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

ENGLISH RIVER FIRST NATION, SASKATCHEWAN

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PHASE 1 DESKTOP GEOSCIENTIFIC PRELIMINARY ASSESSMENT

TERRAIN AND REMOTE SENSING STUDY

ENGLISH RIVER FIRST NATION, SASKATCHEWAN

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EXECUTIVE SUMMARY

In January 2012, the English River First Nation (ERFN), Saskatchewan, expressed interest in learning more about the Nuclear Waste Management Organization's (NWMO) nine-step site selection process, and requested that a preliminary assessment be conducted to assess the potential suitability of the ERFN 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 ERFN 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 ERFN area (Golder, 2013). The main information sources used include the Canadian Digital Elevation Data (CDED) elevation model, the SPOT satellite imagery, and the maps and reports from the Saskatchewan Geological Survey (SGS). 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 report provides an overview of the bedrock and Quaternary geology within the ERFN area, including estimates of overburden thickness. Drainage divides delineated in the Prairie Farm Rehabilitation Administration (PFRA) sub-basin file were reviewed and further sub-divided to assess surface water flow patterns. Most of the area's drainage network is contained within five major tertiary level watersheds. Each of these watersheds was further sub-divided into quaternary level watersheds. All surface water flow in the ERFN area is to the Churchill River, which flows to Hudson Bay, except for a small area in the northwest near Birch Lake that drains to the Arctic

Ocean. Shallow groundwater flow within surficial and bedrock aquifers in the ERFN 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 constraint in the ERFN area is the lack of existing roads to facilitate site characterization activities in the best areas of exposed bedrock. Any new roads would need to be routed around the many lakes, rivers, wetlands and steep slopes that characterize the rugged terrain of the Precambrian Shield. No roads related to forest harvesting are present within the area.

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1 INTRODUCTION

In January 2012, the English River First Nation (ERFN) 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 ERFN 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 study completed as part of the desktop geoscientific preliminary assessment of the ERFN area (Golder, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the ERFN area contains general siting areas that are potentially suitable for hosting a deep geological repository based on available geoscientific information and the geoscientific evaluation factors outlined in the NWMO site selection process. The study focussed on the ERFN area and adjacent areas shown on Figure 1.

1.1 OBJECTIVES

This report presents a synopsis of the terrain in the ERFN 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 are the Canadian Digital Elevation Data (CDED) elevation model, the SPOT satellite imagery, and the maps and reports describing the surficial geology of the ERFN area produced by the Saskatchewan Geological Survey (SGS). 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 ERFN area (Section 1.2) using the data and methodology described in Section 1.3.

1.2 LOCATION

Based on the initial screening of the ERFN area (Golder, 2011), the areas located in the Athabasca Basin and Western Canada Sedimentary Basin (Regions 1 and 3) have been excluded from further consideration as potentially suitable for hosting a deep geological repository. Only the Canadian Shield region (Region 2) is considered in this report. To maintain continuity with the initial screening report for the ERFN area (Golder, 2011) and thus avoid confusion during cross-reference, the regional boundary for this preliminary geoscientific assessment is also referred to as Region 2. The ERFN area is a rectangular area approximately 119 by 126 km in size, encompassing an area of about 15,000 km^2. The approximate western, northern, eastern and southern limits of the ERFN area are (UTM Zone 13, NAD83): 321700, 6308800, 439900, and 6182300 m. The ERFN area was further divided into sub-regions near the reserve lands, which were reviewed in greater detail. The sub-regions are referred to as Sub-region 2.1 (Haultain Lake), Sub-region 2.2 (Porter Lake and Flatstone Lake) and Sub-region 2.3 (Dipper Rapids, Primeau Lake, Knee Lake and Elak Dase). Figure 1 shows the extent of these sub-regions, which are further described in the desktop geoscientific preliminary assessment (Golder, 2013).

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 ERFN area, including an evaluation of the quality of the data. The data sets used in this study are all publically available.

1.3.1 SGS MAPS AND REPORTS

The available surficial mapping for the ERFN area is regional in scale. As a result, considerable reliance has been placed on the use of other datasets such as SPOT and CDED for any detailed interpretations or analysis, such as for delineating and characterizing the main areas of exposed bedrock and thin drift.

Overburden deposits within the ERFN 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 two main SGS Quaternary geology map sheets covering the ERFN area (Figure 1) are the Mudjatik and Ile a la Crosse areas (Schreiner, 1984d, e). In addition, the eastern margin of the ERFN area is included within the Foster Lake and Lac la Ronge areas (Schreiner, 1984c; Schreiner and Alley, 1984). Mapping of the Mudjatik and Ile a la Crosse areas was conducted in 1976 and 1977. One hundred and twenty nine sites were visited in the Mudjatik area (Schreiner et al., 1976; Schreiner, 1977), accessed entirely by float-equipped aircraft, as there were no roads in the area at the time of mapping. At virtually all sites, an overburden sample was collected as well as a lake sediment sample collected using a torpedo-like sampler. Twenty-eight sites were inspected within the Ile a la Crosse area, which were located within the northeast portion of the map sheet, where the Precambrian Shield is exposed. Aside from the brief descriptions of the Quaternary geology provided in the SGS summary of investigations (Schreiner et al., 1976; Schreiner, 1977), there are no reports dedicated to describing the drift deposits and terrain conditions of these map areas. 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 useful for understanding terrain conditions in the ERFN area.

In addition to the surficial geology maps and reports described above, areas of extensive drift cover lacking bedrock outcrops have been delineated in maps covering parts of the three sub-regions within the ERFN area (Munday, 1977; Pearson, 1977; Scott, 1977). Scanned copies of these maps have been georeferenced and included in this report. Section 5.2.5 provides an evaluation of the drift cover delineation presented in these maps based on a comparison of the surficial geology map and remote sensing data.

1.3.2 CDED

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

Canadian Digital Elevation Data (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 ERFN area. The digital elevation models (DEM) used for this study were constructed by the Mapping Information Branch of Natural Resources Canada (NRCan) using 1:50,000 scale source data from the National Topographic Data Base (NTDB). The topographic 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 data sets 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 ERFN 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. This relief calculation was useful for delineating areas of thin drift (Section 3.2). The second was defined as the range in elevation within a circular window.

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 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 rock outcrops, wetlands and other features within the ERFN area (GeoBase, 2011b). SPOT multispectral data consist of several bands, each recording reflected radiation within a particular spectral range, and each having a radiometry of 8-bits (or a value ranging from 0-255) (Table 1). SPOT 4 and 5 images were acquired using the HRV-IR and HRG sensors, respectively. Each image covers a ground area of 60 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). A comparison of lake shorelines in the SPOT imagery with those delineated in the CanVec 1:50,000-scale waterbody file suggests that the georeference is generally accurate to within 20 to 40 m or better.

Nine SPOT images (or ‘scenes’) provided complete coverage for the ERFN area (Table 2). The scenes are from both SPOT 4 and 5 satellites acquired between 2006 and 2009, with seven of the scenes acquired during the late summer/early fall (Sep. or Oct.) and two during the late spring (May or Jun). The images captured during May and June cover the east-central and southeast parts of the ERFN area, covering parts of the Haultain Lake and Primeau Lake areas.

In order to assist with the interpretation of the location and extent of bedrock outcrops in the ERFN 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 mode generally represents waterbodies, but it 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 good 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 & 5 multispectral bands.

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

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

Scene ID	Satellite	Date of image
S4_10548_5653_20090914	SPOT 4	September 14, 2009
S4_10626_5558_20060516	SPOT 4	May 16, 2006
S4_10641_5653_20060902	SPOT 4	September 2, 2006
S4_10658_5626_20060902	SPOT 4	September 2, 2006
S4_10712_5558_20080910	SPOT 4	September 10, 2008
S4_10752_5626_20081011	SPOT 4	October 11, 2008
S5_10611_5626_20070604	SPOT 5	June 4, 2007
S5_10737_5653_20060911	SPOT 5	September 11, 2006
S5_10805_5558_20061027	SPOT 5	October 27, 2006

After some effort in attempting to produce good results from the unsupervised classification, it was found that there remained challenges in using this technique to make an accurate appraisal of the extent of bedrock exposure. One issue was that different landscape features could exhibit similar spectral characteristics as bedrock. For example, exposed mineral soil, certain parts of wetlands, and alluvial sediment in creek valleys display similar spectral properties as bedrock. Another issue was the altered vegetation patterns associated with a history of forest fires throughout the area including several large recent burns, which complicates attempts at unsupervised classification. The ERFN area lies within the Observation Zone of the

Saskatchewan Wildfire Management Plan, where wildfires are observed rather than supressed, with intervention considered based on the value of the loss compared with the costs of suppression. Consequently, our interpretation of bedrock exposures from the SPOT imagery has relied on the PCA composite images rather than on unsupervised classification.

1.3.4 Drill holes and water wells

A preliminary review was made of data on overburden thickness obtained from databases compiled by the SGS and the Saskatchewan Water Security Agency.

Water well records were acquired for the ERFN area from the Water Well Information Database produced by the Water Security Agency. Six wells were found within the ERFN area, located near the Northern Hamlet of Patuanak (Figure 1). One additional well was found near Highway 918 about 5 km south of the southern boundary of the ERFN area. The coordinates of three of the wells are accurate to within a quarter section (± 570 m) whereas those of the other four are accurate to within a section (± 1,140 m). The wells were drilled between 1974 and 1992. Six of the seven wells contain information on depth to bedrock (see 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 eight holes drilled in the Phanerozoic basin within or a short distance beyond the southwest corner of the ERFN area. Four of these records contain data on depth to bedrock. The La Ronge database contains records for 10 drill holes within the ERFN area and another 19 a short distance to the east, all of which contain data on depth to bedrock. The vertical depth to bedrock was computed using borehole inclination and depth down the inclined borehole 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 Branch of the Ministry of Environment is responsible for identifying and describing the forested areas of the Province of Saskatchewan. They provide a Forest Vegetation Index dataset, part of which identifies non-forested areas such as rock, muskeg, and developed agricultural land. The Forest Vegetation Index was created based on the interpretation of 1:15,000 air photos, as well as ground truthing and aerial reconnaissance (Saskatchewan Environment, Forest Service, 2004). Close inspection of the dataset indicates that in some areas, the polygons have smooth boundaries that appear to have been delineated manually. In other parts of the dataset, the polygon boundaries are pixelated, which gives the impression that the mapping was done somewhat automatically from a raster image.

This could be a useful dataset for gaining an appreciation of the extent of exposed bedrock over the entire ERFN area. However, these data are only available for the south central part of Sub-region 2.3 and an area extending south of the southern boundary of the ERFN area. The majority of the “non-productive” polygons are classified as treed rock or clear rock. A comparison of the SPOT imagery with the non-productive areas mapped around Knee Lake indicates that several significant areas of exposed bedrock shown in the SPOT imagery were not mapped in the Forest Resource Inventory. Consequently, even if these data were available for the entire ERFN area, additional mapping would be required to complete the delineation of exposed bedrock.

2 SUMMARY OF GEOLOGY

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

2.1 REGIONAL BEDROCK GEOLOGY

The ERFN area lies on rocks of the Canadian Shield. The Canadian Shield is a collage of ancient (Archean) cratons, accreted juvenile arc terranes, and sedimentary basins that were progressively amalgamated over a period of more than 2 Ga during the Proterozoic Eon. Among the major orogenies that contributed to the assembly of the Canadian Shield is the Trans-Hudson Orogen, which resulted from the closure of the Manikewan ocean and terminal collision of the Rae-Hearne, Superior and Sask cratons during the approximate period 1.9 to 1.8 Ga (Ansdell, 2005; Corrigan et al., 2005; Corrigan et al., 2007; Corrigan et al., 2009; Hajnal et al., 2005; Whitmeyer and Karlstrom, 2007). The Canadian Shield now forms the stable core of North America, and was the first part of the continent to be permanently elevated above sea level.

Regional geophysical surveys have been 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 ERFN 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 include airborne magnetic, gravity, airborne radiometric, audio magnetotelluric and deep seismic surveys (Lucas et al., 1993; Lewry et al., 1994; Hajnal et al., 2005; White et al., 2005). The geophysical trends of the major Precambrian structures within the regional area (i.e., Mudjatik and Wollaston domains) can be traced to the south beneath the Western Canada Sedimentary Basin (White et al., 2005), particularly the magnetic high of the Wollaston domain, which is one of the most prominent magnetic features in the Canadian Shield. These geophysical trends are traceable to some degree to the north, beneath the Athabasca basin. These trends reflect the fact that the rocks of the regional area are the oldest, forming the stable continental craton beneath the entire area, which were then overlain by the younger rocks adjacent to the regional area (Whitmeyer and Karlstrom, 2007; Corrigan et al., 2009). The aeromagnetic response decreases into the Mudjatik domain.

The ERFN area is located within the Hearne craton, which forms the eastern portion of the Western Churchill Province of the Canadian Shield. The Hearne craton (south of the Athabasca basin) is generally composed of high-grade metamorphic Archean to Paleoproterozoic rocks older than 1.8 Ga, such as gneissic granitoid rocks, metasedimentary rocks and granitic rocks (Orrell et al., 1999). The Hearne craton (historically called Cree Lake zone) is further divided into several lithostructural domains (Figure 2) (Lewry and Sibbald, 1980), with most of the ERFN area being primarily located within the Mudjatik domain and only a small portion of it in the Wollaston domain in the south-east corner near Knee Lake and the north-east corner east of Haultain Lake (Figure 2). The western boundary of the Mudjatik domain, to the west of the ERFN area, has been historically marked by the Cable Bay shear zone. This structural feature divides the Mudjatik domain from the Virgin River domain further to the west. However, a new domainal reclassification has been proposed where these two domains are to be merged and renamed as the Mudjatik domain (Card, 2012). For the purpose of simplicity, the old domainal classification has been retained in this report, given that it is used by all referenced sources and does not impact the objectives of this assessment.

To the east, the Mudjatik domain is generally thought to pass transitionally into the Wollaston domain (e.g., Munday, 1977, 1978; 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 (Lewry and Sibbald, 1980). Annesley and Madore (1989, 1991, 1994) and more recently Annesley et al. (2005), however, have argued that the boundary between both domains corresponds with a major crustal transcurrent fault-shear zone or 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 have been reported in the literature. Furthermore, Tran et al. (1999) did not find evidence of this structural feature in the McKenzie Falls area, and Tran and Smith (1999) pointed out that such a structural feature was not existent in the area of the Cup-Keller-Schmitz Lakes and that if a domain boundary existed then it must have existed in pre-Hudsonian Orogeny time.

The eastern portion of the ERFN area, which falls in the Wollaston domain, is bounded to the east by the Needle Falls shear zone, adjacent to the Wathaman batholith of the Reindeer zone (Delaney, 1993; Yeo and Delaney, 2007). The Needle Falls shear zone is a prominent topographic feature. The contact with the Needle Falls shear zone is sharp and distinct (Munday, 1978). The Reindeer zone consists, from west to east, of the Wathaman batholith and the Rottenstone, La Ronge, Kisseynew, Glennie and Flin Flon domains (Ansdell, 2005), where the Wathaman batholith stitches the Archean Hearne Province to the domains of the Reindeer zone.

The rocks of the Mudjatik and Wollaston domains are bounded on the south and overlain by Phanerozoic rocks of the Western Canada sedimentary basin, in the southwest corner of the ERFN area, whereas to the north, rocks of the Hearne Province are overlain by sedimentary rocks of the Athabasca Group, within the Athabasca basin (Figure 2).

The Mudjatik domain consists of extensive 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 that distinguishes the Mudjatik domain from 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 metasedimentary rocks and subordinated metavolcanic rocks of the Wollaston domain form the Wollaston Supergroup (as defined by Yeo and Delaney, 2007), which was deposited along the eastern edge of the Hearne craton first in a rift/passive margin setting marking the opening of the Manikewan ocean, and later in a foreland basin setting, due to the 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 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.

2.2 Geological history

Direct information on the geological and structural history of the ERFN 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. 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 ERFN 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 chronology of tectonic events that occurred during the Trans-Hudson Orogeny provides a framework for the understanding of the structural conditions of the region and in particular for the ERFN area. The important phases of the Trans-Hudson Orogeny that influenced the present structural conditions observed in the rocks of the region are summarized in Table 3, based on several past geological investigations in the region (e.g., Cumming and Scott, 1976; Lewry and Sibbald, 1980; Stauffer and Lewry, 1993; Ansdell, 2005, Ansdell et al., 2005; Corrigan et al., 2005; Hajnal et al., 2005; Card and Bosman, 2007; Corrigan et al., 2007; Whitmeyer and Karlstrom, 2007; Card et al., 2008; Corrigan et al., 2009).

Around 2.075 Ga initial deposition of the Wollaston Supergroup took place in a passive to incipient rift setting on the eastern side of the Hearne craton. Between 1.92 and 1.88 Ga, deposition continued on the Hearne craton. To the east of the Hearne craton, a series of tectonic assemblages, including the La Ronge-Lynn Lake arc and a series of arc oceanic assemblages coexisted in the Manikewan ocean. Late during this interval, the Manikewan ocean began closing, due to a subsequent reversal in the subduction polarity, bringing together various arc assemblages against each other and against the Hearne craton, resulting in the formation of the Wollaston domain in a back-arc basin setting and the Rottenstone magmatic arc. The collision and associated regional D_1 deformation overprint imparted an early (S_1) foliation within the felsic gneisses.

Ongoing subduction between ca. 1.88 and 1.865 Ga resulted in the accretion of juvenile island arc terranes (La Ronge-Lynn Lake) to the southeastern margin of the expanded Rae-Hearne craton forming the Rottenstone accretionary complex. During the same period of time, the Wollaston back-arc basin shifted to a foreland basin.

Table 3 Summary of the geological and structural history of the ERFN 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 S_1 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 the formation of the Rottenstone accretionary complex, while the Wollaston back-arc basin shifted to a foreland basin.
1.865 to 1.83	Closure of Wollaston basin at approximately 1.86 Ga with concomitant emplacement of Wathaman batholith between ca. 1.865-1.855 Ga along eastern margin of Rae-Hearne craton. Regional D_2 ductile deformation produced upright folds that overprinted the S_1 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 NNE-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 (1.8 Ga ago) and the D_5 steep-brittle faults observed within the Wollaston domain, extending into the Mudjatik domain.
1.72 to 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.

Final accretion of the La Ronge Arc along the eastern margin of the Rae-Hearne craton brought closure of the Wollaston basin (approx. 1.86 Ga) and emplacement of the Wathaman batholith sometime between ca. 1.865-1.855 Ga. Ongoing subduction between ca. 1.845 and 1.83 Ga was associated with the accretion of the Glennie-Flin Flon domain to the Hearne craton and the northward migration of the Sask craton micro-continent. The deformation involved underthrusting beneath the Rae-Hearne craton along the Pelican thrust, Duck Lake shear zone, Granville Lake structural zone, and Nistowiak thrust. A contemporaneous, ca. 1.865 to 1.83 Ga, D_2 ductile deformation event produced upright folds that overprinted the S_1 foliation.

Terminal collision with the Superior craton and final closure of the Manikewan ocean occurred between ca. 1.83 and 1.8 Ga. The collision produced the thick-skinned imbrication evident in the Mudjatik domain and it produced the thin-skinned imbrication evident in the Wollaston domain. Deformation features that formed during this event of crustal shortening are assigned to the D_3 ductile deformation episode. D_3 created north-northeast-striking upright folds, dominant in the Wollaston domain, and resulted in D_3 activation (re-activation?) of the Needle Falls and Virgin River shear zones at ca. 1.83 Ga. Subsequently, D_4 ductile deformation created NW-striking upright folds orthogonal to F_3. D_4 is poorly constrained in absolute timing but is interpreted to have post-dated the formation of the Virgin River and Cable Bay shear zones (e.g., Card et al., 2007).

Later deformation involved the development of regional-scale brittle structure, including the Tabbernor fault zone (ca. 1.80 Ga) and the steeply-dipping brittle faults observed within the Wollaston domain (Figure 2). These brittle structures are assigned to the D_5 deformation phase. An additional brittle deformation event, D_6, may also be included in the deformation history. Although poorly constrained, the D_6 event is interpreted to encompass all post-1.695 Ga brittle deformation events that overprinted the entire region. The dominant feature associated with D_6 is the large-scale Tabbernor fault system, which has a long history of re-activation that may have continued until the Mesozoic Era (e.g., Byers, 1962; Elliott, 1996).

Mesoproterozoic rocks (i.e., approximately 1.6 Ga) of the Athabasca Basin nonconformably overlie Precambrian basement rocks approximately 40 km to the north of the ERFN area. The Athabasca Basin has an elliptical shape in map view, extending over 400 km in the east-west direction and over 200 km in the north-south direction. The basin consists primarily of fluvial sandstones derived from the Hudsonian mountains and deposited in a shallow tropical sea basin. The maximum thickness of the basin is about 1.5 km at its centre (Card et al., 2010). The unconformity between the flat-lying and weakly deformed Athabasca Group and the highly strained underlying Archean basement rocks is where the uranium deposits of northern Saskatchewan are typically found (Jefferson et al., 2007).

Phanerozoic rocks (i.e., rocks younger than 541 Ma) 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 and the southwest corner of the ERFN area (Figure 2). 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 of Ordovician age (approximately 485 to 443 Ma) nonconformably overlie the Precambrian basement approximately 200 km southeast of the ERFN area. These rocks represent 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 close 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, it can be suggested that the ERFN 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 (i.e., 252 to 66 Ma). The erosional edge of the Mesozoic succession cuts across the southwest corner of the ERFN area and is characterized by sedimentary rocks of Cretaceous age (i.e., 145 to 66 Ma). 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 Mesozoic cover in the ERFN area is uncertain. However, given the proximity of the erosional edge of these rocks, it is likely that coverage was extensive in the ERFN area.

2.3 REGIONAL STRUCTURAL HISTORY

The tectonic and structural history of the Hearne craton, as described above, includes several regionally distinguishable deformation episodes inferred to also have overprinted the bedrock geological units of the ERFN area (Byers, 1962; Munday, 1977; Munday, 1978; Tran and Smith, 1999; Card and Bosman, 2007; Yeo and Delaney, 2007; Card et al., 2008). Although the age of these deformations is difficult to determine precisely, within the Mudjatik and Wollaston domains, five phases of deformation (referred to as D_1 to D_5 below, with corresponding fold sets indicated by F_n, and foliation indicated by S_n) can be identified (Yeo and Delaney, 2007; Card et al., 2008), and are consistent with the geological history described in Section 2.2 above. The numbering system established by Card et al. (2008) is adopted here and in the following discussion.

There is some disagreement between different authors regarding the sequence of deformation events in this part of northern Saskatchewan. For example, a discrepancy in the application of the D_x terminology to distinct folding events whereby Annesley et al. (2005) do not appear to recognize the same number of folding events as were recognized by Card and Bosman (2007) and Card et al. (2008). The study by Annesley et al. (2005) was undertaken in the area to the east of the Athabasca Basin, much further from the ERFN area than the work undertaken by Card and Bosman (2007) and Card et al. (2008). For the discussion below, the primary sources for the interpretation was the report by Card and Bosman (2007) and Card et al. (2008). It is understood that this is only a preliminary interpretation for the ERFN area, which may be altered if the community is chosen by the NWMO and if they decide to remain in the siting process.

The earliest recognizable deformation event (D_1) resulted in supracrustal and felsic rocks being isoclinally folded. 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 ERFN area. Little information is available regarding this event, and it was not reported in earlier studies (e.g., Munday, 1978).

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 ERFN area and towards the Needle Falls shear zone near the southeast corner of the ERFN 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 late during or after the D_3 event, 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) note that the F_4 folds are 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 ERFN area, crosscutting the structures associated with the D_1 to D_4 events (Figure 2). These features have likely had a long history of re-activation consistent with the interpretation that they are related to the Tabbernor fault system, located about 150 km to the east of the ERFN area. The orientations of D_5-related lineaments are dominantly north-northwest and minor east-northeast sets (Figure 2), possibly associated with movement along the north-south-striking Tabbernor fault. The Tabbernor fault initially formed during the Trans-Hudson Orogeny approximately 1.83 Ga, but has likely had more recent periods of reactivation, as features in overlying sedimentary rocks and apatite fission track dating indicate reactivation of the fault in the late Devonian and early Cretaceous (Elliot, 1996; Davies, 1998; Hajnal et al., 2005).

2.4 QUATERNARY GEOLOGY

The Quaternary deposits in the ERFN area comprise different types of glacial deposits that dominantly accumulated with the progressive retreat of the ice sheet during the end of the Wisconsinan glaciation. Regionally, the main surficial deposits include morainal plains, and glaciofluvial plains, with sparse occurrences of glaciolacustrine plains. Glaciofluvial plains mainly consist of flat outwash deposits located within meltwater channels. Both types of glacial deposits are primarily sandy, with varying amounts of silt and clay (Schreiner, 1984a).

The Cree Lake moraine extends through the ERFN area (Figure 3). This moraine is the most prominent and significant end moraine on the Precambrian Shield of Saskatchewan, tracing for about 800 km across the Shield, east into Manitoba and northwest into Alberta (Schreiner, 1984b). The moraine extends discontinuously as a band of hummocky debris from northwest to southeast across the ERFN area, where the width of the moraine is typically about 2 km in the northwest and about 500 m in the southeast. The Cree Lake moraine is better expressed topographically outside of the ERFN area, where it can reach heights of 45 to 75 m above the surrounding landscape (Schreiner, 1984b). Locally, the moraine consists of dominantly sandy till covered in boulders (Schreiner et al., 1976).

A spillway along the Mudjatik River cuts through the Cree Lake moraine in the northwest part of the ERFN area, indicating that the moraine acted as a temporary dam, ponding melt water to the north where some isolated glaciolacustrine deposits associated with Glacial Cree Lake are mapped. Black Birch Lake is a modern lake formed against the moraine (Figure 3). Schreiner (1977) suggests that the overburden deposits north of the moraine are dominated by sand and gravel. South of the moraine, thin deposits of sandy till form the predominant drift deposit type outside of the Mudjatik and Haultain river valleys, which represent major meltwater channels associated with extensive outwash deposits. Drumlins are mapped just outside and to the east of the ERFN area, and eskers are generally restricted to the northeast part of the area.

Since the disappearance of the ice sheets and the gradual draining or drying up of glacial lakes approximately 9,000 years ago, modern streams have developed alluvial flood plains and organic deposits have accumulated in wet depressions. The largest organic deposits mapped in the ERFN area are associated with the major outwash deposits (Figure 3). Many organic deposits of peat and muck much smaller than can be represented on a regional surficial geology map are located in the depressions between rock and till ridges. Many of these deposits are delineated as wetlands in the 1:50,000 scale topographic map data. Section 5.2 provides further detail on the distribution, composition and thickness of surficial deposits in the ERFN area.

3 TOPOGRAPHY

The ERFN 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 ERFN area rely heavily on the representation of the landscape by the CDED digital elevation model.

3.1 ELEVATION

The landscape surrounding the ERFN area (Figure 4) ranges in elevation from about 631 metres above sea level (masl) near Norbert Lake to 385 masl on the Churchill River in the southeast near Sandfly Lake, and it features two major topographic highs, informally referred to here as the Haultain and Norbert highs after lakes situated on the highlands. The two highlands are divided by the valley of the Haultain River. The Haultain high extends southwest from near Haultain Lake towards the centre of the ERFN area. A subsidiary highland in the centre of the ERFN area, somewhat of an extension of the Haultain high, contains Blackstone, Complex and Holt lakes. The Norbert high represents a prominent northeast trending highland in the east-central part of the ERFN area. Local summits on the Haultain and Norbert highs are at about 620 to 631 m elevation, representing 200 to 250 m of relief down to the Churchill River.

The major topographic lows in the area are informally referred to here as the Heddery and Churchill lows (Figure 4). The Churchill low represents the area of lowermost elevation within the ERFN area where the Mudjatik and Haultain rivers empty into the Churchill River, which traverses along the southern fringe of the Precambrian Shield. The Heddery low is the low-relief outwash plain south of where the Cree Lake moraine is best expressed within the area, from its junction with the Mudjatik River to Black Birch Lake. The Heddery low forms a plain extending eastward into the Haultain high, disconnecting the highland around Complex Lake from the main part of the Haultain high to the northeast. The Heddery low represents a prominent Quaternary landform in the ERFN area, perhaps even more prominent than the Cree Lake moraine. It makes up an area of about 1,400 km^2 and the flatness of the sand plain is interrupted only occasionally by rock ridges that extend like islands from the surrounding outwash plain. There is also a smaller outwash plain located in the valley of the Haultain River, here referred to as the Sylvester plain, a short distance downstream of the Cree Lake moraine, at the intersection of Sylvester Creek. The relatively large size of the Heddery low compared with the Sylvester plain could suggest that the Mudjatik River was the dominant outflow for Glacial Cree Lake in this area.

3.2 RELIEF

Relief is a metric that can be defined in different ways, and the calculated value of relief depends on the horizontal dimension considered in the calculation. Relief was calculated in two ways. The first was by subtracting the average elevation within a certain radius from the elevation value in the processing cell (termed departure), providing an indication of the degree to which a point is expressed negatively or positively 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 establish broad areas of topographic prominence where overburden deposits are typically thinnest and bedrock exposures are relatively abundant. This provides further definition of the Haultain and Norbert highs and the area of high ground around Complex Lake. The inset map provided on Figure 5 shows the areas with at least 15 m of prominence. The Norbert high appears as a relatively intact zone of high ground about 15 km wide by 90 km long extending north-northeast and coinciding with the area of the Wollaston domain mapped as felsic gneiss (Figure 2). In contrast, the Haultain high and the highland around Complex Lake appear to be much more fragmented, perhaps reflecting the dome and basin structural style of the Mudjatik domain. The major depression containing the Haultain River is likely a product of preferential erosion of the weak underlying pelitic and psammitic gneisses compared with the relatively erosion resistant felsic gneisses in the adjacent highlands, although it is also possible that the valley was eroded along a major transcurrent fault-shear zone (e.g., Annesley et al., 2005).

The inset map in Figure 5 reveals the blocks of high ground within the sub-regions where bedrock exposure and thin drift are most likely. The areas with at least 15 m of prominence match closely with the areas mapped as morainal veneer or bedrock in the inset map in Figure 3, although in many cases, the areas with 15 m of prominence provide a better definition of the areas of thin drift and abundant bedrock exposure suggested in the SPOT imagery. As a result, it is worth describing the blocks of high ground within the sub-regions.

Within Sub-region 2.1, no blocks of high ground east of Highway 914 are shown on Figure 5, which is consistent with the area being mapped as drift-covered in Figure 3. A short distance west of Highway 914, there are two small areas of high ground southeast of Haultain Lake. One of the more rugged blocks of high ground in the sub-region is a roughly north south trending chain of hills between Selmes and Lunnin lakes in the centre of the sub-region. The largest blocks of high ground in Sub-region 2.1 are located in the northwest corner, where the SPOT imagery displays many hills with exposed bedrock scattered amongst small lakes and wetlands. Except for the northwest quadrant, drift fills the lows more extensively in the other quadrants in this sub-region and this is believed to be an important part of the reason why very few major north-northwest trending faults have been mapped here (Figure 2).

There is an alignment of drumlinized rock ridges extending parallel with and about 15 km to the north of the line marked as the Churchill low (Figure 5). Many of these ridges display steeper slopes on the up-ice (or stoss) sides and there is a weak tendency for a streamlined or teardrop shape on the down-ice side. These hills extend through both Sub-regions 2.2 and 2.3. The hills within this chain with the best bedrock exposure are located in the north-central part of Sub-region 2.3. The glacially sculpted morphology of these hills combined with abundant drift deposits surrounding the hills is expected to obscure the identification of major faults in the north-central part of the sub-region. The only major north-northwest trending faults mapped in the sub-region are located in the eastern third of the sub-region (Figure 2), which represents the least interrupted large area of thin drift in the sub-region.

In Sub-region 2.2, areas of morainal veneer with exposed bedrock extend further north into the northwest quadrant of the sub-region than is suggested by Figure 3, and these areas are outlined very generously by the blocks of high ground shown on the Figure 5 inset. Some of the best exposure there is found on ridges south and southwest of Thompson Lake. Apart from these isolated areas, most of the exposed bedrock within Sub-region 2.2 is located east of the Mudjatik River. The best bedrock exposure in the sub-region is found on hills in the northeast corner, near

Porter Lake. The hills delineated in this area (Figure 5 inset) are very small, narrow features bounded by steep slopes and an intricate pattern of lakes.

In Sub-region 2.3, there are several north-northeast trending rock ridges with abundant bedrock exposure located in the north-central part of the sub-region, and most of the best areas of exposed bedrock are delineated by the areas of at least 15 m of topographic prominence shown on the Figure 5 inset. The blocks of high ground on the Figure 5 inset provide a more accurate image of the areas of thin drift than the generalized image provided by the surficial geology map (Figure 3 inset). Gentle slopes are present on the tops of some of the ridges. The eastern third of the sub-region contains abundant high ground associated with the southern extension of the Norbert high and the felsic gneisses of the Wollaston domain. The area of the sub-region east of Highway 914 and north of Gordon Lake contains many rock outcrops distributed amongst small lakes and wetlands. Bedrock outcrops appear to occur in association with steep slopes, with the only relatively flat-lying areas being covered by lakes, wetlands or overburden deposits. The most impressive areas of exposed bedrock are located southeast of Zaharik Lake and northwest of Wanamaker Lake.

A map of departures from the average elevation within a 2 km radius (Figure 6) can be used to further delineate local rock ridges and hills where overburden thickness is usually thinnest and bedrock exposures are relatively abundant. In many cases, the hills delineated using a 2 km search radius provide a refined delineation of the best areas of exposed bedrock over what is provided using a 20 km radius. The inset map shown on Figure 6 displays the areas with at least 10 m of prominence at this scale of calculation.

The extensive low-relief areas generally associated with thicker overburden deposits are shown in beige on Figure 6. The sand plains associated with the Heddery low and Sylvester plain stand out distinctly in this image. Many of the areas shown as strong negative departures on Figure 6 represent linear depressions associated with major bedrock structures. Many of these linear depressions are lake-filled or contain organic deposits. During deglaciation, it is expected that glaciolacustrine sedimentation associated with local ponding of meltwater would have occurred within many of these linear topographic lows. As a result, it is expected that excavation into the overburden deposits contained within these trench-like landforms would reveal late-glacial to post-glacial stratified silts and clays, which could record neotectonic deformation if the underlying bedrock structures have been reactivated post-glacially. Section 7 provides further discussion on the prospect of identifying evidence of paleo-seismic events from lake sediments contained within the linear depressions shown in blue on Figure 6.

A map showing the range in elevation within a 250 m radius (Figure 7) illustrates the distribution and extent of localized high and low relief areas within the ERFN area. The upper limit of relief calculated at this scale is about 115 m. Two important low-relief areas shown on Figure 7 are the Heddery low and the Sylvester plain. Local rock ridges typically from one to five kilometres in size extend as much as 50 m or more above the surrounding landscape.

3.3 SLOPE

Figure 8 is a map of slopes equal to or greater than 6° within the ERFN area, with an inset map showing the distribution of slopes at least 10°. Only about 14% of the ERFN area contains a value of slope of at least 6°, and about 4% of the ERFN area displays a slope value of 10° or more. As a result, in this landscape a value of slope of about 6° is considered steep. Areas of steep slope form the margins of many of the rugged landforms in the ERFN area such as ridges and trenches.

Note that in order for a lineament to be identified in the DEM, there would have to be some amount of slope to define the feature. Many of the areas lacking steep slopes are relatively flat due to the presence of overburden filling the topographic lows. As a result, a map showing the density of steep (≥6°) slopes within a 2 km radius was prepared to delineate the areas where the thickness of overburden might be concealing lineaments (Figure 9). Using this metric, the inset map on Figure 9 attempts to depict areas of thick drift where low surface lineament density would be expected due to the masking effect of drift. Note the general match between the areas of high slope density and the areas of thin drift shown on the Figure 3 inset.

The areas of low slope density shown on Figure 9 are areas where the DEM and to a lesser extent the SPOT imagery could be less reliable in identifying the presence or absence of a lineament. These are the areas where the lineament interpreter is blinded to some extent by the presence of thick overburden. The use of low slope density as an indicator of low confidence in identifying the presence or absence of a lineament also accounts for the areas covered by lakes, as the lakes are represented as flat surfaces in the digital elevation model. The use of slope density in this way is not entirely applicable to the identification of lineaments from the SPOT imagery. For example, some lineaments do not have a strong topographic expression, but are visible in satellite images by vegetation patterns associated with variations in moisture conditions. The slope density map is provided to suggest a broad pattern of the areas of thicker overburden where the lineament interpreter should expect a low density of lineaments mapped from the DEM.

It is worth noting the relative strengths and weaknesses of using topographic prominence (e.g., Figure 5 inset) versus slope density (Figure 9 inset) to generate an image of thin drift and abundant bedrock exposure in this landscape. Topographic prominence is generally believed to provide a better definition of the areas of thin drift. This is mainly because of the way that overburden deposits tend to accumulate in topographic lows. Slope density is insensitive to whether the steep slopes are associated with a topographic high or low. As a result, high slope density can be found in drift-filled topographic depressions where meltwater erosion has formed a steep-sided valley cut largely through drift deposits. The slope density calculation is also very coarse and provides a generalized image of thin drift. Whereas the topographic prominence calculations shown on Figure 5 and Figure 6 provide better detail and in many cases more accuracy in the delineation of thinly drift-covered areas.

4 DRAINAGE

The distribution of surface water and surface water drainage are important factors to consider in the preliminary assessment. The larger lakes, some of which are 5 to 10 km across, can conceal geological structures, and surface flow is a useful surrogate for groundwater flow at shallow depth. Section 4.1 provides information on the size and distribution of lakes and wetlands in the ERFN area. Section 4.2 describes the existing watershed map file and the drainage analysis conducted by JDMA, and Section 4.3 describes surface drainage within the ERFN area.

4.1 WATERBODIES AND WETLANDS

The ERFN area contains a large number of lakes of various sizes, with roughly 13% of the area occupied by waterbodies (Figure 10). About 98% of the waterbodies mapped in the ERFN area are smaller than 1.0 km^2, and many of these represent lakes formed within elongate depressions associated with geological structures. Only seventeen lakes within the ERFN area are larger than 10 km^2 (Table 4). The largest waterbodies represent a chain of lakes extending along the Churchill River within and around Sub-region 2.3. These waterbodies cover 338 km^2 and include Lac Ile a la Crosse, Shagwenaw Lake, Dipper Lake, Primeau Lake and Knee Lake. These lakes and some of the other large lakes are sufficiently large to conceal the surface expression of geological structures several kilometres in length. Many of the largest lakes are located in areas of thicker overburden cover. As a result, the combination of thick drift and extensive lakes in certain areas can result in considerable structural uncertainty. In contrast, the vast majority of lakes in the ERFN area do not conceal major structures, and some of the large lakes contain elongate bays and channels formed within structurally controlled depressions. Holt Lake and Blackstone Lake are two of the large lakes in the area that conceal virtually no major structures due to the intricate shape of their basins being controlled almost entirely by linear or arcuate bedrock depressions.

Within Sub-region 2.1, Haultain Lake is the largest lake and the main lake with potential to conceal geological structures. In Sub-region 2.2, Porter Lake and Flatstone Lake are the main lakes that could conceal structures. Porter Lake contains many channels and elongate bays that accentuate the bedrock structure, but the larger basin in the north could hide structures. In Sub-region 2.3, lakes along the Churchill River are the largest lakes, and they have significant potential to conceal lineaments from being detected in the lineament analysis (JDMA, 2013). Soaring Lake, Keller Lake and Gordon Lake could also obscure structures.

Table 4 Major lakes and river systems within the ERFN area.

Lake[1]	Perimeter (km)	Area (km^2)
Churchill River	916.0	338.4
Black Birch Lake	169.5	66.6
Porter Lake	270.2	53.8
Keller Lake	115.4	28.5
Gordon Lake	79.8	28.3
Haultain Lake	65.4	22.4
Ithingo Lake	52.7	18.3
Flatstone Lake	61.3	18.3
Unnamed Lake	61.5	17.2
Little Flatstone Lake	56.4	17.1
Heddery Lake	21.6	15.8
Soaring Lake	68.3	13.2
George Lake	49.5	12.6
Forcier Lake	20.7	11.4
Holt Lake	73.4	11.1
Blackstone Lake	102.4	10.4

[1]Metrics obtained from CanVec waterbody file

Wetlands depicted on Figure 10 are from the 1:50,000 CanVec topographic data produced by Natural Resources Canada, including a wetland file and a file depicting string bogs. These files suggest that wetlands cover 13% of the ERFN area (1,962 km^2). This is a reasonably complete image of the wetlands in the area, as determined using the SPOT imagery. However, many small wetlands throughout the area are not included. Many of these unmapped wetlands are small features located within bedrock depressions, although several unmapped wetlands of intermediate size exist in the southwest and heavily drift-covered portion of Sub-region 2.3.

The distribution of extensive wetlands in the ERFN area should correlate with the main areas of extensive, flat-lying, poorly drained overburden deposits (Figure 10). The Heddery low, Sylvester plain and the valley of the Mudjatik River between Thompson and Forcier lakes contain the most extensive wetlands in the area. In contrast, wetlands in areas of thin drift are relatively limited in size. The Norbert high and the topographic high containing Blackstone, Complex and Holt lakes are examples of thinly drift-covered areas with wetlands of small size. Wetlands of intermediate size can be found in areas of thicker drift, where the wetland is confined by topographic highs associated with morainal or bedrock topography. For example, most wetlands south of the Churchill low are elongate features confined between morainal ridges; the largest wetlands north of the Cree Lake moraine are expected to be associated with thicker drift deposits confined within bedrock depressions.

Bathymetric maps are a potentially useful source of information for identifying surface structures and for understanding the vertical extent of lake basins. Unfortunately, no contoured bathymetric maps exist for lakes within the ERFN area. Shagwenaw Lake is the only lake in the ERFN area for which a depth survey is known to have been conducted by the Saskatchewan Ministry of Environment. Shagwenaw Lake records a maximum water depth of 16.5 m. Depth information is available for several large lakes outside of the ERFN area (Table 5), which indicate maximum depths ranging from about 15 to 60 m.

Table 5 Depth data on large lakes outside the ERFN 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 regional and local groundwater and surface flow directions.

The best available drainage area delineation for the ERFN 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 ERFN area average around 5,000 km^2 in size and include subdivisions of the Environment Canada tertiary drainage areas extending into the ERFN area.

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 are shown on 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 subdivide the PFRA sub-basins where possible. It is important to note that the PFRA sub-basins do not represent the smallest catchments that can be delineated in most areas, as local ridges and highland complexes that serve to divide surface flow are present within many of the basins. The average extent of the watersheds delineated by JDMA that are completely contained within the ERFN area is about 500 km^2, an order of magnitude smaller than the PFRA sub-basins in this area.

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 JDMA had to limit the minimum size of basin in order to maintain a consistent scale of delineation across the ERFN area. Where drainage divides created by JDMA matched reasonably with the PFRA sub-basin boundaries, the procedure was to accept the existing 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 JDMA and PFRA (0) or only JDMA (1).

4.3 SURFACE FLOW

All of the surface flow within the ERFN area drains through the Churchill River towards Hudson Bay, except for a small area around Black Birch Lake draining towards the Arctic Ocean through the Athabasca River. PFRA sub-basins extending into the area are drained by the Churchill, Clearwater, Haultain, Mudjatik and Wheeler rivers.

Surface flow within Sub-region 2.1 is divided between the Haultain and Mudjatik tertiary watersheds by a northeast trending drainage divide in the northwest corner of the area (Figure 11). Most of the flow draining into the Haultain River is divided into two watersheds by a linear complex of bedrock knobs extending south from near the west tip of Haultain Lake. The largest catchment in the sub-region contains several small lakes, of which Lunnin Lake is an example. The watercourses in this area typically display an orthogonal fabric of north-northwest and east-northeast trending features reflecting the influence of bedrock structure. Most of the wetlands in the area are confined within the narrow troughs between bedrock highs, with only a few relatively large wetlands in locations expected to be more broadly covered with thick drift deposits, such as west of Lunnin Lake and south of Selmes Lake.

Surface flow within Sub-region 2.2 is complex, with flow in adjacent watersheds oriented in opposite directions. Flow from the high ground surrounding Porter Lake is directed north into Porter Creek, while in the central part of the sub-region it is directed southward along the Mudjatik River. Aside from the high ground in the northeast, poorly drained outwash plains and drumlinoid ground moraine dominate much of the terrain in the sub-region, where some of the most extensive wetlands in the ERFN area are found. Hydrometric gauging stations existed historically at Porter Lake and on the Mudjatik River near the southern boundary of the sub-region. Stream flow was recorded on the Mudjatik River for 25 years from 1971 to 1995 with an average monthly discharge of about 25 m^3/s.

The main drainage features in Sub-region 2.3 are the chain of large lakes associated with the Churchill River and the mouth of the Haultain River. Flow within the Churchill River is directed eastward through Dipper, Primeau, and Knee lakes. A large delta is formed where the Churchill empties into Dipper Lake, and another delta extends for several kilometres where the Haultain River empties into the Churchill River. Drainage from the high ground north of the sub-region is directed along several unnamed creeks. The west half of the Sylvester plain contains an extensive wetland. The portion of the sub-region south of the Churchill River is poorly drained, as indicated by the abundance of relatively large wetlands (Figure 10). The southeast corner of the sub-region is within the Central Churchill watershed (Figure 11).

5 TERRAIN CHARACTERISTICS

An understanding of the distribution and thickness of overburden within the ERFN 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. Information on the distribution of drift deposits is also important for understanding the distribution of unfavourable bedrock formations such as ultramafic rocks, marble and pelitic and amphibolitic gneisses. For example, many of the areas of thick and extensive drift in the Mudjatik domain were broadly mapped by default as felsic gneiss for lack of any bedrock exposures to indicate the presence of other rock types. Conversely, most of the areas in the Mudjatik domain mapped as rocks other than felsic gneiss are located in thinly drift-covered areas. As a result, areas of exposed bedrock or thin drift are more readily amenable to site characterization for a deep geological repository, as such locations would enable further investigation of the potentially suitable bedrock formations through outcrop mapping of bedrock structures and lithologies and preliminary rock mass characterization.

Details on the expected composition, distribution and thickness of surficial deposits within the terrain units mapped in Figure 3 are presented in Section 5.2. Section 5.1 summarizes the limited available information on overburden thickness from water well and drill hole data.

5.1 WATER WELL AND DRILL HOLE DATA

5.1.1 WATER WELL DATA

As described in Section 1.3.4, the Water Well Information Database contains seven water wells that are located within or a short distance (5 km) south of the ERFN area. The five wells near Patuanak with data on depth to bedrock indicate overburden thicknesses of about 30 to 60 m with an average of 40 m (Table 6).The well located south of the ERFN area near Highway 918 indicates a much greater overburden thickness (90 m) than the wells near Patuanak. The well data provide an indication for the possible depths of overburden over the Western Canada Sedimentary Basin (Figure 2).

Table 6 Data on depth to bedrock from water well data.

Well ID	Date	Water use	Location	Depth to bedrock (m)	Well depth (m)
013343	1974.03.08	Research	South of ERFN area[1]	89	90
102271	1992.09.01	Municipal	Patuanak	31	36
013344	1974.03.06	Domestic	Patuanak	58	59
054962	1976.09.02	Municipal	Patuanak	35	37
055442	1976.09.03	Domestic	Patuanak	31	37
047630	1976.03.24	Domestic	Patuanak	45	49
047631	1976.03.23	Domestic	Patuanak	n/a	37

[1]Well located about 5 km south of the southern boundary of the ERFN area near Highway 918.

5.1.2 DRILL HOLE DATA

The SGS maintains drill hole databases for cores held in the Regina and La Ronge core libraries. The available drill hole data were introduced in Section 1.3.4 and data from the two databases have been plotted separately on Figure 3.

Four of the eight drill holes in the Phanerozoic basin (Regina database) within or near the ERFN area contain depth to bedrock data that indicate overburden thickness of about 15 to 60 m. These values are generally consistent with those obtained from the water well data, supporting the expectation that thick drift deposits cover the Phanerozoic basin within this area.

The 29 drill holes in the La Ronge database within or near the ERFN area indicate depths to bedrock ranging from zero to about 40 m with an average of 8 m. Although these data are limited in terms of spatial distribution and number of available drill holes, they are generally consistent with the image of terrain conditions generated from regional surficial geology mapping (Figure 3). That is, thinner overburden deposits are suggested in areas mapped as rock. For example, drill holes located in areas mapped as rock on the Norbert high indicate depths to bedrock of about 1 to 10 m. In contrast, most of the higher values of depth to bedrock are located within mapped surficial deposits. For instance, two holes advanced in or near the glaciofluvial deposit within the small valley west of Hewetson Lake (east of the ERFN area) indicate depths to bedrock of about 35 to 40 m; and the two holes drilled in the glaciolacustrine deposit west of Pederson Lake (east of the ERFN area) indicate depths of about 15 to 20 m.

5.2 SGS TERRAIN UNITS

This section provides details on the expected composition, distribution and thickness of surficial deposits within the terrain units mapped in Figure 3.

5.2.1 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). As is discussed further in Section 5.2.5, the morainal veneer (Mv) map unit and the rock (R) map unit shown on Figure 3 were determined to be essentially equivalent in the ERFN area after inspecting the amount of exposed bedrock and the degree to which the bedrock structure is expressed in both units throughout the area.

In contrast with areas mapped as moraine plains and drumlinoid moraine, bedrock topography is only minimally obscured in areas of morainal veneer. The surface expression of faults, shear zones and other geological structures are generally displayed clearly in these areas. After mapping the northern two thirds of the ERFN area, Schreiner (1977) suggested that south of the Cree Lake moraine, sandy till is so thin in some areas that the underlying bedrock structure is detectable. Topographic maps (Section 3) suggest that the high ground containing Blackstone, Complex and Holt lakes is a good example of an area where thin drift results in a pronounced surface expression of the bedrock structure. In areas of thicker ground moraine, preferrential deposition of till in low areas between rock ridges can mask the relief of the bedrock topography. Areas of thicker more continuous ground moraine are generally represented as morainal plain, hummocky moraine or drumlinoid moraine (Schreiner, 1984b). In some areas, ground moraine occurs in association with small unmapped areas of glaciolacustrine silts and clays typically deposited in depressions.

Schreiner (1984b) describes drumlins north of the ERFN area that are approximately 30 m thick from the top of the drumlin to the bedrock surface. Flutings are restricted to areas of thicker drift. They represent smoothly rolling ridges and troughs with relief on the order of 10 m. Although no drill hole data from within mapped morainal deposits on the Precambrian Shield portion of the ERFN area exist, drill holes on the Norbert high (Section 5.1.2) advanced in areas mapped as rock are likely representative of values expected in the broad areas mapped as morainal veneer in Figure 3.

5.2.2 Glaciofluvial

Within the ERFN area, sand and gravel can be found along the valleys of the Mudjatik and Haultain rivers, which functioned as major meltwater channels during deglaciation (Schreiner et al., 1976). Schreiner (1984b) suggests that of the Mudjatik, Haultain, Foster and Paull rivers, the Mudjatik and Haultain were the more substantial meltwater channels, as indicated by the wide sand plains bordering these rivers, especially south of the Cree Lake moraine. Eskers have been mapped within the north and northeast parts of the ERFN area.

Schreiner (1984b) indicates that large outwash fans or aprons composed of stratified sands occur south of the Cree Lake moraine, and he suggests that the thickness of most outwash deposits in northern Saskatchewan is between 5 and 10 m. North of the Cree Lake moraine, the outwash material is generally coarser, ranging from stratified sand to sand and gravel, and the outwash occurs as a discontinuous veneer of sand and gravel overlying till or bedrock.

Two drill holes advanced in a glaciofluvial deposit mapped west of Hewetson Lake (east of the ERFN area) reported depths to bedrock of about 35 to 40 m, indicating that total overburden thickness can be quite large within these deposits.

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.

5.2.3 Glaciolacustrine

Schreiner et al. (1976) observed a scarcity of glaciolacustrine deposits in the Ile a la Crosse map area, which includes the southern part of the ERFN area, and they suggested that glacial Lake Agassiz did not extend this far westward. Glaciolacustrine deposits, which were likely associated with Glacial Cree Lake, have been mapped within the northwest and northeast parts of the ERFN area (Figure 3). Other glaciolacustrine deposits have been mapped near Little Flatstone Lake and Fiest Lake (east of the ERFN area). Total overburden thickness recorded in two boreholes advanced within the glaciolacustrine deposit west of Pederson Lake (east of the ERFN area) range from about 15 to 20 m.

As noted in Sections 5.2.1 and 5.2.5, glaciolacustrine deposits too small to be included within the regional surficial geology map are expected to exist within areas mapped as morainal veneer or bedrock, where the glaciolacustrine deposits occur as silts and clays deposited in depressions.

These unmapped glaciolacustrine deposits could be associated with local ponding of meltwater during deglaciation, and they are mentioned in Section 7 for the possibility that the stratified silts and clays could record deformation associated with post-glacial reactivation of lineaments due to isostatic uplift following deglaciation.

5.2.4 ORGANIC

Organic deposits are composed of peat and muck, and they are generally associated with stagnant drainage or wet surface conditions. Within the ERFN area, the major organic deposits are located within the Heddery low, Sylvester plain and along the valley of the Mudjatik River between Thompson Lake and Forcier Lake (Figure 3). Wetlands, such as swamps, bogs, fens, and muskeg are established on most organic deposits. As a result, a much more detailed image of the organic deposits in the ERFN area than what is presented in Figure 3 can be obtained from the map of wetlands shown on Figure 10 and discussed in Section 4.1.

Exceptionally poor engineering characteristics can be found within organic deposits. Peat and muck have very low shear strength and high compressibility. Groundwater tables are at or near the surface within organic deposits, and flooding is common and 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. Organic deposits overlying the extensive outwash deposits described above are expected to be relatively thin compared with those deposited within high-relief basins in the areas mapped as morainal veneer or rock. The locations of deeper pockets of organic material are difficult to predict reliably without test drilling.

Organic deposits are important features to consider in road routing. Part of the rationale for locating Highway 914 along the valley of the Haultain River (Mollard et al., 1977) was that the organic deposits in the outwash plains along the valley were suspected to be much thinner from those deposited within deep basins within the bedrock terrain along the alternate route to the east.

5.2.5 BEDROCK

In general, northern Saskatchewan contains large tracts of land that consist of rugged to undulating bedrock terrain that generally contain a thin mantle of drift, which can be much thicker locally, especially in the lows between bedrock hills. Within areas mapped as bedrock, patches of sandy till should be the dominant deposit type, although glaciolacustrine silt and clay could occupy depressions, especially in areas bordering onto lowlands. The thickness of drift over the bedrock surface should vary substantially over short distances, and in general, it should be relatively thin (up to 1 to 2 m) on ridge tops and thicker in depressions. Within areas mapped as rock, bearing capacities are usually excellent, blasting is required for excavations, earth borrow is scarce, groundwater resources are unpredictable, and trafficability is poor.

After inspecting the distribution of rock outcrops displayed in the SPOT imagery and the degree to which the bedrock structure was expressed in the DEM, it was found that the amount of bedrock exposure and the degree to which the rock structure was expressed in the DEM appeared to be equivalent in the areas mapped as morainal veneer and rock. The delineation of rock versus morainal veneer in some cases on the surficial geology map appears poorly selected. The most realistic image of the extent of thin drift and abundant bedrock exposure using the available surficial geology map is provided when the bedrock and morainal veneer map units are grouped (Figure 3 inset). As a result, the information presented in this section should apply equally to the areas mapped as morainal veneer.

Drill holes located in areas mapped as rock on the Norbert high (some of which are shown on Figure 3) indicate depths to bedrock of about 1 to 10 m. These values are probably typical of much of the areas in Figure 3 mapped as rock or morainal veneer. An isolated borehole in an area mapped as rock near Zaharik Lake in the northeast corner of Sub-region 2.3 indicates 19 m of overburden. However, it is possible that drilling was conducted on a lake-ice platform and the height of the water column was included in the anomalous depth to bedrock value reported in the drill hole database.

The georeferenced bedrock maps presented in Figure 12 to Figure 14 provide an alternate source of information on areas of thicker drift deposits, and conversely on areas of thin drift and abundant bedrock exposure, to that presented in Figure 3. These maps have been provided as an additional dataset for understanding the extent of overburden deposits in the sub-regions. A comparison of the drift covered areas shown on the bedrock maps was made with those shown on Figure 3 to illustrate some limitations of both datasets for the purpose of quality control. The comparison is described below for Sub-region 2.1 followed by Sub-region 2.3.

Figure 12 illustrates a close match between the areas not mapped as drift in the bedrock map and those mapped as morainal veneer in the surficial map for Sub-region 2.1. This suggests that the areas not mapped as drift in the bedrock map are roughly equivalent to the morainal veneer map unit in Figure 3. However, there are some large areas not mapped as drift in the bedrock map, which were mapped as thicker drift deposits in the surficial map. Examples include the area east of Highway 914 in the southern part of the sub-region and the area in the southwest part of the sub-region. This observation largely points out a limitation in the completeness of the drift mapping depicted on the bedrock map. Another issue identified in this comparison was that the two areas near Haultain Lake mapped as rock in the surficial map appear to be poorly selected, pointing out the unreliability of the areas mapped as rock in the surficial map. That is, the area depicted as rock south of Haultain Lake represents an east west trending depression with small lakes and wetlands. It is unclear why this depression was depicted as rock in the surficial geology map. In addition, the area mapped as rock to the northwest of Haultain Lake was delineated as drift and muskeg in the bedrock map.

It is worth pointing out some discrepancies between the areas mapped as drift in the bedrock and surficial geology maps in Sub-region 2.3 to illustrate further the limitations of the 1:250,000 scale surficial mapping. Figure 14 presents bedrock mapping by Scott (1977) at the scale of 1:63,360, which shows a realistic image of the areas of least drift cover being located along the tops of rock ridges, as discussed in Section 3.2. However, many of these areas were not mapped as morainal veneer or rock in the surficial map. This illustrates how the coarse scale of the surficial geology mapping results in large areas of thin drift not being delineated as morainal veneer or bedrock.

Section 3.2 provided a relief map (Figure 5 inset) that delineated blocks of high ground within each sub-region. This map and the associated descriptions of the main areas of exposed bedrock provide the best available information on the areas of exposed bedrock in the sub-regions.

5.2.6 TERRAIN SUMMARY

An assessment of the areas of thin drift and exposed bedrock is important for the siting of a deep geological repository. Areas of exposed bedrock or thin drift are more readily amenable to site characterization for a deep geological repository, as such locations would enable the investigation of bedrock formations within and surrounding the siting area through surface-based bedrock, structural and engineering geological mapping. The morainal veneer and rock classes in the regional surficial geology map provide a reasonable image of the areas of thin drift and exposed bedrock in the ERFN area. However, the inset map in Figure 5 shows the main blocks of high ground where the SPOT imagery generally suggest the main areas of thin drift and a relative abundance of exposed bedrock are located. This map also has limitations, but it is generally believed to provide a reasonably accurate and more detailed image of the areas of thin drift than Figure 3. The blocks of high ground within each sub-region were described in Section 3.2. In this landscape, the inset map in Figure 5 provides a more detailed image of the main areas of thin drift than the slope density map (Figure 9), as described in Section 3.3.

6 GROUNDWATER

Golder (2013) provides a thorough discussion of the hydrogeology of the ERFN 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 (Figure 11). Steep slopes and the general absence of thick drift deposits in the highland areas mapped as rock or morainal veneer should promote surface runoff into the valleys and low areas. The Haultain and Norbert highs and the high ground centred on Complex Lake represent the major highlands from where surface flow and shallow groundwater flow will recharge the major aquifers in the adjacent topographic lows represented by the valleys of the Mudjatik, Haultain and Churchill rivers. The rivers and lakes within the three main river valleys represent the regional discharge zones.

Shallow bedrock aquifers within the highland areas mapped as rock or morainal veneer are expected to be associated with discontinuities. A large proportion of the groundwater in this terrain is probably confined to discontinuities in the upper 40 to 60 m of bedrock, with permeability varying from impervious to highly pervious, depending on discontinuity spacing, persistence and aperture. Major structures such as the steeply dipping, north-northwest trending brittle faults mapped throughout the highlands could represent the deepest bedrock aquifers in the highlands, and they could recharge aquifers in the major valleys.

Thick and extensive drift deposits within the three major valleys create uncertainty in the extent to which major structures could exist within the valleys and to what extent such structures could be associated with deeper bedrock aquifers. The valley of the Haultain River, which forms the boundary between the Wollaston and Mudjatik domains, could be a major transcurrent fault-shear zone (e.g., Annesley et al., 2005). The outwash deposit forming the Sylvester plain is a potentially important type of aquifer, given its location at the intersection of a major north-northwest trending brittle structure and the boundary between the Wollaston and Mudjatik domains. The flat and depressed expression of the plain could reflect a zone of weakness associated with a major fault intersection, in which case the outwash deposit would represent a surficial aquifer underlain by a deeper bedrock aquifer associated with the fault intersection. Apart from the possibility of deeper bedrock aquifers described above, 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

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 overprinted onto the tectonic stress field may result in seismic events related to displacements along ancient discontinuities in the bedrock. In addition, the advance of glacial ice may also exert stresses near the bedrock surface during its motion across the landscape. For instance, the glacier can thrust itself against topographic barriers and this can damage the rock and may cause movement along existing discontinuities.

The study of neotectonic features in the area may reveal the timing and magnitude of glacially-induced seismic activity and deformations. Conclusive identification of features indicative of reactivation of ancient bedrock structures due to cycles of glacial loading and unloading could not be made using the 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 events. Relatively large glaciolacustrine deposits have been mapped (Figure 3) in the northeast corner of Sub-region 2.1 and in the southwest corner of Sub-region 2.2 near Little Flatstone Lake. However, in these areas of thick overburden cover it is impossible to identify any lineaments. In order to find evidence of post-glacial reactivation of major geological structures, the search for deformed glaciolacustrine sediments would need to be conducted in the areas mapped as morainal veneer or rock, where glaciolacustrine sediments have been deposited within well-defined linear topographic lows reflecting the eroded out damage zones of major geological structures. The expected stratified glaciolacustrine sediments within these depressions (much too small to have been mapped in the surficial geology map) would have been deposited due to local ponding of meltwater during deglaciation. The north-northwest trending steeply-dipping structures mapped throughout the areas of thin drift form distinct linear topographic depressions that could have been partly filled by glaciolacustrine sediments during deglaciation.

8 ACCESSIBILITY CONSTRAINTS

The most significant accessibility constraint in the ERFN area is the limited number of roads. Topography and the distribution of wetlands and general areas of poor drainage also represent important constraints that would need to be considered carefully in road route planning or the selection of a site for the construction of a surface facility.

The Key Lake road (Highway 914) is a gravel road that provides access to the eastern part of the ERFN area from the south, including direct access to the eastern parts of Sub-regions 2.1 and 2.3. Highway 918 provides access to the southwest part of the ERFN area, but does not extend near Sub-region 2.2. There is an absence of forest harvesting roads in the area to facilitate field reconnaissance. Surficial mapping crews in the 1970s used float-equipped aircraft to access the larger lakes.

Within Sub-region 2.1, there are two small areas of high ground southeast of Haultain Lake a short distance west of Highway 914. One of the more rugged blocks of high ground in the sub-region is a roughly north-south trending chain of hills between Selmes and Lunnin lakes in the centre of the sub-region. The largest blocks of high ground in Sub-region 2.1 are located in the northwest quadrant, where the SPOT imagery displays many hills with exposed bedrock scattered amongst small lakes and wetlands. As a result, access to the main areas of thin drift in the sub-region would require 5 to 20 km of road routing west of Highway 914.

In Sub-region 2.2, isolated areas of thin drift and abundant bedrock exposure exist in the northwest quadrant of the sub-region west of the Mudjatik River (e.g., south and southwest of Thompson Lake). Apart from these areas, most of the exposed bedrock within the sub-region is located east of the Mudjatik River and the best exposure is found on hills in the northeast quadrant, near Porter Lake. The hills delineated in this area are very small, narrow features bounded by steep slopes and an intricate pattern of lakes, which could render the area topographically unsuitable for the siting of a deep geological repository. Access to the northern part of the sub-region would require 50 to 75 km of road routing north from the end of Highway 918 at Patuanak. The valley of the Mudjatik River north of Patuanak contains considerably more wetlands than that of the Haultain River, where Highway 914 has been routed. These organic deposits would pose challenges to road routing, as would the rugged bedrock terrain closer to Porter Lake.

In Sub-region 2.3, several north-northeast trending rock ridges with abundant bedrock exposure are located in the north-central part of the sub-region, north of Dipper, Primeau and Knee lakes. These areas would require 10 to 50 km of road routing from either Highway 914 or 918, with creek and river crossings and negotiating rock ridges representing significant accessibility constraints. The eastern third of the sub-region contains abundant areas of high ground east and west of Highway 914, which would be more accessible than the areas in the north-central part of the sub-region described above. The area of the sub-region east of Highway 914 and north of Gordon Lake contains many rock outcrops distributed amongst small lakes and wetlands, where outcrops occur in association with steep slopes and the only flat areas are covered by lakes, wetlands or overburden deposits. The most impressive areas of exposed bedrock are located southeast of Zaharik Lake and northwest of Wanamaker Lake.

9 SUMMARY

This report presents an analysis of the terrain in the English River First Nation (ERFN) area using available remote sensing and geoscientific information sources. The ERFN area was further divided into sub-regions near the reserve lands that were reviewed in greater detail. The sub-regions are referred to as Sub-region 2.1 (Haultain Lake), Sub-region 2.2 (Porter Lake and Flatstone Lake) and Sub-region 2.3 (Dipper Rapids, Primeau Lake, Knee Lake and Elak Dase). The main information sources relied on in this study are the Canadian Digital Elevation Data (CDED) elevation model, the multispectral SPOT satellite imagery, and the maps and reports from the Saskatchewan Geological Survey (SGS).

The report provides an overview of the bedrock and Quaternary geology within the ERFN area. Maps and descriptions of the Quaternary deposits were presented based on the 1:250,000 scale surficial mapping by the SGS. The Cree Lake moraine extends through the centre of the ERFN area and it impounded Glacial Cree Lake, which drained through the Mudjatik and Haultain rivers in this area. Extensive outwash plains are located south of the moraine at its intersections with the Mudjatik and Haultain rivers. These outwash plains form some of the largest areas where bedrock is not exposed within the Precambrian Shield portion of the ERFN area, and these sand plains are associated with the most extensive organic deposits in the ERFN area. Outwash deposits south of the moraine are generally composed of stratified sands, whereas to the north they consist of sand and gravel. West of the Mudjatik River and south of the Churchill River, the ground moraine is, with few exceptions, thick enough to mask all of the bedrock ridges.

The CDED digital elevation model was analysed and interpreted to infer pertinent information on the topography, drainage and overburden deposits in the ERFN area. Maps of elevation, relief, and slope were presented. The north to south elevation gradient and the two major northeast trending topographic highs are the first-order controls on drainage. These major topographic highs are a reflection of competency contrasts between the felsic gneisses in the Wollaston and Mudjatik domains versus the relatively weak paragneisses forming the western boundary of the Wollaston domain, which are expressed as the depression formed around the Haultain River. These major topographic highs are also the main areas mapped as morainal veneer or bedrock in the regional surficial geology map. The relief maps provide a good indication of the distribution of topographically prominent landforms, which are almost invariably associated with thinner overburden and a relative abundance of rock outcrops. The relief maps also show the low relief areas where overburden deposits have filled in the bedrock lows. The relief maps suggest that there are rock ridges within each of the sub-regions where rock outcrops can be found, and descriptions of the main rock ridges in each sub-region have been provided in Section 3.2. However, many of the areas devoid of thick overburden deposits, which is a favourable attribute for the siting of a deep geological repository, display remarkable examples of rugged shield topography. Steep-sided to cliff-bounded ridges are common positively expressed landforms in these areas. Steep-walled, narrow to broad and flat-floored trenches are the surface expression of lineaments, and many are lake-filled or contain thick organic deposits. These aspects of the topography would need to be considered carefully in road route planning or the selection of a site for the construction of a surface facility.

Drainage divides delineated in the sub-basin file produced by the Prairie Farm Rehabilitation Association (PFRA), which represents the authoritative file for drainage areas in the Prairie watershed, were confirmed using the CDED surface model. The average area of the PFRA sub-basins extending into the ERFN area is about 5,000 km^2. In addition to confirming drainage boundaries, most of the PFRA sub-basins were subdivided based on the presence of continuous highlands dividing flow into smaller watersheds. An updated watershed file was produced that specifies the drainage divides delineated in this study not present in the PFRA sub-basin file. The average area of the basins in the updated watershed file entirely within the ERFN area is about 500 km^2.

Estimates of overburden thickness were generated based on SGS reports, water well and borehole data. Ground moraine represents the most common glacial deposit in the Precambrian Shield portion of the ERFN area, typically represented as veneers and blankets of sandy ablation till distributed amongst lakes, muskegs, and bedrock outcrops. Ground moraine thickness within the areas mapped as morainal veneer or bedrock is expected to range from less than 1 m to 10 m or more with a typical value of perhaps 5 m. Extensive outwash deposits on the Mudjatik and Haultain rivers downstream of the Cree Lake moraine are expected to be 5 to 10 m thick and dominantly composed of stratified sands. Organic deposits overlying the extensive outwash deposits described above are expected to be relatively thin compared with those deposited within high-relief basins in the areas mapped as morainal veneer or bedrock. The thickest drift deposits in the Precambrian Shield portion of the ERFN area are expected to be located in the valleys of the Mudjatik, Haultain and Churchill rivers and probably exceed thicknesses of 40 to 60 m. Overburden deposits over the Phanerozoic basin in this area are generally quite thick, with water well and drill hole data indicating values as high as 60 to 90 m.

Bedrock exposures are displayed in the multispectral SPOT imagery examined in this study. A composite image was created based on principal component analysis, which effectively displays the bedrock outcrops as well as other land cover types, such as wetlands and outwash plains. Qualitative checking of the SPOT imagery has confirmed that the areas of positive relief delineated from the CDED surface model are the main locations where rock outcrops can be found. Descriptions of the main rock ridges in each sub-region have been provided in Section 3.2. Attempts to classify rock outcrops using unsupervised classification were largely unsuccessful due to the inability of the method to distinguish between rock outcrops and the abundant areas of exposed mineral soil found within outwash plains and to the complications introduced by the extensive areas burned by wildfire. As a result, the SPOT imagery was ineffective at providing the type of area-wide image of overburden deposits that the DEM generated.

Shallow groundwater flow within drift deposits and shallow bedrock aquifers in the ERFN 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. The regional groundwater recharge zones are the three highland areas mapped as morainal veneer or bedrock: the Haultain and Norbert highs and the highland containing Blackstone, Complex and Holt lakes. Recharge of shallow bedrock aquifers in the highlands is expected to occur through discontinuities, with permeability depending on discontinuity spacing, persistence and aperture. Runoff and groundwater flow from the highlands will recharge the relatively thick surficial aquifers contained within the adjacent topographic lows formed by the valleys of the Mudjatik, Haultain and Churchill rivers. Deeper bedrock aquifers could be associated with major structural features mapped in the highland areas. However, no information beyond what was presented in the initial screening study (Golder, 2011) on groundwater flow at repository depth was presented.

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. One type of feature that could be targeted during field reconnaissance is deformed glaciolacustrine deposits draped over lineaments. Investigation of such features would likely require excavation with a backhoe to enable a large enough exposure of stratified silt and clay to be inspected for deformation structures recording post-glacial displacements along the lineament. Although few glaciolacustrine deposits have been mapped in the ERFN area, small unmapped deposits of stratified silt and clay associated with local ponding during deglaciation are expected to exist within linear topographic lows throughout the areas mapped as morainal veneer or bedrock. The relief maps presented provide a delineation of deep linear topographic lows where glaciolacustrine material could be deposited within small basins formed on the surface of lineaments.

The principal accessibility constraint in the ERFN area is the lack of existing roads into the three sub-regions. Highway 914 passes through Sub-regions 2.1 and 2.3, however, Sub-region 2.2 is not readily accessible. In order to access the best areas of exposed bedrock, new roads would need to be routed around the many lakes, rivers, wetlands and steep slopes that characterize much of the ERFN area. No roads related to forest harvesting are present within the area to assist with site reconnaissance.

The distribution of extensive overburden deposits and lakes can generate a background of structural and lithological uncertainty in certain areas. These features can conceal major geological structures and unfavourable bedrock formations. For example, the mapped distribution of rocks other than felsic gneiss in the Mudjatik and Wollaston domains is partly a function of bedrock exposure. A map of slope density was generated, which provides a generalized image of the areas where identification of lineaments could be more or less reliable (Section 3.3). For example, the areas of low slope density could be underlain by thicker overburden, resulting in the identification of fewer lineaments on a DEM.

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REPORT SIGNATURE PAGE

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FIGURES

Figure 1 Location and overview of the ERFN area

Figure 2 Bedrock geology of the ERFN area

Figure 3 Surficial geology of the ERFN area

Figure 4 Elevation and major topographic features

Figure 5 Departure from average elevation within 20 km radius

Figure 6 Departure from average elevation within 2 km radius

Figure 7 Range in elevation within 250 m radius

Figure 8 Areas 6° or steeper in the ERFN area

Figure 9 Density of steep (≥6°) slopes within 2 km radius

Figure 10 Surface drainage features of the ERFN area

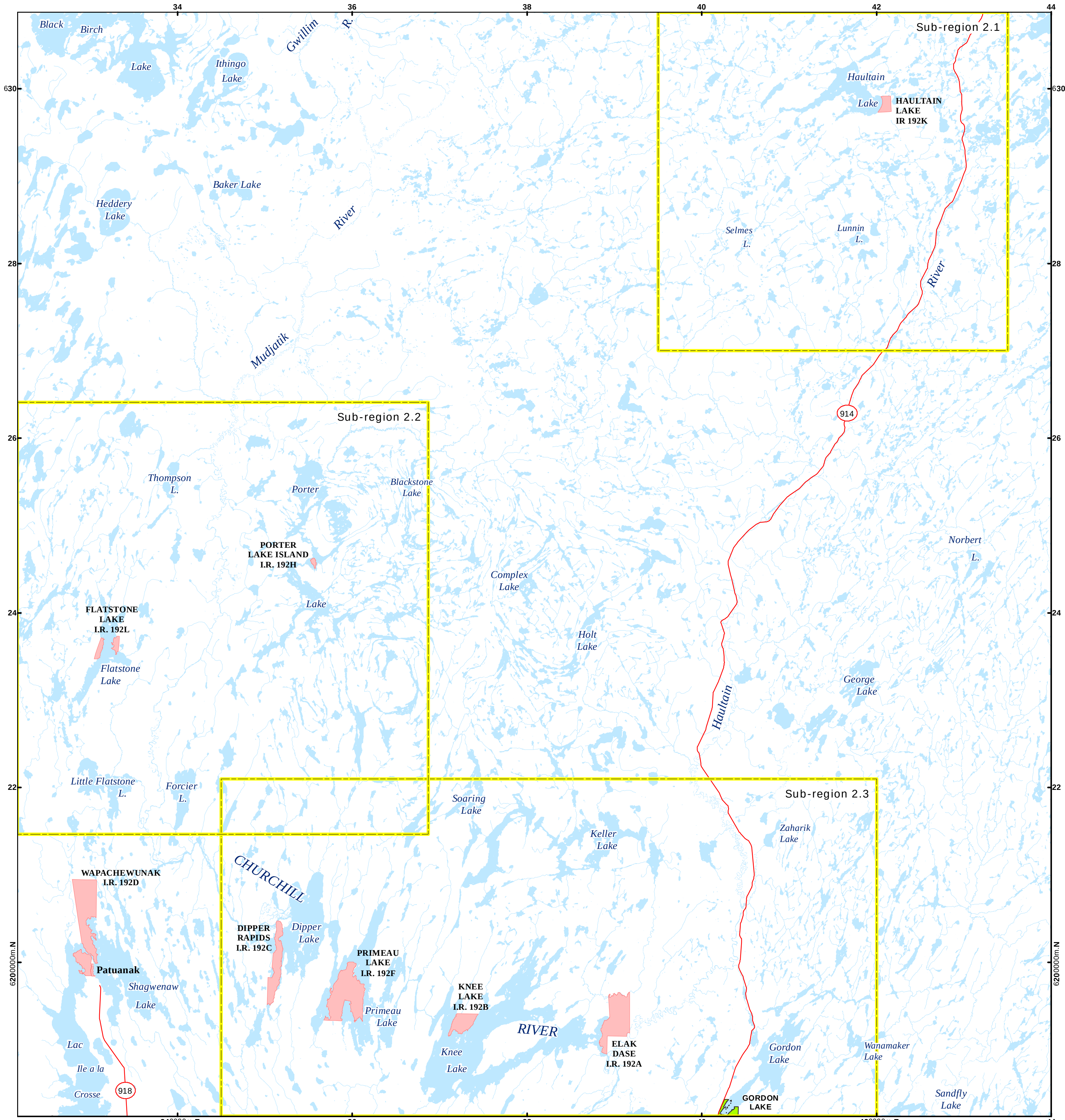
Figure 11 Watersheds within the ERFN area

Figure 12 Bedrock map of Sub-region 2.1

Figure 13 Bedrock map of Sub-region 2.2

Figure 14 Bedrock map of Sub-region 2.3

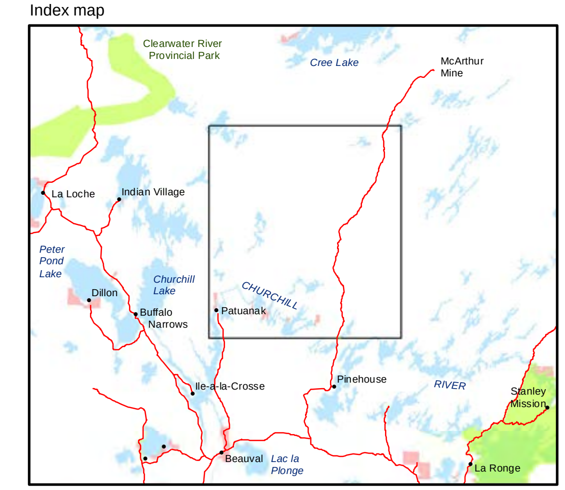
FIGURES



LEGEND

- Detailed area
- Main road
- First Nation reserve
- Recreation site
- Waterbody
- Watercourse

Index map



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

Data sources:
First Nation reserve: Sask Admin
Recreation site: Sask Admin
Main road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

5 km

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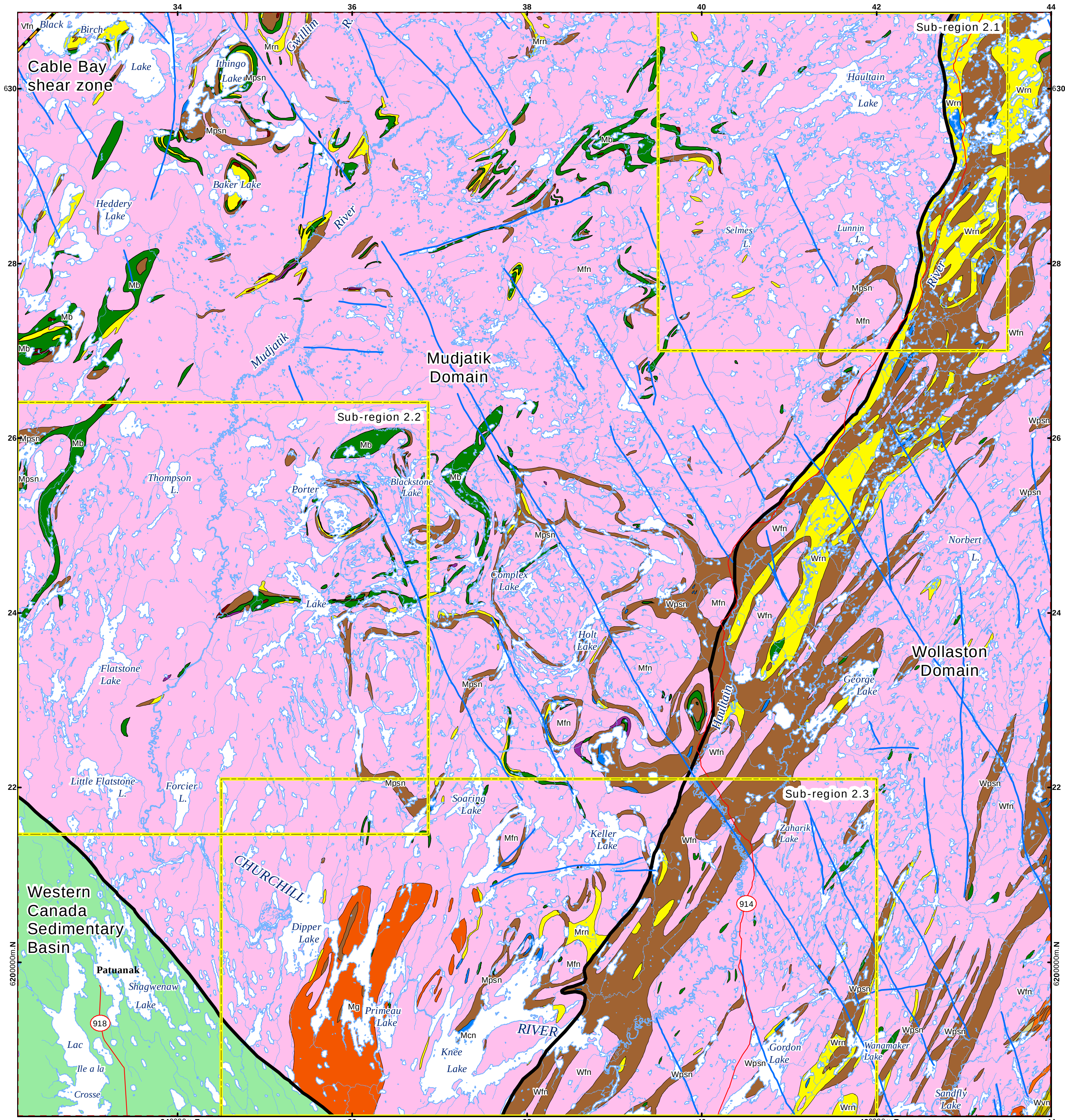
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, ERFN AREA, SASKATCHEWAN

TITLE
Location and overview of the ERFN area

DESIGN	DVZ	25 JUN 2012	FIGURE 1	REVISION 3
GIS	DVZ	06 AUG 2013		UTM ZONE 13
CHECK	JIC	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



LEGEND

- Detailed area
- ERFN area
- Main road
- Mapped fault
- Mapped shear zone
- Domain boundary
- Waterbody
- Watercourse

Western Canada sedimentary basin

- Km - Manville Group

Mudjatik domain

- Mcn - Calc-silicate rock, marble
- Mfn - Felsic gneiss
- Mg - Leucogranite
- Mif - Banded iron formation
- Mb - Mafic gneiss
- Mpsn - Pelitic, psammopelitic and psammitic gneisses
- Mm - Psammitic to meta-arkosic gneiss
- Mu - Ultramafic rock

Virgin River domain

- Vfn - Felsic gneiss

Wollaston domain

- Wcb - Massive coarse grained calc-silicate
- Wcn - Calc-silicate rock, marble
- Wfn - Felsic gneiss
- Wg - Leucogranite, granite, monzogranite, granodiorite
- Wm - Amphibolite
- Wma - Amphibolite (Archean)
- Wpsn - Pelitic, psammopelitic gneiss
- Wpx - Migmatized supracrustal rocks
- Wq - Metaquartzite
- Wr - Meta-arkose
- Wm - Psammitic to meta-arkosic gneiss
- Wvn - Biotitic mafic gneiss

Data sources:
Geology: Sask Geological Atlas 1:250,000
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

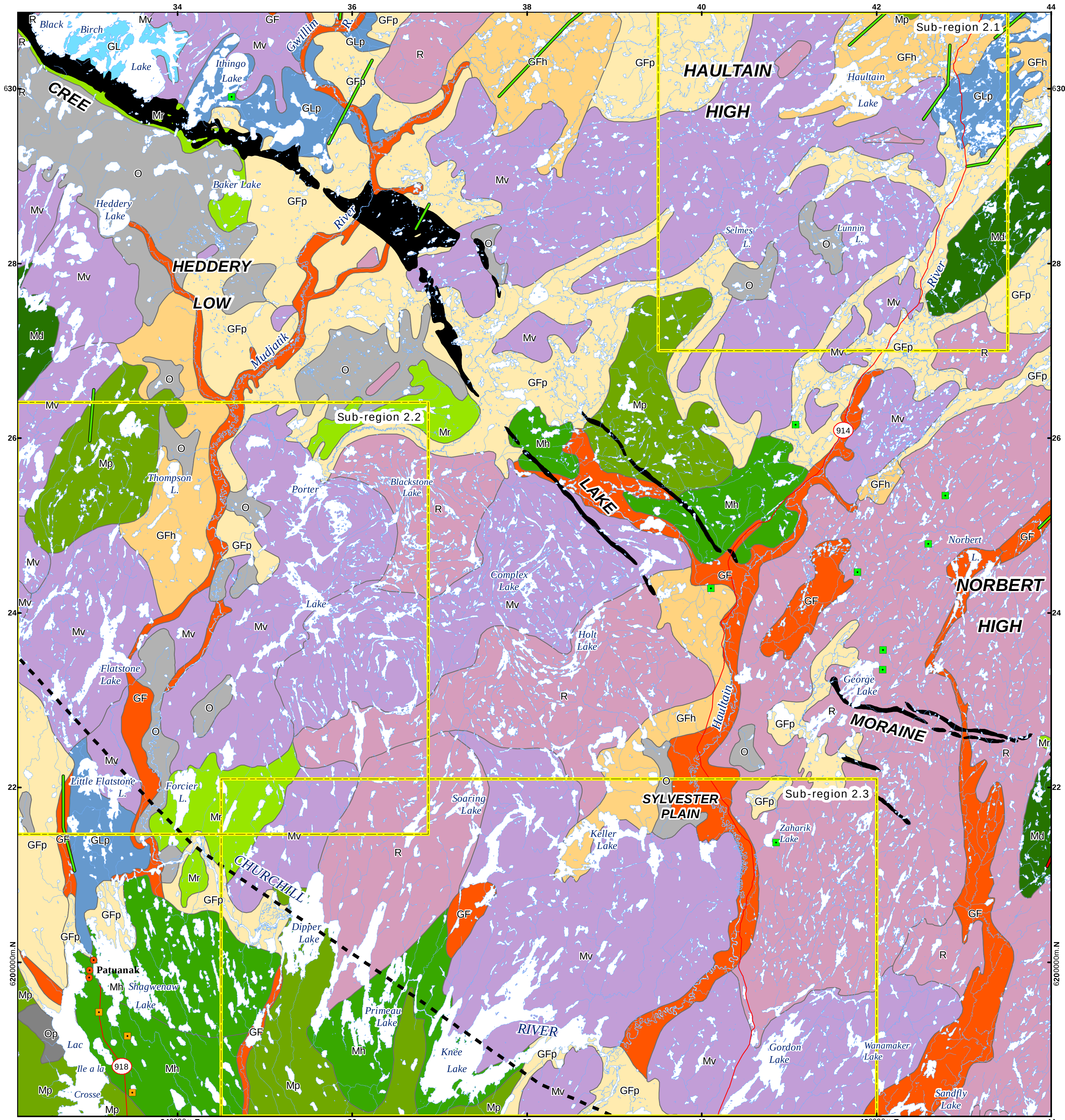
5 km

J D MOLLARD

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

TITLE
Bedrock geology of the ERFN area

DESIGN	DVZ	25 JUN 2012	FIGURE 2	REVISION 3
GIS	DVZ	06 AUG 2013		UTM ZONE 13
CHECK	JIS	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



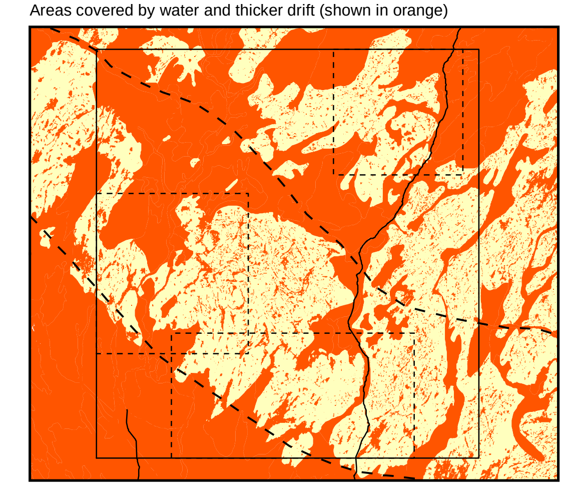
LEGEND

- Detailed area
- Water well
- Drill hole (Regina database)
- Drill hole (La Ronge database)
- Main road
- Churchill low
- Drumlin
- Esker
- Waterbody
- Watercourse
- Cree Lake Moraine

Surficial geology

- O - Organic
- Op - Organic plain
- GF - Glaciofluvial
- GFh - Glaciofluvial hummocky
- GFp - Glaciofluvial plain
- GL - Glaciolacustrine
- GLp - Glaciolacustrine plain
- Md - Morainal drumlinoid
- Mh - Morainal hummocky
- Mp - Morainal plain
- Mr - Morainal ridged
- Mv Morainal veneer
- R - Rock

Areas covered by water and thicker drift (shown in orange)



- Surfical or water (roughly 50%)
- Morainal veneer or rock (roughly 50%)

Data sources:
Geology: Sask Geological Atlas 1:250,000
Drill holes: Sask Geological Atlas
Water well: Water Well Information Database
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

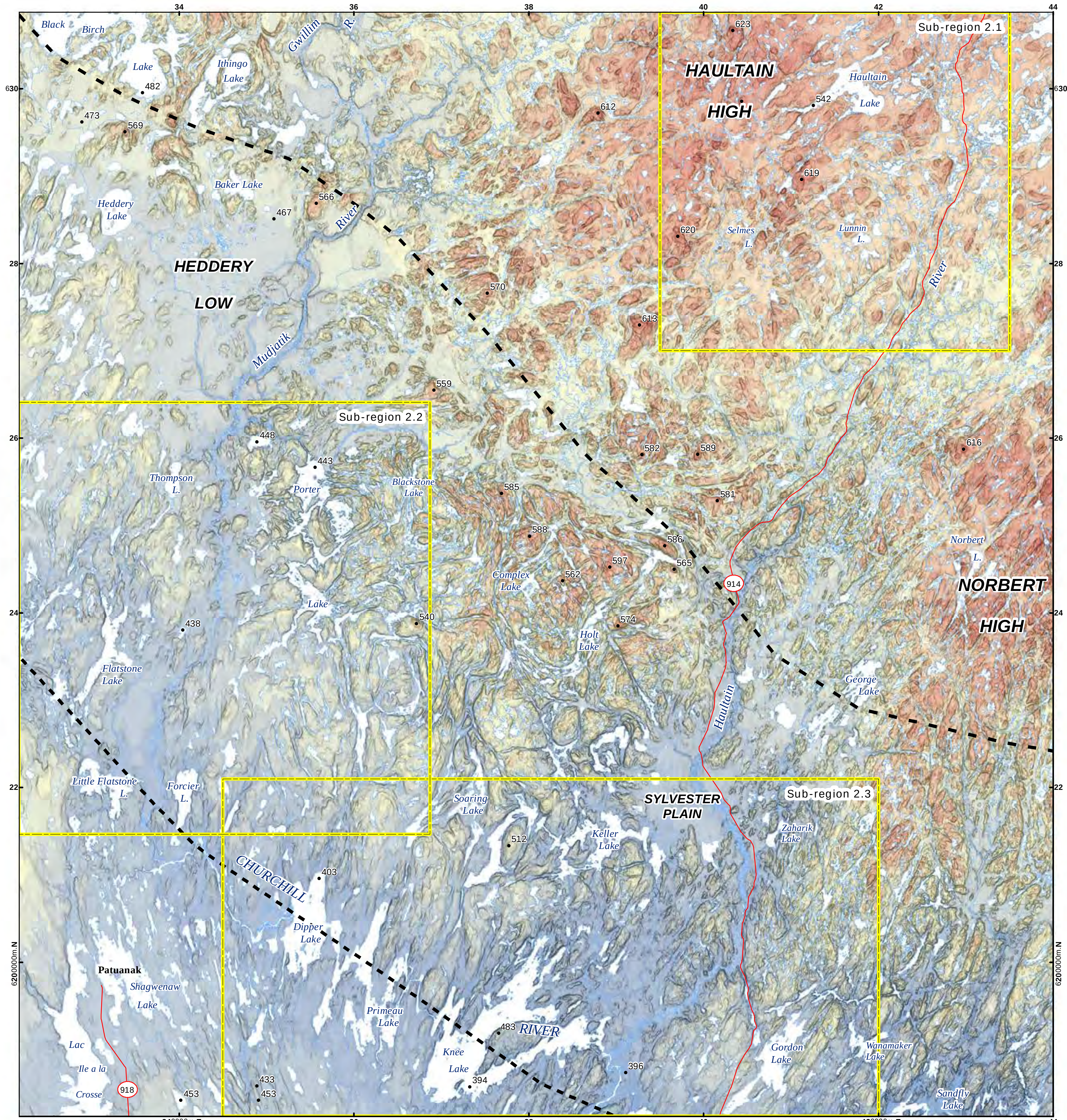
5 km

J D MOLLARD

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

TITLE
Surficial geology of the ERFN area

DESIGN	DVZ	25 JUN 2012	FIGURE 3	REVISION 3
GIS	DVZ	06 AUG 2013		UTM ZONE 13
CHECK	JIC	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



LEGEND

- Detailed area
- Cree Lake Moraine
- Churchill low
- Spot height (m)
- Main road
- Waterbody
- Watercourse

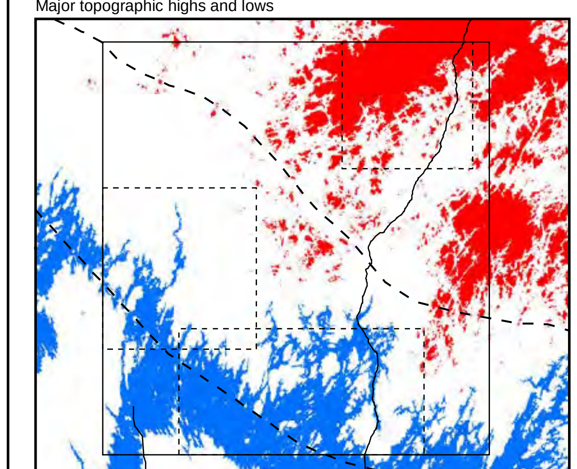
Elevation (m)

- 385 - 396.4
- 396.5 - 420.6
- 420.7 - 444.9
- 445 - 469.1
- 469.2 - 493.4
- 493.5 - 517.6
- 517.7 - 541.8
- 541.9 - 566.1
- 566.2 - 590.3
- 590.4 - 614.6
- 614.7 - 631

Slope (°)

- 0 - 0.3
- 0.4 - 1.9
- 2 - 3.5
- 3.6 - 5.1
- 5.2 - 6.7
- 6.8 - 8.3
- 8.4 - 9.9
- 10 - 11.5
- 11.6 - 39.9

Major topographic highs and lows



Elevation (m)

- 370 - 430
- 431 - 540
- 541 - 634

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

NORTH

5 km

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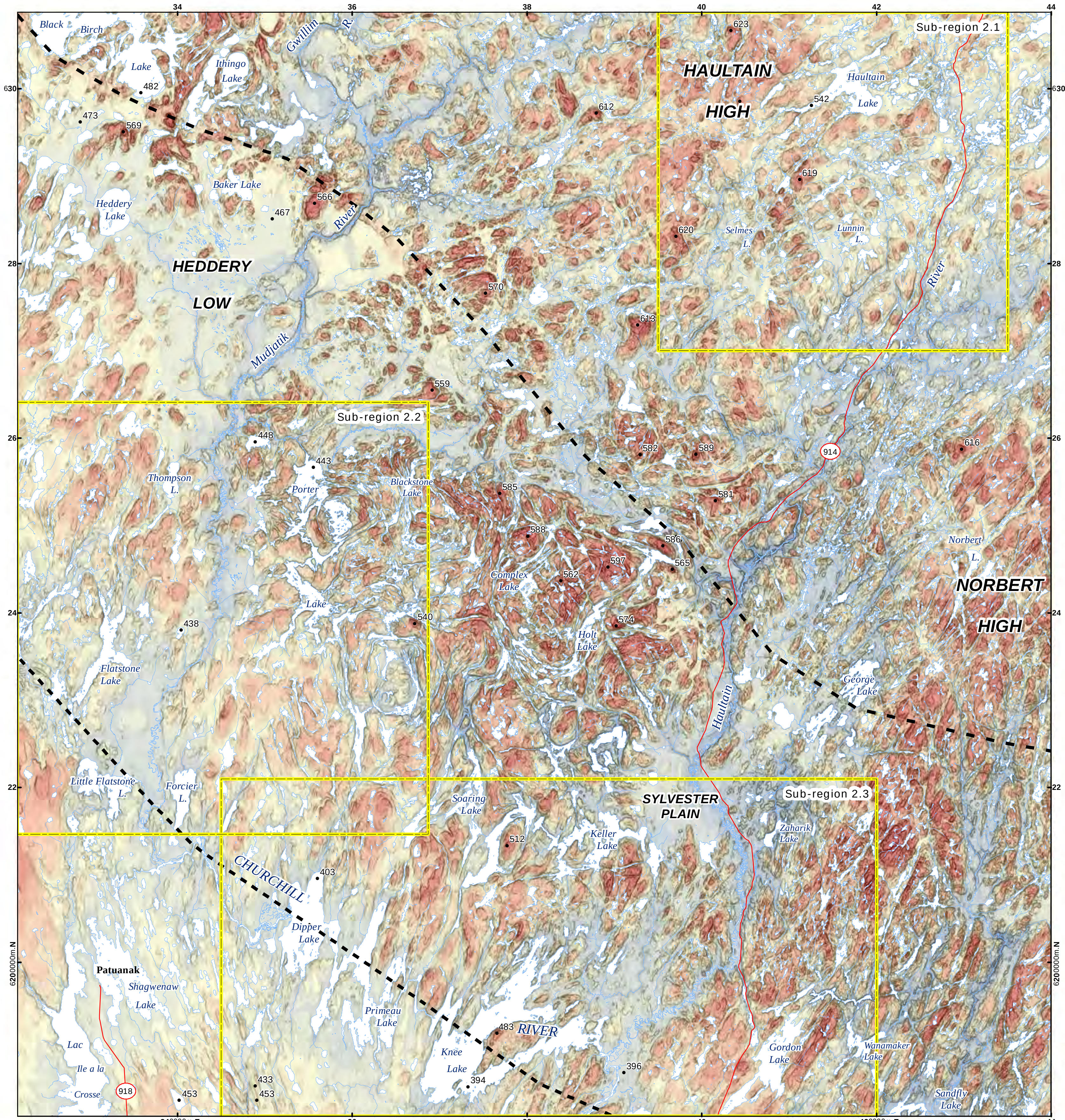
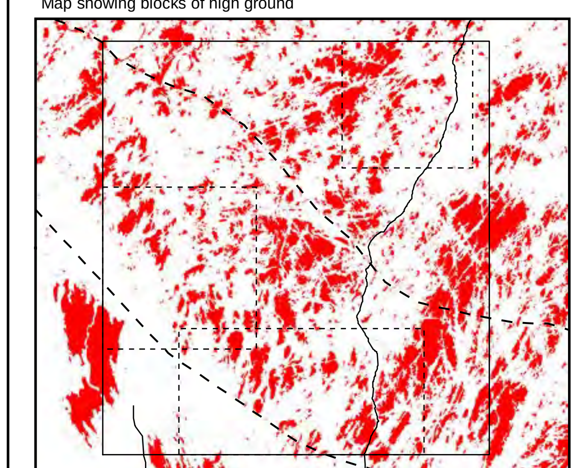
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, ERFN AREA, SASKATCHEWAN

TITLE
Elevation and major topographic features

DESIGN	DVZ	25 JUN 2012	FIGURE 4	REVISION 3
GIS	DSM	06 AUG 2013		UTM ZONE 13
CHECK	DVZ	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



Map showing blocks of high ground



Relief (m)

- -63 - 15
- 16 - 108

LEGEND

- Detailed area
- Cree Lake Moraine
- Churchill low
- Spot height (m)
- Main road
- Waterbody
- Watercourse

Relief (m)

- -63 - -59
- -58 - -49
- -48 - -38
- -37 - -27
- -26 - -16
- -15 - -6
- -5 - 5
- 6 - 16
- 17 - 26
- 27 - 37
- 38 - 48
- 49 - 59
- 60 - 108

Slope (°)

- 0 - 0.3
- 0.4 - 1.9
- 2 - 3.5
- 3.6 - 5.1
- 5.2 - 6.7
- 6.8 - 8.3
- 8.4 - 9.9
- 10 - 39.5

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

NORTH

5 km

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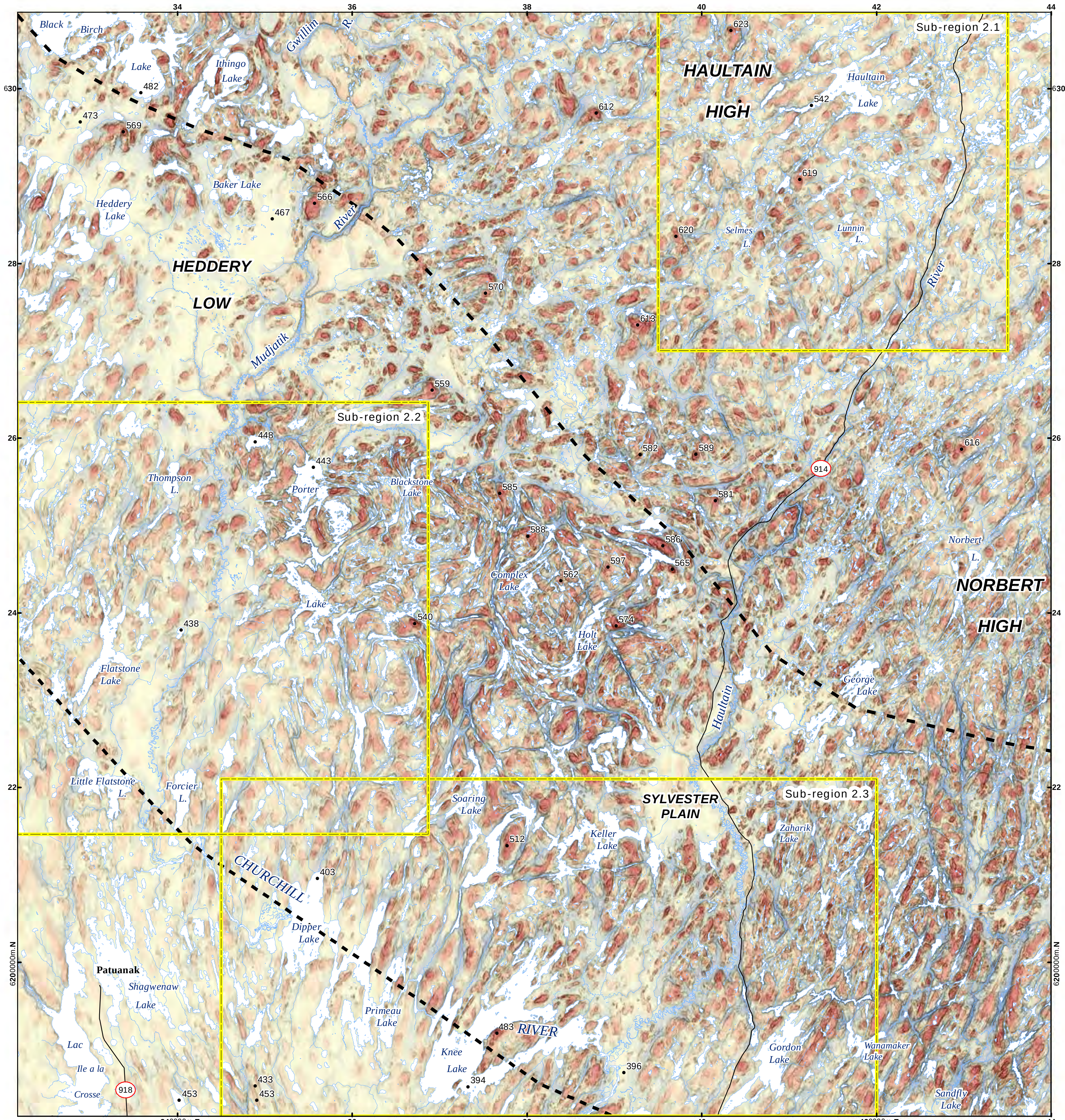
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, ERFN AREA, SASKATCHEWAN

TITLE
Departure from average elevation within 20 km radius

DESIGN	DVZ	25 JUN 2012	FIGURE 5	REVISION 3
GIS	DSM	06 AUG 2013		UTM ZONE 13
CHECK	DVZ	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



LEGEND

- Detailed area
- Cree Lake Moraine
- Churchill low
- Spot height (m)
- Main road
- Waterbody
- Watercourse

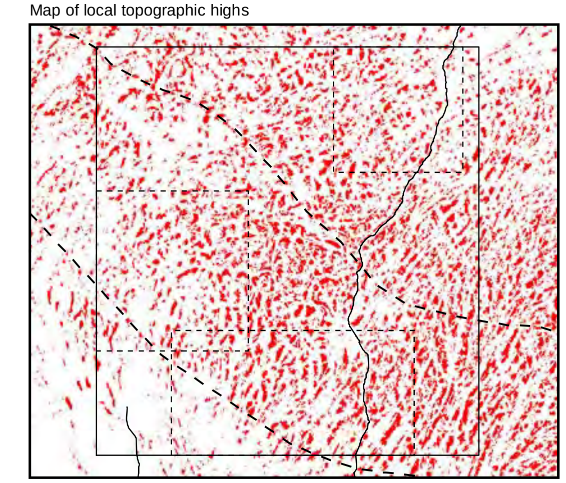
Relief (m)

- -57.1 - -36
- -35.9 - -29.5
- -29.4 - -23
- -22.9 - -16.5
- -16.4 - -10
- -9.9 - -3.5
- -3.4 - 3
- 3.1 - 9.5
- 9.6 - 15.9
- 16 - 22.4
- 22.5 - 28.9
- 29 - 35.4
- 35.5 - 81.1

Slope (°)

- 0 - 0.3
- 0.4 - 1.9
- 2 - 3.5
- 3.6 - 5.1
- 5.2 - 6.7
- 6.8 - 8.3
- 8.4 - 9.9
- 10 - 11.5
- 11.6 - 39.9

Map of local topographic highs



Relief (m)

- -57 - 10
- 11 - 83

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

NORTH

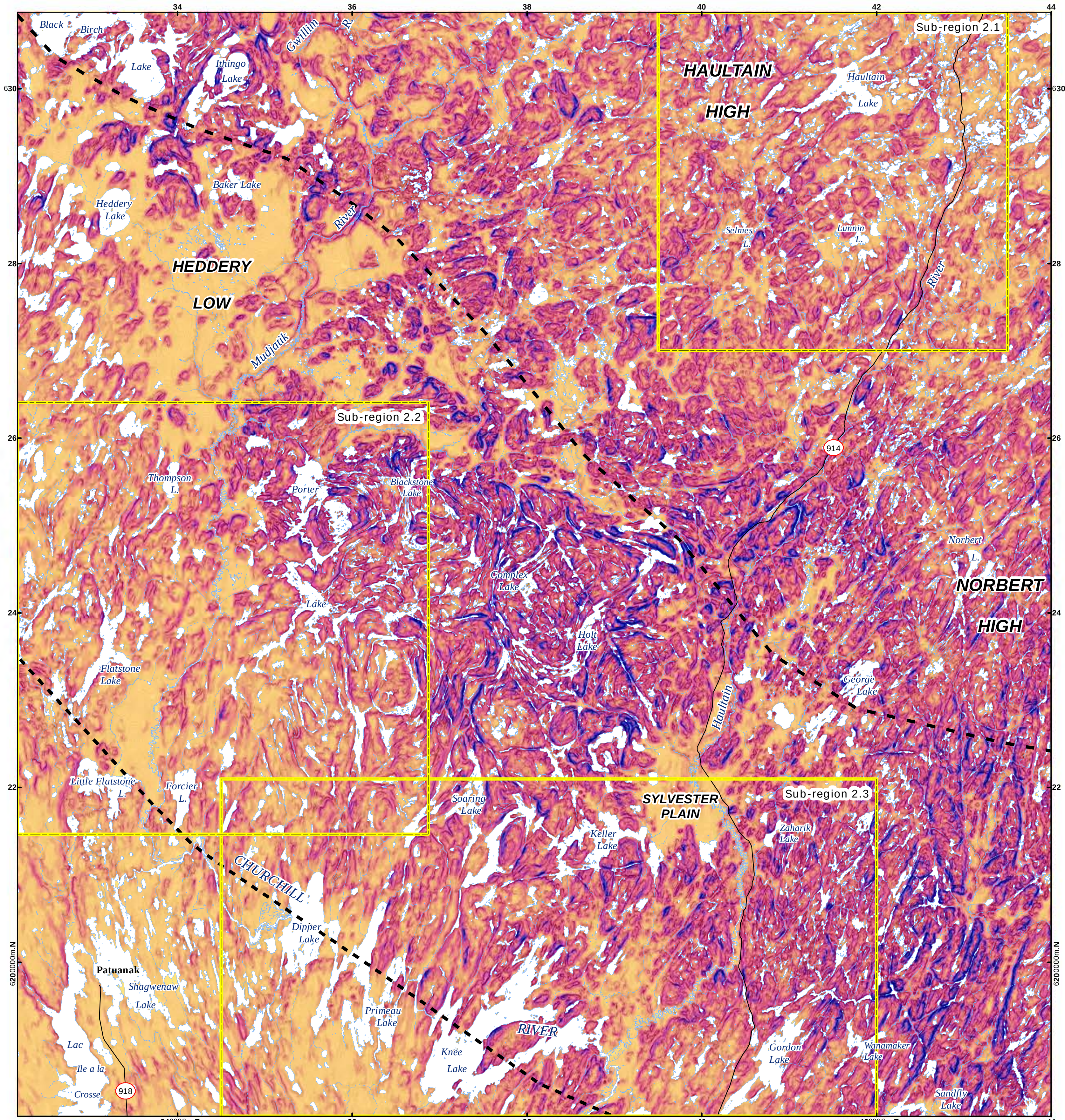
5 km

J D MOLLARD

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

TITLE
Departure from average elevation within 2 km radius

DESIGN	DVZ	25 JUN 2012	FIGURE 6	REVISION 3
GIS	DSM	06 AUG 2013		UTM ZONE 13
CHECK	DVZ	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



LEGEND

- Detailed area
- Cree Lake Moraine
- Churchill low
- Main road
- Waterbody
- Watercourse

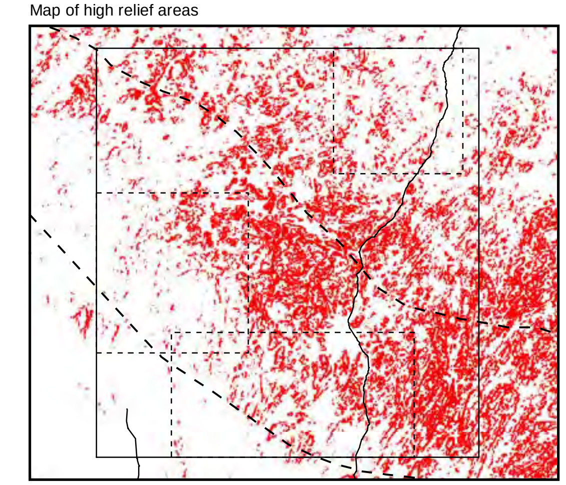
Relief (m)

- 0 - 0.5
- 0.6 - 7.6
- 7.7 - 14.8
- 14.9 - 22
- 22.1 - 29.2
- 29.3 - 36.4
- 36.5 - 43.6
- 43.7 - 50.7
- 50.8 - 57.9
- 58 - 116

Slope (°)

- 0 - 0.3
- 0.4 - 1.9
- 2 - 3.5
- 3.6 - 5.1
- 5.2 - 6.7
- 6.8 - 8.3
- 8.4 - 9.9
- 10 - 11.5
- 11.6 - 39.9

Map of high relief areas



Relief (m)

- 0 - 30
- 31 - 116

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

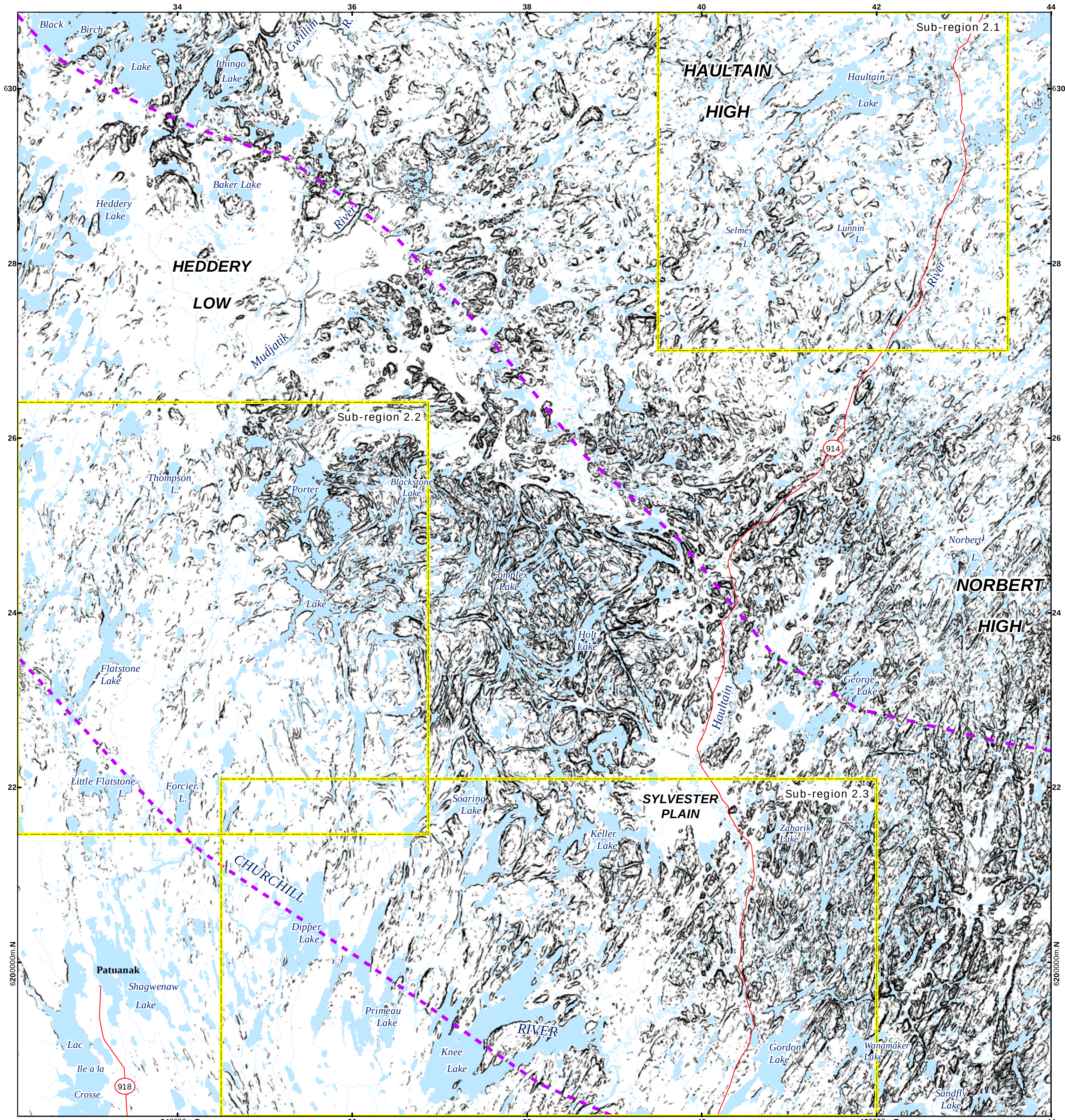
PROJECT

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

TITLE

Range in elevation within 250 m radius

DESIGN	DVZ	25 JUN 2012	FIGURE 7	REVISION 3
GIS	DSM	06 AUG 2013		UTM ZONE 13
CHECK	DVZ	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



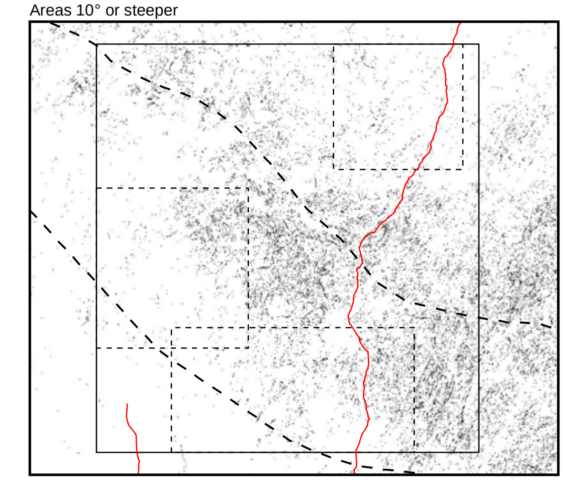
LEGEND

- Detailed area
- Cree Lake Moraine
- Churchill low
- Main road
- Waterbody
- Watercourse

Slope (°)

- 0 - 6
- 6.1 - 39.9

Areas 10° or steeper



Slope (°)

- 0 - 10
- 10.1 - 39.5

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

NORTH

5 km

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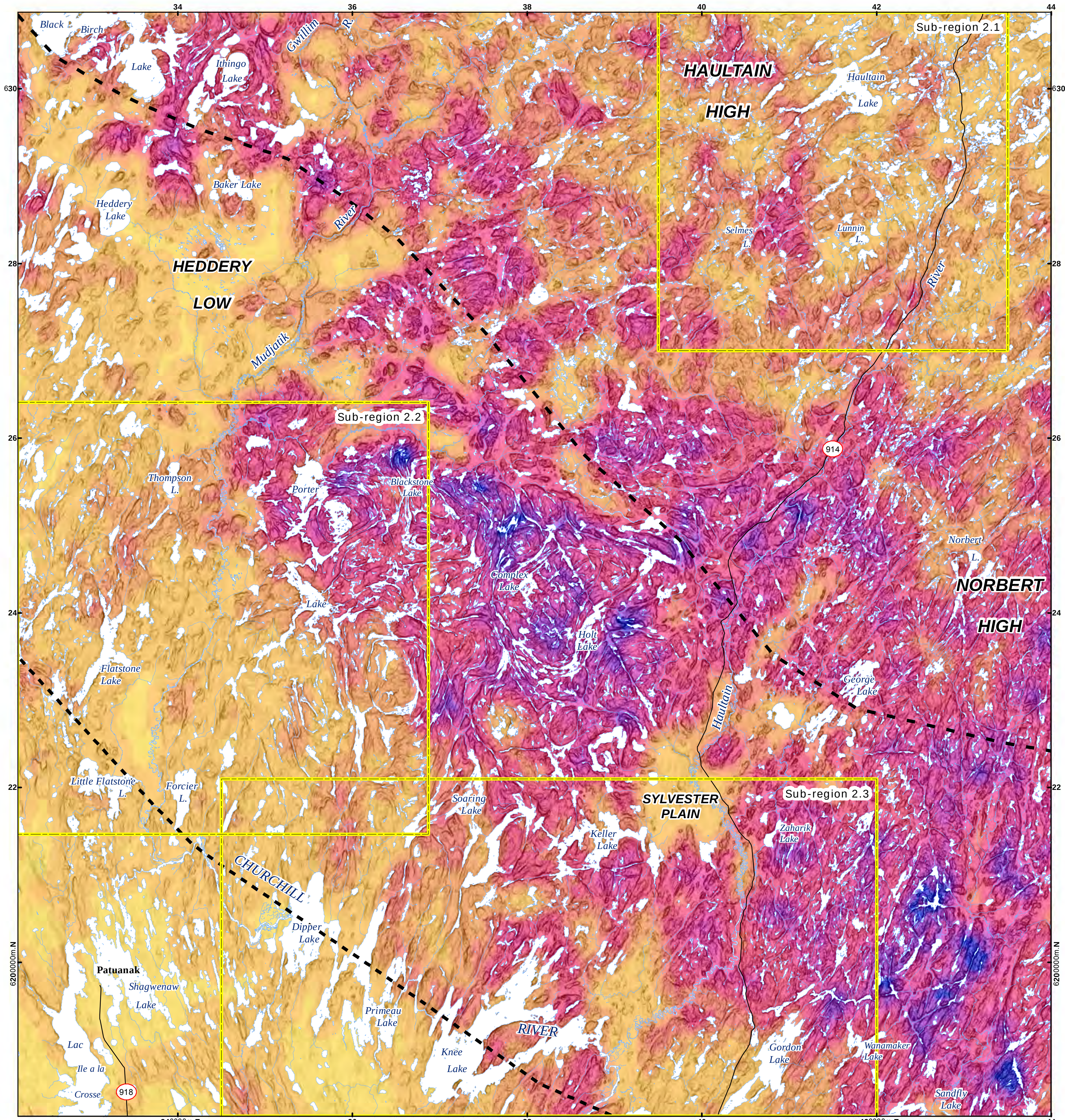
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, ERFN AREA, SASKATCHEWAN

TITLE
Areas 6° or steeper in the ERFN area

DESIGN	DVZ	25 JUN 2012	FIGURE 8	REVISION 3
GIS	DSM	06 AUG 2013		UTM ZONE 13
CHECK	DVZ	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



LEGEND

- Detailed area
- Cree Lake Moraine
- Churchill low
- Main road
- Waterbody
- Watercourse

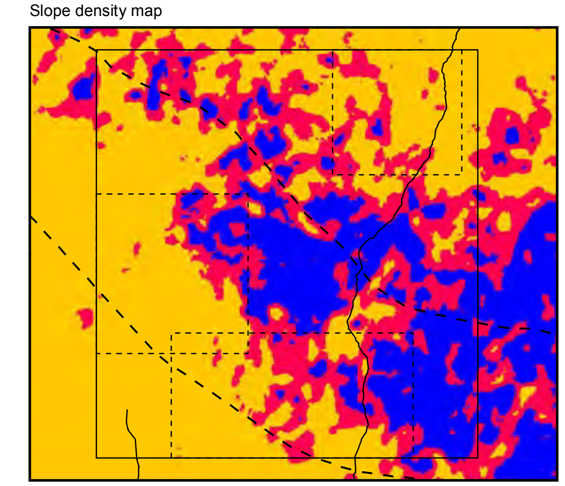
Slope density
Points\km^2

- 0 - 11.6
- 11.7 - 149.9
- 150 - 288.2
- 288.3 - 426.6
- 426.7 - 564.9
- 565 - 703.2
- 703.3 - 841.5
- 841.6 - 979.8
- 979.9 - 1,118.2
- 1,118.3 - 1,303.5

Slope (°)

- 0 - 0.3
- 0.4 - 1.9
- 2 - 3.5
- 3.6 - 5.1
- 5.2 - 6.7
- 6.8 - 8.3
- 8.4 - 9.9
- 10 - 11.5
- 11.6 - 39.9

Slope density map



Slope density
Points/km^2

- 0 - 300
- 301 - 600
- 601 - 1,322

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

NORTH

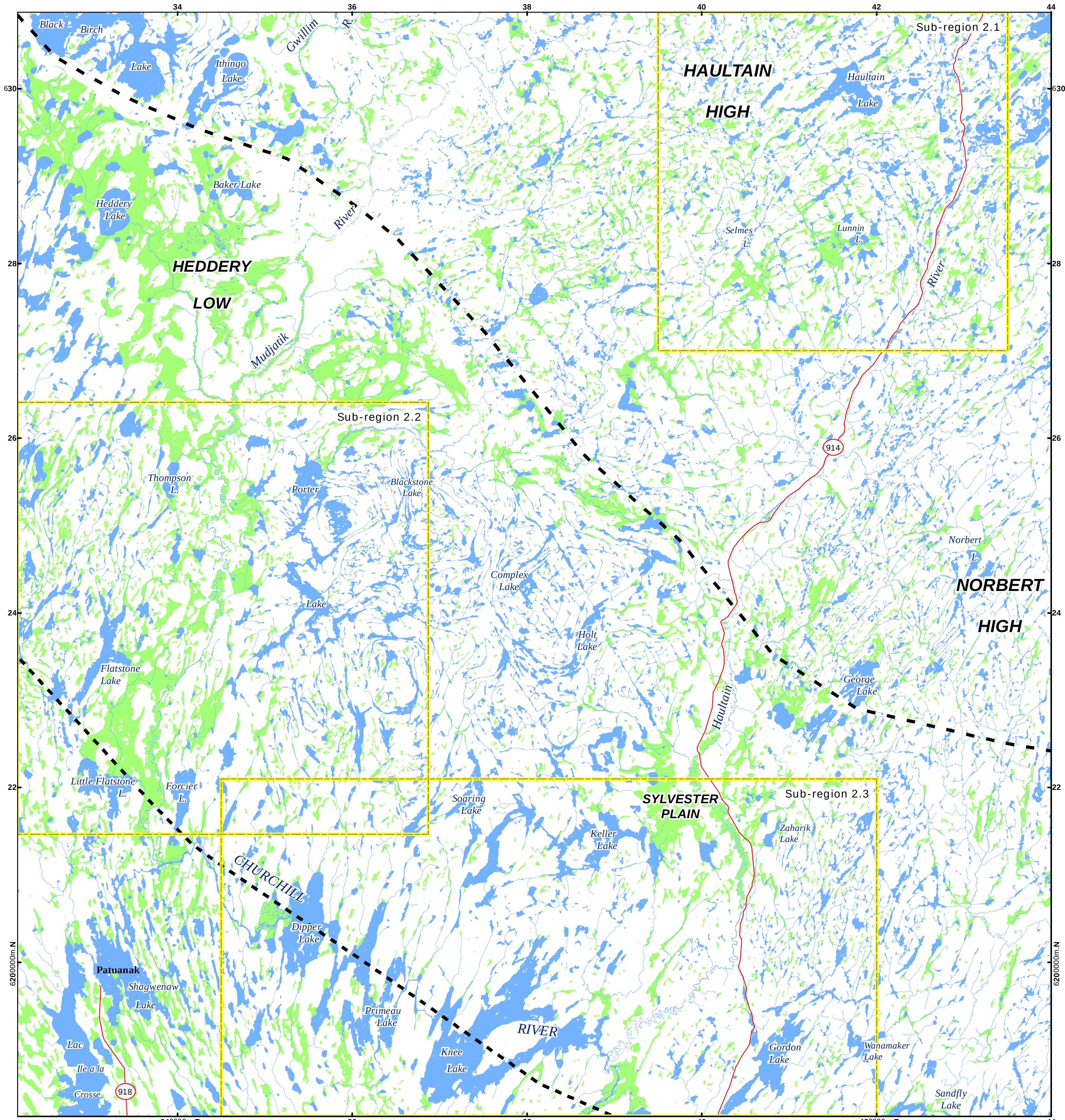
5 km

J D MOLLARD and associates (2010) limited

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

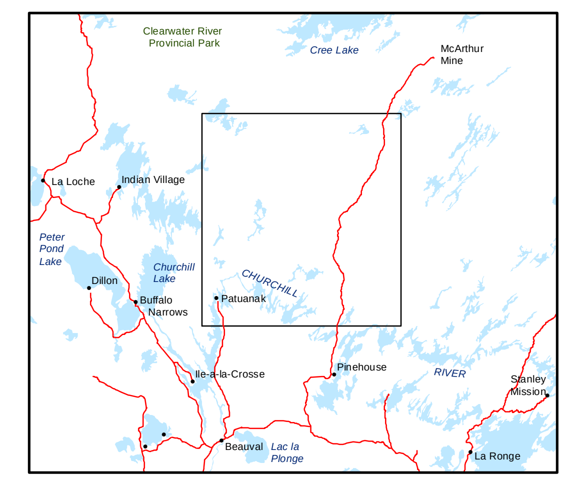
TITLE
Density of steep (≥6°) slopes within 2 km radius

DESIGN	DVZ	25 JUN 2012	FIGURE 9	REVISION 3
GIS	DSM	06 AUG 2013		UTM ZONE 13
CHECK	DVZ	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



LEGEND

- Detailed area
- Cree Lake Moraine
- Churchill low
- Main road
- Waterbody
- Watercourse
- Wetland



- Main road
- ERFN area
- Large lake

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

NORTH

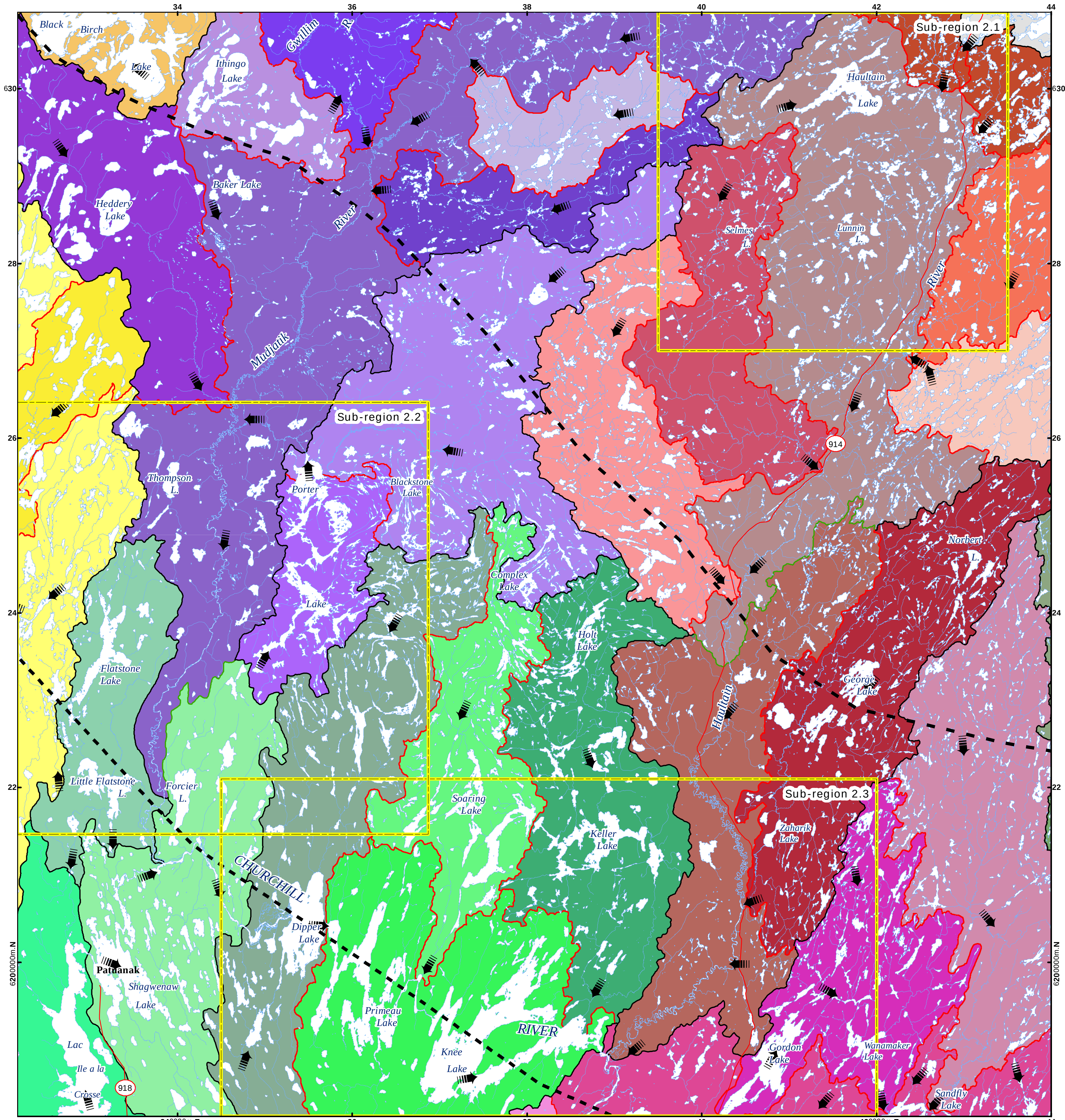
5 km

J D MOLLARD

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

TITLE
Surface drainage features of the ERFN area

DESIGN	DVZ	25 JUN 2012	FIGURE 10	REVISION 3
GIS	DSM	06 AUG 2013		UTM ZONE 13
CHECK	DVZ	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



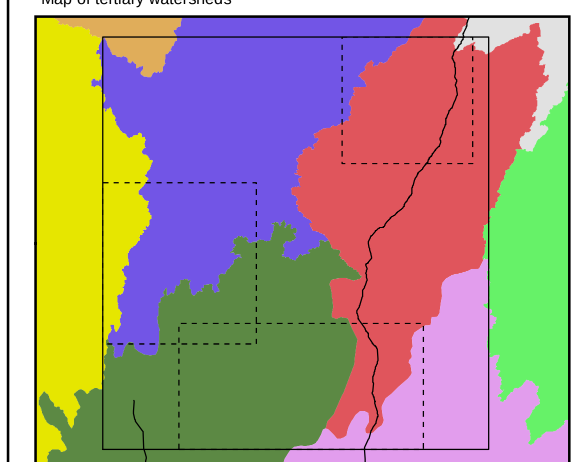
LEGEND

- Detailed area
- Flow direction
- Cree Lake Moraine
- Churchill low
- Main road
- Waterbody
- Watercourse

Drainage divide

- Confirmed (PFRA & JDMA)
- Modelled by JDMA
- Delineated by PFRA

Map of tertiary watersheds



- Upper Churchill
- Mudjatik
- Haultain
- Foster
- Cochrane
- Clearwater
- Churchill Lake
- Central Churchill

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

NORTH

5 km

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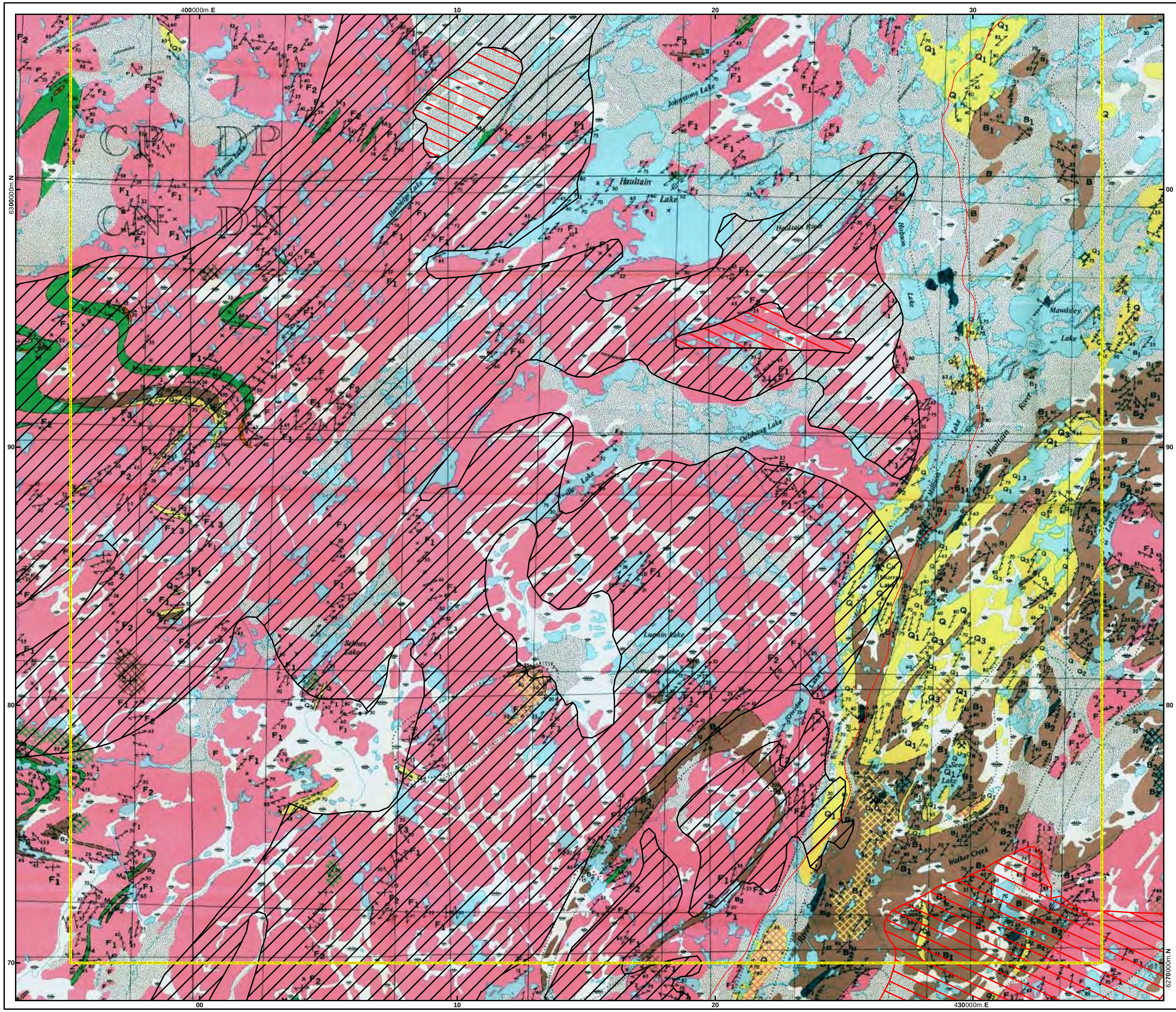
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, TERRAIN AND REMOTE SENSING STUDY, ERFN AREA, SASKATCHEWAN

TITLE
Watersheds within the ERFN area

DESIGN	DVZ	25 JUN 2012	FIGURE 11	REVISION 3
GIS	DSM	06 AUG 2013		UTM ZONE 13
CHECK	DVZ	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:550,000



LEGEND

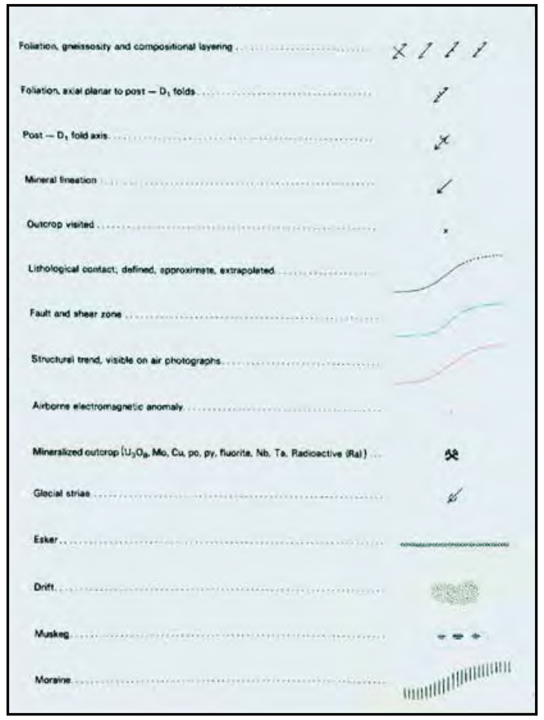
Detailed area

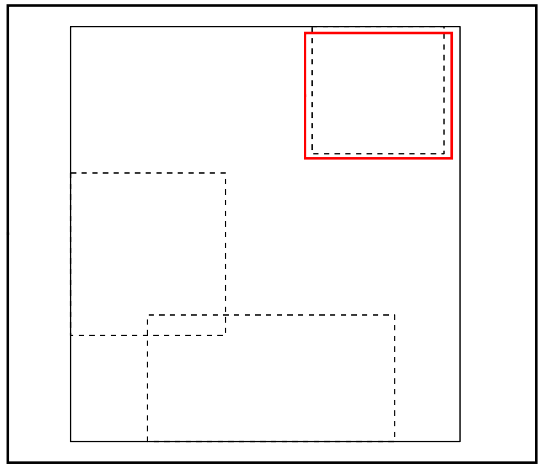
Main road

Surficial geology

R - Rock

Mv - Morainal veneer





NORTH

2 km

Data source:
Bedrock geology: (Munday, 1977) 1:100,000
Surficial geology: Sask Geo. Atlas 1:250,000

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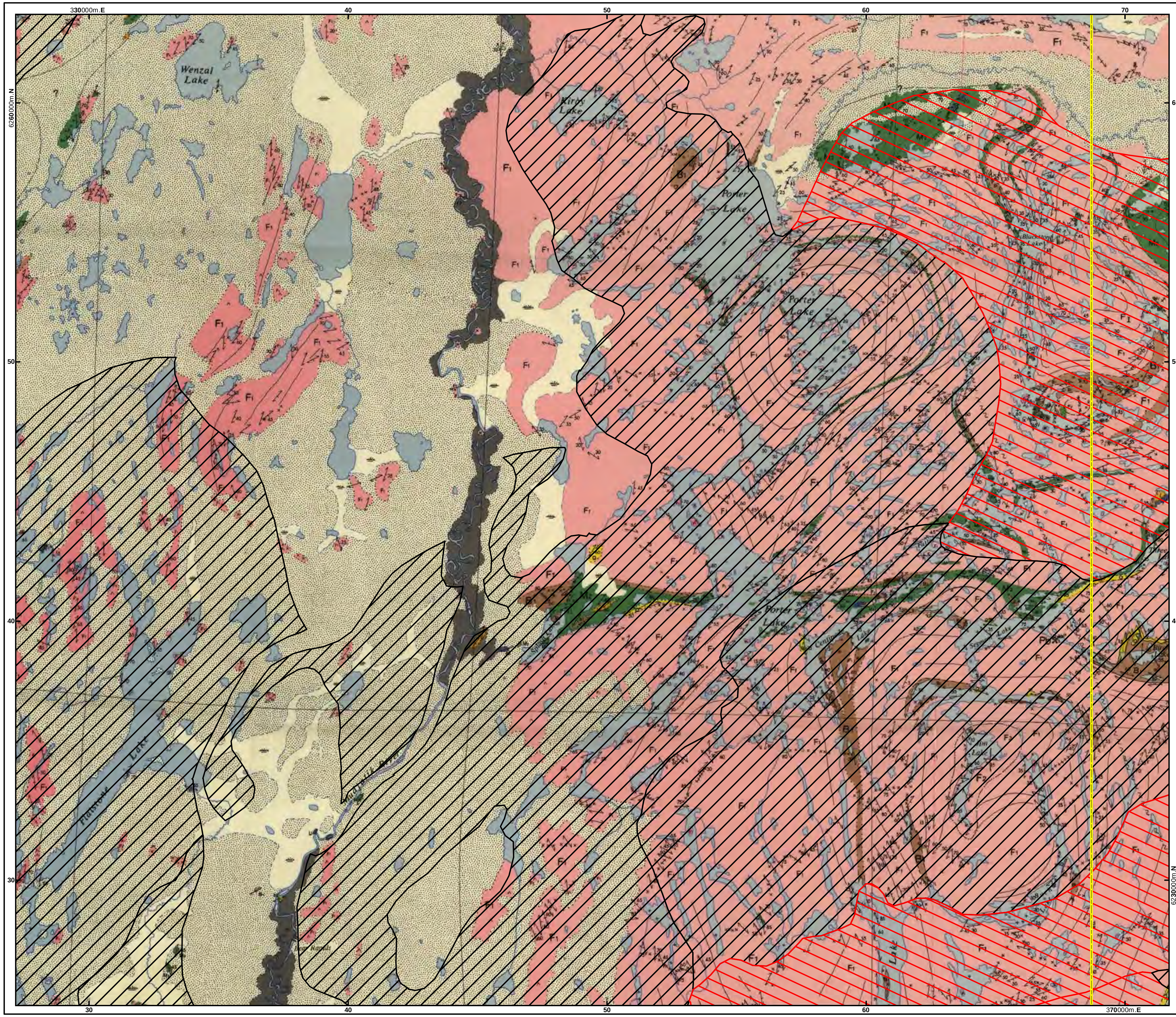
PROJECT

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

TITLE

Bedrock map of Sub-region 2.1

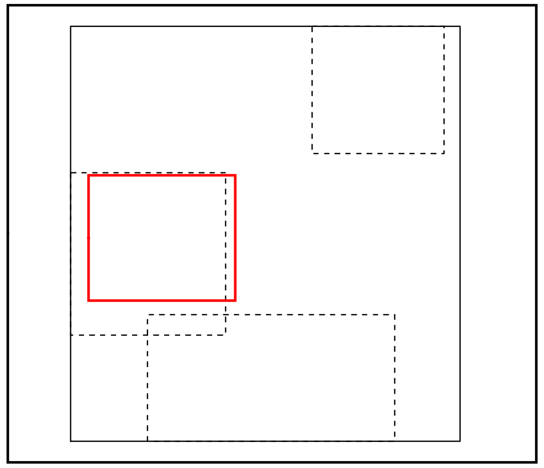
DESIGN	DVZ	25 JUN 2012	FIGURE 12	REVISION 2
GIS	DVZ	06 AUG 2013		UTM ZONE 13
CHECK	JIC	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:150,000



LEGEND

- Detailed area
- R - Rock
- Mv - Morainal veneer

Rock outcrop, area of rock outcrop, observed from the air	
Dip and strike of foliation at an outcrop (dip values reported to nearest 5°)	
Geological boundary (defined, approximate, assumed, gradational)	
Geological boundary inferred below drift	
Foliation trace or "structural trend"	
Fault	
Esker	
Muskeg	
River and edge of meander cut-off belt	
Mineral prospect	× Pb
Reef or small island	
Drift cover	



NORTH

2 km

Data source:
Bedrock geology: Pearson (1977) 1:100,000
Surficial geology: Sask Geo. Atlas 1:250,000

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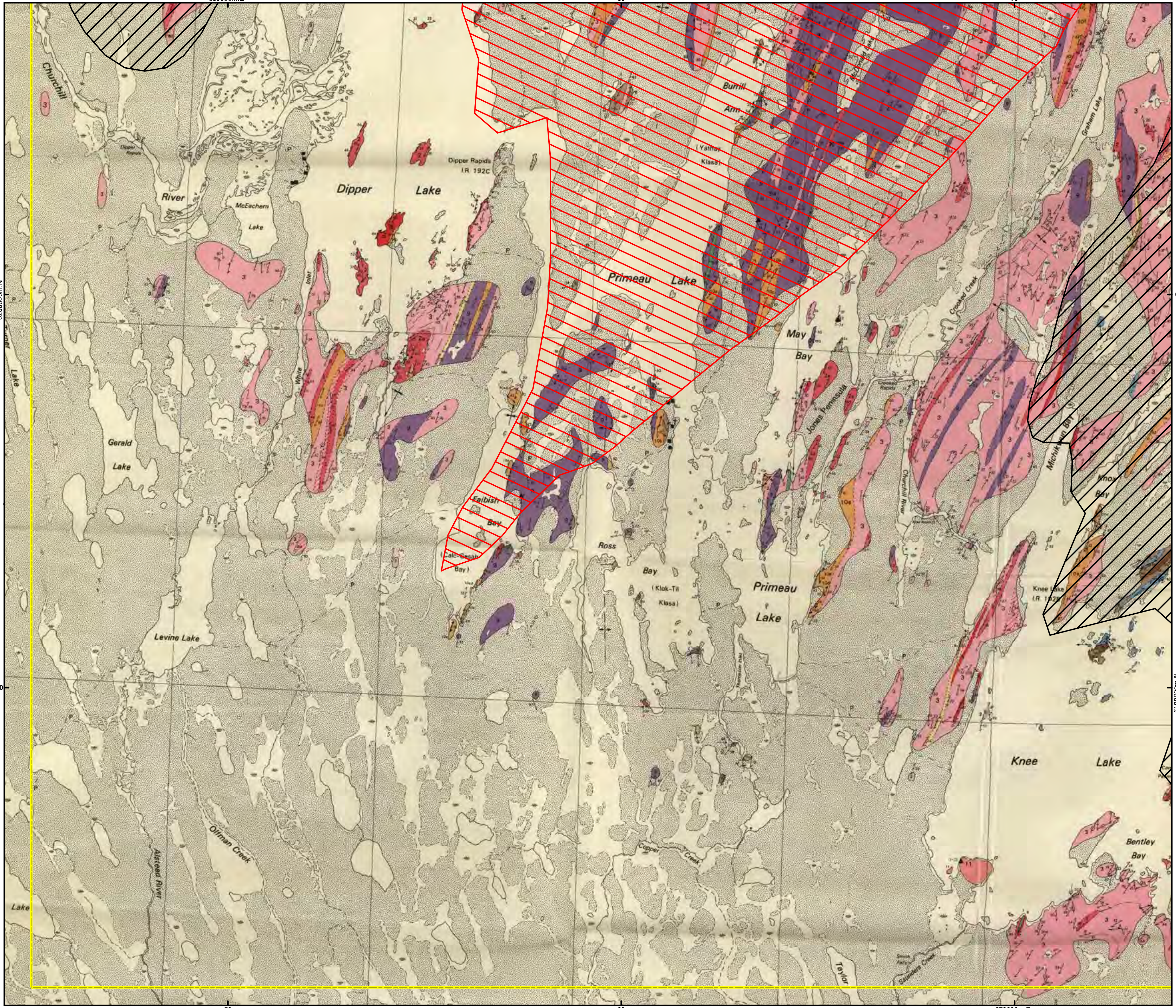
PROJECT

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

TITLE

Bedrock map of Sub-region 2.2

DESIGN	DVZ	25 JUN 2012	FIGURE 13	REVISION 2
GIS	DVZ	06 AUG 2013		UTM ZONE 13
CHECK	JIC	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:150,000



LEGEND

Detailed area

Surficial geology

R - Rock

Mv - Morainal veneer

Anticline, with approximate direction of plunge

Syncline, with approximate direction of plunge

Glacial striae

Esker

Drift cover

Muskeg

Approximate extent of outcrop in area of glacial drift

Swampy shoreline, with long grass or willows

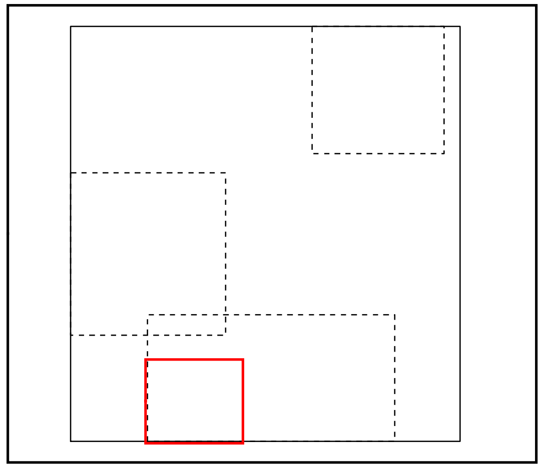
Reef or small island

Beach or shoal

Stream (navigable, not navigable by canoe)

Portage

Rapids



NORTH

1 km

Data source:
Bedrock geology: Scott (1977) 1:63,360
Surficial geology: Sask Geo. Atlas 1:250,000

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

TITLE
Bedrock map of Sub-region 2.3

DESIGN	DVZ	25 JUN 2012	FIGURE 14	REVISION 2
GIS	DVZ	06 AUG 2013		UTM ZONE 13
CHECK	JIC	06 AUG 2013		NAD 1983
REVIEW	GS	06 AUG 2013		1:100,000