NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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

NORTHERN VILLAGE OF PINEHOUSE, SASKATCHEWAN

APM-REP-06144-0060

NOVEMBER 2013

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

PHASE 1 DESKTOP GEOSCIENTIFIC PRELIMINARY ASSESSMENT

TERRAIN AND REMOTE SENSING STUDY

NORTHERN VILLAGE OF PINEHOUSE, SASKATCHEWAN

November 2013

Prepared for:

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

Nuclear Waste Management Organization
22 St. Clair Avenue East 6th Floor
Toronto, Ontario
Canada M4T 2S3
NWMO Report Number: APM-REP-06144-0060

Prepared by:

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

EXECUTIVE SUMMARY

In March 2012, the Northern Village of Pinehouse, Saskatchewan, expressed interest in continuing to learn more about the Nuclear Waste Management Organization (NWMO) nine-step site selection process, and requested that a preliminary assessment be conducted to assess the potential suitability of the Pinehouse area for safely hosting a deep geological repository (Step 3). This request followed the successful completion of an initial screening conducted during Step 2 of the site selection process.

The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. The findings of the overall preliminary assessment are reported in an integrated report (NWMO, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Pinehouse 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 desktop geoscientific preliminary assessment of the Pinehouse area (Golder, 2013). The main information sources relied on were the Canadian Digital Elevation Data (CDED), the SPOT satellite imagery, the maps and reports from the Saskatchewan Geological Survey (SGS), and the Saskatchewan Forest Resource Inventory (FRI). The assessment 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 Pinehouse area is bounded by two major topographic highs, a high relief, rugged zone in the northeast, and a broad, low relief highland in the southwest. The vast majority of the Pinehouse area represents a lowland associated with the Churchill River and Pinehouse Lake. Most areas of exposed bedrock are located on the tops or sides of ridges, and the ridges themselves represent

areas of thin drift. Areas of thicker drift in the northeast half of the Pinehouse area are located in the lows between ridges and are associated with extensive wetland complexes.

Most of the area's drainage network is contained within two tertiary level watersheds. All surface water flow in the Pinehouse area is to the Churchill River, which flows to Hudson Bay. Shallow groundwater flow within surficial and bedrock aquifers in the Pinehouse area is expected to mimic the pattern of surface flow, with groundwater divides coinciding with drainage divides and discharge occurring into creeks, rivers, lakes and wetlands.

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

The main accessibility constraints in the Pinehouse area include the large lakes occupying the central lowland, the limited number of roads providing access into areas of thin drift, and the rugged terrain across which new roads would need to be constructed.

TABLE OF CONTENTS

LIST OF FIGURES (in order following text)

LIST OF TABLES

1 INTRODUCTION

In March 2012, the Northern Village of Pinehouse expressed interest in continuing to learn more about the Nuclear Waste Management Organization's (NWMO) nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the Pinehouse area for safely hosting a deep geological repository (Step 3). The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability; engineering; transportation; environment and safety; as well as social, economic and cultural considerations (NWMO, 2013).

This report presents the findings of a terrain and remote sensing assessment completed as part of the desktop geoscientific preliminary assessment of the Northern Village of Pinehouse and its periphery, referred to as the "Pinehouse area" (Golder, 2013). The objective of the geoscientific desktop preliminary assessment is to determine whether the Pinehouse area (Section 1.2), contains general areas that have the potential to meet the NWMO's geoscientific site evaluation factors.

1.1 OBJECTIVES

This report presents a synopsis of the terrain in the Pinehouse area using existing remote sensing and geoscientific information sources. The report provides information on the nature and distribution of overburden deposits in the area, and discusses the role of these deposits in concealing and censoring the lengths of lineaments. The main information sources relied on in this study are the Canadian Digital Elevation Data (CDED), the SPOT satellite imagery, the maps and reports on surficial geology produced by the Saskatchewan Geological Survey (SGS), and the Forest Resource Inventory (FRI) data produced by the Forest Service Branch of the Saskatchewan Ministry of Environment.

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

- Evaluate the nature, areal extent and depth of overburden materials;
- Delineate 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 Pinehouse area (Section 1.2) using the data and methodology described in Section 1.3.

1.2 Location

The Pinehouse area is approximately 58 km by 50 km in size, encompassing an area of about 2,914 km^2 (Figure 1). The approximate western, northern, eastern and southern limits of the Pinehouse area are (UTM Zone 13, NAD83): 373000, 6182340, 431100, and 6132200 m. The settlement area of Pinehouse is located on the western shore of Pinehouse Lake.

1.3 Data and methods

This section summarizes the remote sensing and geoscientific data sources that were used to address the objectives of the terrain study for the Pinehouse area, including an evaluation of the quality of the data. The datasets used in this study are all publically available.

1.3.1 SGS maps and reports

Overburden deposits within the Pinehouse area were mapped as part of a regional surficial mapping program covering the Precambrian Shield of Saskatchewan undertaken between 1974 and 1984 by the Saskatchewan Research Council under contract to the Saskatchewan Geological Survey (SGS). Schreiner (1984b) provides a description of the mapping campaign, the purpose of which was to provide a database for mineral and resource exploration and development, as well as for geochemical studies, land use planning, and other terrain studies. Headed by E.A. Christiansen and B.T. Schreiner, the program resulted in the first overall systematic mapping of Quaternary geology within twenty 1:250,000 scale NTS map sheets. Field investigations were preceded by interpretation of aerial photographs at a scale of about 1:60,000 and photo-mosaics at a scale of about 1:50,000. Data on bedrock exposure, drift cover and thickness, surface texture, landforms and water features were recorded on photo-mosaics at a scale of about 1:250,000. Much of the field campaign consisted of shoreline mapping around lakes large enough to accommodate float-equipped aircraft, with typically about 150 sites visited per NTS sheet (typically about one site per 100 km^2). In addition, in map areas where roads existed, field investigations were conducted along roads where exposures and borrow pits provided valuable sections. Field data such as field notes, photographs, and lithologic logs are kept on file at the Saskatchewan Research Council.

The Pinehouse area is enclosed almost entirely within the Île-à-la-Crosse map sheet (Schreiner, 1984c), with only the eastern margin of Figure 3 covered by the La Ronge map sheet (Schreiner and Alley, 1984). Mapping of the Île-à-la-Crosse area was conducted in 1976 and 1977. Twenty-eight sites were inspected within the northeast portion of the map sheet, where the Precambrian Shield is exposed. Highway 914 had not been constructed at that time, so the sites must have been accessed entirely by using float-equipped aircraft. Apart from the brief descriptions of the Quaternary geology provided in the SGS summaries of investigations (Schreiner et al., 1976; Schreiner, 1977), there are no reports dedicated to describing the drift deposits and terrain conditions within the Pinehouse area. The report by Schreiner (1984b), which is the principal report on the Quaternary geology of the Precambrian Shield in Saskatchewan, and is accompanied by a compilation map at a scale of 1:1,000,000 (Schreiner, 1984a), contains descriptions of physiography and drainage, surficial deposits and landforms, and Quaternary stratigraphy and history that are relevant to conditions in the Pinehouse area.

The regional surficial geology mapping available for the Pinehouse area, described above, provides a reasonable representation of the terrain conditions in the Pinehouse area in terms of topography and the nature and thickness of overburden deposits. However, Section 5 attempts to integrate the surficial geology map with other datasets such as SPOT, CDED (Section 3), and the Saskatchewan Forest Resource Inventory (Section 1.3.5) to characterize the terrain in greater detail.

In addition to the surficial geology maps and reports described above, areas of extensive drift cover lacking bedrock outcrops have been delineated in a bedrock map covering the northern part of the Pinehouse area (Munday, 1978b). A scanned copy of this map has been georeferenced and included in this report. Section 5.2.2 describes how the areas of thicker drift cover in this map were delineated in better detail than in the surficial geology map. The areas of exposed bedrock delineated in the Forest Resource Inventory (Section 1.3.5) have been overlain on the georeferenced bedrock maps to provide an indication of the actual extent of exposed bedrock within the areas not delineated as drift-covered.

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 using the CDED elevation model as the representation of the landscape.

Canadian Digital Elevation Data (CDED), 1:50,000 scale, 0.75 arc second (20 m) elevation models (GeoBase, 2011a) served as important data sources for analyzing and interpreting the terrain in the Pinehouse area. The digital elevation models (DEM) used for this study were constructed by the Mapping Information Branch of Natural Resources Canada (NRCan) and by the Landscape Analysis and Applications section of the Canadian Forest Service using 1:50,000 scale source data from the National Topographic Data Base (NTDB). The source data were produced by the Surveys and Mapping Branch of Energy, Mines and Resources Canada based on black and white air photographs acquired mainly in the 1950s to 1970s at scales of 1:50,000 to 1:70,000. Four main NTDB data types were used: contours, spot heights, streams, and lakes. 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. Apart from this issue, no additional imperfections have been found in the elevation data acquired for the Pinehouse area.

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

Surface analyses were performed on the digital elevation model in order to characterize slope and relief. Slope was calculated using the standard grid-based method employed in ArcGIS, which involves fitting a plane to the elevation values of a three by three neighbourhood centred on the processing cell. Slope is defined as the maximum slope of that plane, which can also be thought of as the dip of the plane, and aspect is equivalent to the dip direction. Relief was calculated in two ways. The first was by subtracting the average elevation within a radius from the elevation value in the processing cell. The second was defined as the range in elevation within a circular window. The first relief calculation represents a high pass filter, and it was useful for delineating topographically prominent rock ridges in the Pinehouse area (Section 3.2), which are often characterized by thin drift and a relative abundance of exposed bedrock (Section 5).

The density of steep slopes was calculated as the number of points within a 2 km radius with a slope of at least 6°. The threshold of 6° was found to be reasonably effective in distinguishing, in a generalized manner, between the rugged bedrock-controlled areas and the areas of gentle slope associated with thicker overburden cover. The slope density map provides a generalized image of the areas where CDED could be less reliable for identifying lineaments (Section 3.3).

1.3.3 SPOT

SPOT multispectral orthoimagery at a resolution of 20 m and panchromatic imagery at 10 m resolution formed an important information source for identifying exposed bedrock within the Pinehouse area (GeoBase, 2011b). 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 the North American Datum 1983 (NAD83).

Five SPOT images (or 'scenes') provided complete coverage for the Pinehouse area (Table 2). The scenes are from the SPOT 4 and SPOT 5 satellites with two images acquired in May 2006 and three in June 2007, October 2007, and September 2008, respectively. The images captured during May 2006 and June 2007 cover the majority of the Pinehouse area.

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

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

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
S5_10541_5531_20071007	SPOT 5	October 7, 2007
S4_10600_5503_20070610	SPOT 4	June 10, 2007
S4_10712_5558_20080910	SPOT 4	September 10, 2008
S4_10642_5531_20060516	SPOT 4	May 16, 2006
S4_10626_558_20060516	SPOT 4	May 16, 2006

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

After some effort in attempting to produce good results from the unsupervised classification, it was found that there were challenges in using unsupervised classification to map the exposed bedrock accurately and reliably. For instance, certain parts of wetlands can exhibit similar spectral characteristics as exposed bedrock. Alluvial sediments exposed in creek valleys also display similar spectral properties. Additional issues contribute to the unreliability of this technique. As a result, our interpretation of the SPOT imagery has relied on the PCA composite images rather than on unsupervised classification.

In addition to the use of SPOT imagery described above, Google Earth imagery and FlySask imagery were also examined to confirm observations and interpretations made from the SPOT imagery. FlySask imagery represents colour orthorectified aerial imagery at a ground resolution of 0.62 m produced by the Saskatchewan Geospatial Imagery Collaborative (SGIC, 2013) and maintained by the Saskatchewan Research Council. Complete FlySask coverage of the Pinehouse area was acquired during the months of September and October in 2010 and 2011.

1.3.4 DRILL HOLES AND WATER WELLS

Limited information on overburden thickness is available from water well and diamond drill hole databases compiled by the SGS and the Saskatchewan Water Security Agency (WSA).

The Water Well Information Database produced by the Water Security Agency was searched for water well records in the Pinehouse area. No water wells were found within the Pinehouse area, but three wells were found a short distance south of the southern boundary of the area. A well near Highway 914 was drilled in 1996, and its location is accurate to within one section (± 1,140 m). The other two wells were drilled in one location on the south shore of Besnard Lake in 1980, and their coordinates are accurate to within one quarter section (± 570 m). None of the wells encountered bedrock, so the well depths provide minimum values for the depth of overburden at these sites. These data are described in Section 5.1.1.

Information on drift thickness can be extracted from the Geological Atlas of Saskatchewan drill hole databases. There are two SGS drill hole databases, one for cores held in Regina and the other for the core library in La Ronge. The accuracy of the drill hole coordinates is unknown. The Regina database contains data on fifteen holes drilled in the Phanerozoic basin within or a short distance west of the Pinehouse area. Ten of these records contain data on depth to the top of bedrock, and these are shown in Figure 3. The La Ronge database contains records for fifteen drill holes within the Pinehouse area. Seven of these records, located around Musqua and Degryse lakes, appear to match four records in the Regina database, with the depth to bedrock roughly equal between the paired drill holes. For drill holes from the La Ronge database, the vertical depth to bedrock was computed using borehole inclination and uncorrected depth to bedrock. Section 5.1.2 summarizes the information on overburden thickness obtained from the drill holes.

1.3.5 Forest Resource Inventory

The Forest Service of the Saskatchewan Ministry of Environment maintains a forest inventory for the commercial zone of the provincial forest in Saskatchewan. The forest inventory database, herein referred to as the forest resource inventory (FRI), includes a polygon file that identifies forest polygons, clearings, and non-productive land. Non-productive land classes include treed rock, clear rock, treed muskeg, clear muskeg, brushland, meadow, clearing, sand, and non-productive burn-over. The treed rock and clear rock classes can be used to obtain an indication of the extent of exposed bedrock.

FRI coverage exists for the entire Pinehouse area. These data were generated based on the interpretation of 1:12,500 air photos dominantly from 1980, with small parts of the Pinehouse area being mapped using air photos acquired between 1981 and 1997. The interpretation team would carry out an initial helicopter reconnaissance survey along the centre of each (sometimes every second) photo acquisition flight line. Follow up ground inspection was made in accessible areas of typical forest conditions as well as sites where the forest type changes, with the interpreter aiming towards a sampling intensity of one site for every square kilometre of accessible terrain. A final field inspection would occur as problems arose. The field audit would have heavily favoured productive over the non-productive sites.

The non-productive land classes of treed rock and clear rock have been plotted in Figure 12 to provide an indication of the extent of exposed bedrock within the Pinehouse area. Comparison with the SPOT imagery indicates that the treed and clear rock classes generally provide a reasonable image of the extent of exposed bedrock throughout the Pinehouse area. However, it is clear that the extent of exposed bedrock is generally underestimated in Figure 12, particularly in areas where the exposed bedrock appears in the form of small outcrops (< 100 m in extent) distributed throughout an area. A few larger unmapped areas of exposed bedrock were also found.

Muskeg mapped in the FRI are included with the 1:50,000 scale CanVec wetlands shown in Figure 10 to provide a more complete image of wetlands in the Pinehouse area (Section 4.1). The CanVec wetland mapping in the Pinehouse area, as in many other areas, is incomplete.

As discussed in Sections 3.2 and 5.2.1, the areas of treed or cleared rock are mainly located along the sides and tops of positive relief features, such as bedrock-controlled ridges, peninsulas and islands. The FRI data have been overlain on the bedrock map of Munday (1978b), which was introduced in Section 1.3.1 (Figure 13), in order to provide an indication for the extent of exposed bedrock within the areas not delineated as drift-covered.

2 SUMMARY OF GEOLOGY

A detailed discussion of the geological setting of the Pinehouse area is provided in a separate report (Golder, 2013), from which the following sections on bedrock geology and structural history were extracted.

The Pinehouse area lies on rocks of the Canadian Shield. The Canadian Shield is a collage of Archean cratons and accreted juvenile terranes and sedimentary basins that were progressively amalgamated over a period of more than 2 billion years during the Proterozoic Eon. Among the major orogenies that contributed to the assembly of the Canadian Shield is the Trans-Hudson Orogeny, which resulted from the closure of the Manikewan ocean and terminal collision of the Rae-Hearne, Sask and Superior cratons during the approximate period of 1.9 to 1.8 billion years (Ansdell, 2005; Corrigan et al., 2005; Hajnal et al., 2005; Corrigan et al., 2007; Whitmeyer and Karlstrom, 2007; Corrigan et al., 2009). The Canadian Shield now forms the stable core of North America. Unlike the exposures of the Canadian Shield recognized and mapped in Ontario, the shield exposures in Saskatchewan do not appear to host pervasive mafic dyke swarms.

The Pinehouse area is mostly located within the Hearne craton (historically called Cree Lake zone) that comprises the eastern portion of the Western Churchill Province of the Canadian Shield (Figure 2). A small portion of the Pinehouse area extends into the adjacent Reindeer zone to the east. The Hearne craton (south of the Athabasca basin) is generally composed of high grade Archean to Paleoproterozoic metamorphic rocks older than 1.8 billion years (Orrell et al., 1999; Card et al., 2008) that are overlain by sedimentary rocks of the Athabasca Group within the Athabasca Basin and Phanerozoic sedimentary rocks within the Western Canada Sedimentary Basin, north and south of the Pinehouse area, respectively. In the Canadian Shield, these rocks continue southward, with increasing depth beneath the sedimentary rocks of the Western Canada Sedimentary Basin, and northward outcropping again along the northern margin of the Athabasca Basin. The Hearne craton is bounded to the west by the Rae craton along the Snowbird tectonic zone and to the east side by the Reindeer zone along the Needle Falls shear zone (Figure 2). These shear zones are oriented in a north-northeast direction (azimuth of approximately 020°), and reflect the predominant alignment of major Precambrian structural features and lithologies in northern Saskatchewan (Munday, 1978a). The Hearne craton is further divided into three lithostructural domains (Lewry and Sibbald, 1980), from west to east, the Virgin River, Mudjatik, and Wollaston domains. A new proposed domainal reclassification has been advanced where the Virgin River and Mudjatik domains are to be merged and renamed as Mudjatik domain (Card, 2012). For the purpose of simplicity, the old domainal classification has been retained given that it is the one used by all sources utilized and because it does not have any impact in the objective of this assessment. The Pinehouse area is primarily located within the Wollaston domain, with two small portions lying on the Mudjatik domain and the Wathaman batholith, in the northwest corner and southeast corners of the Pinehouse area, respectively (Figure 2).

The eastern Mudjatik domain consists of Archean felsic gneisses with interspersed mafic gneisses (Annesley et al., 2005). Metamorphic grade in this area is between upper amphibolite to granulite metamorphic facies (Tran, 2001). Felsic gneisses predominate among any other type of rock found in the Mudjatik domain. These gneisses are also found in the literature as granitic gneisses and occasionally as eastern gneisses. The origin of the mafic gneisses is uncertain, but is generally interpreted as metamorphosed gabbroic and dioritic sills or dykes (Annesley et al., 2005). The Archean felsic gneiss rocks are thought to have served as a basement for the deposition of the metasedimentary rocks, which are dominated by psammopelitic to pelitic rocks and amphibolite (Card and Bosman, 2007). The metasedimentary rocks occur in narrow, arc-shaped bands throughout the Archean felsic gneiss, defining a dome and basin pattern in many parts of the Mudjatik domain which are absent in the Virgin River domain to the west and the Wollaston domain to the east (Card et al., 2008).

The Wollaston domain is characterized as a north-northeast-trending, tightly folded belt of Archean felsic orthogneissic rocks and Archean to Paleoproterozoic metasedimentary rocks with minor metavolcanic rocks (Delaney, 1993). Generally, the felsic gneisses of the Wollaston domain range in composition from syenogranite to granodiorite (Annesley et al., 2005). The Archean metasedimentary rocks are part of the basement to the Proterozoic metasedimentary rocks and subordinated metavolcanic rocks of the Wollaston domain that form the Wollaston Supergroup (as defined by Yeo and Delaney, 2007). The Wollaston Supergroup was deposited along the eastern edge of the Hearne craton first in a rift/passive margin setting, and later in a foreland basin setting, due to the opening and closure of the Manikewan ocean between the Hearne and Superior cratons. These rocks are mapped as narrow bands of psammitic to pelitic gneisses, defining the north-northeast-trending linear grain in the Wollaston domain. The predominance of metasedimentary gneisses of the Wollaston Supergroup in the north and central parts of the Wollaston domain declines to the south, where they become discontinuous in bands intercalated with Archean felsic (ortho) gneiss and younger granitoid rocks.

The eastern boundary of the Mudjatik domain is generally thought to be transitional with the western boundary of the Wollaston domain (e.g., Munday, 1977, 1978a; Lewry and Sibbald, 1980; Tran, 2001), where a marked change in structural style from arcuate to linear, and a less apparent change in lithology in some areas, has been observed (e.g., Lewry and Sibbald, 1980; Annesley and Madore (1989, 1991, 1994); Delaney, 1993; Card et al., 2006; Yeo and Delaney, 2007). More recently, Annesley et al. (2005) have argued that the boundary between both domains corresponds to a major crustal strike-slip fault-shear zone or a thermotectonic discontinuity, at least in the northern segment of the domain boundary nearby the Athabasca basin where they have found evidence of mylonitization and abundant kinematic indicators along the boundary zone. To the south, no evidence of major structural features has been reported in the literature. Nor did Tran et al. (1999) find evidence of this structural feature in the Mackenzie Falls area. Tran and Smith (1999) pointed out that such a structural feature did not exist in the area of the Cup-Keller-Schmitz Lakes and that if a domain boundary existed then it must have existed prior to the Hudsonian Orogeny.

The Wollaston domain is separated to the east from the Reindeer zone by the Needle Falls shear zone (Delaney, 1993; Yeo and Delaney, 2007) (Figure 2). The contact with the Needle Falls shear zone is sharp and distinct (Munday, 1978a). The Reindeer zone consists, from west to east, of the Wathaman batholith, and the Rottenstone, La Ronge, Kisseynew, Glennie and Flin Flon domains (Lucas et al., 1996). The Reindeer zone is generally composed of approximately 1.92 to 1.83 Ga volcano-plutonic assemblages and marginal sedimentary basins, derived from various tectonic settings (Lucas et al., 1996).

The Needle Falls shear zone is a crustal scale feature that extends for over 400 km separating the Hearne craton to the west and the Wathaman batholith to the east (Figure 2). It is well defined by a strong magnetic anomaly, and geophysical surveys suggest the shear zone extends an additional 300 km to the south, beneath the Paleozoic cover (Stauffer and Lewry, 1993). Seismic imaging suggests this feature dips steeply to the west (Lewry et al., 1994). Field evidence suggests that the shear zone developed late, during the Trans-Hudson Orogeny approximately 1.83 Ga with (most recent) dextral movement of 40 to 60 km (Stauffer and Lewry, 1993; Orrell et al., 1999; Hajnal et al., 2005).

The Wathaman batholith is a very large megacrystic monzogranite-granodiorite intrusive body that extends for about 900 km along the eastern boundary of the Hearne craton and the Needle Falls shear zone, separating the craton from the Reindeer zone. The batholith was emplaced during the Trans-Hudson Orogeny in a compressional tectonic regime (Fumerton et al., 1984).

Regional geophysical surveys were used to assist in mapping geologic structures within the Precambrian provinces and zones of northern Saskatchewan (Hajnal et al., 2005; White et al., 2005). A cross section through the Trans-Hudson Orogen in the Pinehouse area was constructed by White et al. (2005) based on geophysical surveys conducted as part of the Lithoprobe project (a multi-year continent-scale geophysical subsurface mapping initiative). Geophysical surveys conducted as part of this initiative included airborne magnetic, gravity, airborne radiometric, audio magnetotelluric and deep seismic surveys (Lucas et al., 1996; Lewry et al., 1994; Hajnal et al., 2005; White et al., 2005). Coupled geophysical modelling of Lithoprobe data for a west-east geophysical transect, located approximately 50 km south of the boundary between the Canadian Shield and the Western Canada Sedimentary Basin, estimates the Archean basement rocks of the Mudjatik domain to extend to depths from 5 to 10 km (White et al., 2005). The Archean basement rocks extend to similar depths in the Wollaston domain. Where present, the metasedimentary rocks of the Wollaston domain are expected to extend to depths ranging from approximately 5 to 8 km (White et al., 2005). Although the data were collected approximately 50 km to the south of the Pinehouse area, these estimates provide some insight with respect to the approximate thickness and continuity of major rock units proximal to the Pinehouse area.

2.1 LOCAL BEDROCK GEOLOGY

The reader is directed to Golder (2013) for a detailed description and discussion of the bedrock and structural geology of the Pinehouse area. The main lithological units in the Pinehouse area include felsic gneiss in the Wollaston and Mudjatik domains, supracrustal rocks in the Wollaston domain, and megacrystic granitoid rocks of the Wathaman batholith in the Reindeer zone (Figure 2). Golder (2011) identifies the felsic gneiss in the Wollaston and Mudjatik domains, as well as the Wathaman batholith as being potentially suitable for hosting a deep geological repository in the Pinehouse area.

2.1.1 FELSIC GNEISS

Felsic gneiss covers a substantial portion of the Wollaston domain and is the predominant rock type found in the Mudjatik domain. The term felsic gneiss was first used by Sibbald (1973) to describe a complex group of rocks of broadly granitic composition (noting that it was before the appearance of terminology by Streckeisen (1976), in which the minerals quartz, plagioclase and K-feldspar range between 10% to 40% with minor components of biotite, hornblende, hypersthene, garnet, cordierite and magnetite, and which fabric covers a broad range between well-developed layering, including lit-par-lit, to massive unfoliated domains. Harper (1988a, b) later on refined this term by classifying the felsic granitoid gneisses in central and northwestern Mudjatik domain in three different units: tonalitic orthogneiss, generally-layered felsic gneiss of probable supracrustal origin, and granite and granite pegmatite, whereas Card et al. (2008) considered them all to be orthogneisses. While the first two lithologies are thought to underlie the supracrustal rocks, mainly metasedimentary gneissic rocks, the latter intrude them all. In the Wollaston domain, metasedimentary rocks of the Wollaston Supergroup either overlay or occur infolded within the felsic gneiss. The exact thickness of the felsic gneiss in the Pinehouse area is unknown, but regional geophysical studies (White et al., 2005; Hajnal et al., 2005) have interpreted its thickness to be in the range of 5 to 10 km in the Mudjatik domain and 5 to 8 km in the Wollaston Domain. The Archean felsic gneiss has an approximate crystallization age of 2.7 billion years (Orrell et al., 1999).

Despite the overall presence of tonalitic gneiss mentioned above, Tran (2001) reported the predominance of variably-migmatized quartz monzonite to granodiorite and lesser syenogranite, in several areas of the Wollaston domain. This lithology is homogenous, weakly to unfoliated, with mineral composition comprising 5-30% quartz, 30-60% K-feldspar, 5-40% plagioclase, 5-10% biotite, and traces of hornblende and magnetite. Near Keller Lake some 10 km northwestward of the Pinehouse area, Tran (2001) reported the existence of smaller, usually unmappable bodies such as discrete units of magnetite-rich or pyroxene-bearing granite to granodiorite; charnockite to quartz monzocharnockite; granodiorite to tonalite sheets, and orthogneisses sheets, intruding the predominant quartz monzonite to granodiorite unit.

2.1.2 METASEDIMENTARY AND METAVOLCANIC ROCKS

Metasedimentary and metavolcanic rocks unconformably overlie the felsic gneiss in both the Wollaston and Mudjatik domains (Card and Bosman, 2007). The transition from the Mudjatik domain to the Wollaston domain is defined by the decrease in predominance of north-northeast-trending linear grain of metasedimentary and minor metavolcanic rocks in the northwest corner of the Pinehouse area. The boundary between the Mudjatik and Wollaston domains is a complexly deformed and highly metamorphosed area (Munday, 1978a). Near the mapped boundary, the metasedimentary and minor metavolcanic rocks are interspersed with migmatites and felsic gneiss of similar description as mentioned above. The metasedimentary rocks consist primarily of psammitic and pelitic metasedimentary rocks with minor marble and calc-silicate rocks. The minor metavolcanic rocks consist primarily of thin slivers of amphibolite gneiss.

The psammitic and pelitic gneisses are fine- to coarse-grained, generally well foliated, and commonly porphyroblastic and biotite rich. These gneisses can include cordierite, garnet, sillimanite, graphite and magnetite (Thomas and Slimmon, 1985). Metasedimentary psammitic to meta-arkosic gneiss consist of fine to medium grained, massive to foliated rocks, which can be locally colour banded. These rocks can include the following minerals in any outcrop-scale assemblage: quartz, feldspar, biotite, muscovite, sillimanite, cordierite, garnet, diopside, epidote and andalusite (Thomas and Slimmon, 1985).

The metasedimentary and metavolcanic rocks also occur in relatively thin linear bands with a north-northeast strike through the center and towards the southeast corner of the Pinehouse area. These bands of rock are generally parallel to the Needle Falls shear zone and range in width from less than 1 km to over 5 km (Figure 2).

2.1.3 WATHAMAN BATHOLITH

A small portion of the Pinehouse area extends onto the Wathaman batholith to the east of the Needle Falls shear zone (Figure 2). The geological characteristics of the Wathaman batholith are potentially favourable as a repository host rock type. However, the limited volume of this rock in the Pinehouse area and the proximity of the Needle Falls shear zone preclude any further consideration. The Wathaman batholith underlies a triangular shaped parcel of land at the southeast corner of the Pinehouse area measuring some 7 km along its base by 20 km toward the north. The Needle Falls shear zone forms the northwest side of this triangle of land.

The Wathaman batholith is homogeneous, with no evidence of multiple intrusions, although it retains a penetrative internal foliation that can reach augen gneissosity and mylonitic banding in areas of intense deformation (Fumerton et al., 1984). This batholith is variable compositionally. Most of the batholith is composed of a relatively uniform core of megacrystic monzogranite-granodiorite, which is surrounded by marginal zones of non-megacrystic granite, pegmatite, and alaskite (Fumerton et al., 1984; Money, 1965). Although the exact thickness of these rocks in the Pinehouse area is unknown, the Wathaman batholith is expected to be less than 10 km thick, as interpreted from regional geophysical studies (White et al., 2005).

2.1.4 FAULTS AND SHEAR ZONES

Structural features mapped in the Pinehouse area include major northeast- to north-northeast-trending ductile shear zones, and a predominant set of north- to north-northwest-trending brittle faults (Figure 2).

The Hearne craton is bounded to the west by the Rae craton along the Snowbird tectonic zone and is bounded to the east by the Reindeer zone along the Needle Falls and Parker Lake shear zones. These shear zones are oriented in a northeast to north-northeast direction, which is the predominant alignment of major structural features and lithologies within the Precambrian basement in northern Saskatchewan.

The Cable Bay shear zone is a sub-vertical to steeply northwest-dipping crustal scale feature that defines the boundary of the Mudjatik domain with the Virgin River domain to the west (pers. comm. Card, 2012). It has a width of 200 to 300 m (Gilboy, 1985), and a length of more than 200 km, extending from just north of the Western Canada Sedimentary Basin to the middle of the eastern portion of the Athabasca Basin (Card and Bosman, 2007), and exhibits a significant aeromagnetic anomaly. The Cable Bay shear zone does not occur within the Pinehouse area, but it is interpreted to continue under the Athabasca Basin in the Cree Lake area. The Cable Bay shear zone does not appear to be a major lithologic boundary (Card and Bosman, 2007). Based on geophysical evidence, it is sub-vertical with a steep dip to the northwest (pers. comm. Card, 2012).

The Needle Falls shear zone is a crustal scale feature that extends for over 400 km separating the Hearne craton to the west and the Wathaman batholith to the east (Figure 2) (Stauffer and Lewry, 1993). The mylonites associated with this zone were derived from the adjacent Wathaman batholith (Stauffer and Lewry, 1993). Seismic imaging and mapping by Coombe (1994) suggests this feature dips steeply to the west (Lewry et al., 1994). Field evidence suggests that the shear zone developed late during the Trans-Hudson Orogeny between approximately 1.83 and 1.80 billion years with a (most recent) dextral movement of 40 to 60 km (Stauffer and Lewry, 1993; Orrell et al., 1999; Hajnal et al., 2005). This is bracketed by the emplacement of the Wathaman batholith at approximately 1.865 billion years and post orogenic uplift and cooling which was likely complete by 1.79 billion years ago (Stauffer and Lewry, 1993).

The results of geophysical surveys conducted as part of the Lithoprobe Trans-Hudson Orogen transect (White et al., 2005) suggest the presence of two low dipping faults that are sub-horizontal to low-dipping to the east at depths of about 5 km and 13 km beneath the Mudjatik domain. The mapped contact between the Archean basement rocks and the supracrustal rocks of the Wollaston domain may also be associated with some faulting. It should be noted that the above faults were identified along a transect located 50 to 100 km south of the Pinehouse area and should therefore be only considered an indicator of possible conditions within the Pinehouse area.

A series of steeply dipping north-northwest-trending brittle faults are noted at the east end of the Wollaston domain, close to the Needle Falls shear zone (Figure 2; White et al., 2005). The longest of these brittle structures is over 120 km in length and appears as prominent topographical lineament. These faults have been associated with brecciation, shearing, mylonitization and hydrothermal alteration (Byers, 1962). Sinistral horizontal displacement of up to 800 m is documented along the faults, and geophysical interpretations suggest near vertical dips for the fault planes. Some evidence suggests that reactivation and displacement has occurred along these faults as recent as the Cretaceous period (Byers, 1962). Hajnal et al. (2005) interpreted these steep faults to be part of the Tabbernor fault system (discussed below). Hajnal et al. (2005) further noted numerous east-dipping fracture zones within the upper portions of the Wollaston domain. These features were also noted along the east side of the Mudjatik domain, but are much less abundant to absent in the central to western portions of the Mudjatik domain.

The Tabbernor fault is a north-south trending topographical, geophysical and geological lineament that extends a lateral distance greater than 1,500 km from the Northwest Territories to the states of North and South Dakota (Giroux, 1995). Based on geophysical evidence, the fault system extends to a depth of approximately 30 km (White et al., 2005). In Saskatchewan, the fault has a north-south strike and displays sinistral movement. Several researchers have discussed evidence that the Tabbernor fault system was active as recently as the Phanerozoic (Elliot, 1996; Davies, 1998; Kreis et al., 2004). This is suggested by an outlier of Ordovician dolomite positioned 150 m below the projected base of the unconformity. Parallel glacial striae indicate that the more recent deformation occurred before the last glaciation (Elliot, 1996). The Tabbernor fault is indicated, on the regional bedrock compilation map of Saskatchewan, to have overprinted the Paleozoic sedimentary rocks located along its southern extension. In addition, features in overlying sedimentary rocks and apatite fission track analyses indicate reactivation of the fault in the late Devonian and early Cretaceous (e.g., Byers, 1962).

2.1.5 METAMORPHISM

The Mudjatik and Wollaston domains belong to the Western Churchill Province (Corrigan et al., 2009). As such, all Archean and Paleoproterozoic rocks of the Mudjatik and Wollaston domains record a part of the regional metamorphism characteristic of which the Churchill structural province was subjected to. The metamorphic overprint of the Trans-Hudson Orogeny on the Superior Province was primarily focused within a restricted zone along the western border of this craton. Conversely, the metamorphic effects of the Trans-Hudson Orogeny on the western Churchill Structural Province were substantially more profound (Corrigan et al., 2009) and involved substantial reworking of the internal portions of the orogen (e.g., Reindeer zone) and the hinterland (Hearne craton). For example, in the exposed area of the Reindeer zone near the Saskatchewan-Manitoba border, high-temperature metamorphism, widespread anatexis and migmatization (e.g., Ansdell et al., 1995; Lucas et al., 1996; Gale et al., 1999; Machado et al., 1999) attest to the occurrence of a pervasive regional-scale metamorphic overprint.

Rocks of the Hearne craton (Mudjatik and Wollaston domains) were exposed to high grade metamorphism, reaching upper amphibolite to granulite facies (e.g., Pearson, 1977a, b; Tran, 2001). Orrell et al. (1999) posed that all metamorphic fabrics observed in the Hearne craton were the result of a single thermotectonic cycle caused by the Trans-Hudson Orogeny. This view has been disputed by other authors (e.g., Bickford et al., 1994; Tran, 2001; Card et al., 2008) who have interpreted the high-grade metamorphism undergone by rocks of the Hearne craton as having occurred during two distinct periods of high temperature, low pressure metamorphism. It is quite possible though that M2 may have occurred as a continuum of substages rather than occurring as a single event. For example, Annesley et al. (2005) reported three metamorphic events associated to the peak of the Trans-Hudson Orogeny.

The timing of the first metamorphic event has remained poorly constrained, mostly due to lack of evidence by almost complete overprinting of M1 by M2. For example, Tran (2001) proposed underplating of the Hearne craton associated to the beginning of rifting in its eastern margin as a source for M1, which would place a minimum age of approximately 2.075 billion years for M1 (Ansdell et al., 2000). Bickford et al. (1994) in turn suggested that thermotectonic reworking could have occurred as early as approximately 2.3 billion years, possibly associated with the Thelon Orogeny, whereas Annesley et al. (2005) suggested two granulite-facies metamorphic events around 2.689 and 2.566 billion years, respectively. Although the timing may remain elusive, M1 seems to have begun before peak D1 conditions and to have outlasted them (e.g. Tran, 2001; Card et al., 2006; Card and Bosman, 2007).

The second metamorphic period occurred concomitantly with the peak of the Trans-Hudson Orogeny, during the approximate period 1.84 to 1.80 billion years, and later outlasted it (Tran, 2001). Orrell et al. (1999) calculated peak metamorphic conditions at 750±50°C and about 5.5 kbar. These values agree with those estimated by Tran (2001), 725°C and a maximum pressure of 5 kbar followed by decompression to >600°C and >3.4 kbar, and those estimates of Annesley et al. (2005) for three stages comprising initial pressure conditions of >4-5 kbar, increased to 6-9 kbar at >775°C and later followed by decompression at 3 kbar and increased temperatures of 750-825°C.

2.2 Geological history

Direct information on the geological and structural history of the Pinehouse area is limited. The geological and structural history summarized below integrates the results from studies undertaken elsewhere throughout and proximal to the area shown on Figure 2, drawing particularly on information from the Creighton, Saskatchewan area. It is understood that there are potential problems in applying a regional D_x numbering system into a local geological history. Nonetheless, the summary below represents an initial preliminary interpretation for the Pinehouse area, which may be modified after site-specific information has been collected, if the community is selected by the NWMO and remains interested in continuing with the site selection process.

The tectonic events that occurred ca. 2.1 to 1.9 billion years ago during the Trans-Hudson Orogeny imparted the predominant bedrock structure in the Pinehouse area. Based on studies undertaken throughout Northern Saskatchewan, five discernible stages of deformation (D1 to D5) have been distinguished which can provide a framework for understanding the structural history of the Pinehouse area. These important phases of the Trans-Hudson Orogeny, as well as events that both pre- and post-date the main orogenic event, are summarized in Table 3 (Cumming and Scott, 1976; Stauffer and Lewry, 1993; Andsell, 2005; Corrigan et al., 2005; Hajnal et al., 2005; Corrigan et al., 2007; Whitmeyer and Karlstrom, 2007; Corrigan et al., 2009).

The development of the Wollaston domain is intimately related to the Wilson cycle recorded by the Hearne craton and by the Trans-Hudson Orogeny that together took place approximately during the period of 1.90 to 1.5 Ga. Deposition of thick sequences of sediments on the eastern margin of the Hearne craton took place initially under rifting conditions and later under passive margin conditions, forming the Wollaston Supergroup (Yeo and Delaney, 2007). As a continental arc (Rottestone arc) formed due to reversal of tectonic plate and initiation of subduction under the Hearne craton, change in both environment of deposition and type of lithology followed in rocks of the Wollaston Supergroup (Ansdell, 2005). With time, the Wollaston domain became an extensive back-arc basin and a first episode of metamorphism was imprinted to both rocks of the Wollaston Supergroup and the Archean basement (Tran, 2001). Around 1.88 Ga, collision of the eastern La Ronge island arc with the Hearne craton, initiated build-up of an orogen, deposition of very thick sequences of molasse rocks, and thrusting. Westward shift of forebulge was accompanied by uplift and erosion, and the Wollaston domain became a foreland basin (Tran, 2001; Ansdell, 2005). Progressive infilling of the Wollaston Basin closed it around 1.86 billion years (Yeo and Delaney, 2007). Emplacement of the massive Wathaman batholith and concurrent final accretion of the La Ronge Arc to the craton developed large overthrust structures and imbrication of strata. At the same time, the basement and supracrustal rocks of the Wollaston domain underwent regional amphibolite to granulite facies metamorphism associated with development of tight to isoclinal folds and extensive gneissosity and migmatization (Lewry and Sibbald, 1980; Tran 2001). The subsequent arrival of the Superior Province (ca. 1.83 Ga) developed the Needle Falls shear zone in the eastern margin of the Wollaston domain, either by response to the oblique collision with the Hearne craton or by counter-clockwise oroclinal rotation (Stauffer and Lewry, 1993).

Phanerozoic rocks of the Western Canada Sedimentary Basin nonconformably overlie Precambrian basement rocks over the entire southern half of Saskatchewan. The present day zero thickness erosional edge of the basin trends northwesterly across the province to the southwest corner of the Pinehouse area. Regional Phanerozoic depocentres of the Hudson Bay and the Western Canada Sedimentary basins, preserved to the northeast and south of the exposed Precambrian basement rocks in northern Saskatchewan, respectively, suggest that the sedimentary cover was formerly much more extensive. Much of the present surface of the Canadian Shield lies close to an exhumed paleoplain interpreted to be of Ordovician age (Brown et al., 1995).

Paleozoic sedimentary rocks nonconformably overlie the Precambrian basement approximately 180 km south of the Pinehouse area. This began with the deposition of the Deadwood formation (upper Cambrian to lower Ordovician at approximately 0.5 Ga) which also outcrops in the west central portion of the Pinehouse area. This Paleozoic outlier represents a remnant of the Cambrian to Devonian sedimentary succession that was deposited while much of the Churchill Province was inundated by shallow seas during the Paleozoic Era. Given the proximity of the Western Canada Sedimentary Basin to the south and the apparent continuation of the sequence in the Hudson Bay area of Manitoba to the northeast suggests that the Pinehouse area was also previously covered by an undetermined amount of Paleozoic strata.

A long period of uplift, exposure and erosion separated the Paleozoic strata from the overlying Mesozoic strata. The erosional edge of the Mesozoic succession, located in the southwest corner of the Pinehouse area, is characterized by sedimentary rocks of Cretaceous age. The Cretaceous strata were deposited during a series of regressions and transgressions of the Cretaceous sea over the western interior of North America (Mossop and Shetsen, 1994). The prior extent of Cretaceous cover in the Pinehouse area is uncertain. However, given the proximity of the erosional edge of these rocks, it is likely that coverage was extensive in the Pinehouse area.

Table 3 Simplified geological and structural history of the Pinehouse area.

Time period (Ga)	Geological event
2.7	Approximate crystallization age of the felsic gneiss in the region that comprises the Hearne craton.
2.1 to 1.92	Initiation of rifting on the eastern margin of the Hearne craton and opening of the Manikewan ocean. Passive margin in the eastern margin of Hearne craton during rifting, with sedimentation of the Wollaston Supergroup.
1.92 to 1.88	Initiation of subduction underneath the eastern margin of Hearne craton leading to the beginning of both closure of the Manikewan Ocean and creation of the Rottenstone magmatic arc. Continued deposition of Wollaston Supergroup in a back-arc basin. This was followed by collisional compression of the rocks of the Wollaston Supergroup, Rottenstone and La Ronge domains. Collision resulted in D_1 ductile deformation that produced isoclinal folds and imparted the S1 foliation to felsic gneiss.
1.88 to 1.865	Ongoing subduction resulted in the accretion of juvenile island arc terranes (La Ronge-Lynn Lake) to the southeastern margin of the expanded Rae-Hearne craton resulting in theformation of Rottenstone accretionary complex, while Wollaston back-arc basin shifted to foreland basin.
1.865 to 1.83	Closure of Wollaston basin at ca. 1.86 billion yearswith concomitant emplacement of Wathaman batholith between ca. 1.865-1.855 billion yearsalong eastern margin of Rae-Hearne craton. Regional D_2 ductile deformation produced upright folds that overprinted the S1 foliation. Ongoing subduction resulted in the accretion of the Glennie-Flin Flon complex to the Rae-Hearne craton. Collision of the Sask craton with the Rae-Hearne craton, which thrusted the accreted juvenile terranes over the Sask craton.
1.83 to 1.80	Terminal collision of Superior craton with the Rae-Hearne craton leading to final closure of the Manikewan ocean. Crustal shortening that occurred during this period resulted in movement along the Needle Falls shear zone. D_3 ductile deformation creates NE-striking upright folds dominant in the Wollaston domain. Activation (re-activation?) of the Needle Falls and Virgin River shear zones at ca. 1.83 Ga. Development of thick-skin imbrication in Mudjatik domain and thin-skin imbrication in Wollaston domain. D_4 ductile deformation creates NW-striking upright folds orthogonal to F_3 after movement on the Virgin River and Cable Bay shear zones.
1.80 to 1.72	Activation of the Tabbernor fault zone (ca. 1.8 Ga) and the D_5 steep-brittle faults observed within the Wollaston domain, extending into the Mudjatik domain.
1.72 - 1.5	Development of successor basins across parts of the Hearne craton, including formation of Athabasca basin.
< ca. 0.5	Deposition of Deadwood Formation in Phanerozoic Williston basin. Progressive infilling of Phanerozoic Western Canadian Sedimentary Basin in southern Saskatchewan and other regional areas.

2.3 REGIONAL STRUCTURAL HISTORY

Five main stages of deformation (D_1 to D_5) associated with the Trans-Hudson Orogeny can be distinguished for the Pinehouse area, based on regional studies (e.g., Byers, 1962; Munday, 1978a; Tran and Smith, 1999; Annesley et al., 2005; Hajnal et al., 2005; White et al., 2005; Card and Bosman, 2007; Yeo and Delaney, 2007; Card et al., 2008). The following description is a summary of this previous work, primarily following the numbering system established by Card et al. (2008).

The earliest recognizable deformation event (D_1) resulted in supracrustal and felsic rocks being isoclinally folded (F_1). A prominent mineral foliation imparted by this phase, S_1, is a composite fabric defined by the compositional layering and alignment of metamorphic minerals. It also included rootless isoclinal hinges and rare boudins and intrafolial folds.

A second deformation (D_2) identified by Card et al. (2008) is marked by rare intrafolial folds with hinges defined by the S_1 foliation. Card and Bosman (2007) indicate D_2 involved the development of upright, northwest-trending F_2 folds that re-oriented the S_1 fabric in an area to the north of the Pinehouse area. Little information is available regarding this event, and it was not reported in earlier studies (e.g., Munday, 1978a).

The third deformation event, D_3, was characterized by the development of upright, north-northeast-trending folds that also reoriented the S_1 foliation. The north-northeast-trending F_3 fold limbs generally tighten towards the Virgin River and Cable Bay shear zones to the northwest of the Pinehouse area and towards the Needle Falls shear zone in the southeast corner of the Pinehouse area. The folds are more open within most of the Mudjatik domain away from the zones of higher strain.

The Virgin River, Cable Bay and Needle Falls shear zones developed during the latter stages of the D_3 event or later as evidenced by the shear displacement along F_3 fold limbs, but prior to the development of a second (weak) phase of northwest-trending folds (F_4), during a localized D_4 event in the westernmost part of the Mudjatik-Virgin River domains. The shear zone deformation is therefore ascribed to a D_3 event. Card et al. (2008) noted that the F_4 folds are generally orthogonal to the north-northeast-trending F_3 fold axial planes. The result of these two orthogonal-folding events was the development of a local dome and basin pattern outlined by the re-oriented S_1 fabric in the westernmost part of the Mudjatik domain. Card and Bosman (2007) and Card et al. (2008) suggested that these F_4 folds postdate the Virgin River and Cable Bay shear zones and are likely of Trans-Hudson age.

Brittle, D_5, deformation resulted in a late series of dominantly north- to north-northwest-trending faults that bisect the Pinehouse area, and cross-cut the structures associated with the D_1 to D_4 events. These features have likely had a long history of re-activation consistent with the interpretation that they are related to the Tabbernor fault located about 200 km to the east of the Northern Village of Pinehouse. The Tabbernor fault initially formed during the Trans-Hudson Orogeny approximately 1.83 Ga, likely with more recent periods of reactivation. Features in overlying sedimentary rocks and apatite fission track analyses indicate reactivation of the fault in the late Devonian and early Cretaceous periods (Elliot, 1996; Davies, 1998; Hajnal et al., 2005).

2.4 QUATERNARY GEOLOGY

The advance and retreat of continental glaciers has occurred several times across the Precambrian Shield in northern Saskatchewan during the Quaternary Period (Schreiner, 1984b). Although older till units have been identified in northern Saskatchewan in boreholes and deeper sediment exposures, most of the surficial materials and landforms in the Pinehouse area are expected to be the product of the last major ice advance, referred to as the Late Wisconsinan glaciation, during which time the Laurentide ice sheet covered the area.

This section provides an overview of the Quaternary geology and history of the Pinehouse area. Section 5 provides a description of the nature, distribution and thickness of surficial deposits in the Pinehouse area based on an integration of the surficial geology data (Figure 3) with other data, such as SPOT, CDED and FRI.

Radiocarbon dates collected throughout northern Saskatchewan and summarized by Schreiner (1984b: 45-47) suggest that the Pinehouse area was beneath the Laurentide ice sheet at about 11,000 to 10,000 years B.P. The ice had retreated north of the Pinehouse area to the Cree Lake moraine by about 10,000 to 9,500 years B.P. At this time, the Haultain and Bélanger rivers served as the main meltwater channels north of the Pinehouse area. The formation of deltas at the mouths of these channels suggests that the Churchill River in this area was flooded by glacial Lake Agassiz at that time. Although Schreiner (1984b) suggested a maximum lake level of about 425 m, Smith and Fisher (1993) found strandlines near Wasekamio Lake (Figure 1 inset) suggesting a stable Lake Agassiz shoreline at 438 m and a possible maximum elevation of 484 m.

Schreiner et al. (1976) and Schreiner (1977) provided the best known descriptions of the Quaternary deposits found within the portion of the Pinehouse area underlain by the Precambrian Shield (Section 1.3.1). Till is the main drift cover within the area, ranging from sandy till in the northwest to a more silty till in the southeast. A belt of sand and gravel extends along the Haultain River (north of the Pinehouse area) to Dreger Lake, where a large delta was formed as sediment carried within a meltwater channel on the Haultain River was delivered into the Churchill River. Other sand deposits, and a few silt and clay occurrences, can be found along the margins of the larger lakes, but no extensive glaciolacustrine sediments have been observed. The scarcity of glaciolacustrine sediments suggested to Schreiner et al. (1976) that Lake Agassiz did not extend into this area. North of Besnard Lake, a site was investigated in order to check for raised beaches associated with Lake Agassiz (Schreiner, 1977). All that was found was a large boulder field (felsenmeer) and several short, low-relief eskers.

Ice flow directions in the Pinehouse area are indicated by a few small eskers, mainly located in the southeast part of the area, and by several roches moutonées, particularly around Santo Bay, which indicate a northeast to southwest glacial flow (Figure 3). Striae recorded during bedrock mapping programs around Duddridge Lake and Knee Lake (north of the Pinehouse area) indicate similar ice flow directions. In many areas of northern Saskatchewan, the ice flow direction was nearly parallel with the structural grain of the Precambrian rocks, with the result that erosion has accentuated the structural grain (Schreiner, 1984b). The narrow ridges, peninsulas and islands displayed in the Pinehouse area east of Highway 914 and north of Cotter Lake represent good examples of areas where glacial erosion has accentuated the northeast trending structural grain.

3 TOPOGRAPHY

The Pinehouse area is located in the Kazan Upland Physiographic Region of the western Precambrian Shield (Bostock, 1970). Kazan Upland topography is typical of the Canadian Shield, with large areas of bedrock that form broad, smooth uplands and lowlands. First-order relief is smooth and gently rolling, whereas second-order relief is more complex, consisting of bedrock-controlled ridges and valleys. Much of this relief was produced during glaciation due to preferential erosion of structural and lithological weaknesses. Ice movement and meltwater erosion smoothed and polished resistant bedrock hills and scoured out weakness zones in the bedrock. Valleys and depressions between rock ridges and knolls typically contain lakes, bogs and relatively thick overburden deposits.

Topography is an important aspect of the terrain, as it plays a role in controlling surface and groundwater flow directions and can reveal much about the bedrock structure and overburden deposits. The following descriptions of the topography in the Pinehouse area rely heavily on the representation of the landscape by the CDED digital elevation model.

3.1 Elevation

The landscape within the Pinehouse area ranges in elevation from 385 to 521 m, representing 136 m of relief across the area (Figure 4). The lowest elevations in the Pinehouse area are associated with the Churchill River downstream of Snake Rapids and with Pinehouse Lake. The elevation of this lake-complex is approximately 385 m, although the minimum elevation would occur at the downstream limit of the system, on Sandfly Lake, where the Churchill River crosses the eastern boundary of the Pinehouse area. The maximum elevation of 521 m occurs on a hill southwest of Snake Rapids. This hill is the only location in the Pinehouse area where elevations exceed 500 m. The map of elevation allows for the delineation of the major topographic features in the Pinehouse area. Section 4.3 describes drainage patterns associated with the topographic highs and lows.

The Pinehouse area is bounded by two major topographic highs informally referred to here as the Norbert and Belton highs as shown in the inset map of Figure 4. The Norbert high is the rugged zone along the northeast margin of the Pinehouse area and further north that extends north of the Churchill River. The Belton high is a low-relief highland located west of the Pinehouse area. The vast majority of the Pinehouse area can be thought of as a lowland associated with the Churchill River and Pinehouse Lake, as shown in the inset map of Figure 4.

Estimates of the maximum elevation of glacial Lake Agassiz in northern Saskatchewan range from about 425 m (Schreiner, 1984b) to as much as 484 m (Smith and Fisher, 1993). Regardless of the exact maximum level obtained, large parts of the Pinehouse area would have been flooded by Lake Agassiz during deglaciation, as can be deduced from the map of elevation shown in Figure 4.

3.2 RELIEF

Areas of positive relief within the Precambrian Shield are sometimes indicative of areas of thin drift and abundant bedrock exposure. The amplitude of irregularities associated with bedrock topography in Precambrian Shield terrain is often larger than the amplitude associated with surficial deposits. As a result, relief can often be used to suggest areas of thin drift and abundant bedrock exposure.

Relief is a metric that can be defined in different ways, and the calculated value of relief depends on the horizontal dimension considered in the calculation. Relief was calculated in two ways. The first was by subtracting the average elevation within a 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 within an area. The second was defined as the range in elevation within a circular window, providing an indication of the maximum relief within the window.

A map of departures from the average elevation within a 20 km radius (Figure 5) can be used to delineate broad areas of relatively high ground within the Pinehouse area where drift deposits could be relatively thin. The inset map provided on Figure 5 shows the areas that are at least 15 m higher than average at this scale of calculation. The line depicting the south limit of exposed bedrock in Figure 5 is important because the topographically prominent areas south of this line are generally not associated with thin drift. Many of the elongate, northeast trending ridges, peninsulas and islands around Santo Bay display abundant bedrock exposure in the SPOT imagery. A map of departures from the average elevation within a 2 km radius (Figure 6) can be used to provide tighter definition on the parts of ridges where thin drift and abundant bedrock exposure are likely. Ridges are shown in shades of red in Figure 6 whereas depressions are shown in shades of blue. Most of the positive relief features shown in Figure 6 are located north of the south limit of exposed bedrock, where the ridges generally are associated with thin drift and exposed bedrock, as confirmed by Figure 12. South of this line, the areas of positive relief are aligned generally to the northwest in association with a morainal fabric, where the ridges actually represent areas of thicker drift at the tops of morainal ridges. The northeast alignment of the ridges, peninsulas and islands north of Cotter Lake and east of Highway 914 is a reflection of the structural fabric of the Wollaston domain.

A map showing the range in elevation within a 250 m radius (Figure 7) provides an indication of the distribution and extent of localized high and low relief areas within the Pinehouse area. The upper limit of relief within the area shown in Figure 7 calculated at this scale is about 100 m. Many of the ridges where bedrock outcrops are located are associated with 25 to 100 m of relief.

3.3 Slope

The map of slopes 6° or steeper shown in Figure 8 illustrates that gentle slopes are far more common in the Pinehouse area than are steep slopes. For example, only 4% of the Pinehouse area displays a slope value of 6° or more, and only 1% displays a slope value of 10° or more. Most of the steep slopes are located north of the line depicting the south limit of exposed bedrock, where steep slopes are generally associated with bedrock topography. The steep slopes occur along the flanks of the rock ridges, and the tops of many of the ridges are relatively flat.

As steep slopes in the Pinehouse area are generally associated with irregularities in the bedrock topography, with some exceptions (e.g., fluvial incisions into thick overburden), the presence of steep slopes in the Pinehouse area can be an approximate indicator of minimal overburden cover. Many of the extensive areas lacking steep slopes are relatively flat due to the presence of drift filling lows in the bedrock topography.

A map showing the density of steep (≥ 6°) slopes within a 2 km radius was prepared to provide a general indication of the areas where the thickness of overburden might be relatively low and conversely where the surficial deposits could be thicker (Figure 9). As described further in Section 5.2, there is a general correspondence between the areas of high slope density shown in the Figure 9 inset and the areas of thin drift delineated in the classified surficial geology map shown in the Figure 3 inset.

Note that the relief maps presented in Figure 5 and Figure 6 resolve the areas of thin drift in much more detail than does the map of slope density. The closest match between the areas of exposed bedrock mapped in the FRI data shown in Figure 12 and any of the topographic parameters mapped in this study is provided by the areas with at least 10 m of topographic prominence as shown in Figure 12. The slope density map provides only a generalized image of thin drift much like that depicted in the surficial geology map (Figure 3).

The presence of lower densities of steep slopes in an area suggests a higher likelihood of thick drift, which would obstruct the identification of bedrock structures. Consequently, areas of low slope density can be expected to be areas of low surface lineament density due to masking of the surface expression of lineaments by drift. In addition, thick drift can hinder bedrock-mapping activities, which can result in less confidence in the geologic model developed for an area. The use of low slope density as an indicator of low confidence in identifying the surface expression of a lineament also accounts for the areas covered by lakes.

4 DRAINAGE

The distribution of surface water and surface water drainage are important factors to consider in the preliminary assessment. The larger lakes in the area represent areas where less information can be obtained on rock types and geological structures. Surface water flow is a useful indicator of groundwater flow at shallow depth. Section 4.1 provides information on the size, distribution and depth of lakes in the Pinehouse area. Section 4.2 describes the existing watershed map file and the drainage analysis conducted by JDMA, and Section 4.3 describes runoff patterns within the Pinehouse area.

4.1 WATERBODIES AND WETLANDS

As stated in Section 3.1, a major portion of the Pinehouse area is represented by a topographic low associated with the Churchill River and Pinehouse Lake. The largest lake in the area is Pinehouse Lake, which is about 240 km^2 in extent. Other large lakes within or near the Pinehouse area include Knee Lake, Sandfly Lake, Sandy Lake, Besnard Lake and Gordon Lake. Waterbodies cover 24% (707 km^2) of the Pinehouse area (Figure 10). Even though some of the lake shorelines display bedrock outcrops, the lakes themselves conceal the bedrock surface, adding lithological and structural uncertainty to the parts of the Pinehouse area covered by large lakes.

Wetlands are areas where the water table is at or close to the surface for a large part of the year, and many of the larger wetland complexes in the Pinehouse area are indicative of extensive overburden deposits. Comparison of the 1:50,000 scale CanVec wetlands against wetlands shown in the SPOT imagery indicated that the mapping was far from complete, with CanVec suggesting that only 10% of the area is covered by wetlands. The muskeg delineated in the Forest Resource Inventory (FRI) included many features not included in the CanVec data. As a result, the wetlands shown in Figure 10 are from both CanVec and FRI.

Wetlands shown in Figure 10 contain the organic deposits described in Section 5.2.5. The thick, poorly drained and low relief overburden deposits in the southwest half of the Pinehouse area support a relatively large concentration of extensive wetlands. The largest wetland complexes in the northeast half of the Pinehouse area, though all smaller than those in the southwest, are indicative of thicker, more extensive overburden deposits. The delta at the mouth of the Haultain River that extends to Dreger Lake supports a large wetland. A smaller wetland complex is associated with the delta at the mouth of the Belanger River. The trough extending northeast from McDonald Bay contains a large wetland complex.

Bathymetric maps provide information on the vertical extent of lake basins. The Saskatchewan Ministry of Environment completed depth surveys of selected lakes in the late 1970s and early 1980s. The resulting depth maps consist of contour plots based on soundings. Figure 10 identifies the few lakes within the Pinehouse area for which bathymetric data exist. Except for Besnard Lake, which shows a maximum depth of about 26 m, surveys exists only for a few small, shallow lakes in the south half of the Pinehouse area (Table 4). Depth information is available for several large lakes outside of the Pinehouse area (Table 5), which indicate maximum depths ranging from about 15 to 60 m.

Table 4 Maximum and mean depths of lakes within the Pinehouse area.

Lake	Area (km^2)	Volume (km^3)	Max depth (m)	Mean depth (m)
Besnard	159	1.75	25.6	10.9
Musqua	3.4	0.01	5.0	3.0
Domino	0.23	0.001	6.0	4.1
Unnamed	0.16	0.001	4.0	2.4

Data from Saskatchewan Bathymetric maps

Table 5 Depth data on large lakes outside the Pinehouse area.

Lake[1]	Maximum depth (m)	Area (km^2)
Churchill Lake	24	559
Cree Lake	60	1434
Frobisher Lake	19	516
Lac La Loche	16	206
Lac La Ronge	41	1413
Peter Pond Lake	24	552

[1]Metrics obtained from ILEC (2013)

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. JDMA conducted a drainage basin analysis in order to confirm and, where possible, partition the most detailed available mapping of watersheds by the Prairie Farm Rehabilitation Association. The delineation of drainage divides is essential to infer surface water and shallow groundwater flow directions.

The best available watershed delineation for the Pinehouse area is the sub-basin file produced by the Prairie Farm Rehabilitation Association (PFRA), which has been renamed recently as Agriculture and Agri-Food Canada (AAFC). According to the metadata for this file, the sub-basin delineation of the PFRA Watershed Project consists of 47 sub-basins delineated at a scale of roughly 1:250,000 covering the Canadian Prairies. The spatial extent of the sub-basin file covers all of Alberta, Saskatchewan and Manitoba, and portions of adjacent jurisdictions (British Columbia, the Northwest Territories, Nunavut, Ontario, and the United States) into which Prairie watersheds extend. The sub-basin file is the authoritative source for gross and effective drainage areas in the Prairie Provinces. The PFRA sub-basins extending into the Pinehouse area generally match the Environment Canada sub-sub-division of drainage areas (a.k.a. tertiary watersheds), with the main difference being that the PFRA drainage boundaries are more detailed and accurate than the Environment Canada boundaries.

The locations of hydrometric gauging stations and boundaries of the PFRA sub-basins were delineated manually from paper topographic maps of the National Topographic Survey (NTS), usually at a scale of 1:50,000. The drainage boundaries were then digitized by personnel at the Saskatchewan Water Corporation, with digitizing information such as mapsheet number, name, edition, publication year, projection and datum, who digitized the map, date digitized, and root mean squared error were recorded in a binder and later transferred to a spreadsheet. The horizontal positional accuracy of the sub-basin boundaries is variable depending on the distinctiveness of the drainage boundary and the accuracy of the topographic data, and thus cannot be quantified without onsite investigation and verification. In addition, the hand-mapping process influences the positional accuracy, with a 1 mm thick hand-drawn boundary on the map producing a 50 m error at 1:50,000 and a 250 m error at 1:250,000. Additional errors would be introduced during digitization.

JDMA modelled the movement of water over the landscape using the watershed analysis function in the program TNTmips with the CDED elevation model as the surface model. The CDED digital elevation model used for this study was created by NRCan using the same NTS topographic data that is shown in the 1:50,000 scale NTS topographic maps. As a result, the DEM used here is comparable with the data used by the PFRA to construct the sub-basin boundaries.

The procedure that JDMA followed in the drainage analysis was to confirm the PFRA sub-basin boundaries and then to subdivide the sub-basins where possible. It is important to note that the sub-basins do not represent the smallest catchments that can be delineated in most areas, as local ridges and highland complexes are present within many of the sub-basins that serve to divide surface flow directions within the basin.

The result of the drainage analysis is a single set of lines and polygons, which represents a merged watershed file (Figure 11). It is important to note that many of the watersheds delineated in the merged file could be further subdivided, but that JDMA had to limit the minimum size of basin in order to maintain a consistent scale of delineation across the Pinehouse area. Where drainage divides created by JDMA matched reasonably with the PFRA sub-basin boundaries, the procedure was to accept the existing sub-basin boundary. Newly delineated drainage divides were then used to subdivide the sub-basins. A field entitled 'Type' was created in the merged file denoting whether each portion of the catchment boundary was delineated by both JDMA and PFRA (0) or only JDMA (1). JDMA made an effort to ensure that the newly delineated drainage divides honoured the existing watercourse map file where possible.

4.3 SURFACE FLOW

The Pinehouse area is contained entirely within the Churchill River drainage area, which drains into Hudson Bay through the Churchill River. The Churchill River generally flows from west to east across the northern part of the Pinehouse area through Dreger Lake, Sandy Lake, McDonald Bay, Pinehouse Lake and Sandfly Lake. All watercourses within the Pinehouse area drain into the lowland occupied by the chain of lakes that make up the Churchill River system.

The vast majority of the Pinehouse area is contained within the Central Churchill tertiary watershed (Figure 11 inset). Only the northwest corner of the Pinehouse area is contained within the Upper Churchill watershed.

The ridge extending through Snake Rapids (Figure 5) is one of the most prominent highlands dividing flow within the Central Churchill tertiary watershed (Figure 11). North of this feature, flow is directed towards the Churchill River through Gavel Lake, Sandy Lake and Dreger Lake. South of this feature, flow is directed into Pinehouse Lake. Other prominent drainage divides within the Central Churchill watershed include the northeast trending ridges east of Pinehouse Lake. The prominent rock ridges located southwest of Sandfly Lake direct runoff to the south towards Bar Lake, eventually flowing to Pinehouse Lake through the Smith Channel. Another set of prominent ridges to the southeast of Sandfly Lake appear to direct surface flow to the south towards Besnard Lake. The rugged topography throughout the northern margin of the Pinehouse area results in complex runoff patterns, with reversals in direction occurring across short distances.

5 TERRAIN CHARACTERISTICS

An understanding of the distribution and thickness of overburden deposits within the Pinehouse area is essential for interpreting the distribution of lineaments mapped from satellite imagery and topographic data (JDMA, 2013), particularly with respect to lineament length and density. Thick drift deposits are able to mask the surface expression of lineaments. In areas of sporadic drift deposits, the drift can conceal minor lineaments, producing low apparent lineament density, and it can censor the lengths of major structures. In areas of thick and extensive overburden, major structures could exist that would be completely undetected from SPOT and CDED, particularly if these areas also contain large lakes. In addition, areas of exposed bedrock or thin drift are more readily amenable to site characterization, as such locations would enable further investigation of the potentially suitable bedrock formations through outcrop mapping of bedrock structures and preliminary rock mass characterization.

The purpose of this section is to characterize the terrain in the Pinehouse area in terms of the nature and extent of overburden deposits. Section 5.1 presents and interprets the available water well and drill hole data on overburden thickness. Section 5.2 provides information on the expected characteristics of the terrain units mapped in Figure 3. Due to the generalized nature of the available surficial geology mapping, the CDED and FRI data have been used in Section 5.2 to provide better detail on the distribution of drift deposits.

5.1 WATER WELL AND DRILL HOLE DATA

5.1.1 WATER WELL DATA

As stated in Section 1.3.4, there are only three water wells within the Water Well Information Database located immediately south of the Pinehouse area, with no well records stored in the database for the Northern Village of Pinehouse. Two of the well logs are from a property located on an esker on the south shore of Besnard Lake (east of the Pinehouse area). These well logs report sand and gravel to at least 10 m depth, and the esker ridge is about 10 to 15 m in height above the surrounding landscape according to the CDED elevation model. The other location where a water well record exists is near Highway 914, southwest of Pinehouse Lake (south of the Pinehouse area). This record consists of a water test hole extending 22 m depth without encountering bedrock, providing a minimum overburden thickness at that location. The well encountered till interbedded with sand and gravel.

5.1.2 DRILL HOLE DATA

As stated in Section 1.3.4, a small number of drill hole records with data on depth to bedrock exist within or near the Pinehouse area. The available records from the Regina and La Ronge databases with data on depth to bedrock have been plotted separately in Figure 3.

The drill holes located within the Phanerozoic basin (Figure 2), near the southwest part of Pinehouse Lake, and near Musqua and Degryse lakes, indicate overburden thickness from about 20 to 100 m (Figure 3). These values are expected to be representative of the great thicknesses of overburden generally covering the Phanerozoic basin in this area. The other two locations where drill hole data exist are near the south shore of Neale Lake and the west shore of Duddridge Lake. The single hole near Neale Lake indicates 8 m of overburden. The seven drill holes west of Duddridge Lake indicate drift thickness ranging from less than 2 m to about 8 m. This order of magnitude is expected to provide a reasonable indication of drift thickness within many of the areas located north of the line depicting the south limit of exposed bedrock on Figure 3.

5.2 SGS TERRAIN UNITS

This section provides details on the expected composition, distribution and thickness of surficial deposits within the Pinehouse area based on an integration of the surficial geology information with the SPOT, CDED and FRI datasets.

5.2.1 BEDROCK

As stated in Section 1.3.5, the FRI data shown in Figure 12 were generated based on 1:12,500 scale air photos and aerial reconnaissance, with limited field checking in the non-productive areas of treed and clear rock shown in Figure 12. The FRI delineation of treed or clear rock suggests that the most extensive areas of exposed bedrock are located within or near the northern margin of the lowland associated with the Churchill River. That is, the most extensive areas of exposed bedrock are located southeast of Sandy Lake and on the ridges, islands and peninsulas between Cotter Lake, Santo Bay and Sandfly Lake. Notably, the FRI data suggest less exposed bedrock on the highland north of the Churchill River. This overall pattern is generally consistent with the pattern of exposed bedrock interpreted from the SPOT imagery. As stated in Section 1.3.5, the FRI data generally underestimate the extent of exposed bedrock, particularly in areas where the exposures are small and scattered across an area. The underestimation of exposed bedrock is expected to be roughly equal across the area.

The areas displaying at least 10 m of topographic prominence delineated using 2 km and 20 km search radii are shown in Figure 12 to highlight areas expected to be characterized by thin drift. Much of the exposed bedrock shown in Figure 12 is distributed along the tops and sides of the ridges shown in shades of pink. However, on some of the ridges, extensive areas of exposed bedrock have not been mapped. In some of these cases, the true extent of exposed bedrock could be more than is suggested by the FRI data, but, in general, the ridges delineated in this figure are expected to be areas of thin drift even if the extent of exposed bedrock is minimal. The summits and ridges delineated using a 2 km search radius are expected to provide a refined delineation of the areas most likely to contain thin drift within the broader ridges delineated using a 20 km search radius. The combination of the CDED and FRI data described above and presented in Figure 12 provides the best available information on the extent of thin drift and exposed bedrock within or near the Pinehouse area. Note that the ridges south of the line depicting the south limit of exposed bedrock are not expected to be areas of thin drift. In fact, the ridges delineated using a 2 km search radius located south of that line are expected to be locations of thicker drift at the tops of morainal ridges.

It is worth pointing out some of the shortcomings in the surficial geology map (Figure 3) as they relate to the mapped extent of exposed bedrock in the Pinehouse area. Some of the most extensive areas of exposed bedrock within or near the Pinehouse area (Figure 12) were not mapped as rock or thin drift in Figure 3. For example, the ridge on the south shore of Sandy Lake was mapped as a glaciofluvial plain, yet this ridge displays a significant amount of exposed bedrock. Similarly, some of the distinct northeast trending ridges, peninsulas and islands around Santo Bay were mapped as a morainal plain in Figure 3.

Drift deposits on the ridges delineated in Figure 12 are expected to be mainly composed of sandy till, as Schreiner et al. (1976) reported that till was the main drift cover in the area. The thickness of the deposits should be generally less than 1 to 2 m on the tops of the ridges and could increase to several metres or even tens of metres between ridges and in deep troughs formed within ridge complexes. In some areas, it is possible that local deposits of rhythmically bedded silt and clay associated with local ponding of meltwater during deglaciation exist within the depressions formed between rock ridges, but in many cases, these poorly drained deposits would be expected to be overlain by organic deposits. It is possible that raised beach deposits associated with glacial Lake Agassiz exist along the flanks of some ridges. Boulder fields could exist on the tops of some ridges, as was found by Schreiner (1977) in an area north of Besnard Lake.

5.2.2 Morainal

Ground moraine represents the most common glacial landform in northern Saskatchewan, typically represented as veneers and blankets of sandy ablation till distributed amongst lakes, muskegs, and bedrock outcrops (Schreiner, 1984b). Sandy to silty till is the main drift cover in the northeast part of the Pinehouse area (Schreiner et al., 1976).

Within the Precambrian Shield of Saskatchewan, areas of thicker more continuous ground moraine are generally represented as moraine plains and drumlinoid moraine (Schreiner, 1984b). Preferrential deposition of till in low areas between bedrock ridges and hills in these areas can mask the relief of the bedrock topography. Areas depicted in Figure 3 as being underlain by thicker ground moraine have been displayed using shades of green. However, note that some of the areas mapped as morainal plain would have been better mapped as morainal veneer or rock. For example, the areas delineated as morainal plain around Santo Bay and north of Besnard Lake display some of the most extensive bedrock exposures shown in Figure 12.

Thinner ground moraine deposits in northern Saskatchewan are typically mapped as morainal veneer (Mv). The concept behind the morainal veneer class (Mv) is similar to the rock class (R) in that the bedrock topography is only minimally obscurred by drift deposits. The surface expression of faults, shear zones and other geological structures are generally displayed clearly in these areas. However, as noted above, the areas mapped as morainal plain around Santo Bay and north of Besnard Lake (Figure 3) could have been mapped as morainal veneer or rock. Furthermore, within parts of the broad areas mapped as morainal veneer in or near the Pinehouse area, drift deposits are sufficiently thick that the bedrock structure is definitely masked. For example, the trough extending northeast of McDonald Bay (Figure 12) was mapped as morainal veneer but contains abundant organic deposits overlying other drift deposits (probably till). The ridges delineated using the relief maps in Figure 12 are believed to provide a much better indication of the areas of morainal veneer than those shown in the surficial geology map.

An SGS bedrock map, produced at a scale of 1:100,000, was georeferenced to provide an additional dataset delimiting areas of thicker drift (Figure 13). The areas of thicker drift shown on this map are generally located in the topographic lows between rock ridges. The areas of thick drift have been resolved with greater detail in the bedrock map than in the regional surficial map (Figure 3).

5.2.3 GLACIOFLUVIAL

The most obvious glaciofluvial deposits within or north of the Pinehouse area are the sand and gravel deposits within the valleys of the Haultain and Bélanger rivers and at their mouths, and the few small eskers mapped in Figure 3. An extensive belt of sand and gravel extends along the Haultain River and into Dreger Lake (mostly north of the Pinehouse area), where a large delta was formed when meltwater carried along the Haultain spillway was responsible for depositing sediment into the Churchill River (Schreiner et al., 1976), which was flooded by glacial Lake Agassiz at the time. Glaciofluvial deposits of sand and gravel are also found along the Bélanger and Massinahigan rivers.

The eskers mapped in the area generally display a north to northeast trend and they are dominantly located in the southern part of the Pinehouse area (Figure 3). The CDED elevation data indicate that the eskers typically stand about 10 to 20 m above the surrounding landscape.

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, and airport locations.

5.2.4 GLACIOLACUSTRINE

Schreiner et al. (1976) indicated a scarcity of glaciolacustrine deposits in the northeast part of the Pinehouse area. Schreiner (1977) searched for raised beach deposits in an area north of Besnard Lake and found no indication of such deposits. As noted in Section 5.2.1, minor deposits of bedded silt and clay associated with local ponding of meltwater during deglaciation could exist within small linear bedrock basins. Raised beach deposits associated with glacial Lake Agassiz could exist along the flanks of ridges.

5.2.5 ORGANIC

Organic deposits were not delineated explicitly in the surficial geology map (Figure 3). Rather, areas where organic deposits were common were delineated as organic plains. A much better appreciation for the extent of organic deposits can be obtained from the map of wetlands shown in Figure 10. The wetlands, particularly the larger ones, are generally expected to occur in areas underlain by poorly drained, thicker overburden deposits. Some of the smallest organic deposits fill small bedrock depressions. For example, organic deposits can be found in local depressions at the tops of rock ridges.

Exceptionally poor engineering characteristics can be found within areas mapped as organic terrain. Peat and muck have very low shear strength and high compressibility. Groundwater tables are at or near the surface in organic terrain. Flooding is common in organic terrain, and this forms a significant constraint on most types of development. Although peat and muck deposits usually occur as relatively thin surficial layers, in places, these organic materials can be several metres thick, and the thickness can change drastically over very short distances.

6 GROUNDWATER

Golder (2013) provides a thorough discussion of the hydrogeology of the Pinehouse area. This section mainly describes regional recharge and discharge zones and shallow groundwater flow directions based on surficial geology, topography and surface drainage patterns

Shallow groundwater flow is expected to mimic the pattern of surface flow suggested by Figure 11. The major recharge areas are the highlands to the north and west of the Pinehouse area. The regional discharge zone is the lowland associated with the Churchill River and Pinehouse Lake.

Recharge of the low-relief highland near Belton Lake will dominantly occur within thick surficial aquifers overlying the Phanerozoic basin. Groundwater flow will be directed north towards Gavel Lake and east towards Pinehouse Lake. Stagnant drainage conditions are common on this poorly drained highland.

Recharge of the rugged highland along the northeast margin of the Pinehouse area and further north will occur into both bedrock and surficial aquifers. Steep slopes in this area will generally promote runoff rather than recharge. The main surficial aquifers are located within the creek and river valleys and other bedrock depressions. Runoff from the rock ridges will recharge these surficial aquifers, which, in turn, will discharge into the creeks and rivers that flow into the Churchill River system. Sand and gravel deposits within the Bélanger and Haultain rivers are expected to be important surficial aquifers to the north of the Pinehouse area. Bedrock aquifers in this area are generally expected to be shallow, perhaps restricted to depths of 40 to 60 m, with permeability a function of the spacing, persistence and aperture of discontinuities. Any possible deeper bedrock aquifers or significant deviations in groundwater flow directions from surface runoff patterns would likely be associated with major structures, such as the northeast or northwest trending structures, or structurally damaged rock units such as the pelitic gneisses of the Wollaston domain.

No information beyond what was presented in the initial screening study (Golder, 2011) on groundwater flow at typical repository depths (approximately 500 m) was found during this study.

7 NEOTECTONIC FEATURES

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

The movement and interaction of tectonic plates creates horizontal stresses that result in the compression of crustal rocks. The mean of the current major principal stress orientation in central North America, based on the World Stress Map (Heidbach et al., 2009), is northeast (063° ± 28°). This orientation coincides roughly with both the absolute and relative plate motions of North America (Heidbach et al., 2009; Baird and McKinnon, 2007), and is controlled by the present tectonic configuration of the North Atlantic spreading ridge (Sbar and Sykes, 1973), which has likely persisted since the most recent Paleocene-Eocene plate reorganization (Rona and Richardson, 1978; Gordon and Jurdy, 1986).

Repeated cycles of glaciation and deglaciation throughout the Quaternary have induced stresses by sequentially loading and unloading the Earth's crust. The loads associated with glaciation are sufficient to depress the crust by hundreds of metres. Crustal rebound takes place once the weight of the ice is removed and rebound continues to occur today in this area, albeit slowly. The greatest rates of rebound typically occur near the ice-centres, such as around the margins of Hudson Bay. The stresses associated with cycles of ice loading and unloading interacting with the tectonic stress field may result in seismic events related to displacements along ancient discontinuities in the bedrock.

The study of neotectonic features in the Pinehouse area may reveal the timing and magnitude of glacially-induced seismic activity and deformations. Conclusive identification of features indicative of reactivation of ancient bedrock structures due to cycles of glacial loading and unloading could not be made using the information sources available in the current study. Field investigation would be required to identify such features. Under the appropriate conditions, glaciolacustrine deposits may preserve neotectonic features indicative of paleo-seismic activity. Although the Pinehouse area is generally devoid of extensive glaciolacustrine deposits, there could be local deposits preserved within bedrock trenches. Trenching or drilling would be required to investigate these features.

8 ACCESSIBILITY CONSTRAINTS

The main accessibility constraints in the Pinehouse area are the limited number of roads and the rugged terrain in many of the areas of thin drift and exposed bedrock. The large lakes in the area also represent significant accessibility constraints, and to a lesser extent so do the extensive wetlands in parts of the area.

Highway 914, commonly known as the Key Lake Road, is the unpaved highway that extends through the Pinehouse area (Figure 1). It extends through the Northern Village of Pinehouse and crosses the Churchill River at Snake Rapids. Highway 910 is the road that leads to the Besnard Lake Provincial Recreation site near the southwest corner of the Pinehouse area. At the north end of this road, there are a few roads leading further north, including one that extends past Domino Lake to the west shore of Duddridge Lake.

There is a general lack of forest harvesting roads in the area. The only logging roads that could be identified in satellite and aerial imagery extend west from Highway 914 in the southern part of the Pinehouse area, south of Musqua Lake. It appears that recent forest harvesting has been limited to the southwest part of the Pinehouse area. As a result, field activities using road access would be limited to the Highway 914 corridor or would require the use of a helicopter or float-equipped, fixed-wing aircraft.

The ridges and peninsulas around Santo Bay contain some of the most extensive areas of exposed bedrock in the Pinehouse area (Figure 12), including several ridges underlain by felsic gneiss (Figure 2). However, road access into these areas would require about 20 to 30 km of new road construction from Highway 910. Many of these ridges are narrow in extent, which could render them unsuitable for construction activities. A larger ridge, about 4 km wide and 12 km long, underlain by felsic gneiss is located northeast of Santo Bay. About 40 km of new road construction would be required to access this site.

In contrast to all of the sites mentioned above, the glacially scoured ridge on the south shore of Sandy Lake is located a short distance (2 to 5 km) west of Highway 914, about 20 km north of the Northern Village of Pinehouse. Access to this site would require the least amount of new road construction of any of the sites described in this section. This ridge contains some of the most extensive areas of exposed bedrock in the Pinehouse area (Figure 12).

9 SUMMARY

This report presents an analysis of the terrain in the Pinehouse area using publicly available remote sensing and geoscientific information sources. Section 1.3 described the datasets and methods used in this study. Further information on data sources and methodologies were presented in appropriate report sections. The main information sources relied on were the Canadian Digital Elevation Data (CDED), the SPOT satellite imagery, the maps and reports from the Saskatchewan Geological Survey (SGS), the Saskatchewan Forest Resource Inventory (FRI), and the drainage areas drawn by the Prairie Farm Rehabilitation Association (PFRA).

A summary of the Quaternary geology and history of the Pinehouse area provides context to the description of terrain features. The Pinehouse area was beneath the Laurentide ice sheet at about 11,000 to 10,000 years B.P. followed by ice recession north to the Cree Lake moraine by about 10,000 to 9,500 years B.P. At this time, the Haultain and Bélanger rivers served as the main meltwater channels north of the Pinehouse area. The formation of deltas at the mouths of these channels suggests that the Churchill River in this area was flooded by glacial Lake Agassiz at that time. Till is the main drift cover within the area, and no extensive glaciolacustrine sediments have been observed. Ice flow directions in the Pinehouse area are indicated by a few small eskers, several roche moutonnée, and glacial striae, which indicate a northeast to southwest glacial flow. Ice flow was nearly parallel with the structural grain of rocks within the Wollaston domain, which accentuated the northeast trending fabric by eroding the pelitic gneisses.

The Pinehouse area is bounded by two major topographic highs, a high relief, rugged zone in the northeast, and a broad, low relief highland in the southwest. The vast majority of the Pinehouse area represents a lowland associated with the Churchill River and Pinehouse Lake.

The areas of thin drift and exposed bedrock within the Pinehouse area were delineated using a combination of the areas mapped as exposed bedrock in the FRI with the areas of topographic prominence delineated using the CDED elevation model. Most of the areas of exposed bedrock are located on the tops or sides of ridges. The ridges themselves represent areas of thin drift. As a result, the ridge delineation provides a map of the areas of thin drift. Areas of thicker drift in the northeast half of the Pinehouse area are located in the lows between ridges, where the location of the most extensive overburden deposits is indicated by the presence of extensive wetland complexes delineated in the 1:50,000-scale CanVec and 1:12,500-scale FRI datasets. The distribution of these terrain units described above provides a much more detailed image of the extent of thin and thick drift deposits in the Pinehouse area than is provided by the available 1:250,000-scale surficial geology map.

The available subsurface data on drift thickness is quite limited in the Pinehouse area, and it is generally restricted to the southwest half of the area. Drill hole data indicate overburden thickness ranging from 20 to 100 m over the Phanerozoic basin. The limited data available in the northeast half of the area indicate values an order of magnitude smaller.

Much of the central portion of the Pinehouse area is characterized as a lake-filled lowland associated with the Churchill River and Pinehouse Lake. In fact, about a quarter of the area is covered by lakes. The Churchill River is represented in this area by a chain of lakes extending from west to east through the Precambrian Shield in the northern half of the Pinehouse area not far from the northern limit of the Western Canada sedimentary basin. All runoff in the Pinehouse area is directed to the Churchill River, with runoff received from the heavily drift-covered Phanerozoic basin to the south and from the Precambrian Shield to the north. The PFRA sub-basins in the area were subdivided using the CDED elevation model.

Shallow groundwater flow is expected to mimic the pattern of surface flow, with recharge occurring in highlands on both the Phanerozoic basin and the Precambrian Shield and the ultimate discharge zone represented by the Churchill River and Pinehouse Lake. Sand and gravel deposits within the Bélanger and Haultain rivers are expected to be important surficial aquifers north of the Pinehouse area. Bedrock aquifers in this area are generally expected to be shallow, perhaps restricted to depths of 40 to 60 m. Any possible deeper bedrock aquifers or significant deviations in groundwater flow directions from surface runoff patterns would likely be associated with major structures or tectonically damaged rock units, such as the pelitic gneisses of the Wollaston domain. No information beyond that presented in the initial screening study on groundwater flow at repository depths (approximately 500 m) was found during this study.

Field investigation would be required to identify features indicative of reactivation of ancient bedrock structures due to cycles of glacial loading and unloading. One possible type of evidence to search for in the field could be deformed silt and clay deposits within lineament trenches where meltwater ponded locally during deglaciation.

Significant accessibility constraints in the Pinehouse area include the large lakes occupying the central lowland, the limited number of roads providing access into areas of thin drift, and the rugged terrain across which new roads would need to be constructed. Most of the ridges where the exposed bedrock and thin drift are found generally are quite irregular in shape. There is a general lack of forest harvesting roads in the area to facilitate field activities. Several areas of exposed bedrock and thin drift were described in terms of the primary accessibility constraints. Access to several of the sites would require 10 to 20 km of new road construction.

REFERENCES

Annesley, I.R. and C. Madore, 1989. The Wollaston Group and its underlying Archean basement in Saskatchewan: 1989 fieldwork and preliminary observation. In: Summary of Investigations 1989, Saskatchewan Geological Survey, Sask. Energy and Mines, Misc. Rep. 89-4, 87-91.

Annesley, I.R. and C. Madore, 1991. The Wollaston Group and its underlying Archean basement: final report. Sask. Research Council, Pub. R-1230-4-C-91, 140p.

Annesley, I.R. and C. Madore, 1994. A geological study of the Wollaston-Mudjatik domain boundary in the Wollaston Lake area, Hearne Province, Saskatchewan. Sask. Research Council, Pub. R-1230-6-C-94, 162p.

Annesley I.R., C. Madore and P. Portella, 2005. Geology and thermotectonic evolution of the western margin of the Trans-Hudson Orogen: evidence from the eastern sub-Athabasca basement, Saskatchewan. *Canadian Journal Earth Science*, 42, 573-597.

Ansdell, K.M., 2005. Tectonic evolution of the Manitoba-Saskatchewan segment of the Paleoproterozoic Trans-Hudson Orogen, Canada. *Canadian Journal of Earth Sciences*, 42, 741-759.

Ansdell, K.M., S.B. Lucas, K.A. Connors and R.A. Stern, 1995. Kisseynew metasedimentary gneiss belt, Trans-Hudson Orogen (Canada); back-arc origin, and collisional inversion. *Geology*, 23, 1039-1043.

Ansdell, K.M., A. MacNeil, G.D. Delaney and M.A. Hamilton, 2000. Rifting and development of the Hearne craton passive margin: Age constraint from the Cook Lake area, Wollaston domain, Trans-Hudson Orogen, Saskatchewan. GeoCanada 2000, Calgary, Alta., May 2000, Extended Abstract 777 (Conference CD).

Baird, A. and S.D. McKinnon, 2007. Linking stress field deflection to basement structures in southern Ontario: results from numerical modelling. *Tectonophysics*, 432, 89-100.

Bickford, M.E., K.D. Collerson and J.F. Lewry, 1994. Crustal history of the Rae and Hearne provinces, southwestern Canadian Shield, Saskatchewan: constraints from geochronologic and isotopic data. *Precambrian Research*, 68, 1-21.

Bostock, H.S., 1970. Physiographic subdivisions of Canada. In: R.J.W. Douglas (ed.), Geology and Economic Minerals of Canada. Geological Survey of Canada.

Brown, A., R.A. Everitt, C.D. Martin and C.C. Davison, 1995. Past and future fracturing in AECL research areas in the Superior Province of the Canadian Precambrian Shield, with emphasis on the Lac Du Bonnet Batholith. Whiteshell Laboratories, Pinawa, Manitoba.

Byers, A.R., 1962. Major faults in western part of the Canadian Shield with special reference to Saskatchewan. In: The tectonics of the Canadian Shield. The Royal Society of Canada, Special Publication, 4, 40-59.

Campbell, J.B., 1987. Introduction to Remote Sensing. The Guilford Press.

Card, C., 2012. Personal Communications.

Card, C.D. and S.A. Bosman, 2007. The Cree Lake South Project: Reconnaissance Bedrock Mapping in the Mudjatik and Virgin River Domains, and the Virgin River Shear Zone near the Southwest Margin of the Athabasca Basin. In: Summary of Investigations 2007, Volume 2, Saskatchewan Geological Survey, Miscellaneous Report 2007-4.2.

Card, C.D., C.T. Harper, N. Barsi, J. Lesperance and J.S. Smith, 2006. Investigation of the Wollaston-Mudjatik transition, Charcoal Lake and Cochrane River (parts of NTS 64L-9, -10, -11, -14, -25, and -16). In: Summary of Investigations 2006, Saskatchewan Geological Survey, Miscellaneous Report 2006-4.

Card, C.D., B. McEwan and S.A. Bosman, 2008. The Cree Lake South Project 2008: Regional implications of bedrock mapping along the Virgin River Transect. In: Summary of Investigations 2008, Volume 2, Saskatchewan Geological Survey, Miscellaneous Report 2008-4.2.

Coombe, W., 1994. Geology of the Duddridge-Meyers Lakes Area, Map 213-11 (parts 73O-9, -16 and 73P-12. -13). Saskatchewan Energy and Mines.

Corrigan, D., A.G. Galley and S. Pehrsson, 2007. Tectonic Evolution and Metallogeny of the Southwestern Trans-Hudson Orogen. In: Goodfellow, W.D., (ed.), Mineral deposits of Canada: A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods. Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, pp. 881-902.

Corrigan, D., Z. Hajnal, B. Nemeth and S.B. Lucas, 2005. Tectonic framework of a Paleoproterozoic arc-continent to continent-continent collision zone, Trans-Hudson Orogen, from geological and seismic reflection studies. *Canadian Journal of Earth Sciences*, 42, 421-434.

Corrigan, D., S. Pehrsson, N. Wodicka and E. de Kemp, 2009. The Paleoproterozoic Trans-Hudson Orogen: a prototype of modern accretionary processes. Geological Society, London, Special Publications, 329, 457-479.

Cumming, G.L. and B.P. Scott, 1976. Rb/Sr Dating of rocks from the Wollaston Lake Belt, Saskatchewan. *Canadian Journal of Earth Sciences*, 13(2), 355-364.

Davies, J.R., 1998. The origin, structural style, and reactivation history of the Tabbernor Fault Zone, Saskatchewan, Canada. M.Sc. Thesis. McGill University.

Delaney, G.D., 1993. A Re-examination of the Context of U-Cu, Cu and U Mineralization, Duddridge Lake, Wollaston Domain. In: Summary of Investigations 1993, Saskatchewan Geological Survey, Miscellaneous Report 93-4, pp. 73-85.

Elliot, C.G., 1996. Phanerozoic deformation in the “stable” craton, Manitoba, Canada. *Geology*, 24(10), 909-912.

Fumerton, S.L., M.R. Stauffer and J.F. Lewry, 1984. The Wathaman Batholith: largest known Precambrian pluton. *Canadian Journal of Earth Sciences*, 21, 1082-1097.

Gale, D.F., S.B. Lucas and J.M. Dixon, 1999. Structural relations between the polydeformed Flin Flon arc assemblage and Missi Group sedimentary rocks, Flin Flon area, Manitoba and Saskatchewan. *Canadian Journal of Earth Sciences*, 36, 1901-1915.

GeoBase, 2011a. Canadian Digital Elevation Data: http://www.geobase.ca/.

GeoBase, 2011b. GeoBase Orthoimage 2005-2010: http://www.geobase.ca/.

Giroux, D.L., 1995. Location and Phanerozoic history of the Tabbernor Fault. In: Summary of Investigations 1995, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 95-4, pp. 153-155.

Golder (Golder Associates Ltd.), 2011. Initial Screening for Siting a Deep Geological Repository for Canada’s Used Nuclear Fuel. The Northern Village of Pinehouse, Saskatchewan. Nuclear Waste Management Organization, March 2011.

Golder (Golder Associates Ltd.), 2013. Phase 1 Desktop Geoscientific Preliminary Assessment of Potential Suitability for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel, Northern Village of Pinehouse, Saskatchewan. Report prepared for the Nuclear Waste Management Organization (NWMO). NWMO Report Number: APM-REP-06144-0059.

Gordon, R.G. and D.M. Jurdy, 1986. Cenozoic global plate motions, *J. Geophys. Res*., 91, 12,389-12,406.

Hajnal, Z., J. Lewry, D.J. White, K. Ashton, R. Clowes, M. Stauffer, I. Gyorfi and E. Takacs, 2005. The Sask craton and Hearne Province margin: seismic reflection studies in the western Trans-Hudson Orogen. *Canadian Journal of Earth Sciences*, 42, 403-419.

Harper, C.T., 1988a. Mudjatik domain, geology and gold studies: Ithingo Lake. In: Summary of Investigations 1988, Saskatchewan Geological Survey, Misc. Rep. 88-4, pp. 42-48.

Harper, C.T., 1988b. Mudjatik domain, geology and gold studies: Porter Lake Area. In: Summary of Investigations 1988, Saskatchewan Geological Survey, Misc. Rep. 88-4, pp. 49-53.

Heidbach, O., M. Tingay, A. Barth, J. Reinecker, D. Kurfeß, B. Müller, 2009. The World Stress Map based on the database release 2008, equatorial scale 1:46,000,000, Commission for the Geological Map of the World, Paris, doi:10.1594/GFZ.WSM.Map2009.

ILEC (International Lake Environment Committee Foundation), 2013. World Lake Database. Information retrieved 4 March 2013.

JDMA (J.D. Mollard and Associates Ltd.), 2013. Phase 1 Desktop Geoscientific Preliminary Assessment, Lineament Interpretation, Northern Village of Pinehouse, Saskatchewan. Report prepared for the Nuclear Waste Management Organization (NWMO). NWMO Report Number: APM-REP-06144-0062.

Kreis, L.K., F.M. Haidl, A.R. Nimegeers, K.E. Ashton, R.O. Maxeiner J. and Coolican, 2004. Lower Paleozoic Map Series – Saskatchewan. Saskatchewan Industry and Resources, Misc. Rep. 2004-8.

Lewry, J.F., Z. Hajnal, A.G. Green, S.B. Lucas, D.J. White, M.R. Stauffer, K.E. Ashton, W. Weber and R.M. Clowes, 1994. Structure of a Paleoproterozoic continent-continent collision zone: A LITHOPROBE seismic reflection profile across the Trans-Hudson Orogen, Canada. *Tectonophysics*, 232, 143-160.

Lewry, J.F. and T.I.I. Sibbald, 1980. Thermotectonic evolution of the Churchill Province in northern Saskatchewan. *Tectonophysics*, 68, 45-82.

Lucas, S.B., R.A. Stern, E.C. Syme, B.A. Reilly and D.J. Thomas, 1996. Intraoceanic tectonics, and the development of continental crust: 1.92-1.84 ga evolution of the Flin Flon Belt (Canada). *Geological Society of America Bulletin*, 108, 602-629.

Machado, N., H.V. Zwanzig and M. Parent, 1999. U-Pb ages of plutonism, sedimentation, and metamorphism of the Paleoproterozoic Kisseynew metasedimentary belt, Trans-Hudson Orogen (Manitoba, Canada). *Canadian Journal of Earth Sciences*, 36, 1829-1842.

Money, P. L., 1965. The geology of the area around Needle Falls, Churchill River, comprising the Eulas Lake area (west half), Sandfly Lake area (east half) and Black Bear Island area (west half), Saskatchewan. Saskatchewan Department of Mineral Resources, Report 88.

Mossop, G.D. and I. Shetsen (comp.), 1994. Geological atlas of the Western Canada Sedimentary Basin; Canadian Society of Petroleum Geologists and Alberta Research Council.

Munday, R.J.C. 1977. The Geology of the Mudjatik (East) Area Saskatchewan. Precambrian Geology Division, Saskatchewan Geological Survey, Department of Mineral Resources, Report 168.

Munday, R.J.C., 1978a. The Shield Geology of the Ile-a-la-Crosse (East) Area Saskatchewan. Part of the NTS Area 73-0. Department of Mineral Resources, Saskatchewan Geological Survey, Precambrian Geology Sector, Report 189.

Munday, R.J.C., 1978b. The Shield Geology of the Ile-a-la-Crosse (East) Area Saskatchewan. Part of the NTS Area 73-0. Department of Mineral Resources, Saskatchewan Geological Survey, Precambrian Geology Sector, Map 189A, scale 1:100,000.

NWMO (Nuclear Waste Management Organization), 2010. Moving forward together: process for selecting a site for Canada's deep geological repository for used nuclear fuel, Nuclear Waste Management Organization, May 2010. (Available at www.nwmo.ca).

NWMO (Nuclear Waste Management Organization), 2013. Preliminary Assessment for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel - Northern Village of Pinehouse, Saskatchewan – Findings from Phase One Studies. NWMO Report Number: APM-REP-06144-0057.

Orrell, S.E., M.E. Bickford and J.F. Lewry, 1999. Crustal evolution and age of thermotectonic reworking in the western hinterland of the Trans-Hudson Orogen, northern Saskatchewan. *Precambrian Research*, 95, 187-223.

Pearson, D.E., 1977a. The geology of the Mudjatik Area (Southwest Quarter) Saskatchewan. Report No. 166. Department of Mineral Resources. Saskatchewan Geological Survey.

Pearson, D.E., 1977b. Geology of the Mudjatik (Southwest) Area. Map 166A to accompany Report No. 166. Department of Mineral Resources. Saskatchewan Geological Survey.

Peltier, W.R., 2002. On eustatic sea level history: Last Glacial Maximum to Holocene. *Quaternary Science Reviews,* 21, 377-396

Rona, P.A. and E.S. Richardson, 1978. Early Cenozoic Global Plate Reorganization. *Earth Planet. Sci. Letters*, 40, 1-11.

SGIC (Saskatchewan Geospatial Imagery Collaborative), 2013. Saskatchewan Orthophoto Program 2011. Saskatchewan Research Council, <http://www.flysask.ca>.

Sbar, M.L. and L.R. Sykes, 1973. Contemporary compressive stress and seismicity in eastern North America: An example of intra-plate tectonics: *Geol. Soc. America Bull*., 84, 1861-1882.

Schreiner, B.T., 1977. Reconnaissance Quaternary geology: NTS areas 74B, 74F and 74G. Saskatchewan Geological Survey, Summary of Investigations, pp. 54-59.

Schreiner, B.T., 1984a. Quaternary geology of the Precambrian Shield, Saskatchewan. Saskatchewan Geological Survey, Map 221A, scale 1:1,000,000.

Schreiner, B.T., 1984b. Quaternary geology of the Precambrian Shield, Saskatchewan. Saskatchewan Geological Survey, Open File Report 221.

Schreiner, B.T., 1984c. Quaternary geology of the Ile a la Crosse area (73-O) Saskatchewan. Saskatchewan Geological Survey, Open File Report 84-5, scale 1:250,000.

Schreiner, B.T. and D.W. Alley, 1984. Quaternary geology of the Lac la Ronge area (73-P) Saskatchewan. Saskatchewan Geological Survey, Open File Report 84-4, scale 1:250,000.

Schreiner, B.T., D.W. Alley and E.A. Christiansen. 1976. Quaternary geology - 64D, 64E, 73O, 74C, 74B, 74H areas. In Summary of Investigations 1976, Saskathewan Geological Survey, Miscellaneous Report, 58-62.

Shackleton, N.J., A. Berger and W.R. Peltier, 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 81, 251-261.

Sibbald, T.I.I., 1973. Mudjatik (N.W.). Saskatchewan Department of Mineral Resources, Summary Report, 35-42.

Smith, D.G. and T.G. Fisher, 1993. Glacial Lake Agassiz: The northwestern outlet and paleoflood. *Geology*, 21, 9-12.

Stauffer, M.R. and J.F. Lewry, 1993. Regional Setting and Kinematic Features of the Needle Falls Shear Zone, Trans-Hudson Orogen. *Canadian Journal of Earth Sciences*, 30, 1338-1354.

Streckeisen, A.L., 1976. Classification of the common igneous rocks by means of their chemical composition: a provisional attempt. *Neues Jahrbuch fr Mineralogie, Monatshefte*, 1976, H. 1, 1-15.

Thomas, M.W. and W.L. Slimmon, 1985. Compilation Bedrock Geology, Île-à-la-Crosse, NTS Area 73O. Saskatchewan Energy and Mines, Report 245 (1:250,000 scale map with marginal notes).

Tran, H.T., 2001. Tectonic evolution of the Paleoproterozoic Wollaston Group in the Cree Lake Zone, northern Saskatchewan, Canada. Unpublished Ph.D. thesis, Univ. Regina, 458p.

Tran, H.T. and M. Smith, 1999. Geology of the Cup-Keller-Schmitz Lakes transect of the Wollaston-Mudjatik Domains Bondary. In: Summary of Investigations 1999, Volume 2, Saskatchewan Geological Survey, Miscellaneous Report, 99-4.2

Tran, H.T., G. Yeo and K. Bethune, 1999. Geology of the McKenzie Falls area, Haultain River, Wollaston-Mudjatik domains boundary (NTS 74B-7 and -8). In: Summary of Investigations 1999, Vol. 2, Saskatchewan Geological Survey, Miscellaneous Report, 99-4.2, pp. 55-67.

White, D.J., M.D. Thomas, A.G Jones, J. Hope, B. Németh and Z. Hajnal, 2005. Geophysical transect across a Paleoproterozoic continent–continent collision zone; The Trans-Hudson Orogen. *Canadian Journal of Earth Sciences*, 42, 385-402.

Whitmeyer, S.J. and K.E. Karlstrom, 2007. Tectonic model for the Proterozoic growth of North America. *Geosphere*, 3(4), 220-259.

Yeo, G.M. and G. Delaney, 2007. The Wollaston Supergroup, Stratigraphy and Metallogeny of a Paleoproterozoic Wilson Cycle in the Trans-Hudson Orogen, Saskatchewan. In: C.W. Jefferson and G. Delaney (eds.), EXTECH IV: Geology and Uranium Exploration TECHnology of the Proterozoic Athabasca Basin, Saskatchewan and Alberta. Geological Survey of Canada, Bulletin 588, pp. 89-117.

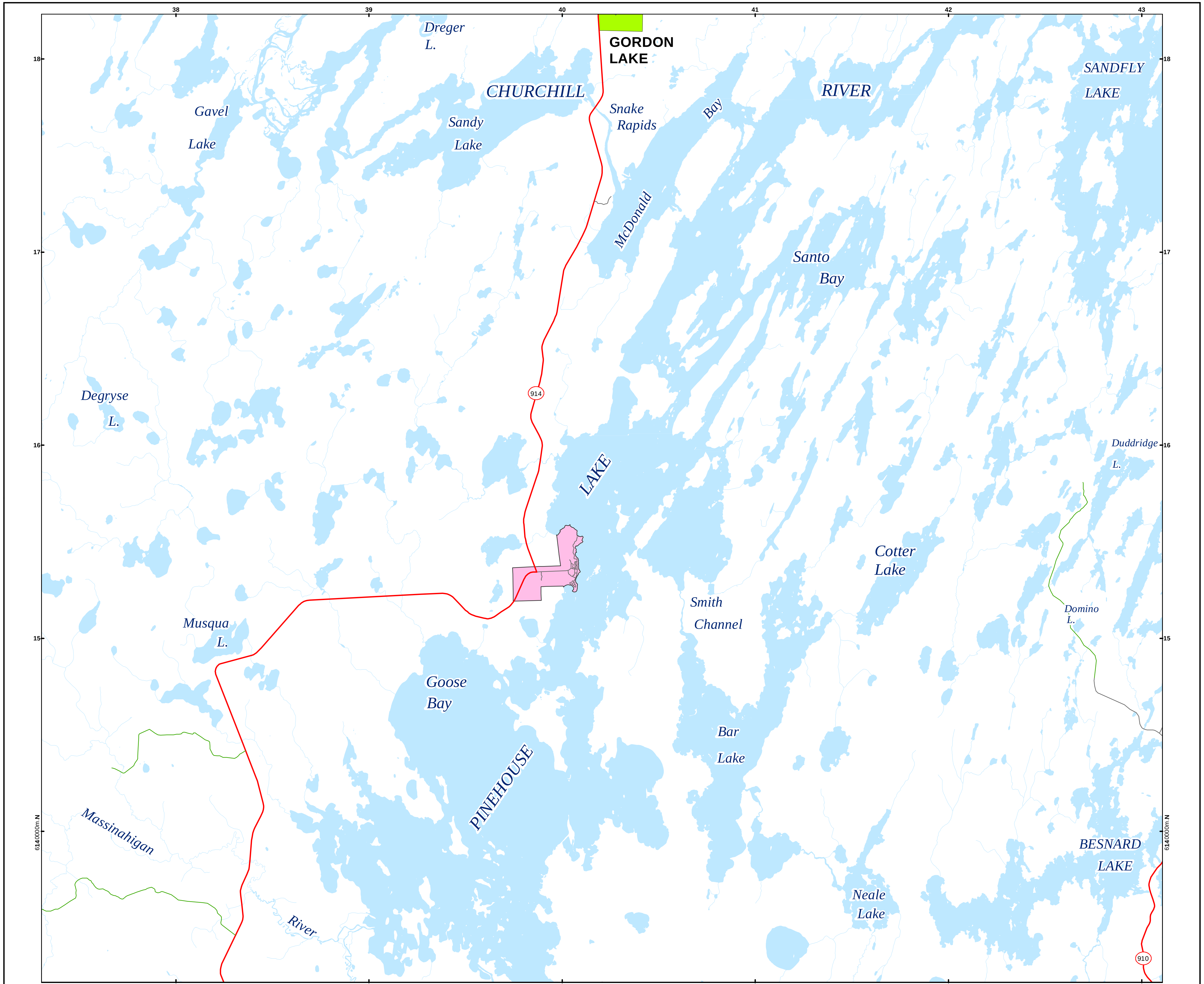
REPORT SIGNATURE PAGE

J.D. Mollard and Associates (2010) Limited

David van Zeyl, M.Sc. | Lynden Penner, M.Sc., P.Eng., P.Geo.

FIGURES

FIGURES



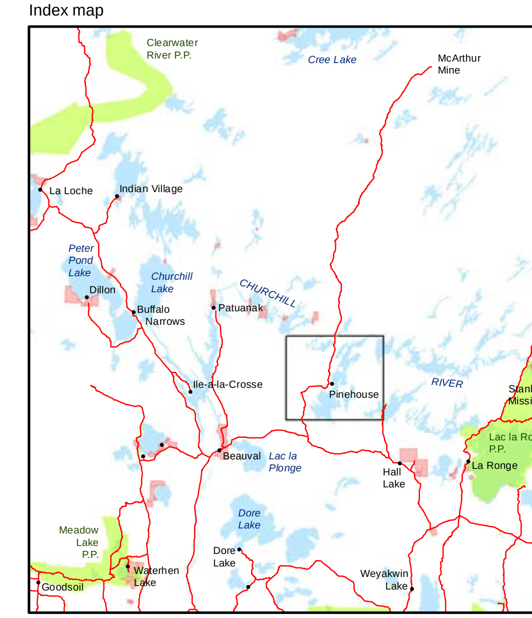
LEGEND

- Road (JDMA)

Road (SURN11)

- Main road
- Local road
- Village of Pinehouse
- First Nation Reserve
- Recreation site
- Waterbody
- Watercourse

Index map



- Pinehouse area
- Main road
- First Nation reserve
- Park
- Large lake

Data sources:
First Nations: SaskAdmin 2012
Recreation site: SaskAdmin 2012
Road (SURN11): ISC SURN11
Road (JDMA): Mapped from SPOT
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Northern Village of Pinehouse and surrounding area

DESIGN	DVZ	25 JUN 2012	FIGURE 1	REVISION 4
GIS	DSM	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000

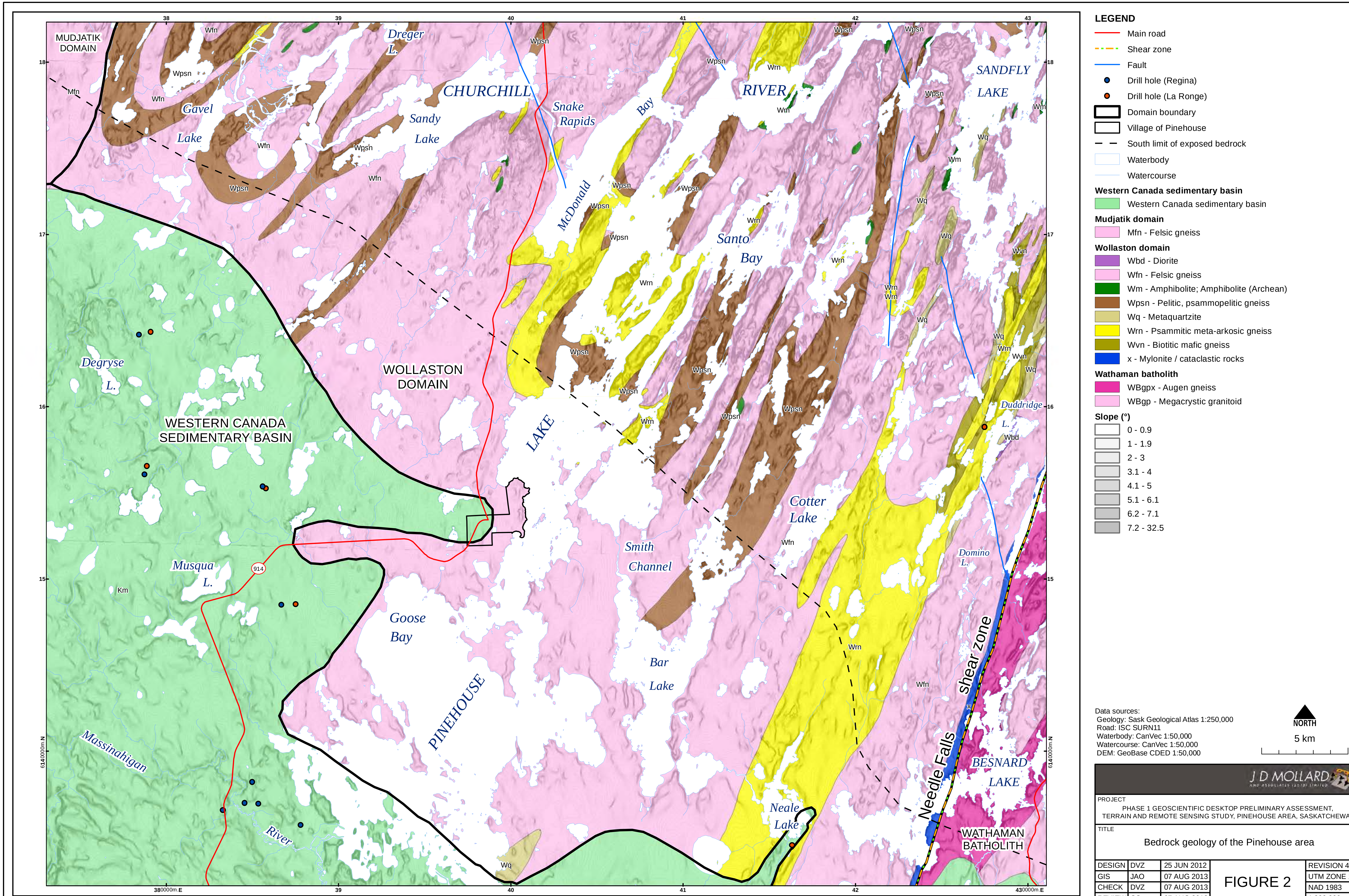
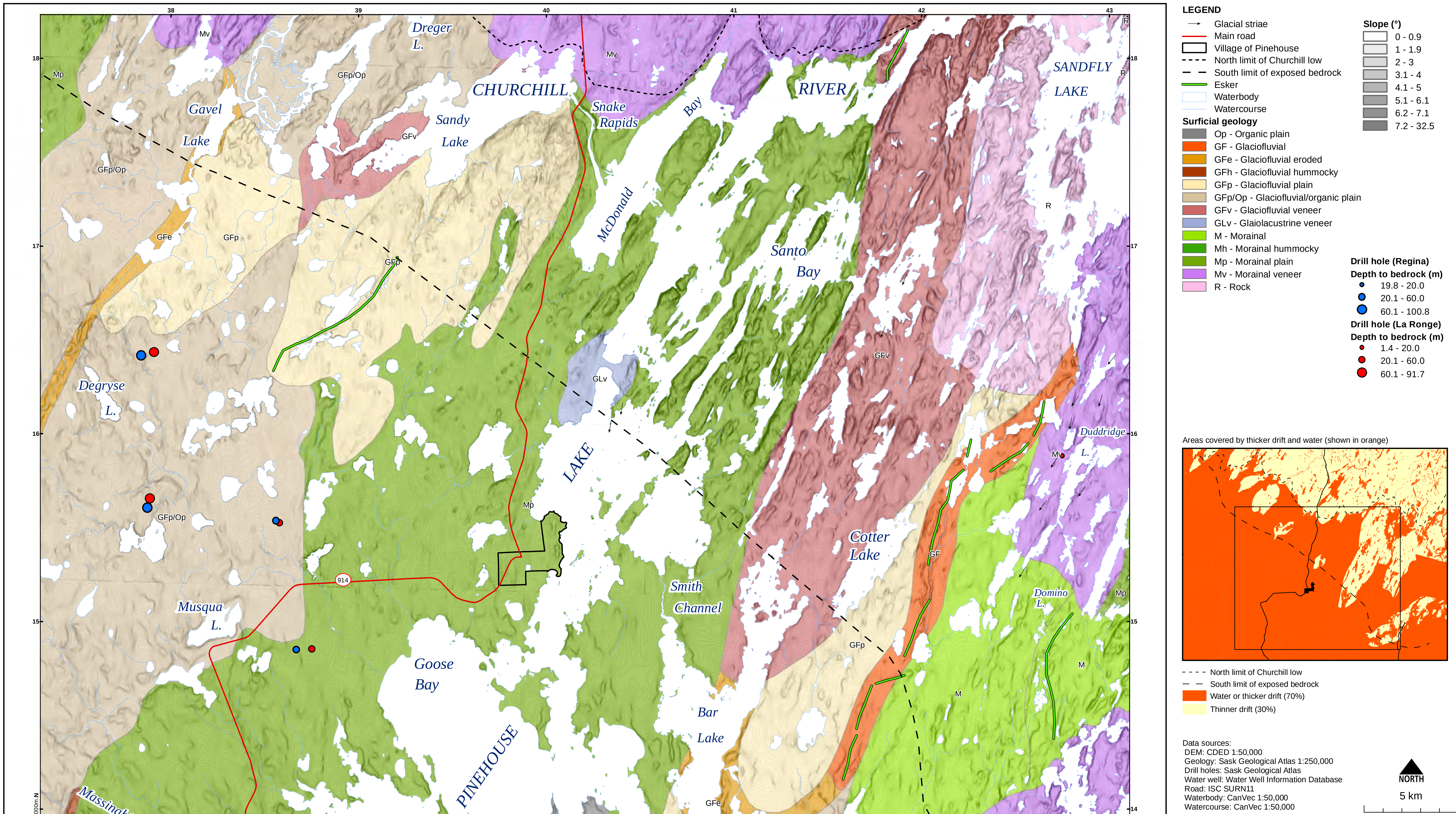


FIGURE 2 Bedrock geology of the Pinehouse area



J D MOLLARD

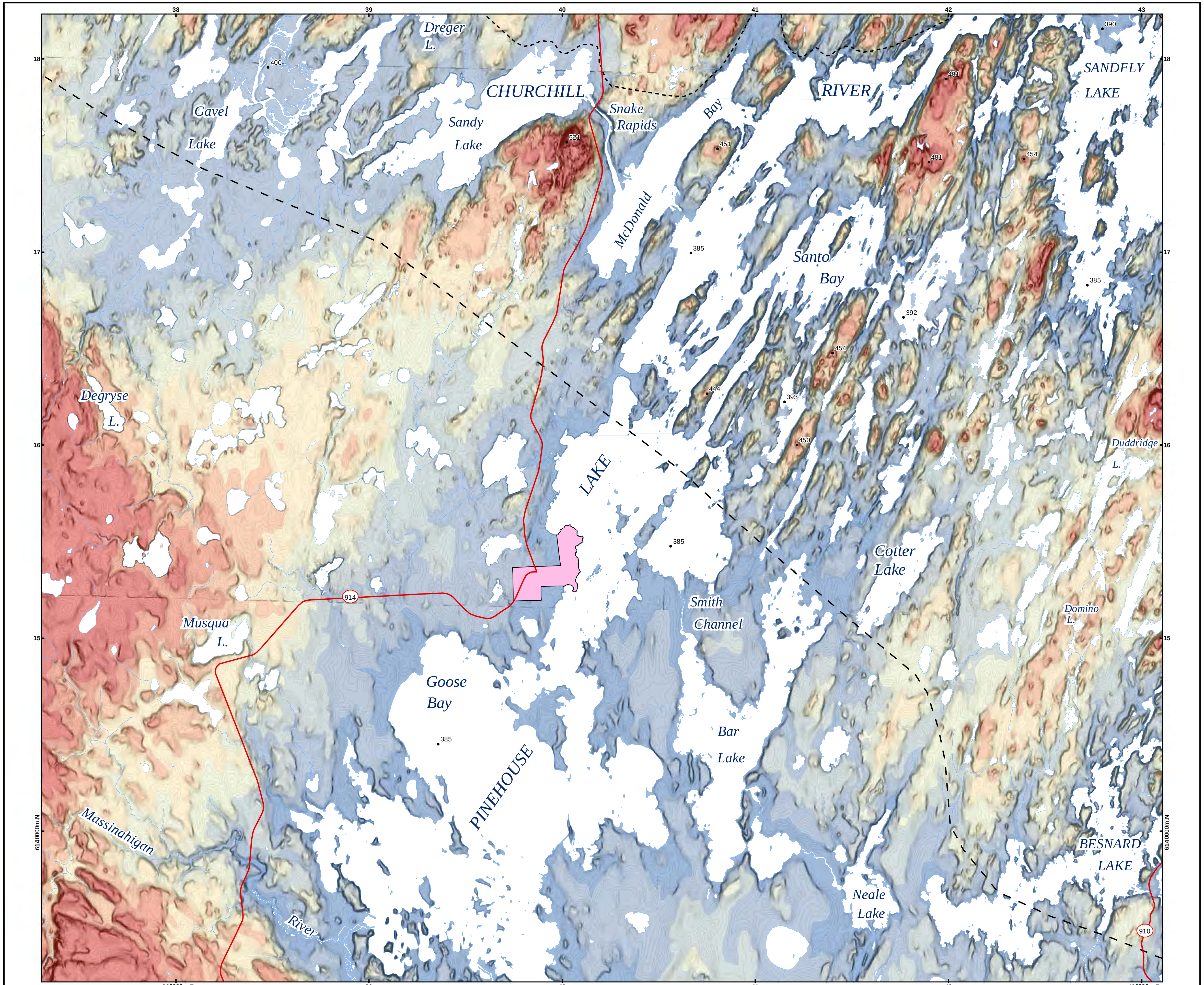
PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE

Surficial geology of the Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 3	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000



LEGEND

- Main road
- Village of Pinehouse
- North limit of Churchill low
- South limit of exposed bedrock
- Spot height (m)
- Waterbody
- Watercourse

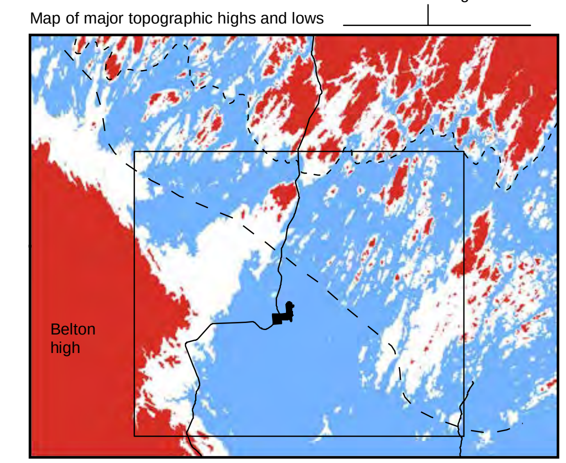
Slope (°)

- 0 - 0.9
- 1 - 1.9
- 2 - 3
- 3.1 - 4
- 4.1 - 5
- 5.1 - 6.1
- 6.2 - 7.1
- 7.2 - 32.5

Elevation (m)

- 384 - 391.6
- 391.7 - 402
- 402.1 - 412.5
- 412.6 - 423
- 423.1 - 433.4
- 433.5 - 443.9
- 444 - 454.3
- 454.4 - 521

Map of major topographic highs and lows



- North limit of Churchill low
- South limit of exposed bedrock

Elevation (m)

- 370 - 410
- 410.1 - 440
- 440.1 - 553

Data sources:
DEM: CDED 1:50,000
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

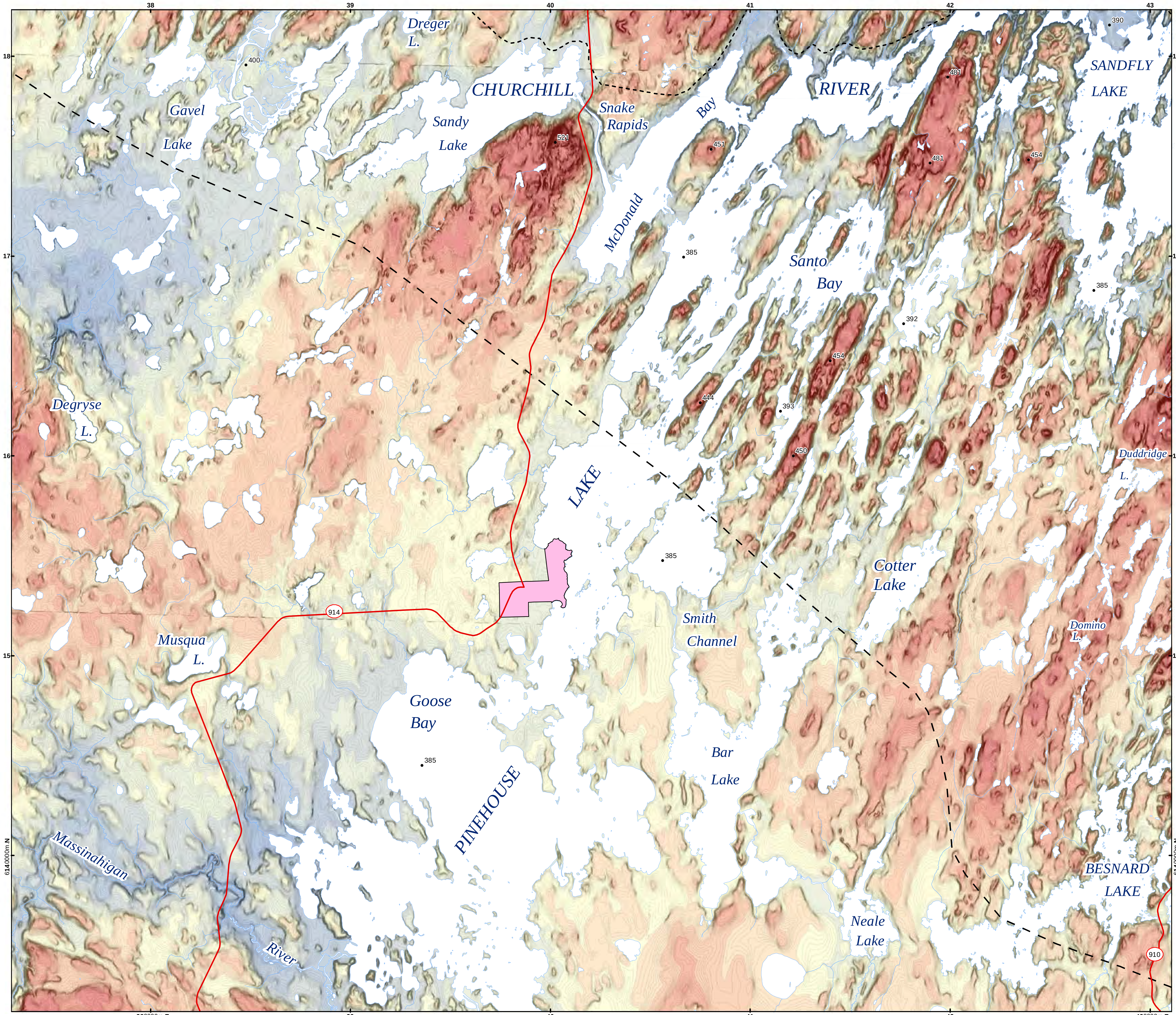
5 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Elevation and major topographic features

DESIGN	DVZ	25 JUN 2012	FIGURE 4	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000



LEGEND

- Main road
- Village of Pinehouse
- North limit of Churchill low
- South limit of exposed bedrock
- Spot height (m)
- Waterbody
- Watercourse

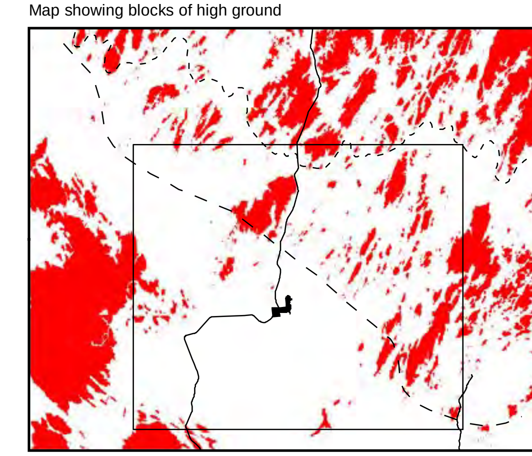
Slope (°)

- 0 - 0.9
- 1 - 1.9
- 2 - 3
- 3.1 - 4
- 4.1 - 5
- 5.1 - 6.1
- 6.2 - 7.1
- 7.2 - 32.5

Relief (m)

- -44.8 - -42.4
- -42.3 - -34.3
- -34.2 - -26.2
- -26.1 - -18.1
- -18 - -10
- -9.9 - -1.9
- -1.8 - 6.2
- 6.3 - 14.3
- 14.4 - 22.4
- 22.5 - 30.5
- 30.6 - 108.5

Map showing blocks of high ground



- North limit of Churchill low
- South limit of exposed bedrock

Relief (m)

- -61 - 15
- 16 - 108

Data sources:
DEM: CDED 1:50,000
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

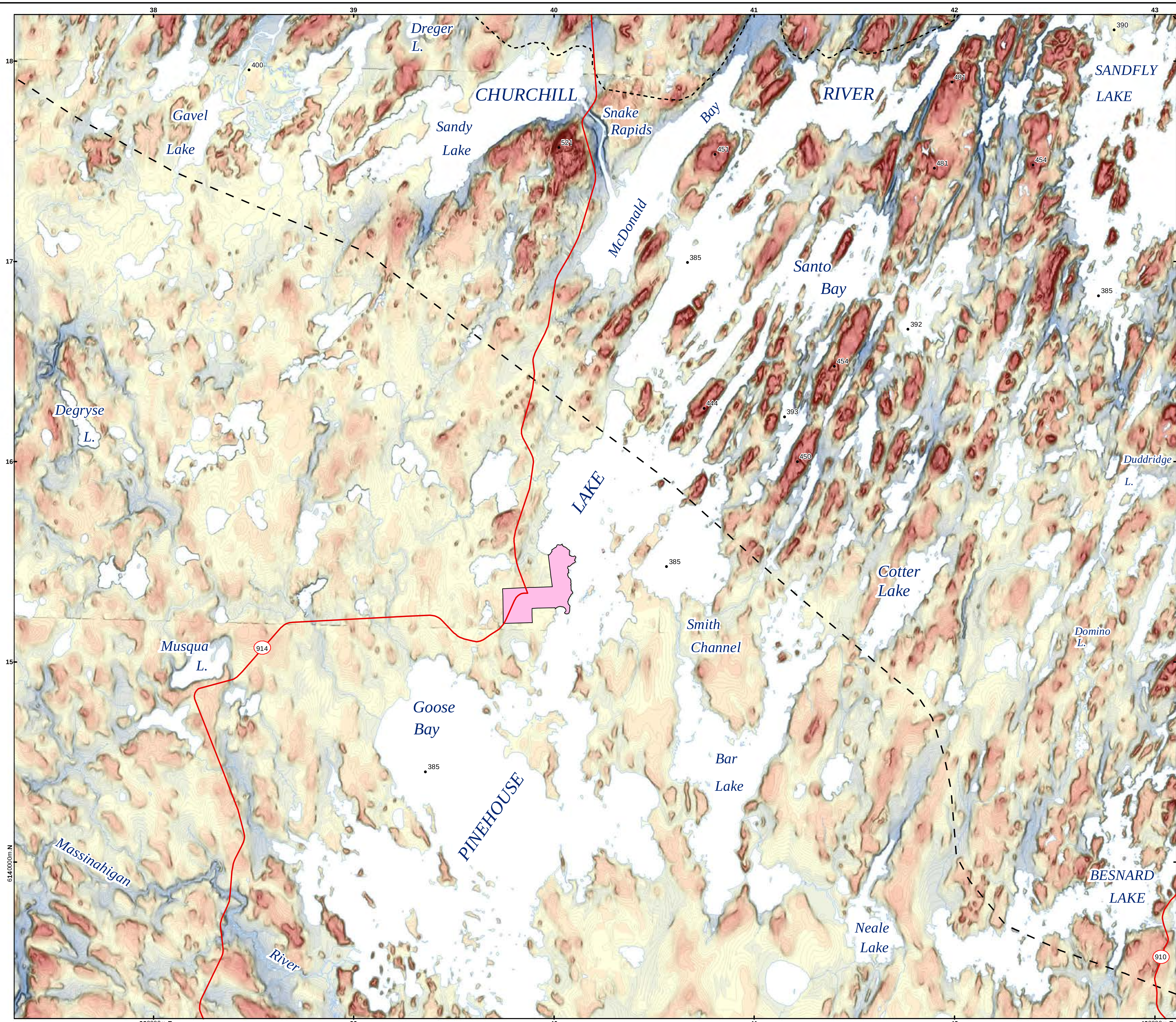
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Departure from average elevation within 20 km radius

DESIGN	DVZ	25 JUN 2012	FIGURE 5	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000



LEGEND

- Main road
- Village of Pinehouse
- North limit of Churchill low
- South limit of exposed bedrock
- Spot height (m)
- Waterbody
- Watercourse

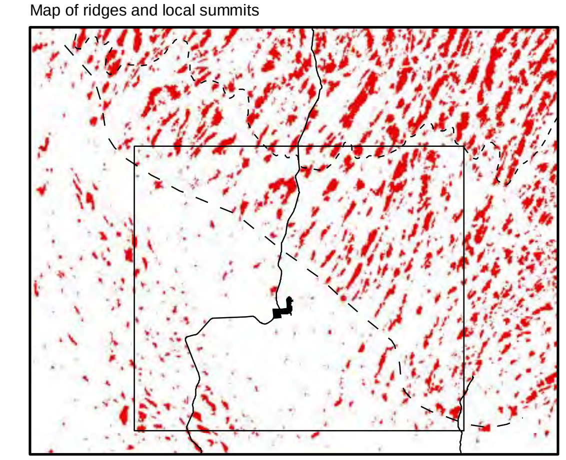
Relief (m)

- -35.1 - -22.8
- -22.7 - -18.7
- -18.6 - -14.7
- -14.6 - -10.6
- -10.5 - -6.5
- -6.4 - -2.4
- -2.3 - 1.7
- 1.8 - 5.8
- 5.9 - 9.9
- 10 - 14
- 14.1 - 18.1
- 18.2 - 22.2
- 22.3 - 75.2

Slope (°)

- 0 - 0.9
- 1 - 1.9
- 2 - 3
- 3.1 - 4
- 4.1 - 5
- 5.1 - 6.1
- 6.2 - 7.1
- 7.2 - 32.5

Map of ridges and local summits



- South limit of exposed bedrock
- North limit of Churchill low

Relief (m)

- -51 - 10
- 11 - 76

Data sources:
DEM: CDED 1:50,000
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

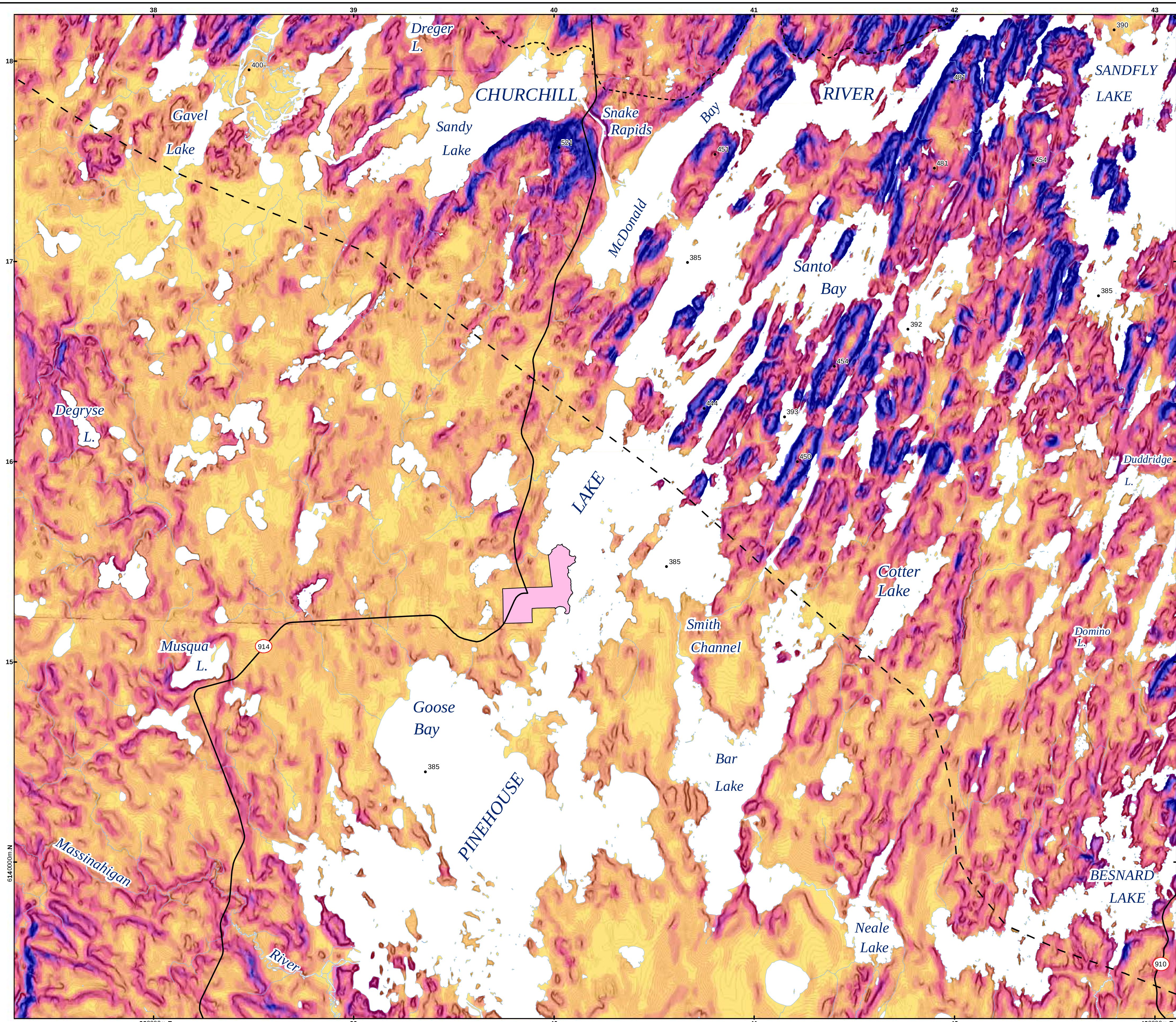
5 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Departure from average elevation within 2 km radius

DESIGN	DVZ	25 JUN 2012	FIGURE 6	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000



LEGEND

- Main roads
- Village of Pinehouse
- North limit of Churchill low
- South limit of exposed bedrock
- Spot height (m)
- Waterbody
- Watercourse

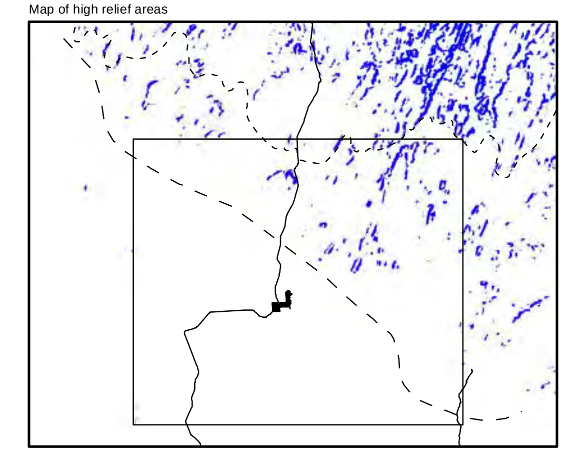
Relief (m)

- 0 - 3.5
- 3.6 - 8.8
- 8.9 - 14
- 14.1 - 19.3
- 19.4 - 24.5
- 24.6 - 29.8
- 29.9 - 35
- 35.1 - 96

Slope (°)

- 0 - 0.9
- 1 - 1.9
- 2 - 3
- 3.1 - 4
- 4.1 - 5
- 5.1 - 6.1
- 6.2 - 7.1
- 7.2 - 32.5

Map of high relief areas



- South limit of exposed bedrock
- North limit of Churchill low

Relief (m)

- 0 - 45
- 46 - 102

Data sources:
DEM: CDED 1:50,000
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

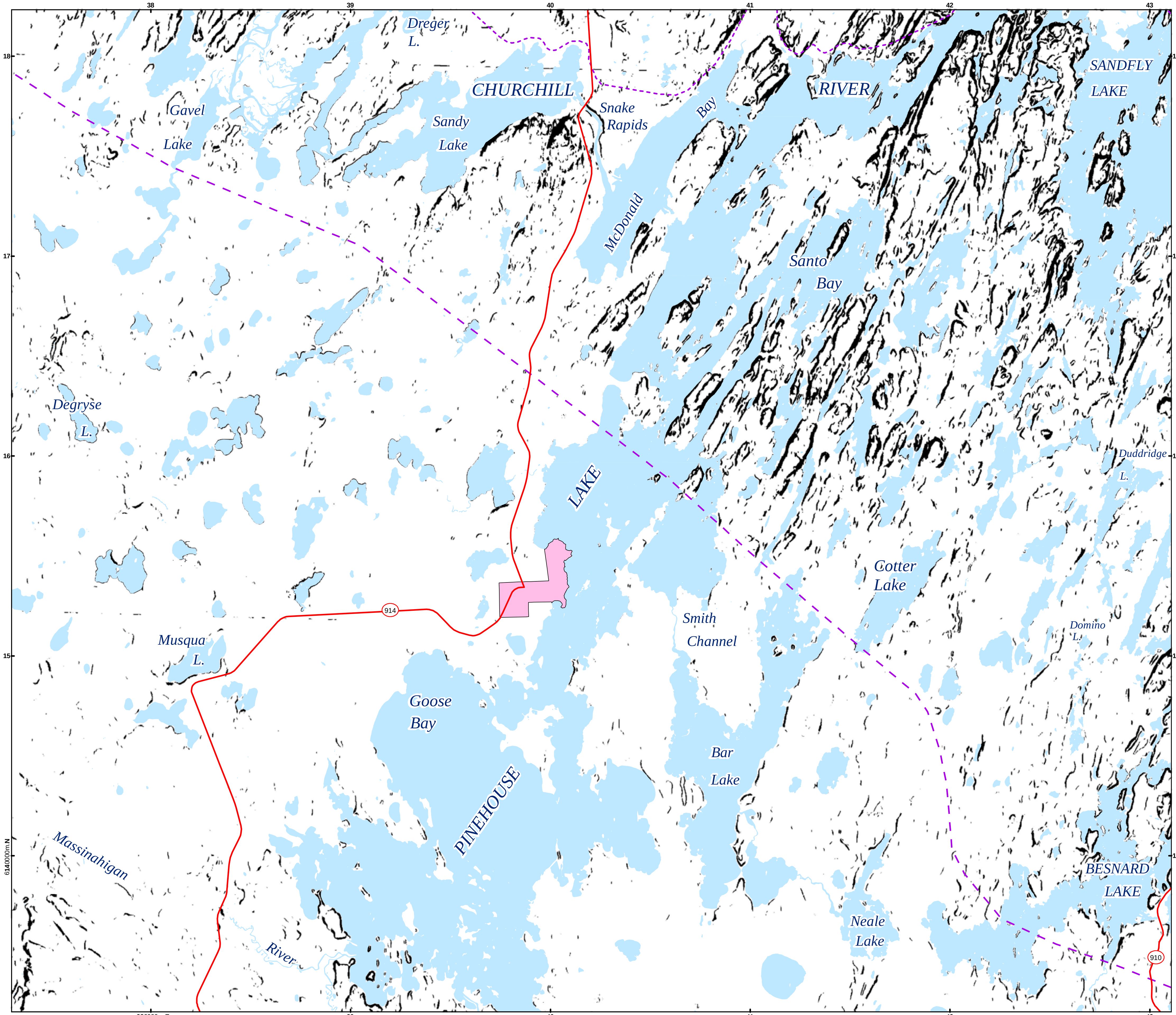
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Range in elevation within 250 m radius

DESIGN	DVZ	25 JUN 2012	FIGURE 7	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000



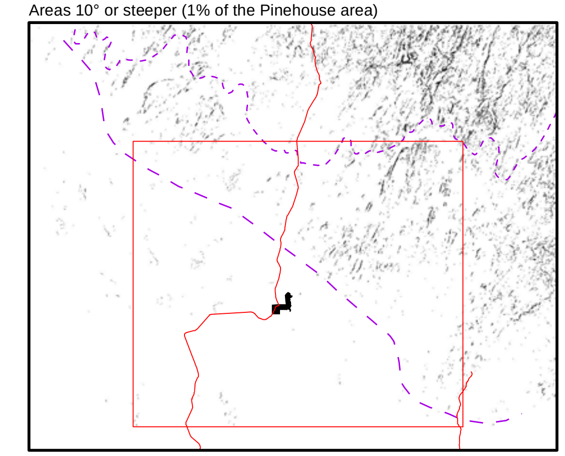
LEGEND

- Main road
- Village of Pinehouse
- North limit of Churchill low
- South limit of exposed bedrock
- Waterbody

Slope (°)

- 0 - 6
- 6.1 - 32.5

Areas 10° or steeper (1% of the Pinehouse area)



- North limit of Churchill low
- South limit of exposed bedrock

Slope (°)

- 0 - 10
- 10.1 - 32.8

Data sources:
DEM: CDED 1:50,000
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

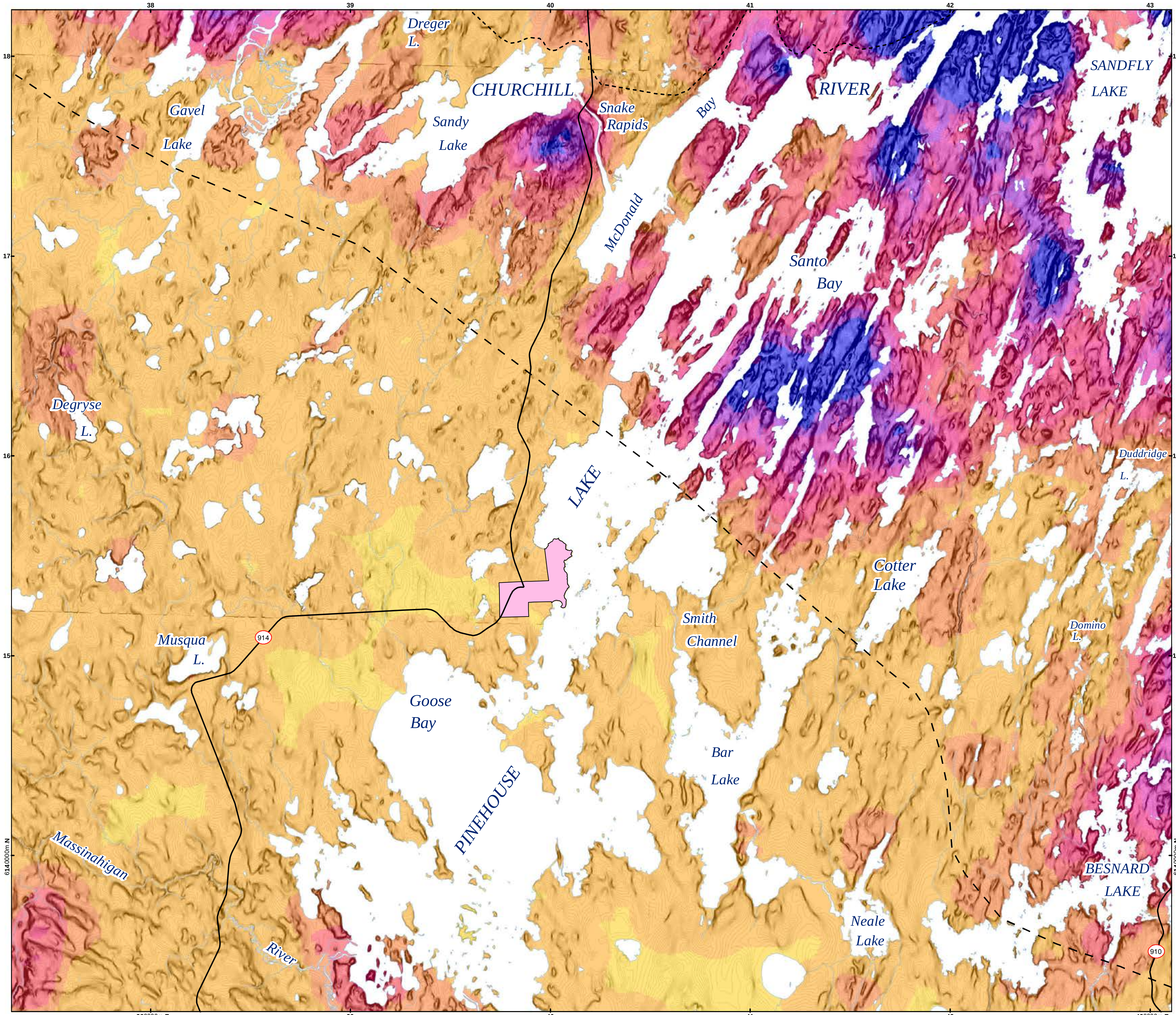
5 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Areas 6° or steeper in the Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 8	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000



LEGEND

- Main road
- Village of Pinehouse
- North limit of Churchill low
- South limit of exposed bedrock
- Waterbody
- Watercourse

Slope density

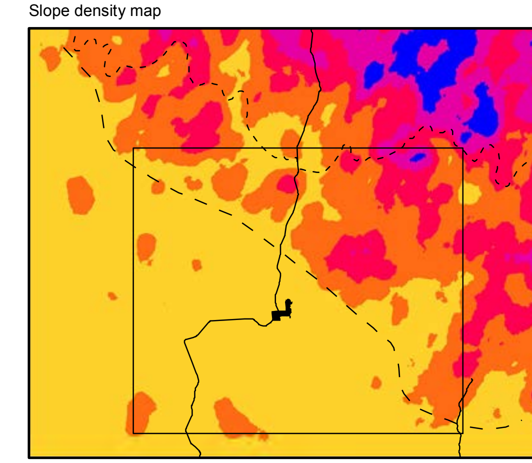
Points\km^2

- 0 - 2
- 2.1 - 73.9
- 74 - 145.8
- 145.9 - 217.8
- 217.9 - 289.7
- 289.8 - 361.6
- 361.7 - 433.5
- 433.6 - 505.5
- 505.6 - 947.4

Slope (°)

- 0 - 0.9
- 1 - 1.9
- 2 - 3
- 3.1 - 4
- 4.1 - 5
- 5.1 - 6.1
- 6.2 - 7.1
- 7.2 - 32.5

Slope density map



- North limit of Churchill low
- South limit of exposed bedrock

Slope Density

Point/km^2

- 0 - 90
- 91 - 353
- 354 - 617
- 618 - 880
- 881 - 1,301

Data sources:
DEM: CDED 1:50,000
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT,
TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE

Density of steep (≥6˚) slopes within 2 km radius

DESIGN	DVZ	25 JUN 2012	FIGURE 9	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000

LEGEND

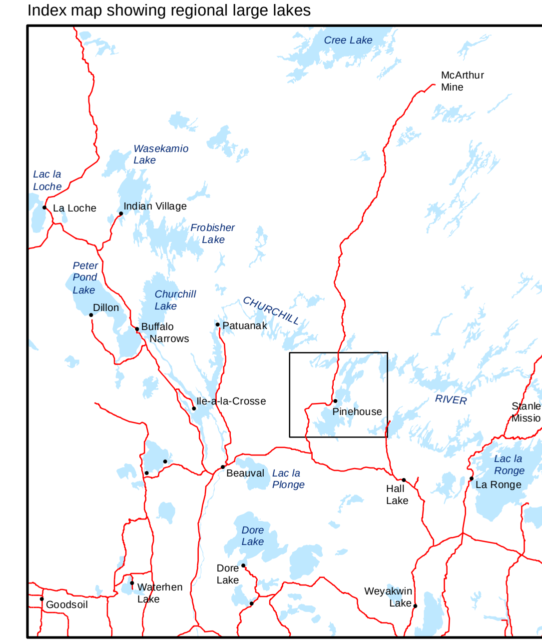
- Village of Pinehouse
- Main road
- North limit of Churchill low
- South limit of exposed bedrock
- Watercourse
- Wetland

Waterbody

Depth data

- Yes
- No

Index map showing regional large lakes



- Pinehouse area
- Main road
- Large lake

Data sources:
Road: CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Wetland: CanVec 1:50,000 & FRI

NORTH

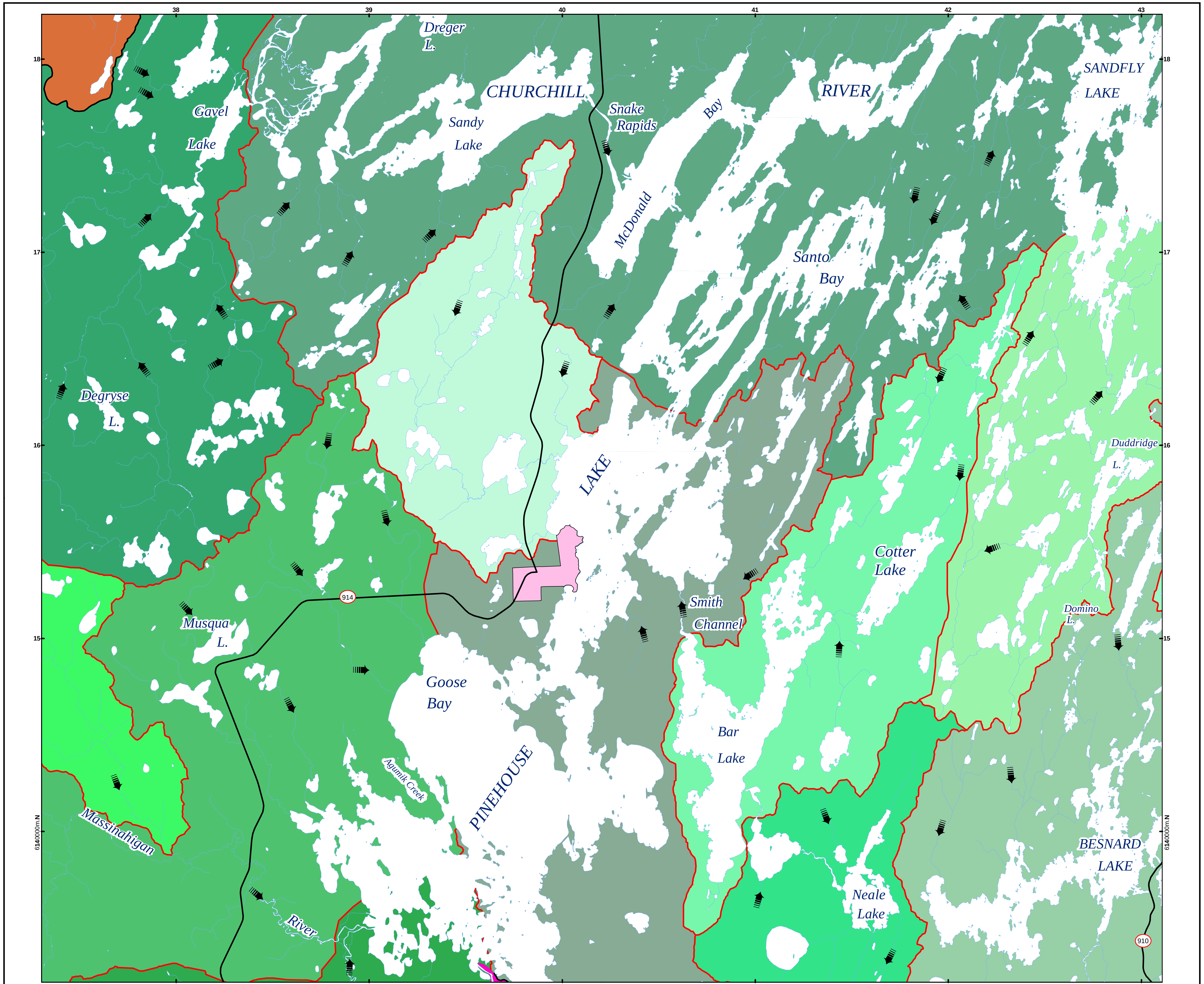
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT,
TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Surface drainage features of the Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 10	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000



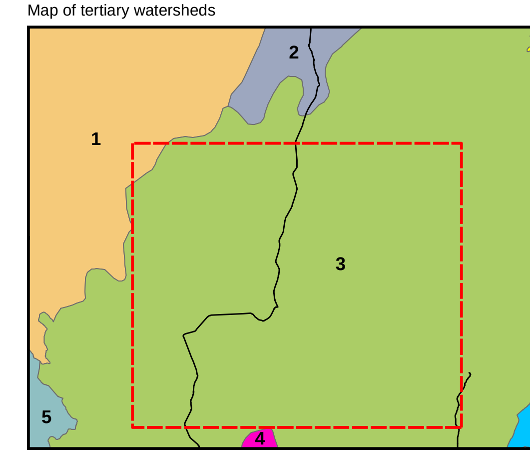
LEGEND

- Main road
- Village of Pinehouse
- Flow direction
- Watercourse
- Waterbody

Drainage divide

- Confirmed (PFRA\JDMA)
- Modelled (JDMA)

Map of tertiary watersheds



Tertiary watershed

- 1 - Upper Churchill
- 2 - Haultain
- 3 - Central Churchill
- 4 - Smoothstone
- 5 - Lower Beaver
- 6 - Foster
- 7 - Rapid

Data sources:
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Watershed: See Section 4.2

NORTH

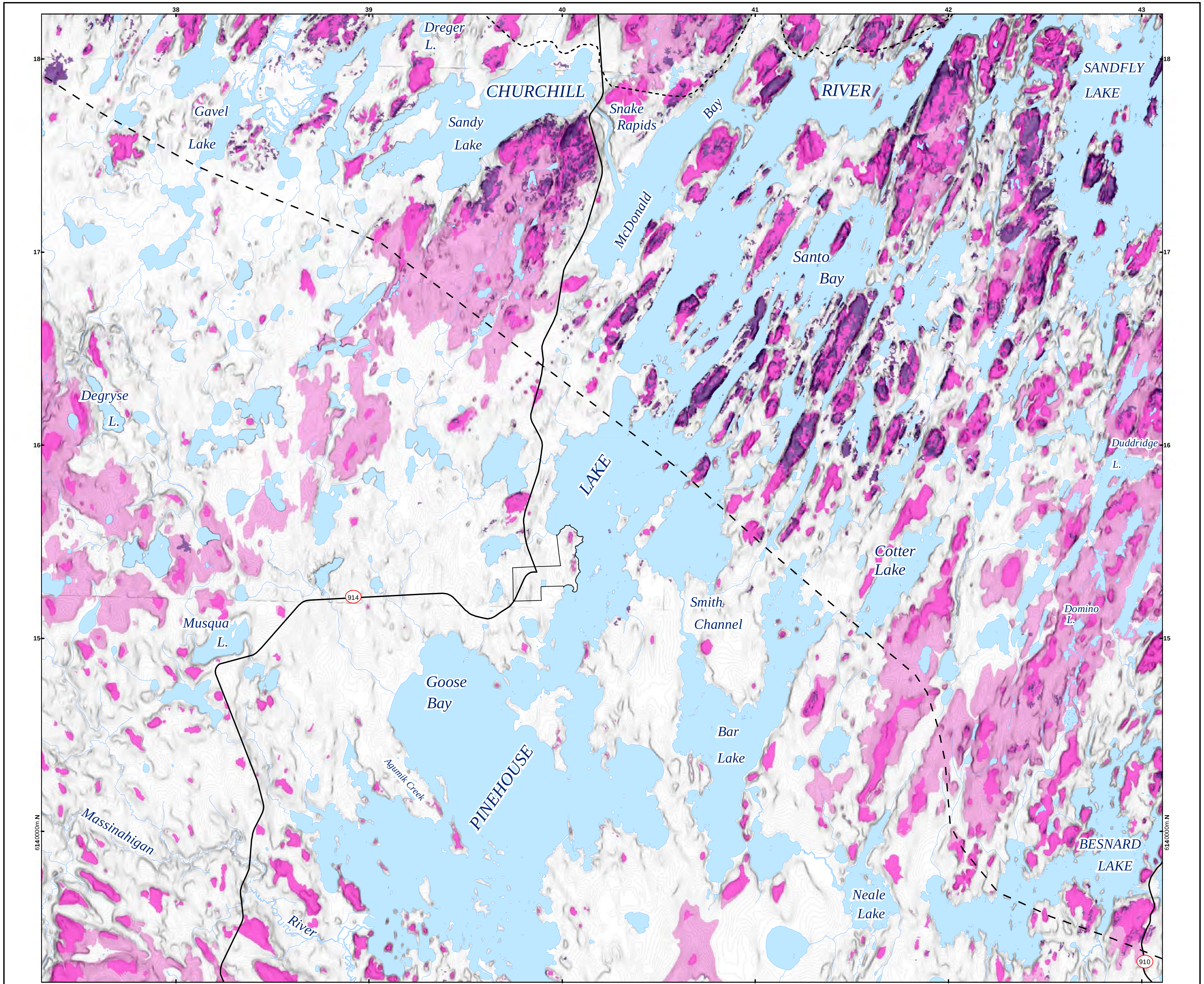
5 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Watersheds of the Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 11	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000



LEGEND

- North limit of Churchill low
- South limit of exposed bedrock
- Main road
- Village of Pinehouse
- Watercourse
- Waterbody

Forest Resource Inventory (FRI)

- Treed or clear rock

Relief (departure) within 2 km

Metres

- -35.1 - 10
- 10.1 - 75.2

Relief (departure) within 20 km

Metres

- -44.8 - 10
- 10.1 - 108.5

Slope (°)

- 0 - 0.9
- 1 - 1.9
- 2 - 3
- 3.1 - 4
- 4.1 - 5
- 5.1 - 6.1
- 6.2 - 7.1
- 7.2 - 32.5

Data sources:
Relief: CDED 1:50,000
Road: ISC SURN11
FRI: Sask Forest Resource Inventory
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

5 km

J D MOLLARD

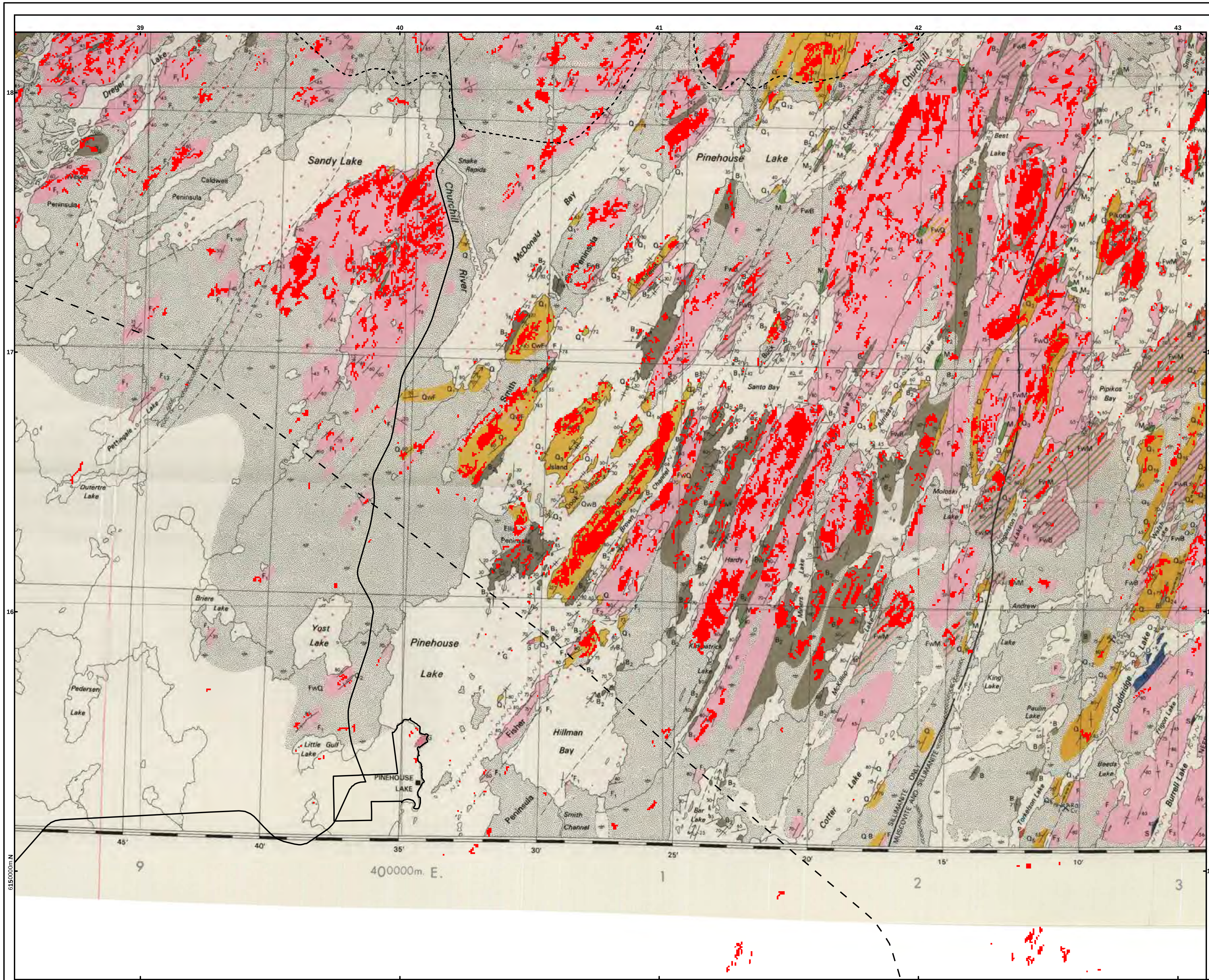
PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE

Sask FRI areas of treed or cleared bedrock

DESIGN	DVZ	25 JUN 2012	FIGURE 12	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:200,000

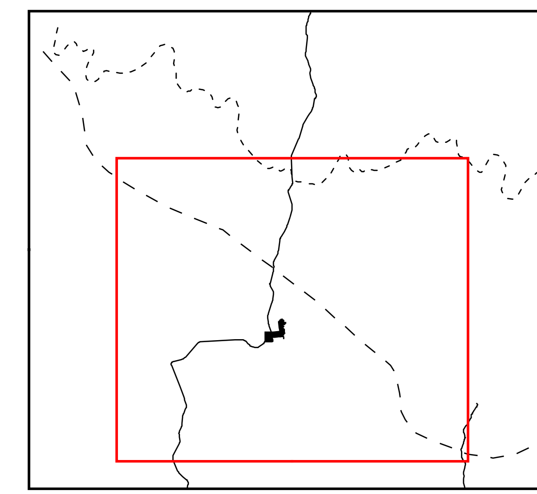


LEGEND

- Main road
- Village of Pinehouse
- North limit of Churchill low
- South limit of exposed bedrock
- FRI treed or clear rock

Post-D_1 fold axis	
Mineral lineation	
Outcrop visited	×
Outcrop, not visited	
Lithological contact; defined, approximate, extrapolated	
Fault or shear zone	
Structural trend, visible on air photographs	
Airborne electromagnetic anomaly	
Mineralized Outcrop (U_3O_8, uranium; Ra, radioactivity; Mo, molyodenum; Cu, copper; po, pyrhotite; py, pyrite; fl, flourite)	
Glacial striae	
Esker	
Muskeg	
Frost heave	△

Glacial drift



Data source:
Geology: Munday (1978b) 1:100,000
FRI: Sask Forest Resource Inventory
Road: ISC SURN11

NORTH
2 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, PINEHOUSE AREA, SASKATCHEWAN

TITLE
Areas of thick drift in east-central part of Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 13	REVISION 4
GIS	JAO	07 AUG 2013		UTM ZONE 13
CHECK	DVZ	07 AUG 2013		NAD 1983
REVIEW	GS	07 AUG 2013		1:150,000