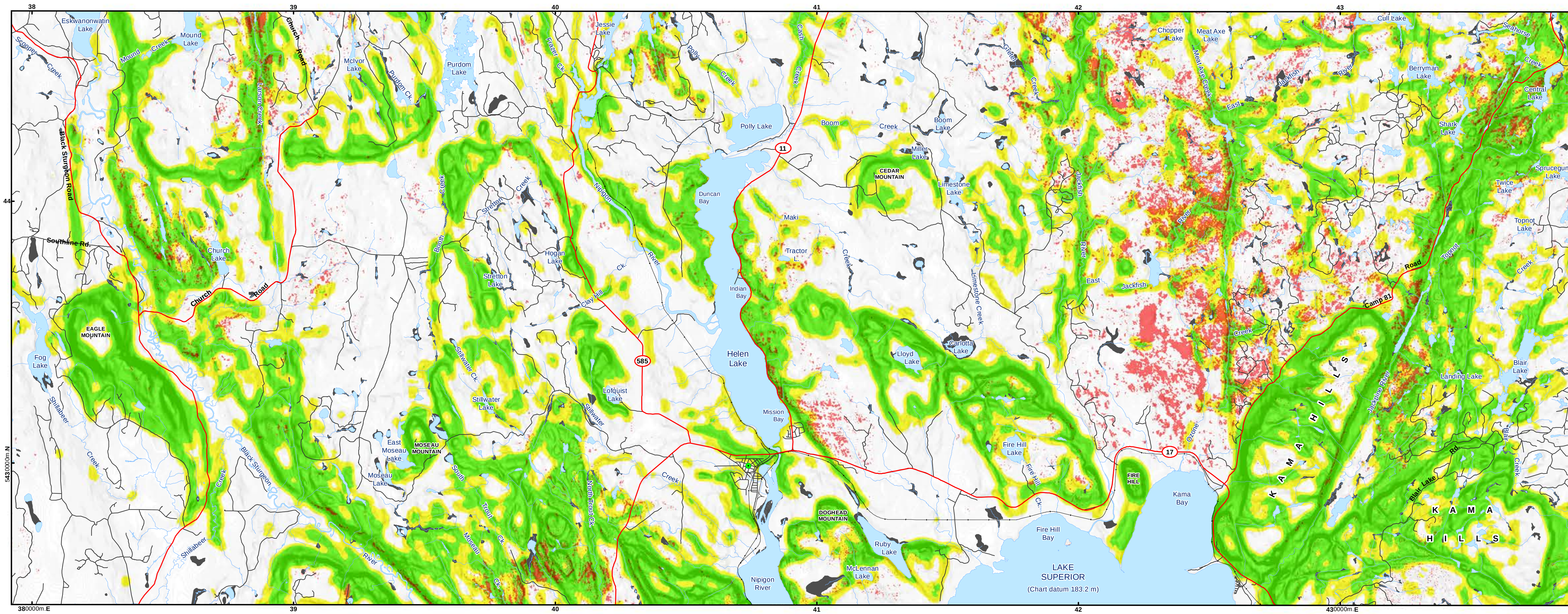
TITLE
Bedrock outcrops mapped from Landsat TM imagery

DESIGN	DVZ	05 SEP 2013	FIGURE 17	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	15 NOV 2013		1:150,000



LEGEND

- Nipigon (settlement)
- Main road
- Local road
- Rail
- Waterbody
- Watercourse
- Wetland
- Bedrock outcrop (Landsat TM)

Slope density (250 m radius)

Points\km^2

- 0 - 500
- 501 - 1,000
- 1,001 - 2,506

Data sources:
Main road: LIO Ontario road segment
Local road: LIO MNR road segment
Waterbody: LIO OHN Waterbody
Watercourse: LIO OHN Watercourse
Wetland: LIO Wetland Unit
Topography: Derived from CDED

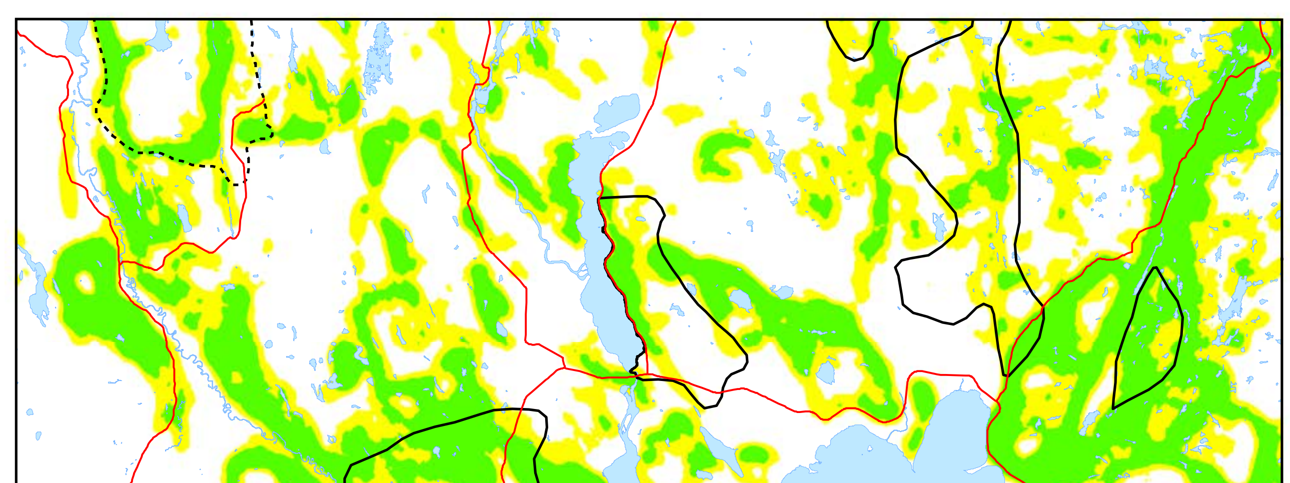
INSET LEGEND

- Main road
- NIP10 burn zone
- Bare rock (Zoltai, 1965b)

Slope density (500 m radius)

Points\km^2

- 0 - 500
- 501 - 1,000
- 1,001 - 2,404



NORTH

5 km

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

TITLE
Accessability map for the Nipigon area

DESIGN	DVZ	05 SEP 2013	FIGURE 18	REVISION 1
GIS	DVZ	11 NOV 2013		UTM ZONE 16
CHECK	LAP	12 NOV 2013		NAD 1983
REVIEW	CWM	15 NOV 2013		1:150,000