



NUCLEAR WASTE SOCIÉTÉ DE GESTION  
MANAGEMENT DES DÉCHETS  
ORGANIZATION NUCLÉAIRES

# Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation

**ENGLISH RIVER FIRST NATION, SASKATCHEWAN**



**APM-REP-06144-0046**

**NOVEMBER 2013**

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# PHASE 1 DESKTOP GEOSCIENTIFIC PRELIMINARY ASSESSMENT

## LINEAMENT INTERPRETATION

### ENGLISH RIVER FIRST NATION, SASKATCHEWAN

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## EXECUTIVE SUMMARY

In January 2012, English River First Nation (ERFN), Saskatchewan expressed interest in continuing to learn more about the Nuclear Waste Management Organization's (NWMO) nine-step site selection process, and requested that a preliminary assessment be conducted to assess potential suitability of the 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 desktop study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. The findings of the overall preliminary assessment are reported in an integrated report (NWMO, 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 lineament investigation assessment completed as part of the desktop geoscientific preliminary assessment of the ERFN area (Golder, 2013). The lineament assessment focused on identifying surficial and geophysical lineaments and their attributes using publicly-available digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the ERFN area in northern Saskatchewan. The assessment of interpreted lineaments in the context of identifying general areas that have the potential to meet NWMO's geoscientific site evaluation factors is provided in the desktop preliminary geoscientific assessment report (Golder, 2013).

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

- Lineaments were interpreted from multiple, publicly-available datasets (aeromagnetic, CDED, SPOT and LandSAT);
- Lineament interpretations were made by documented specialist observers and using a standardized workflow;

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

The distribution of lineaments in the ERFN area reflects the bedrock structure, resolution of the datasets used, and surficial cover. Surface lineament density, as demonstrated in this assessment, is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures. Lineament density was observed to be highest in the eastern part of the ERFN area, where thin surficial cover and exposed bedrock revealed numerous fractures in the crystalline rock. The lowest lineament densities were observed in the western part of the ERFN area or in low lying areas covered by overburden. On the basis of the structural history of the ERFN area, a framework was also developed to constrain the relative age relationships of the interpreted lineaments.

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## 1 INTRODUCTION

In January 2012, the English River First Nation (ERFN), in northern Saskatchewan 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 for safely hosting a deep geological repository (Step 3).

The overall preliminary assessment of potential suitability is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation; environment and safety, as well as social, economic and cultural considerations (NWMO, 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 lineament investigation assessment completed as part of the desktop geoscientific preliminary assessment of the ERFN area (Golder, 2013). The lineament assessment focussed on identifying surficial and geophysical lineaments and their attributes using publicly-available digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the ERFN area in northern Saskatchewan. The assessment of interpreted lineaments in the context of identifying general areas that are potentially suitable for hosting a repository is provided in the desktop preliminary geoscientific assessment report (Golder, 2013).

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. Owing to the large size of the ERFN area and the widely spaced distribution of communities within the area, an initial phase of lineament mapping was carried out to provide coverage of the entire ERFN area. Following completion of the preliminary geoscience review and initial lineament mapping phase, three smaller sub-regions were defined

for additional analysis of lineament mapping results: Sub-Region 2.1 (Haultain Lake), Sub-Region 2.2 (Porter Lake and Flatstone Lake), and Sub-Region 2.3 (Dipper Lake, Primeau Lake, Knee Lake, and Elak Dase Lake). A second pass of the remote sensing datasets was made at this stage to ensure that no significant lineaments were overlooked during the initial lineament mapping phase.

## 1.1 SCOPE OF WORK

The scope of work for this assessment includes the completion of a lineament interpretation of remotely-sensed datasets, including surficial (digital elevation data and satellite imagery) and geophysical (aeromagnetic) datasets for the ERFN area (approximately 15,000 km<sup>2</sup>) in northern Saskatchewan (Figure 1). Within the overall ERFN area, three sub-regions were defined for more detailed analysis: Sub-region 2.1 (1,550 km<sup>2</sup>); Sub-region 2.2 (2,324 km<sup>2</sup>); and Sub-region 2.3 (2,892 km<sup>2</sup>) (Figure 1). The lineament investigation interprets the location and orientation of possible individual fractures or fracture zones and helps to evaluate their relative timing relationships within the context of the local and regional geological setting. For the purpose of this report, a lineament is defined as, ‘an extensive linear or arcuate geologic or topographic feature’. The approach undertaken in this desktop lineament investigation is based on the following:

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



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

At this desktop stage of lineament investigation, the remotely-sensed character of interpreted features allows only for their preliminary categorization, based on expert judgement, into two general lineament classes, including ductile and brittle lineaments. Consistent with the known bedrock geology of the ERFN area, no dyke lineaments were interpreted during this assessment. The two lineament categories employed in the analysis are described in more detail below in the context of their usage in this preliminary desktop assessment.

- **Ductile lineaments:** Features which were interpreted as being associated with the internal fabric of the rock units (including sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation) were classified as ductile lineaments. This category also includes recognizable penetrative shear zone fabric.
- **Brittle lineaments:** Features interpreted as fractures (joints or joint sets, faults or fault zones, and veins or vein sets), including those that offset the continuity of the ductile fabric described above, were classified as brittle lineaments. This category also includes brittle-ductile shear zones, and brittle partings interpreted to represent discontinuous re-activation parallel to the ductile fabric. At the desktop stage of the investigation, this category also includes features of unknown affinity.

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

## 1.2 QUALIFICATIONS OF THE INTERPRETATION TEAM

The project team employed in the lineament interpretation component of the Phase 1 Desktop Geoscientific Preliminary Assessment of Potential Suitability consists of qualified experts from J.D. Mollard and Associates (2010) Limited, Regina (JDMA), Golder Associates Ltd., Mississauga, and Patterson, Grant and Watson, Toronto (PGW). JDMA coordinated the

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

Following is a brief description of the qualifications of project team members.

**Lynden Penner, M.Sc., P.Eng., P.Geo.** has undertaken the advancement of lineament research through the application of aerial and satellite imagery, DEMs, and GIS technology for a variety of projects including oil and gas exploration, potash mine development, groundwater exploration and contamination, CO<sub>2</sub> sequestration studies, and assessing gas leakage from oil and gas wells beginning in 1986 and continuing to present. Given his expertise in mapping and understanding lineaments, Mr. Penner advised project team members on lineament mapping approaches and assisted with mapping lineaments from remotely sensed imagery and worked with the project team to evaluate the significance of the mapped, coincident and linked lineaments.

**Dr. Jason Cosford, Ph.D., P.Geo.** has contributed to a wide range of terrain analysis studies conducted by JDMA, including routing studies (road, rail, pipeline, and transmission line), groundwater exploration, granular resource mapping, and environmental sensitivity analyses. Dr. Cosford, Mr. Penner and Dr. Jack Mollard were responsible for shallow groundwater studies for the Weyburn CO<sub>2</sub> sequestration research project. Dr. Cosford provided interpretation of the surficial lineaments and coordinated the evaluation of lineament attributes, and oversaw the preparation of integrated lineament datasets.

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

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

**Dr. Alex Man, Ph.D., P.Eng.** is a senior geotechnical and geoenvironmental engineer with a diverse background tailored towards the management of nuclear waste in deep geological repositories. He has conducted research on engineered clay barriers for high-level nuclear waste isolation on behalf of NWMO. Dr. Man was responsible for managing a geotechnical laboratory and conducting large-scale demonstration tests in both laboratory and underground environments while at AECL. His field experience includes the drilling of boreholes to depths up to 1,200 m, in situ stress measurements, core orientation (for fracture mapping), hydrogeologic (packer) testing, and installation of hydrogeological monitoring systems for the purpose of site

characterization for nuclear waste management. In addition, Dr. Man has 17 years of experience in the consulting field, where he conducted numerous geological and hydrogeological site investigations across Canada. In this assessment, Dr. Man was the second interpreter of the surficial lineaments.

**Dr. James Misener, Ph.D., P.Eng.** is President of PGW and a senior geophysicist with 37 years of experience in all aspects of geophysics and geophysics software applications. Dr. Misener founded Geosoft Inc. and led its development of world-leading geosciences software applications until he succeeded Dr. Paterson as President of PGW. He has directed implementation of geophysical data processing systems; initiated and managed major continental scale compilations of aeromagnetic/marine magnetic data in North America and worldwide including interpretation of aeromagnetic, radiometric, gravity and electromagnetic surveys in: Algeria, Brazil, Cameroon, Niger, Ivory Coast, Zimbabwe, Malawi, Kenya, China, Suriname, and Ireland. Dr. Misener provided interpretations of geophysical survey data, and provided interpretation of geophysical lineaments.

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

### 1.3 REPORT ORGANIZATION

Section 2.0 describes the geological setting of the ERFN area, which includes subsections on physical geography, bedrock geology, geological and structural history, Quaternary geology, and land use. Section 3.0 provides information on the source data and explains the methodology used to identify and assess lineaments. Section 4.0 presents the findings of the lineament interpretation with a description of lineaments by each dataset and a description and classification of integrated lineaments. Section 5.0 offers a discussion of the findings, specifically the lineament density,

reproducibility and coincidence, lineament length, fault and lineament relationships, and relative age relationships. Section 6.0 is a summary of the report.

The primary source for all of the background information presented herein is the main report written by Golder (2013). This report also draws upon information from the supporting reports on terrain analysis (JDMA, 2013) and geophysics (PGW, 2013).

## 2 SUMMARY OF PHYSICAL GEOGRAPHY AND GEOLOGY

A detailed discussion of the geological setting of the ERFN area is provided in a separate report (Golder, 2013). The following sections on Physical Geography, Bedrock Geology, Structural History, Quaternary Geology and Land Use, present the information presented in Golder (2013), JDMA (2013) and PGW (2013), where applicable, in order to provide the necessary context for discussion of the results of this lineament assessment (Section 5.0).

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 2.0 billion years 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.

The ERFN area is located within the Hearne craton that comprises 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 3). 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.

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.

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 to a major crustal strike-slip 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-Trans-Hudson 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 (Figures 2 and 3), 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 north-northeast-trending linear grain in the Wollaston domain. The predominance of metasedimentary gneisses of the Wollaston Supergroup in the north and central parts of the Wollaston domain declines to the south, where they become

discontinuous in bands intercalated with Archean felsic (ortho) gneiss and younger granitoid rocks.

## 2.1 PHYSICAL GEOGRAPHY

A detailed discussion of the physical geography of the ERFN area is provided in a separate terrain analysis report by JDMA (2013). The physical geography of the ERFN area exhibits topography and drainage that are characteristic of the Canadian Shield, a low-relief, dome-like, gently undulating land surface. Ground surface elevation ranges from about 631 metres above sea level (masl) near Norbert Lake to 385 masl on the Churchill River in the south-east near Sandfly Lake. Elevations and relief are lowest in the south and southeast of the ERFN area along the Churchill River. The low relief in the southwest of the ERFN area results from the cover of Phanerozoic rocks and Quaternary surficial materials. Between the Haultain and Mudjatik Rivers, the topography is very rugged with deeply incised valleys that express the underlying bedrock structures (Figure 5 herein and Figure 4 in JDMA, 2013). The highest elevations are found in the northeastern and eastern portions of the ERFN area.

Two major topographic highs are present within the ERFN area, informally referred to by JDMA (2013) as the Haultain and Norbert highs after lakes situated on the highlands within the ERFN area. The two highlands are divided by the lowland surrounding the Haultain River. The Haultain high extends southwest from near Haultain Lake into the centre of the ERFN area. The Norbert high represents a prominent northeast trending highland in the east-central part of the ERFN area. The tops of these bedrock-controlled uplands exceed 600 m in elevation, representing 150 to 175 m of relief above the surrounding lowlands.

The major topographic lows in the ERFN area are informally referred to by JDMA (2013) as the Hedderly and Churchill lows. 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 Hedderly low is the low-relief outwash plain south of where the Cree Lake Moraine is best expressed within the ERFN area, from its junction with the Mudjatik River to Black Birch Lake. The Hedderly low forms a discontinuous plain extending eastward into the Haultain high thereby rendering the craggy upland surrounding Complex Lake as an isolated summit. It can be argued that the Hedderly low represents the most prominent Quaternary landform in the ERFN area, rather than the Cree Lake Moraine as suggested by Schreiner (1984a and 1984b). It makes up a much larger area than the moraine and the strong contrast provided by the rock ridges extending like tiny



islands from the vast outwash plain forms a distinctive appearance. There is also a smaller outwash plain located at the southern limit of the depression between the Haultain and Norbert highs, at the intersection of Sylvester Creek and the Haultain River, here referred to for convenience as the Sylvester Plain (JDMA, 2013).

Surface water covers a total area of 1,907 km<sup>2</sup>, which represents coverage of approximately 13% of the ERFN area. All of the surface flow within the ERFN area drains through the Churchill River into Hudson Bay, except for a small area around Black Birch Lake, which drains into the Arctic ocean through the Athabasca River (Figure 1). Sub-basins within the ERFN area are drained by the Churchill, Clearwater, Haultain, Mudjatik, and Wheeler rivers.

## 2.2 BEDROCK GEOLOGY

The reader is directed to Golder (2013) for a detailed description and discussion of the bedrock and structural geology of the ERFN area. The ERFN area features three main geological units, including felsic gneiss in the Mudjatik domain, supracrustal rocks with a dominantly sedimentary protolith in the Wollaston domain, and felsic gneiss in the Wollaston domain (Figure 3). Exposed bedrock (including thin, <1 m, morainal veneer) covers 7,735 km<sup>2</sup> or roughly 52% of the ERFN area. Golder (2011) identifies the felsic gneiss in the Mudjatik and in the Wollaston domain as being potentially suitable for hosting a deep geological repository in the ERFN area. There are no mapped dykes in the ERFN area.

### 2.2.1 FELSIC GNEISS

Felsic gneiss is the predominant rock type found in the Mudjatik domain and covers a substantial portion of the Wollaston domain. The term felsic gneiss was first used by Sibbald (1973) to describe a complex group of rocks of broadly granitic composition (noting that it was before appearance of Streckeisen (1976) terminology), in which the minerals quartz, plagioclase and K-feldspar range between 10% to 40% with minor components of biotite, hornblende, hypersthene, garnet, cordierite, and magnetite, and which fabric covers a broad range between well-developed layering, including lit-par-lit, to massive unfoliated domains. Harper (1988a, b) later refined this term by classifying the felsic granitoid gneisses in central and northwestern Mudjatik domain in three different units: tonalitic orthogneiss, generally-layered felsic gneiss of probable supracrustal origin, and granite and granite pegmatite; whereas Card et al. (2008) considered them all to be orthogneisses. While the first two lithologies are thought to underlie the supracrustal rocks, mainly metasedimentary gneissic rocks, the latter intrude them all. Although the exact thickness

of the felsic gneiss in the ERFN area is unknown, regional geophysical studies (White et al., 2005; Hajnal et al., 2005) have interpreted its thickness to be in the range of 5 to 10 km in the Mudjatik domain. The Archean felsic gneiss has an approximate crystallization age of approximately 2.7 Ga (Orrell et al., 1999).

Tonalitic gneiss is the predominant lithology in the felsic gneiss. According to Harper (1988a, b), the tonalitic gneiss is grey, coarse-grained, and has well developed swirly foliation. Presence of hypersthene indicates that the tonalitic gneisses were subjected to granulite-facies metamorphism. In some areas, the tonalitic gneisses may be accompanied by scattered rafts evidencing high-grade migmatization. The tonalitic gneiss is thought to be of igneous origin (orthogneiss), with a crystallization age dated at approximately 2.7 Ga (Orrell et al., 1999).

The layered felsic gneiss is largely migmatitic in origin nature (Harper, 1988b; Orrell et al., 1999). According to Harper (1988b), the paleosome is colour-banded and layered, fine-grained, granoblastic equigranular, predominantly biotitic and quartzofeldspathic, of probable psammitic to psammopelitic origin; although, Card et al. (2008) considered it to be of dominantly tonalitic composition. The neosome resulting from extensive anatexis of the paleosome is a coarser-grained, equigranular, massive to weakly foliated leucogranite, occurring either in fine-banded parallel veins or in irregular masses.

The youngest components of the felsic gneiss are leucogranites and granite pegmatites. Harper (1988b) described the granites as pink to red, varying from fine to coarse to porphyritic in texture, while typically being massive to weakly foliated. He suggested their emplacement as sheet-like bodies into migmatite nappe lobes before the occurrence of dome-and-basin folding. Contact with the other two types of rock is generally gradational, and the transition from the layered gneiss is characterized by progressive increase in neosome and exclusion of supracrustal relicts. Finally, pink granite pegmatite intrudes all rocks other gneissic rocks. Their occurrence occurring as irregular veins in the granites, suggest they are the last phase related to the formation of the granite.

Very similar lithologies to the three ones above described by Harper (1988a, b) have been reported by Orrell et al. (1999) and Card et al. (2008) for northwestern Mudjatik domain, and partly by Card and Bosman (2007) close toward the southern border of the Athabasca basin. Variation to granodiorite from the dominant tonalitic lithology has been reported by Tran (2001) in the eastern Mudjatik domain-western Wollaston domain and by Card and Bosman (2007) and Card et al. (2008) in the northwest of the domain, and Card and Bosman (2007) to the north.

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### 2.2.2 METASEDIMENTARY AND METAVOLCANIC ROCKS

Metasedimentary and metavolcanic rocks of the Mudjatik domain are dominated by psammopelitic to pelitic rocks and amphibolite that unconformably overlie the Archean felsic gneiss (Card and Bosman, 2007). These supracrustal rocks range from Archean to Paleoproterozoic in age, and they may correlate to the basal groups of the Wollaston Supergroup (Card et al., 2008). The supracrustal rocks occur in narrow, arc shaped bands throughout the Archean felsic gneiss, defining a dome and basin pattern (SGS, 2003). Near the mapped boundary, between the Mudjatik and Wollaston domains, is a complexly deformed and highly metamorphosed area where the metasedimentary and minor metavolcanic rocks are interspersed with migmatites and felsic gneiss (Munday, 1978).

The Wollaston Supergroup consists mainly of arkose, quartzite, pelite, orthoquartzite, psammopelite, calc silicate and psammite (Yeo and Delaney, 2007). Pelitic to psammopelitic gneisses found in the region are fine to coarse grained, generally well foliated to gneissic in texture, commonly porphyroblastic and biotite rich. These gneisses can include cordierite, garnet, sillimanite, graphite and magnetite (Thomas and Slimmon, 1985). Metasedimentary psammitic to meta-arkosic gneiss consist of fine to medium grained, massive to foliated rocks, which can be locally colour-banded and may include quartz, feldspar, biotite, muscovite, sillimanite, cordierite, garnet, diopside, epidote, andalusite, interbanded calc-silicates and pelitic gneiss. Slivers of metavolcanic rocks are also evident in the supracrustal package (Thomas and Slimmon, 1985).

The predominance of metasedimentary gneisses of the Wollaston Supergroup in the north and central parts of the Wollaston domain declines towards the south, where they become discontinuous in bands intercalated with Archean felsic (ortho) gneiss and younger granitoid rocks.

### 2.2.3 FAULTS AND SHEAR ZONES

The most prominent structural features in the ERFN area are the domain-bounding shear zones and brittle faults of various orientations that overprint these shear zones.

The Hearne craton is bounded to the west by the Rae craton along the Snowbird tectonic zone and is bounded to the east by the Reindeer zone along the Needle Falls and Parker Lake shear zones. These shear zones are oriented in a north-northeast to northeast direction, which is the predominant alignment of major structural features and lithologies within the Precambrian in northern Saskatchewan (Figure 2).

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

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

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

A series of steeply dipping faults that cross cut a series of sub-horizontal faults are noted at the east end of the Wollaston domain, close to the (subvertical) Needle Falls shear zone (White et al., 2005). These steep faults were interpreted by Hajnal et al. (2005) to be the north-northwest trending faults discussed below (i.e., part of the Tabbemor fault system). Hajnal et al. (2005) further noted numerous east-dipping fracture zones within the upper portions of the Wollaston

domain. These features were also noted along the east side of the Mudjatik domain, but are much less abundant to absent in the central to western portions of the Mudjatik.

A series of steeply dipping and north-northwest-trending brittle faults are noted at the east end of the Wollaston domain, close to the Needle Falls shear zone (White et al., 2005). The longest of these brittle structures are over 120 km in length and appear as prominent topographical lineaments. They have been associated with brecciation, shearing, mylonitization and hydrothermal alteration (Byers, 1962). Sinistral horizontal displacement of up to 800 m is observed along the faults, and geophysical interpretations suggest near vertical dips for the fault planes. Some evidence suggests that reactivation and displacement has occurred along these faults as recent as the Cretaceous period (Byers, 1962). These steep faults were interpreted by Hajnal et al. (2005) to be the north-northwest trending faults discussed above (i.e., part of the Tabbernor fault system (discussed below)). Another prominent trend of relatively long mapped (D5) faults is east-northeast to east-southeast. These faults are much less pervasive and relatively sparsely populated throughout the area compared to the more prominent north-northwest-trending faults discussed above.

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

#### **2.2.4 METAMORPHISM**

The Mudjatik and Wollaston domains belong to the Western Churchill Province (Corrigan et al., 2009). As such, all Archean and Paleoproterozoic rocks of the Mudjatik and Wollaston domains, record part of the regional metamorphism of which the Churchill structural province was

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

Rocks of the Hearne craton (Mudjatik domain and Wollaston domain) were exposed to high grade metamorphism, reaching upper amphibolite to granulite facies (e.g., Pearson, 1977; Tran, 2001). Orrell et al. (1999) posed that all metamorphic fabrics observed in the Hearne craton were the result of a single thermotectonic cycle caused by the THO. This view has been disputed by other authors (e.g., Bickford et al., 1994; Tran, 2001; Card et al., 2007) who have interpreted the high-grade metamorphism undergone by the rocks of the Hearne craton as having occurred during two distinct periods of high temperature, low pressure metamorphism. It is quite possible, though, that M2 may have occurred as a continuum of substages rather than occurring as a single event. For example, Annesley et al. (2005) reported three metamorphic events associated to the peak of the THO.

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

The second metamorphic period occurred concomitantly with the peak of the THO during the approximate period 1.84 to 1.80 Ga, and later outlasted it (Tran, 2001). Orrell et al. (1999) calculated peak metamorphic conditions at  $750\pm 50^{\circ}\text{C}$  and about 5.5 kbar. These values agree very well with those estimated by Tran (2001),  $725^{\circ}\text{C}$  and a maximum pressure of 5 kbar

followed by decompression to  $>600^{\circ}\text{C}$  and  $>3.4$  kbar, and those estimates of Annesley et al. (2005) for three stages comprising initial pressure conditions of  $>4$  to 5 kbar, increased to 6 to 9 kbar at  $>775^{\circ}\text{C}$  and later followed by decompression at 3 kbar and increased temperatures of  $750^{\circ}$  to  $825^{\circ}\text{C}$ .

### 2.3 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 Dx 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 1, 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; Card et al., 2008; Whitmeyer and Karlstrom, 2007; 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.

Final accretion of the La Ronge Arc along eastern margin of 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 Mudjatik domain and the thin-skinned imbrication evident in 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 northwest-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 and Bosman, 2007).

Later deformation involved the development of regional-scale brittle structure, including the Tabernor 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 Tabernor fault system, which has a long history of re-activation that may have continued until the Mesozoic Era (e.g., Byers, 1962; Elliott, 1996).



**Table 1 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 <sub>1</sub> ductile deformation that produced isoclinal folds and imparted the S <sub>1</sub> 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 <sub>2</sub> ductile deformation produced upright folds that overprinted the S <sub>1</sub> 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 thrust 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 <sub>3</sub> 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 <sub>4</sub> ductile deformation creates NW-striking upright folds orthogonal to F <sub>3</sub> after movement on the Virgin River and Cable Bay shear zones.
1.80 to 1.72	Activation of the Tabernor fault zone (1.8 Ga ago) and the D <sub>5</sub> 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.

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 remnants of the Trans-Hudson Orogen that were deposited in a shallow basin. The maximum thickness of the basin is about 1.5 km in its center (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 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.

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## 2.4 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 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 Annesley et al. (2005) study was undertaken in the area to the east of the Athabasca Basin, quite a distance further away 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 NWMO and 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, and cross-cut 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 east of the ERFN area (Golder, 2013; Figure 3.1 therein). 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 analyses indicate reactivation of the fault in the late Devonian and early Cretaceous Periods (Elliot, 1996; Davis, 1998; Hajnal et al., 2005).

## 2.5 QUATERNARY GEOLOGY

Quaternary geology of the ERFN area is described in detail in a separate terrain analysis report by JDMA (2013). Quaternary surficial deposits cover a total of 6,224 km<sup>2</sup> or roughly 42% of the ERFN area (Figure 4), which does not include areas covered by a thin (<1 m thick) veneer of till or glaciolacustrine deposits. This surficial cover comprises different types of glacial deposits that accumulated with the progressive retreat of the ice sheet during the end of the Wisconsinan glaciation. Regionally, the main Quaternary deposits include morainal plains, and glaciofluvial plains, with sparse occurrences of glaciolacustrine plains. Glaciofluvial plains mainly consist of

outwash plains that were incised through the morainal deposits as the glacier receded and melt waters drained. Both types of glacial deposits are primarily sandy, with varying amounts of silt and clay fractions (Schreiner, 1984a). The descriptions of the Quaternary deposits are based on surface mapping, and little to no information is available on the variation of the deposit types and compositions at depth.

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). Within the areas mapped as ground moraine, the area underlain by till is typically equalled by that made up of lakes, muskeg, and bedrock exposures.

Bedrock topography is only minimally obscured in areas of morainal veneer. The surface expressions of faults, shear zones and other geological structures are displayed clearly in these areas. Schreiner (1977) suggested that south of the Cree Lake Moraine within the ERFN area, sandy till is so thin that the underlying bedrock structure is detectable. Preferential deposition of till in low areas between bedrock ridges and hills can mask the relief of the bedrock terrain. Areas of thicker, more continuous, ground moraine are generally represented as moraine plains and drumlinoid moraine (Schreiner, 1984b). In some areas, ground moraine occurs in association with 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.

Sand and gravel are found mainly along the Mudjatic and Haultain Rivers within the ERFN area, which functioned as major melt water channels (Schreiner et al., 1976). Schreiner (1984b) suggests that of the Mudjatic, Haultain, Foster and Paull rivers, the Mudjatic and Haultain were the more substantial melt water channels, as indicated by the wide sand plains bordering these rivers, especially south of the Cree Lake Moraine. The floor of the spillway cut along the Mudjatic River south of this moraine is at least 20 m below the surface of the sand plain, indicating a minimum depth of the stratified sand deposit if the floor of the spillway is within the outwash deposit.

Larger glaciofluvial deposits have the potential to represent significant regional aggregate or groundwater supplies. The good foundation conditions and abundance of suitable borrow and

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granular materials make these landforms ideal for transportation routes, building sites, and airport locations.

Schreiner et al. (1976) indicated a scarcity of glaciolacustrine deposits in the southern part of the ERFN area, and suggested that Lake Agassiz did not extend this far westward. Some isolated glaciolacustrine deposits were mapped within the ERFN area north of the Cree Lake Moraine.

One of the reasons for locating the Highway 914 route along the Haultain River valley (JDMA, 1977) was that the organic deposits in the outwash plains along the valley were suspected to be much thinner than those confined between bedrock highs along the alternate route to the east, which traversed through the bedrock terrain. That is, organic terrain is less common in bedrock terrain, but where present, the peat usually fills deep basins between bedrock knobs and ridges. The material present in organic terrain is peat and muck and within most organic terrain, stagnant drainage or wet surface conditions are common. Large areas of organic terrain are located in the Hedderly low and the Sylvester Plain.

Exceptionally poor engineering characteristics can be found within areas mapped as organic terrain. Peat and muck have very low shear strength and high compressibility. Groundwater tables are at or near the surface in organic terrain. Flooding is common in organic terrain, and this forms a significant constraint on most types of development. Although peat and muck deposits usually occur as relatively thin surficial layers, in places, these organic materials can be several metres thick, and the thickness can change drastically over very short distances. The deposits are generally thin where they overlie flat mineral soil terrain such as outwash and glaciolacustrine plains, whereas they are thicker in high relief till deposits and where they fill bedrock depressions and deep kettle holes. The locations of deeper pockets of organic material are difficult to predict reliably without test drilling.

The Haultain Lake area contains many positively expressed landforms such as ridges and knobs where overburden thickness is low and bedrock exposure is good. The Highway 914 corridor provides access to several of these rock ridges. However, the vast majority of the areas of thin drift and good bedrock exposure are located ten or more kilometres west of the highway. Between these local bedrock highs, the largest wetlands are located in the southern half of the detailed area.

There is currently no road access to the Porter Lake area. Most of the best areas of thin drift and good bedrock exposure are located in the highlands in the northeast part of the area, which is furthest from the existing road (Highway 918). The outwash plains within the valley of the

Mudjatik River within the Porter Lake area contain extensive wetlands, which is an unfavourable attribute for road routing. The intricate fabric of lakes and steep slopes within the uplands poses a different set of access constraints.

The best areas of thin drift and good bedrock exposure within the Primeau Lake area are concentrated north of the Churchill River in the central and east parts of the detailed area. Highway 918 provides direct access to some of these areas. The north-central part of the area has the best outcrop exposure, but road routing into this area would involve creek crossing and sections traversing through rugged bedrock-controlled terrain. The large water bodies associated with the Churchill River and the intricate pattern of lakes on the upland to the north pose additional constraints in this area.

Estimates of overburden thickness within the ERFN area were extracted from descriptions in the available Saskatchewan Geological Survey (SGS) reports. The Cree Lake Moraine represents a significant Quaternary landform in the ERFN area. Its thickness outside of the ERFN area can reach 45 to 74 m, as indicated by its relief above the surrounding landscape, but within the ERFN area, the moraine is represented by a discontinuous band of hummocky debris probably less than 30 m. Glacial deposits in areas mapped as ground moraine are characterized as veneers and blankets of sandy ablation till distributed amongst lakes, muskegs, and bedrock outcrops, with deposit thicknesses typically less than one metre to many tens of metres. Outwash deposits in northern Saskatchewan are typically 5 to 10 m thick. Thin organic deposits are common in low-relief areas of thick drift, whereas they can reach much greater thicknesses where they fill high relief basins formed between bedrock ridges and knobs or in kettle holes.

Quaternary cover has a significant impact on the interpretation of lineaments in the English River First Nation area. Where the Quaternary cover is relatively thin, and the bedrock mostly exposed, bedrock lineaments are more pronounced and can be mapped with greater certainty. In these areas of thin and discontinuous cover, the density of lineaments is notably higher. Areas where the Quaternary cover is relatively thick and continuous, the lineaments are more obscured and are mapped with less certainty. Here, the lineaments exhibit a lower density.

## 2.6 LAND USE

The ERFN area is within a remote part of northern Saskatchewan that is almost completely undeveloped. Uranium deposits discovered north of the ERFN area around Key Lake in the middle 1970s resulted in the routing Highway 914 through the valley of the Haultain River from Pinehouse to the prospective mill site at Key Lake (Mollard et al., 1977).

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Five of the eight First Nations Reserves located within the ERFN area are positioned proximally to the Churchill River, which traditionally represented a major transportation corridor for the areas currently represented by the Provinces of Alberta, Saskatchewan to Manitoba. This was also an important transportation corridor during the fur trade starting with the Hudson's Bay Company in the early 1800s. The communities along the Churchill are the Wapachewunak, Dipper Rapids, Primeau Lake, Knee Lake, and Elak Dase Indian Reserves. Three relatively remote reserves are located along the Mudjatik and Haultain rivers. These are the Flatstone Lake and English River reserves and the Haultain Lake reserve, respectively.

Recreational lodges are located at Complex Lake and Holt Lake, with outfitters at George Lake, Cup Lake and along the Churchill River. The Gordon Lake Recreation Site is located south of the ERFN area.

Land use and cultural features in the ERFN area do not negatively impact on the interpretation of bedrock lineaments.



### 3 METHODOLOGY

#### 3.1 SOURCE DATA DESCRIPTIONS

The lineament interpretation was conducted using available surficial (CDED digital elevation models, SPOT satellite imagery), and geophysical (aeromagnetic) datasets for the ERFN area. Available data were assessed for quality, processed and reviewed before use in the lineament interpretation. SPOT and CDED datasets were used to identify surficial lineaments expressed in the topography, drainage, and vegetation. The resolution of the SPOT and CDED datasets allowed for the identification of surficial lineaments as short as a few hundred metres in length and provided sufficient detail to reveal surficial structural patterns. The geophysical data, in particular aeromagnetic data, were used to evaluate deeper bedrock structures. Comparing SPOT and CDED lineaments to aeromagnetic lineaments allows for the comparison of subsurface and surficial expressions of the bedrock structure. Both the SPOT and CDED datasets offered advantages to characterize the surficial lineaments. The higher resolution of the SPOT imagery allowed for finer structures to be identified that were not resolved by the CDED data; but, the CDED data often revealed subtle trends masked by the surficial cover captured in the SPOT imagery. The aeromagnetic data proved invaluable to identify bedrock structures beneath areas of extensive surficial cover and to aid in establishing the age relationships among the different lineament sets. Table 2 provides a summary of the source datasets used for the lineament interpretation.

##### 3.1.1 SURFICIAL DATA

###### *CDED (Canadian Digital Elevation Data)*

Canadian Digital Elevation Data (CDED), 1:50,000 scale, 0.75 arc second (20 m) elevation models (GeoBase, 2011a) served as important data sources for analyzing and interpreting the terrain in the ERFN area (Figure 5). The digital elevation model (DEM) used for this assessment, shown as a slope raster in Figure 5, was constructed by the Mapping Information Branch of Natural Resources Canada (NRCan) and by the Landscape Analysis and Applications section of the Canadian Forest Service using 1:50,000 scale source data from the National Topographic Data Base (NTDB). The source data were produced by the Surveys and Mapping Branch of Energy, Mines and Resources Canada based on black and white air photographs acquired mainly in the 1950s at scales of 1:60,000 to 1:70,000. Four main NTDB data types were used: contours,

spot heights, streams, and lakes. CDED datasets are provided in geographic coordinates, referenced horizontally using North American Datum 1983 (NAD83) and vertically based on the Canadian Geodetic Vertical Datum 1928 (CGVD28). Ground elevations are recorded in metres relative to mean sea level. It was determined that the resolution of the DEM dataset was sufficient to undertake the lineament interpretation.

The files were transferred 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 was arbitrary. The projected files were then assembled into a mosaic (Figure 5; JDMA, 2013). Table 3 lists the tiles used in the final mosaic.

Hillshaded elevation data was built using the CDED elevation data. The hillshades were built using illuminated azimuths of 045° and 315° and solar incidence angles of 45° from horizon. Slope was calculated using the standard grid-based method employed in ArcGIS, which involves fitting a plane to the elevation values of a three by three neighbourhood centred on the processing cell. Slope is defined as the maximum slope of that plane, which can also be thought of as the dip of the plane, and aspect is equivalent to the dip direction. Figure 5 shows the calculated slope from the CDED elevation data for the ERFN area. The hillshade and slope rasters were most useful for mapping lineaments.

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

SPOT multispectral (20 m resolution) and panchromatic (10 m resolution) orthoimagery, as shown on Figure 6, were important information sources for identifying surficial lineaments and exposed bedrock 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 to 255). SPOT 5 images were acquired using the HRG sensor. Each image covers a ground area of 60 km by 60 km.

Nine SPOT images (scenes) provided complete coverage for the ERFN area (Table 4). 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 (Sept. or Oct.) and two during the late spring (May or June). The images captured during May and June cover the east-central and southeast parts of the ERFN area, including parts of the Haultain Lake and Primeau Lake areas.

**Table 2 Summary of source information for the lineament interpretation of the ERFN area.**

Dataset	Product	Source	Resolution	Coverage	Acquired	Additional Comments
<b>DEM</b>	Canadian Digital Elevation Data (CDED); 1:50,000	Geobase	20 m	Entire ERFN area	1978 - 1995	Hillshade and slope rasters used for mapping
<b>Satellite Imagery</b>	Spot 4/5; Orthoimage, multispectral/panchromatic	Geobase	10 m (panchromatic) 20 m (multispectral)	Entire ERFN area	2006 - 2009	Panchromatic mosaic used for mapping
<b>Geophysics</b>	Cree Lake South (magnetic and radiometric)	Geological Survey of Canada	400 m line spacing Sensor height 127 m	Covers 877.6 km <sup>2</sup> in northwest part of ERFN area	2007	Magnetic and Radiometric data. Mudjatik domain
	Upper Foster Lake (magnetic and radiometric)	Geological Survey of Canada	400 m line spacing Sensor Height 147 m	Covers 1,074.5 km <sup>2</sup> in northeast part of ERFN area	2005	Straddles boundary of Mudjatik and Wollaston domains
	Saskatchewan #5 (magnetic)	Geological Survey of Canada	805 m line spacing Sensor Height 305 m	North-central part of ERFN area	1964	Magnetic data. Recorded on analog charts, Low resolution
	Saskatchewan #8 (magnetic)	Geological Survey of Canada	1609 m line spacing Sensor Height 305 m	SW part of ERFN area	1952	Magnetic data. Recorded on analog charts, Low resolution
	Saskatchewan #9 (magnetic)	Geological Survey of Canada	805 m line spacing Sensor Height 305 m	SE part of ERFN area	1969	Magnetic data. Recorded on analog charts, Low resolution
	Saskatchewan #10 (magnetic)	Geological Survey of Canada	402 m line spacing Sensor Height 305 m	Covers 61.6 km <sup>2</sup> in southeast corner of ERFN area	1958	Magnetic data. Recorded on analog charts. Wollaston domain

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

NTS Tiles:	Ground resolution (m)
73O/ 10-16	20
73P/ 12-13	20
74A/ 04-05	20
74A/ 12-13	20
74B/ 01-16	20

**Table 4 List of SPOT 4 and 5 multispectral images acquired for the lineament interpretation of the ERFN area.**

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

For quality control, Natural Resources Canada (NRCan) provides images that have a maximum of 5% snow and ice cover, 5% cloud cover and a maximum viewing angle of 15°. NRCan orthorectified the SPOT images using three data sources: 1:50,000 scale Canadian Digital Elevation Data (CDED), National Road Network (NRN), and Landsat 7 orthoimagery. The orthoimages are provided in GeoTIFF format, projected using Universal Transverse Mercator (UTM) projection referenced to the North American Datum 1983 (NAD83). It was determined that the resolution of the SPOT dataset was sufficient to undertake the lineament interpretation. The scenes were processed to create a single panchromatic mosaic (Figure 6; JDMA, 2012). An automated contrast matching technique was applied to the images which minimizes sharp variances in pixel intensity, giving the single image a cohesive appearance. The images were extended beyond the defined boundaries of the ERFN area to allow for the mapping of continuous lineaments extending beyond the ERFN area.

### 3.1.2 GEOPHYSICAL DATA

The geophysical dataset incorporates magnetic, gravity and radiometric data available across the entire ERFN area, however only aeromagnetic data were used for this lineament interpretation. The coarse resolution of the gravity and radiometric data were insufficient to interpret lineaments. Table 2 provides a summary of the acquisition parameters for each aeromagnetic dataset used. The magnetic data located within the ERFN area were processed using several common geophysical techniques in order to enhance the magnetic response to assist with the interpretation of geophysical lineaments. The enhanced magnetic grids used in the lineament interpretation include the first and second vertical derivatives, and the tilt angle filter grids. These enhanced grids were processed and imaged using the Geosoft Oasis montaj software package. Acquisition parameters, processing methods and enhanced grids associated with the geophysical datasets used in the lineament interpretation are discussed in detail in PGW (2013). Three additional magnetic grids using a combination of gradient and amplitude equalization filters were prepared using the Encom (Pitney Bowes) Profile Analyst software package in order to highlight the edges of magnetic sources. The combination of all of the enhanced magnetic grids provide much improved resolution of subtle magnetic fabrics and boundaries in areas that appear featureless in the total magnetic field. Figure 7 shows a compilation of the total field (reduced to pole) of each of these aeromagnetic datasets. The quality of geophysical data varied across the ERFN area. The quality of the data is a function of the flight line spacing, the flying height and the age of the survey. The integrity of the higher quality data was maintained throughout. It was determined that overall the quality of the data was sufficient to perform the lineament interpretation at the scale of the ERFN area.

Low to medium resolution magnetic data from the GSC (Saskatchewan #5, #8, #9, and #10) provides coverage over approximately 86 percent of the southern and central portion of the ERFN area (GSC, 2012). These surveys were all flown at terrain clearances of 305 m, with a variability of flight line spacing of 402 m, 805 m, and 1609 m, providing these surveys with a relatively low spatial resolution. Data from these surveys were recorded on analog charts, with navigation and flight paths determined mainly based on analysis of photomosaics.

Two higher resolution magnetic/radiometric surveys published by the Geological Survey of Canada (GSC) provided coverage on the northwest and northeast corners of the ERFN area (GSC, 2012). These surveys were flown at lower terrain clearance of 127 m and 147 m, and slightly tighter line spacing of 400 m. Data from these two surveys comprise the southern portion

of the GSC Athabasca Basin Compilation of airborne geophysical surveys flown between 2004 and 2009.

### **3.2 LINEAMENT INTERPRETATION WORKFLOW**

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

1. Identification of lineaments by two interpreters for each dataset (DEM, SPOT, MAG) and assignment of certainty level (1, 2 or 3);
2. Integration of lineament interpretations by dataset (Figures 8, 9, 10) and first determination of reproducibility (RA\_1); and
3. Integration of lineament interpretations for all three datasets (Figures 12 and 13) and second determination of reproducibility (RA\_2).

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

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

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

#### **3.2.1 STEP 1: LINEAMENT IDENTIFICATION AND CERTAINTY LEVEL**

The first step of the lineament interpretation was to have each individual interpreter independently produce GIS lineament maps, and detailed attribute tables, for each of the three datasets. This action resulted in the production of two interpretations for each of the DEM, SPOT, and aeromagnetic datasets and a total of six individual GIS layer-based interpretations. Each interpreter assigned a certainty/uncertainty descriptor (attribute field 'Certain' = 1-low, 2-

medium or 3-high) to each feature in their interpretation based on their judgment concerning the clarity of the lineament within the dataset. Where a surface lineament could be clearly seen on exposed bedrock, it was assigned a certainty value of 3. Where a lineament represented a bedrock feature that was inferred from linear features, such as orientation of lakes or streams or linear trends in texture, it was assigned a certainty value of either 1 or 2. For geophysical lineaments, a certainty value of 3 was assigned when a clear magnetic susceptibility contrast could be discerned and a certainty value of either 1 or 2 was assigned when the signal was discontinuous or more diffuse in nature. The certainty classification for all three datasets ultimately came down to expert judgment and experience of the interpreter.

The geophysical dataset also allowed the interpreter to assess the brittle feature type of the lineaments. The brittle geophysical lineaments interpreted as linear fractures exhibit magnetic signals that are lower than the surrounding bedrock. Where clear offsets can be determined, the brittle fractures can be further characterized as faults, and attributed accordingly.

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

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

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

	Attribute	Brief Description
18	Rel_age	Relative age of feature, in accord with regional structural history
19	Notes	Comment field for additional relevant information on a feature

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

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

### 3.2.2 STEP 2: REPRODUCIBILITY ASSESSMENT 1 (RA\_1)

The two individual GIS lineament maps from each dataset were then integrated to provide a single interpretation for the DEM (Figure 8), SPOT (Figure 9) and aeromagnetic (Figure 10) data that included the results of the first stage reproducibility assessment (RA\_1). Reproducibility is judged based on the coincidence, or lack thereof, of interpreted lineaments within an assigned buffer zone. For example, if a lineament was identified by both interpreters within an overlapping buffer zone, then it was deemed coincident and assigned a reproducibility value of two (RA\_1 = 2). An initial buffer zone width (Buffer\_RA\_1) of 200 m was selected to evaluate coincidence. For many of the lineaments, coincidence could be demonstrated with a smaller buffer width, and in these cases a buffer width of either 100 m or 50 m, depending on the maximum offset, was entered in the attribute field. Where a lineament was identified by only one of the interpreters, it received a buffer zone width of zero (Buffer\_RA1 = 0) and a reproducibility value of one (RA\_1 = 1) in the attribute table.

Where coincident interpreted lineaments were identified, the one line that appeared to best represent the surficial or geophysical expression of the feature (based on the judgment of the integrator) was retained and assigned attributes. In some instances, where deemed appropriate, either an existing line was edited or a new line was drawn as part of the merging process to best capture the expression of the lineament. The decision of whether to retain or edit an existing line, or to draw a new line, was based largely on expert judgment that followed these guidelines: 1) where one continuous lineament was drawn by one interpreter, but as individual, spaced or disconnected segments by the other, a single continuous lineament was carried forward with a reproducibility value of two (RA\_1 = 2) provided that the continuous lineament was deemed a better representation of the feature; and 2) where two interpreted lineaments were coincident over less than three-quarters of the total length of the longest lineament, the longest lineament was segmented and each portion was attributed with RA\_1 values accordingly. Otherwise, if the two



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lineaments were coincident for more than three-quarters of the length of the longer lineament, they were considered coincident and assigned a reproducibility value of two ( $RA_1 = 2$ ).

### **3.2.3 STEP 3: REPRODUCIBILITY ASSESSMENT 2 ( $RA_2$ )**

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



## 4 FINDINGS

Findings are presented for the ERFN area and for each of the more detailed sub-regions Sub-region 2.1 (Haultain Lake), Sub-region 2.2 (Porter Lake), and Sub-region 2.3 (Primeau Lake) areas.

### 4.1 ENGLISH RIVER FIRST NATION

#### 4.1.1 DESCRIPTION OF LINEAMENTS BY DATASET

##### 4.1.1.1 Surficial datasets (CDED and SPOT)

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

A total of 1,808 lineaments comprise the dataset of merged lineaments (RA\_1) identified by the two interpreters from the CDED digital elevation data (Figure 8). These lineaments range in length from 271 m to 83.5 km, with a geometric mean length of 2.9 km and a median length of 2.8 km. A certainty value of 3 was assigned to 412 (23%) of the lineaments, reflecting a lower degree of confidence with the interpretations made from the CDED data as compared to the satellite data discussed below. Certainty values of 2 and 1 were assigned to 1143 (63%) and 253 (14%) lineaments, respectively. The reproducibility assessment shows coincidence for 339 lineaments (19%) (RA\_1 = 2) and a lack of coincidence for 1469 lineaments (81%) (RA\_1 = 1). These findings for the CDED data appear to be very strongly influenced by the lack of coincidence among shorter lineaments. When lineaments shorter than 5 km in length are excluded from the reproducibility assessment, coincidence increases to 49%. Using this subset of lineaments, the coincidence becomes even more pronounced (58%), when the length of coincident lineaments is compared to the total length of lineaments.

Orientation data for the CDED lineaments show two dominant trends to the north-northeast to northeast and to the northwest to north-northwest (Figure 8). The rose diagram depicts strong north-northeast to northeasterly trends between 020° and 025° and northwest to north-northwesterly trends between 324° and 340°. The latter corresponds to the dominant orientation of mapped brittle faults in the ERFN area (Figure 2).

The satellite lineament dataset (SPOT) compiled from the merger of lineaments identified by the two interpreters yielded a total of 1,082 lineaments (Figure 9). The length of the satellite lineaments range from 500 m to 65.7 km, with a geometric mean length of 4.1 km and a median length of 3.8 km. Of these satellite lineaments, a total of 689 (64%) were assigned the highest level of certainty (Certain = 3). Certainty values of 2 and 1 were assigned to 335 (31%) and 58 (5%) lineaments, respectively. The reproducibility assessment indicates that a total of 824 (76%) lineaments were identified by only one interpreter (RA\_1 = 1), while the remaining 258 (24%) were identified by both interpreters (RA\_1 = 2). This finding can be accounted for by the relatively poor coincidence among lineaments with shorter lengths and by a difference in the approach to mapping ductile lineaments. When lineaments of less than 5 km are excluded from the reproducibility analysis, the coincidence values increase to around 35%. The importance of lineament length on reproducibility is further demonstrated by comparing the length of coincident lineaments to the total length of lineaments. Using this approach for lineaments longer than 5 km, the length of coincident lineaments is 47% of the total length of lineaments. It is important to note that both interpreters identified the long lineaments oriented to the northwest to north-northwest and to the north-northeast to northeast that are the most prominent in the area.

SPOT lineament orientations demonstrate a bimodal distribution of orientation data with two dominant lineament trends toward the north-northeast to northeast and the northwest to north-northwest (Figure 9). The north-northeast to northeasterly oriented lineaments exhibit azimuths between 025° and 045°. The northwest to north-northwesterly oriented lineaments show azimuths between 320° and 340°. These lineament orientations closely match those of the CDED data, which demonstrates that the both datasets capture the main trends of the surficial lineaments.

#### 4.1.1.2 Geophysical data

The airborne geophysical data interpretation was used to distinguish between features that could be interpreted as brittle lineaments (Figures 10). Aeromagnetic features interpreted to reflect ductile lineaments have been mapped separately and are shown on Figure 11. A total of 2,880 lineaments were interpreted as ductile features. Such features are useful in identifying the stratigraphy and degree of deformation within the felsic gneiss and metasedimentary rocks. In this report, the ductile lineaments are shown to provide context to our understanding of the tectonic history of the ERFN area. For example, the dome and basin structures are evident in the Mudjatik domain and the more linear fold pattern, associated with the regional shear zone structure, is visible in the Wollaston domain. Results from the interpretation of the ductile fabric

were not included in the statistical analysis undertaken with the geophysical dataset, except where coincident features were identified in the surficial datasets. Therefore, the following discussion relates only to those lineaments interpreted by the geophysical expert as brittle lineaments, based on the categorization of these structures as described in Section 1.1.

Brittle lineaments, from aeromagnetic survey data, total 547 in the ERFN area (Figure 10). The length of these lineaments range from 2.4 to 126.8 km, with a geometric mean of 18.6 km and a median of 18.1 km. The highest level of certainty (Certainty = 3) was assigned to 483 (88%) of the geophysical lineaments, while 40 (7%) and 24 (4%) of the faults were given certainty values of two and one, respectively. The reproducibility assessment identified coincidence for 511 (93%) (RA\_1 = 2) lineaments and a lack of coincidence for 36 (7%) of the interpreted lineaments (RA\_1 = 1).

Azimuth data for the aeromagnetic lineaments exhibit prominent orientations to the northwest to north-northwest at 325 to 340° and to the north at 005 to 015° and 345 to 355°. There is also a diffuse trend to the east-northeast at 060 to 070° as well as a sharp peak trending east-southeast.

These observations are consistent with the surficial lineaments capturing a surficial expression of the ductile lineaments; whereas the geophysical brittle lineaments capture the large north-northwesterly trending brittle structures pervasive in the ERFN area and regionally (Figures 2 and 3).

It should be noted that the disparity between the number of identified ductile features (n = 2,880) versus brittle features (n = 547) in the aeromagnetic dataset is a result of the interpretation of the strongly linear magnetic character in the Wollaston domain as representing the ductile shear zone fabric. It is likely, although hard to quantify at the remote desktop stage of the investigation, that brittle re-activation of the ductile fabric also occurred in the Wollaston domain. This understanding would suggest that the density of brittle structures interpreted in areas with a strongly developed magnetic (ductile) character should be considered as minimum estimates of the *in situ* brittle lineament density.

#### **4.1.2 DESCRIPTION AND CLASSIFICATION OF INTEGRATED LINEAMENT COINCIDENCE (RA\_2)**

The integrated lineament data set produced by merging all lineaments interpreted from the CDED data, SPOT imagery, and geophysical surveys is presented on Figures 12 and 13. Figure 12 displays the lineament classification based on the coincidence values determined by

Reproducibility Assessment 2 (RA\_2). Figure 13 displays the lineament classification based on length. The merged lineaments were classified by length using four length bins: >10 km, 5-10 km, 1-5 km and <1 km. These length bins were defined based on an analysis of the lineament length frequency distributions for the ERFN area

The merged lineament dataset (RA\_2) contains a total of 2,872 lineaments that range in length from a minimum of 271 m to a maximum of 126.8 km. The geometric mean length of these lineaments is 3.6 km and the median length is 3.3 km. Lineaments in the >10 km and 5-10 km length bins represent 21% (610) and 16% (473) of the merged lineaments, respectively, while lineaments in the 1-5 km and <1 km length bins represent 50% (1,450) and 12% (341) of the merged lineaments, respectively. Spacing between the north-northeast-trending lineaments is generally several hundred metres and ranges from a couple of hundred metres to around a kilometre. This spacing of lineaments is much closer than for the north-northwest- and north-trending lineaments that generally range from one to several kilometres.

Orientation data for the merged lineament dataset include the prominent trends seen in the CDED and SPOT data of the surficial lineaments and in the aeromagnetic data of the subsurface lineaments. While the merged lineament dataset exhibits more scatter in lineament orientation, there remains the two trends, one to the north-northwest at 320-340° and one to the north-northeast at 020-040°, that dominate the surficial lineaments. There are also strong east-west and north-south trends contributed by the aeromagnetic lineaments. The north-northwest trending lineaments show relatively high agreement among all of the datasets (Figure 12) and correspond to known regional brittle fractures. Spacing of these longer structures with higher ranking reproducibility generally ranges from 2 to 10 km. Another prominent direction of relatively long lineaments (>10 km) is east to east-northeast and relate to the regional foliation pattern. These were especially noted in the aeromagnetic data (Figure 10), with less agreement with the SPOT and CDED imagery. The spacing of these features is in the order of 2 to 14 km. They are relatively sparsely populated compared to the more prominent north-northwest trending faults discussed above.

The reproducibility assessment required some lineaments to be broken into several line segments to which different reproducibility values were assigned. This is because lineaments may be coincident for just one segment and not for the entire length. For this reason, the total number of line segments (3207) analyzed in the reproducibility assessment does not match the total number of lineaments in the integrated dataset (2872). The statistics below are, however, calculated based on the initial number of segments (n = 3207), not the final total. Results from the

reproducibility assessment (RA\_2) for this dataset show 2523 lineament segments (79%) that lack a coincident lineament and thus were assigned a value of 1. A total of 582 lineament segments (18%) were coincident with a lineament from one other dataset (RA\_2 = 2) and 102 lineament segments (3%) were identified and coincident on all three datasets (RA\_2 = 3). As with the reproducibility assessment for each of the SPOT and CDED datasets (RA\_1), results of the integrated reproducibility assessment (RA\_2) reflect the lack of coincidence among shorter lineaments. The coincidence of longer lineaments, greater than 5 km in length, is significantly higher at just under 40%. The longest lineaments were identified by multiple interpreters and thus showed the highest reproducibility values.

## **4.2 SUB-REGION 2.1 (HAULTAIN LAKE)**

### **4.2.1 DESCRIPTION OF LINEAMENTS BY DATASET**

#### **4.2.1.1 Surficial datasets (CDED and SPOT)**

Within the detailed area of Sub-Region 2.1, interpretation of the CDED digital elevation data yielded a dataset of 304 lineaments that range in length from 436 m to 80.5 km, with a geometric mean length of 2.9 km and a median length of 2.4 km (Figure 8). The reproducibility assessment shows coincidence for 60 lineaments (20%) (RA\_1 = 2) and a lack of coincidence for 244 lineaments (80%) (RA\_1 = 1). There appears to be greater coincidence among the longest lineaments (51% for lineaments longer than 5 km), particularly those oriented north-northwest and north-northeast.

Satellite imagery (SPOT) interpretation provided 219 lineaments that ranged in length from 477 m to 65.7 km, with a geometric mean of 3.0 km and a median of 2.8 km (Figure 9). Of these lineaments, the reproducibility assessment indicates that a total of 180 (82%) lineaments were identified by only one interpreter (RA\_1 = 1), while the remaining 39 (18%) were identified by both interpreters (RA\_1 = 2). About 35% of lineaments longer than 5 km were reproduced between interpreters. SPOT lineament orientations indicate dominant trends to the north-northwest and north-northeast.

#### **4.2.1.2 Geophysical data**

The Haultain Lake area is cut by 112 lineaments interpreted as faults from the aeromagnetic survey data (Figure 10). These lineaments range in length from 3.0 to 126.8 km, with a geometric mean of 18.0 km and a median of 16.3 km. Azimuths of these lineaments follow three

dominant trends to the north-northwest, north, and east-northeast, which closely match the orientation data of aeromagnetic lineaments across the entire ERFN area. The density of aeromagnetic lineaments in the Haultain area is relatively high compared to the other detailed sites and to the ERFN area in general.

#### **4.2.2 DESCRIPTION AND CLASSIFICATION OF INTEGRATED LINEAMENT COINCIDENCE (RA\_2)**

The integrated lineament dataset for the Sub-Region 2.1 contains a total of 472 lineaments (529 lineament segments) that range in length from a minimum of 436 m to a maximum of 126.8 km, with a geometric mean length of 4.2 km and a median length of 4.1 km (Figures 12 and 13). Results from the reproducibility assessment (RA\_2) for this area show 408 lineament segments (77%) with an RA\_2 = 1, 98 lineament segments (19%) with an RA\_2 = 2, and 23 lineament segments (4%) with an RA\_2 = 3. As observed in the other datasets for this area, the highest reproducibility values appear to be associated with the dominant lineaments oriented toward the north-northwest and north-northeast.

### **4.3 SUB-REGION 2.2 (PORTER LAKE AND FLATSTONE LAKE)**

#### **4.3.1 DESCRIPTION OF LINEAMENTS BY DATASET**

##### **4.3.1.1 Surficial datasets (CDED and SPOT)**

The interpreted CDED digital elevation data in Sub-Region 2.2 yielded a dataset of 228 lineaments that range in length from 274 m to 45.1 km, with a geometric mean of 2.5 km and a median of 2.3 km (Figure 8). As with the SPOT lineaments for this area, the CDED lineaments showed low reproducibility between the interpreters (188 lineaments (82%) were assigned an RA\_1 = 1 and 40 lineaments (18%) were assigned an RA\_1 = 2). For lineaments longer than 5 km, reproducibility is 53%. As with the SPOT data, this result appears to reflect the lack of coincidence among shorter lineaments and those associated with ductile lineaments. The highest coincidence values appear to be related to the north-northwesterly and north-northeasterly trends.

A total of 147 lineaments were identified from satellite imagery (SPOT) within this area (Figure 9). These lineaments ranged in length from 891 m to 41.2 km, with a geometric mean of 3.8 km and a median of 3.5 km. Of these satellite lineaments 37 (25%) were assigned an RA\_1 = 2 and 110 (75%) were assigned an RA\_1 = 1. The coincident lineaments appear to be long and oriented to the north-northwest. About 36% of lineaments longer than 5 km were coincident. The



lineaments that lack coincidence appear to be short in length and associated with the ductile lineaments. Rose diagrams for these lineaments show a strong north-northwesterly trend (Figure 8).

#### **4.3.1.2 Geophysical data**

The geophysical data yielded a total of 113 lineaments within the detailed area that range in length from 4.5 to 126.8 km, with a geometric mean of 23.0 km and a median of 24.0 km (Figure 10). These lineaments appear to be strongly oriented to the north-northwest, north, and east-northeast, which is consistent with the major trends of the geophysical lineaments throughout the entire ERFN area. The density of geophysical lineaments in the Porter lake area is similar to the entire ERFN area, but notably lower than Sub-Region 2.1.

#### **4.3.2 DESCRIPTION AND CLASSIFICATION OF INTEGRATED LINEAMENT COINCIDENCE (RA\_2)**

Sub-Region 2.2 yielded an integrated lineament dataset that contains a total of 421 lineaments (472 lineament segments) that range in length from a minimum of 274 m to a maximum of 126.8 km and a geometric mean length of 4.0 km and a median of 3.4 km (Figures 12 and 13). Results from the reproducibility assessment (RA\_2) for this area show 378 lineament segments (80%) with an RA\_2 = 1, 78 lineament segments (17%) with an RA\_2 = 2, and 16 lineament segments (3%) with an RA\_2 = 3. The rose diagram plotted for this dataset shows lineament trends to the north-northwest and north-northeast.

### **4.4 SUB-REGION 2.3 (DIPPER, PRIMEAU, KNEE AND ELAK DASE LAKES)**

#### **4.4.1 DESCRIPTION OF LINEAMENTS BY DATASET**

##### **4.4.1.1 Surficial datasets (CDED and SPOT)**

Within Sub-Region 2.3, 205 lineaments were interpreted from the CDED digital elevation data (Figure 8). These lineaments range in length from 535 m to 83.5 km, with a geometric mean length of 5.5 km and a median length of 5.1 km. Of these lineaments, 64 (31%) were found to be coincident (RA\_1 = 2) and 141 (69%) lacked coincidence (RA\_1 = 1). Longer lineaments, greater than 5 km, show reproducibility of 52%. Rose diagrams plotted from the orientation data show dominant trends to the north-northwest and north-northeast.

Interpretation and mapping from the SPOT satellite imagery yielded a combined dataset of 205 lineaments within the Primeau Lake area that range in length from 549 m to 37.4 km with a geometric mean length of 4.8 km and a median length of 4.2 km (Figure 9). The reproducibility assessment shows coincidence for 55 lineaments (27%) ( $RA_1 = 2$ ) and a lack of coincidence for 150 lineaments (73%) ( $RA_1 = 1$ ). The highest reproducibility was observed for the longest lineaments oriented to the north-northwest and north-northeast. Lineaments longer than 5 km have reproducibility values of 47%.

#### 4.4.1.2 Geophysical data

Sub-Region 2.3 contains a total of 148 geophysical lineaments that range in length from 3.3 to 126.8 km, with a geometric mean of 18.6 km and a median of 18.1 km (Figure 10). As with the other detailed sites and the entire ERFN area, the orientation of these geophysical lineaments appears to show strong trends to the north-northwest, north, and east-northeast. The density of geophysical lineaments in the Primeau Lake area is slightly higher than the overall ERFN area and the Porter Lake area, but is lower than Haultain Lake.

#### 4.4.2 DESCRIPTION AND CLASSIFICATION OF INTEGRATED LINEAMENT COINCIDENCE ( $RA_2$ )

The integrated lineament dataset for Sub-Region 2.3 contains a total of 484 lineaments (522 lineament segments) that range in length from a minimum of 535 m to a maximum of 126.8 km and a geometric mean length of 6.1 km and a median length of 5.4 km (Figures 12 and 13). Results from the reproducibility assessment ( $RA_2$ ) for this area show 405 lineament segments (78%) with an  $RA_2 = 1$ , 101 lineament segments (19%) with an  $RA_2 = 2$ , and 16 lineament segments (3%) with an  $RA_2 = 3$ . As observed in the other datasets for this area, the highest reproducibility values appear to be associated with the dominant lineaments oriented toward the north-northwest and north-northeast.

#### 4.5 DESCRIPTION OF LINEAMENTS BY GEOLOGICAL DOMAIN

The bedrock geology of the Mudjatik and Wollaston domains within the ERFN area is dominated by felsic gneiss with subordinate, thin lenses of overlying supracrustal rock (Figure 3). The following lineament discussion will focus on the felsic gneiss unit which covers 77% of the total ERFN area. The data description separates the lineament orientations by domain (see inset Figure 14).

Felsic gneiss covers over 8,700 km<sup>2</sup> (90%) of the Mudjatic domain and exhibits a total of 2,156 lineaments. Within the Mudjatic domain, the topography is relatively low and the bedrock is covered extensively with surficial materials that limit the confident identification of lineaments. However, the central and eastern portions are relatively high in elevation and display exposed bedrock from which lineaments are readily mapped. Throughout this domain, but especially in the northeast reaches, the lineaments exhibit a strong north-northwesterly trend of brittle, mapped, bedrock structures that have previously been associated with movement of the regional scale Tabbernor fault (Hajnal et al., 2005). In the central portion of this unit, particularly around the Porter Lake area, many of the interpreted lineaments reflect the orientation of the pre-existing S<sub>1</sub> fabric, which have been folded into a dome-shaped feature. These curvilinear lineaments appear to be cut by the long north-northwesterly trending lineaments associated with brittle deformation and observed throughout the ERFN area.

The eastern portion of the ERFN area consists largely of felsic gneiss in the Wollaston domain that covers an area of 2,600 km<sup>2</sup> from which a total of 815 lineaments were mapped. These gneissic rocks exhibit strong foliation oriented toward the north-northeast. Many of the lineaments mapped in this unit reflect a surficial expression of this foliation. This prominent foliation trend to the north-northeast is cut by long, brittle fractures oriented to the north-northwest that are observed throughout the ERFN area and, as discussed previously, have been associated with movement of the Tabbernor fault.

The bedrock geology of Sub-Region 2.1 consists primarily of felsic gneiss in the Mudjatic and Wollaston domains. Here, lineaments appear to reflect the strong north-northwesterly oriented brittle fractures associated with movement along the Tabbernor fault and the north-northeasterly oriented foliation trend (Figure 14). These bedrock structures are expressed in each of the datasets, resulting in some of the highest reproducibility values in the entire ERFN area.

Sub-Region 2.2 is underlain mostly by felsic gneiss of the Mudjatic domain and exhibits strong ductile deformation and intense folding that provides structural control of the topography and drainage patterns. Lineaments representing these ductile fabrics often appear curved. These ductile structure lineaments appear to be cut by long and straight north-northwesterly trending lineaments associated with brittle structures observed throughout the ERFN area.

Lineaments of Sub-region 2.3, represent structures within the felsic gneiss of the Mudjatic domain. Many of these lineaments show major trends to the north-northeast and to the north-northwest (Figure 14). There are also some lineaments that reflect ductile features in the northwest where there is overlap with Sub-Region 2.2. The lineaments reflect the north-

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northeast-oriented foliation and the cross-cutting brittle fractures oriented to the north-northwest. It appears that lineaments associated with these structures have the highest reproducibility.

## 5 DISCUSSION

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

### 5.1 LINEAMENT DENSITY

Lineament density refers to the length of lineaments per unit area. Lineament density was calculated using the line density method described in ESRI ArcGIS software, which determines the length of lineaments within a moving circular window ( $\text{km}/\text{km}^2$ ). A radius of 1.25 km was used for the moving circular window, based on the repository footprint size and a 50 m cell size.

The lineament density is, in general, fairly uniform across the ERFN area (Figures 12 and 13), ranging between 0.0 and 5.0  $\text{km}/\text{km}^2$ . Notable exceptions primarily reflect areas of increased bedrock exposure versus thicker and more extensive surficial cover. The highest lineament densities are observed in the central and eastern portions of the ERFN area where there is well-exposed bedrock. In particular, high lineament densities were observed around Porter Lake, where there is little surficial cover and numerous well-exposed bedrock structures. The lowest lineament densities appear to be closely related to areas covered by surficial materials. Notably, the lowest lineament densities were observed in the western one-third of the ERFN area, along the Mudjatik River and the outwash deposits of the Hedderly low, and in the lowland along the Haultain River, including the outwash deposits of the Sylvester Plain. It is this latter outwash deposit that has a visible effect on the lineament density distribution in the geological units of the Wollaston domain.

Lineament density patterns appear uniformly distributed across the Haultain Lake area owing to the distribution of exposed bedrock and surficial cover. The highest lineament densities appear to follow the overall north-northwesterly and north-northeasterly trends apparent in each of the lineament datasets.

Lineament density patterns appear unevenly distributed across the Porter Lake area as there are higher densities observed in the east and lower densities observed in the west. As mentioned above, the distribution of lineament density is directly related to the thickness and extent of

coverage by surficial materials. The western part of the area is widely covered by surficial materials and lacks exposed bedrock. Here, the surficial lineaments are poorly expressed. Unlike the western part, the eastern part of the area displays well-exposed bedrock that exhibits numerous ductile lineaments and high lineament densities.

The Primeau Lake area displays an uneven distribution of lineament densities. Surficial materials cover much of the Haultain River valley, including the extensive Sylvester Plain. Not surprisingly, low lineament densities were observed in these areas.

## 5.2 REPRODUCIBILITY AND COINCIDENCE

Reproducibility values assigned to the lineaments provide a measure of the significance of the bedrock structures expressed in the different datasets (Figure 12). The approach used to assign reproducibility values involved checking whether lineament interpretations from different interpreters (RA\_1) and from different datasets (RA\_2) were coincident within a specific buffer zone radius. Reproducibility and coincidence values are discussed in detail in Sections 4.1 and 4.2.

The findings from the reproducibility assessment RA\_1 indicate that approximately 17% of surficial lineaments were identified by both interpreters (see Figures 8 and 9). Importantly, longer lineaments with higher certainty values were identified more often by both interpreters. The reproducibility assessment of the geophysical lineaments shows that over 93% of the lineaments were identified by both interpreters (Figure 10). As with the surficial lineaments, longer geophysical lineaments with higher certainty values were also recognized more often by both interpreters (RA\_1=2). Importantly, longer lineaments with higher certainty values were identified by both interpreters. When all lineaments with a total length of less than 5 km were removed, the percentage of lineaments mapped by both interpreters increased to at least 35%. When percentage of coincidence by length is compared, the reproducibility values increase to around 50%.

Coincidence between features identified in the various datasets was evaluated for the second Reproducibility Assessment (RA\_2). As would be expected, the surficial lineaments interpreted from CDED and SPOT show the highest coincidence at 18%. This is in part explained by the fact that lineaments interpreted from the satellite imagery and the digital elevation data represent surficial expressions of the same bedrock feature. For example, a lineament drawn along a stream channel shown on the satellite imagery is expected to be coincident with a lineament that captures the trend of the associated topographic valley expressed in the digital elevation data. In

contrast, fewer than 7% of the geophysical lineaments were coincident with interpreted surficial lineaments. This low coincidence between surficial and geophysical lineaments is not unexpected, and may be the result of various factors, such as: deep structures that are identified in geophysics may not have a surface expression; surficial features may not extend to great depth; structural features may not possess a magnetic susceptibility contrast with the host rock; surface expressions of lineaments may be masked by the presence of overburden; and/or the geometry of the feature (e.g., dipping versus vertical). All these may be further constrained by the resolution of the datasets.

For these reasons it is necessary to objectively analyze the results of the RA\_2 assessment with the understanding that RA\_2 = 1 does not necessarily imply a low degree of confidence that the specified lineament represents a true geological feature (i.e., a fracture). The true nature of the interpreted features will need to be investigated further during subsequent stages of the site evaluation process, if the community is selected by the NWMO, and remains interested in continuing with the site selection process.

Regardless of the degree of coincidence, the observed overlap in dominant lineament orientation between all datasets (see insets on Figures 8, 9 and 10) suggests that all datasets are identifying the same regional sets of structures. When the ductile lineaments of Figure 11 are included, all of the main lineament orientations are observed in both the surface and geophysical datasets. Among the lineaments with the best reproducibility are those associated with the major structural trends oriented to the north-northwest and north-northeast. Each of the datasets used in this assessment expressed these features and both interpreters identified those with the longest lengths. This is a key finding of the assessment as the north-northwest trending lineaments appear to be major bedrock structures associated with movement of the Tabernor fault (Hajnal et al., 2005) and the north-northeast trending lineaments reflect the regional orientation of the foliation in the major geological units, structural domains and bounding shear zones.

Reproducibility values of the lineaments mapped in the Haultain Lake area appear to be highest with respect to the north-northwesterly trending brittle fractures observed throughout the entire ERFN area and with the north-northeasterly trending orientation of the major geological units in this part of the Mudjatik and Wollaston domains.

Lineaments in the Porter Lake area show low coincidence among the different datasets. The lack of reproducibility seems to be related to the extensive surficial cover over the western portion of the area, where few surficial lineaments were mapped, but strong north-trending geophysical

lineaments were identified. The ductile lineaments in the eastern portion of the area were not mapped consistently by both interpreters.

Reproducibility values in the Primeau Lake area appear to be highest for lineaments that reflect a surficial expression of the north-northeasterly trending foliation associated with the supracrustal rocks and felsic gneisses of the Wollaston domain.

### 5.3 LINEAMENT LENGTH

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

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

Figure 13 shows the interpreted lineaments classified by lineament length. Four lineament length bins (0-1 km, 1-5 km, 5-10 km, >10 km) were used for this analysis and a length weighted frequency rose diagram indicates the dominant lineament orientations (inset of Figure 13). Two prominent lineament orientations to the north-northwest and north-northeast can be recognized in the length-weighted dataset.

### 5.4 FAULT AND LINEAMENT RELATIONSHIPS

As discussed above in Section 2.5.3, there are a number of mapped structural features in the ERFN area with established relative age relationships. The known shear zones and mapped faults that relate to lineaments within the ERFN area include the north-northeast-trending Needle Falls shear zone and the north-northwest-trending brittle faults associated with movement on the Tabernor fault (Figure 3). Based on the compilation of interpreted lineaments orientations shown in the inset of Figures 12 and 13, the lineament sets identified herein appear to correspond in orientation to these features. Although located just outside and to the east of the ERFN area, movement and deformation associated with the Needle Falls shear zone appears related to the



interpreted lineaments that exhibit a dominant north-northeast trend and that reflect the regional north-northeast foliation. These features relate to a likely  $D_5$  re-activation of the fabric developed during the  $D_3$  regional deformation episode. Known mapped faults oriented to the north-northwest occur throughout the ERFN area and have been associated with movement of the Tabernor fault located east of the ERFN area during regional deformation episode  $D_5$ . Interpreted lineaments include many that correspond specifically to the mapped faults and include a prominent set oriented toward the north-northwest that closely follow the trend of these known brittle fractures.

The principle neotectonic stress orientation in central North America is generally oriented approximately east-northeasterly ( $063^\circ \pm 28^\circ$ ; Heidbach et al., 2009), although anomalous stress orientations have also been reported in the mid-continent that include a  $90^\circ$  change in azimuth of the maximum compressive stress axis (Brown et al., 1995) and a north-south maximum horizontal compressive stress (Haimson, 1990). Local variations, and other potential complicating factors involved in characterizing crustal stresses, including the effect of shear stress by mantle flow at the base of the lithosphere (Bokelmann, 2002; Bokelmann and Silver, 2002), the degree of coupling between the North American plate and the underlying mantle (Forte et al., 2010), the effects of crustal depression and Holocene rebound, and the influence of the thick lithospheric mantle root under the Canadian Shield, make it premature to correlate the regional neotectonic stress orientation with the orientation of mapped lineaments at the desktop stage.

However, it is possible to broadly speculate on the potential behavior of the identified lineaments if they were to be reactivated by the regional east-northeasterly neotectonic stress regime. The combined set of lineaments from all sources includes trends to the northeast, north, north-northwest and east to east-northeast. These features were formed by paleostress regimes and constitute zones of weakness that are more amenable to reactivation under certain stress conditions than the surrounding rock mass. On this basis, should the identified lineaments be reactivated under the current stress regime, the north-northeast-oriented lineaments will likely reactivate in tension or as strike-slip faults and the north-northwest-oriented lineaments will likely reactivate as strike-slip or reverse faults.

## 5.5 RELATIVE AGE RELATIONSHIPS

The chronology of tectonic events that occurred during the Trans-Hudson Orogen, outlined in Section 2.3, provides a framework for understanding the structural history and for constraining

the relative age relationships of the interpreted bedrock lineaments in the ERFN area. All of the lineaments identified in the ERFN area reflect the re-activation of structures and fabrics formed during Proterozoic deformational events, or the development of new structures during the latest, brittle, stages of the regional deformation history. It is generally accepted that there is a relationship between the orientation of lineament sets and relative age associated with deformational events. The relative age of the lineament sets can also be established on the basis of cross-cutting relationships.

Based on the available literature of the structural history of the ERFN area and observations of the orientation of lineament sets and cross-cutting relationships, the relative age of the mapped lineaments can be related to re-activation of fabrics developed during the first four distinct regional deformation episodes ( $D_1$  to  $D_4$ ) or to new structures formed during the  $D_5$  event. The earliest fabric recognized by structural geologists in the field (Card and Bosman, 2007; Card et al., 2008) is the composite  $S_1$  fabric formed during  $D_1$ . The  $D_2$  folding event was not assigned to any of the lineaments identified in this assessment. Interference between the  $D_3$  and  $D_4$  orthogonal folding events produced the distinctive dome and basin pattern identified by the surface trace of the curvilinear  $S_1$  foliation (Figure 11). This structural pattern was also altered by shear deformation that reoriented the earlier foliation, and the folds, to produce a dominant northeast lineament trend. This trend is captured in the ductile lineament compilation (Figure 11) and in the surficial datasets (Figures 8 and 9). These deformation events are constrained to have occurred prior to approximately 1.80 Ga (Table 1). The brittle deformation of episode  $D_5$  produced the north-northwest and east to northeast lineament sets clearly distinguished on pre-existing bedrock geology maps. The timing of this late brittle overprint is poorly constrained but may have begun as early as 1.80 Ga, coincident with the timing of activation of the Tabbernor fault system (Table 1). The association between the brittle  $D_5$  structures and the Tabbernor fault system suggests a long-lived history that may include Paleozoic and Mesozoic fault re-activation (e.g., Byers, 1962; Elliot, 1996).

## 6 SUMMARY

This report documents the source data, workflow and results from a lineament interpretation of publicly-available digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the ERFN area in northern Saskatchewan. The lineament analysis provides an interpretation of the location and orientation of possible individual fractures or fracture zones and helps to evaluate their relative timing relationships within the context of the regional geological setting. The three step process involved a workflow that was designed to address the issues of subjectivity and reproducibility. Within this vast region, three areas (Sub-regions 2.1, 2.2, and 2.3) were identified for detailed analyses.

Lineaments were mapped from multiple, publicly-available datasets that include digital elevation models (CDED), satellite imagery (SPOT), and geophysical survey data. The total number of lineaments interpreted from these data sources were 1808, 1082 and 547, respectively. The distribution of lineaments in the ERFN area reflects the bedrock structure, resolution of the datasets used, and surficial cover. Surface lineament density, as demonstrated in this assessment, is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures. Lineament density was observed to be highest in the eastern part of the ERFN area, where thin surficial cover and exposed bedrock revealed numerous fractures in the crystalline rock. The lowest lineament densities were observed in the western part of the ERFN area or in low lying areas covered by overburden.

Reproducibility (RA\_1) and certainty of interpreted lineaments for each dataset appears highest for longer lineaments aligned with the north-northeast trending foliation or the north-northwest trending brittle faults. These lineaments also have high coincidence values in the comparison of interpreted lineaments among the various datasets (RA\_2). Higher coincidence values are observed between surficial lineaments interpreted from the CDED and SPOT datasets than between the surficial and geophysical lineaments. This is in part explained by the fact that lineaments interpreted from the satellite imagery and the digital elevation data represent surficial expressions of the same bedrock feature. The lower coincidence between surficial and geophysical lineaments may be the result of various factors: deep structures identified in geophysics may not have a surface expression; surficial features may not extend to great depth; structural features may not possess a magnetic susceptibility contrast with the host rock; surface expressions of lineaments may be masked by the presence of overburden; and the geometry of the

feature (e.g., dipping versus vertical). These factors are further constrained by the differing resolution of the various datasets.

The main trends in orientation observed for the merged lineaments from all sources include dominant trends to the north-northeast and north-northwest. Lineaments oriented to the north-northeast reflect the orientation of the regional foliation associated with a likely  $D_5$  re-activation of the pre-existing fabric. This relationship is particularly well-expressed in the Wollaston domain. Lineaments oriented to the north-northwest represent brittle fractures that developed during the  $D_5$  regional deformation event that appears to be associated with movement on the Tabernor fault.

Results of the lineament analyses for the entire ERFN area and for each of the detailed areas provide insights on the bedrock structures that serve as important considerations for siting a nuclear waste repository. Comparisons among these different sites and to the overall ERFN area offer some differences for discussion. When comparing the three specific areas, it is apparent that there are differences in lineament density (strongly related to surficial cover) and to lineament characteristics.

Sub-region 2.1 (Haultain Lake) features well-expressed lineaments oriented to the north-northwest that reflect brittle structures associated with the movement of the Tabernor fault and to the north-northeast that reflect the regional foliation trends. The Haultain Lake area consists of both felsic gneiss in the Mudjatik domain and supracrustal rocks in the Wollaston domain. The mapped lineaments appear to be dominated by the strong north-northwesterly oriented brittle fractures associated with movement along the Tabernor fault. These lineaments exhibit among the highest reproducibility values of the entire ERFN area, owing to their prominent surficial expression and their strong effect on magnetic properties of the rock. Lineament density in the Haultain Lake area is relatively high.

Sub-region 2.2 (Porter and Flatstone Lakes) is unique among the specific areas within the English River First Nation because it resides entirely within the Mudjatik domain and exhibits abundant ductile lineaments characteristic of the ductile deformation history, including intense folding. Many of the mapped lineaments trace curving structures in the topography and drainage that reflect the distinct deformational patterns. The ductile lineaments are transected by the long north-northwesterly trending lineaments associated with brittle deformation. Lineament density in the Porter Lake area is highest on the eastern side where there is good bedrock exposure. On the western side of the area, the lineament density is among the lowest in the entire ERFN area

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because of the relatively thick and extensive surficial cover. It should be noted that the geophysical interpretation identified several long north trending features in this area.

Sub-region 2.3 (Dipper Lake, Primeau Lake, Knee Lake, and Elak Dase Lake) exhibits prominent lineaments oriented to the north-northeast that represent surficial expressions of the foliation trend in the geological units of the Wollaston domain. This area also shows the north-northwest oriented lineaments that are so prevalent throughout the ERFN area. Primeau Lake is the largest of the three specific areas within the entire ERFN and it spans all three of the major geological units in the area. The western half of this area is underlain by the felsic gneiss of the Mudjatik domain and is covered with surficial deposits. Nevertheless, lineaments from this area show major trends to the north-northeast and some well-developed ductile layering in the northwest where there is overlap with the Porter Lake area. The eastern portion of this specific area is underlain by felsic gneiss in the Wollaston domain. Lineaments from this geological unit map the surficial expression of the strong north-northeast-oriented foliation and the cross-cutting brittle fractures oriented to the north-northwest.



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## REPORT SIGNATURE PAGE

J.D. Mollard and Associates (2010) Limited



Jason Cosford, Ph.D., P.Ge



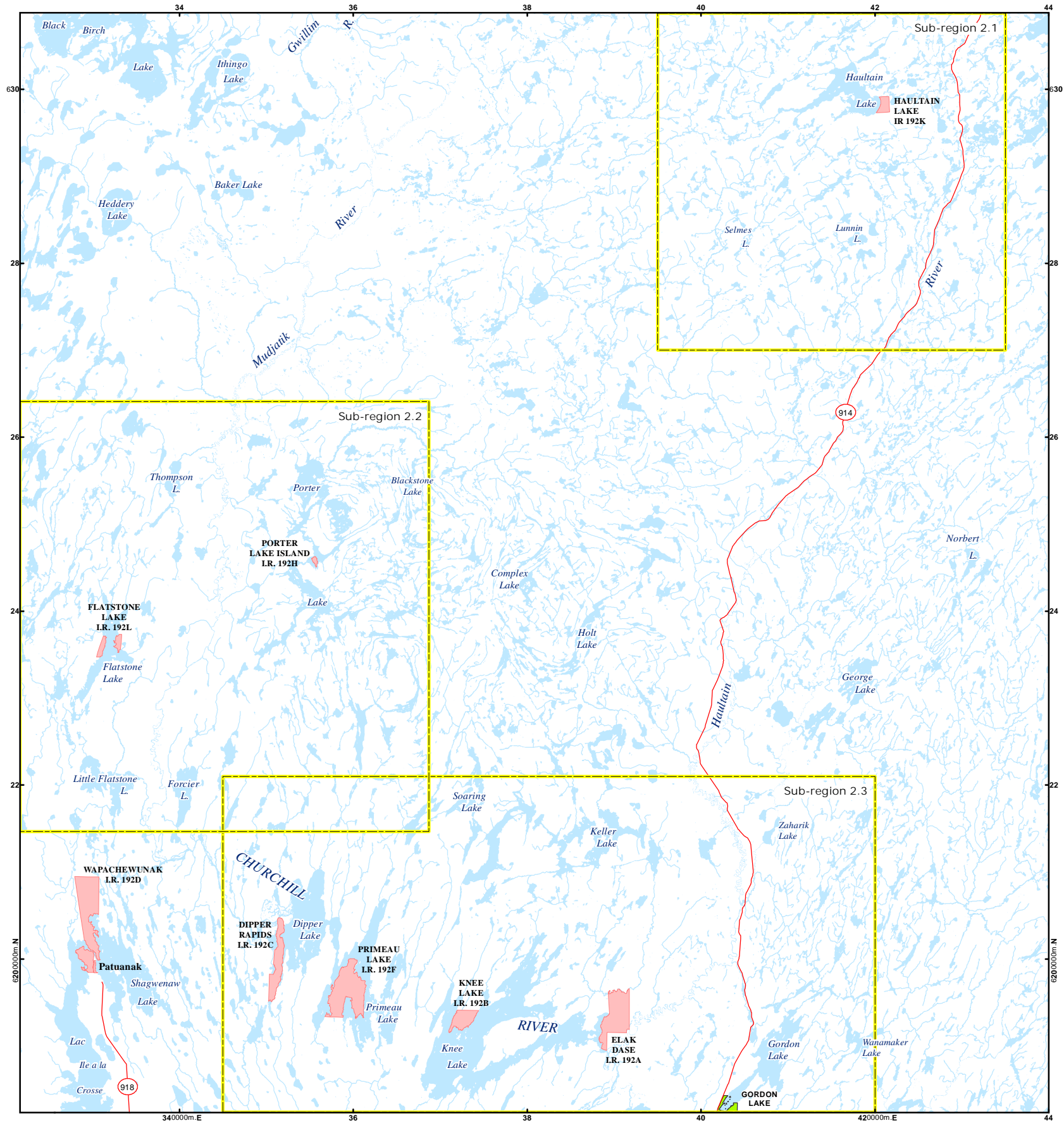
Lynden Penner, M.Sc., P.Eng., P.Ge.



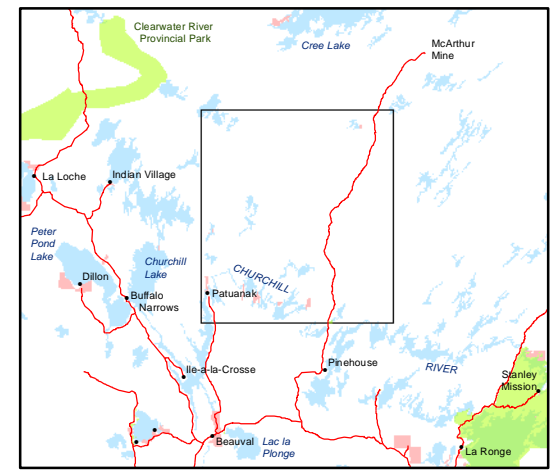
# FIGURES







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



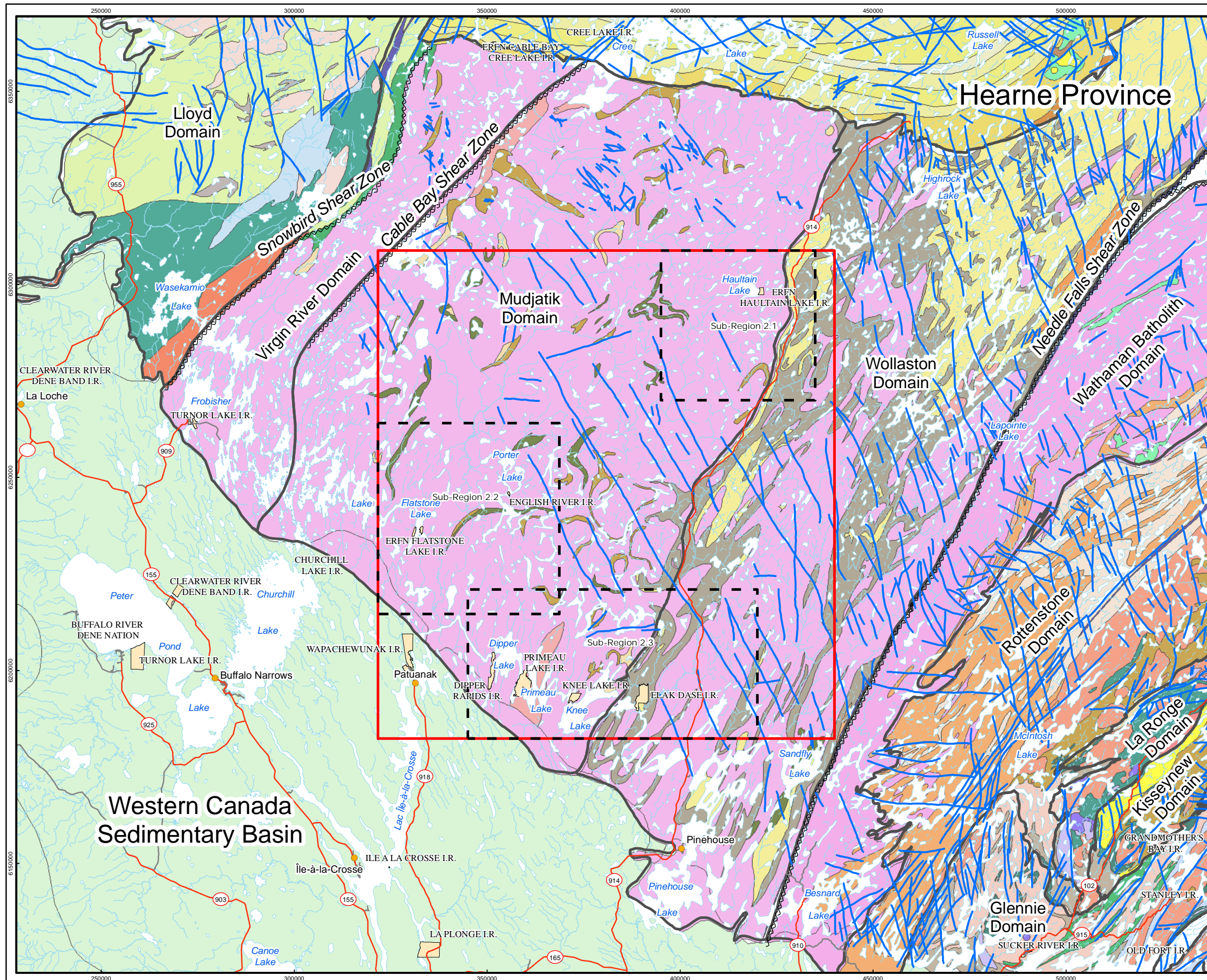
Data sources:  
 First Nation reserve: Sask Admin  
 Recreation site: Sask Admin  
 Main road: ISC SURN11  
 Waterbody: CanVec 1:50,000  
 Watercourse: CanVec 1:50,000



<b>J.D. MOLLARD</b> <small>INCORPORATED 1977</small>			
PROJECT PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE Location and overview of the ERFN area			
DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	08 NOV 2013	UTM ZONE 13
CHECK	JIC	08 NOV 2013	NAD 1983
REVIEW	GS	08 NOV 2013	1:550,000

**FIGURE 1**





**LEGEND**

- ERFN area
- Detailed study area
- Community
- Main road
- Secondary road
- Mapped fault
- Mapped shear zone
- First Nation reserve
- Domain boundary
- Waterbody
- Watercourse

**Western Canada Sedimentary Basin**

- Western Canada Sedimentary Basin

**Athabasca Basin**

- MFb-l - Manitou Falls: Lower conglomeratic quartzarenite
- MFc - Manitou Falls: Quartzarenite
- MFd - Manitou Falls: Clay-intraclast-rich quartzarenite
- MFw-cr - Manitou Falls: Clay-intraclast-rich quartzarenite
- MFw-lp - Manitou Falls: Lower conglomeratic quartzarenite
- MFw-s - Manitou Falls: Quartzarenite
- MFw-up - Manitou Falls: Upper quartz-pebbly quartzarenite
- Md - Mackenzie diabase dykes and sills
- RD - Read: Quartzarenite, conglomerate, local pebbly mudstone
- Wpsn - Pelitic, psammopelitic gneiss
- Wr - Calcareous arkose, arkose, psammopelite, calc-silicate
- Wm - Psammitic meta-arkosic gneiss

**Lloyd Domain**

- RJ - Megacrystic granite
- Ra - Felsic-mafelsic gneiss (plutonic)
- Ran - Anorthosite
- Rb - Mafic-mafelsic gneiss (volcanic)
- Rf - Quartzofeldspathic gneiss
- Rg - Garnet-feldspar gneiss
- Rgn - Granite-granodiorite gneiss
- UPS - Unexposed Precambrian Shield

**Virgin River Domain**

- MFb-l - Manitou Falls: Lower conglomeratic quartzarenite
- Mf - Felsic gneisses, mainly plutonic
- Mp - Pelitic gneiss
- Mrp - Psammitic/psammopelitic gneiss
- Mv - Metavolcanics, mainly basic
- RJ - Megacrystic granite
- Ra - Felsic-mafelsic gneiss (plutonic)
- Rb - Mafic-mafelsic gneiss (volcanic)
- z - Mylonitic gneiss

**Mudjatik Domain**

- MFb - Manitou Falls: fluvialite conglomerate
- MF-l - Manitou Falls: Lower conglomeratic quartzarenite
- Mb - Mafic Gneiss
- Mf - Felsic gneisses, mainly plutonic
- Mg - Late granitoids
- Mp - Pelitic gneiss
- Mrp - Psammitic/psammopelitic gneiss
- Wf - Felsic orthogneiss
- Wp - Pelitic gneiss
- Wr - Calcareous arkose, arkose, psammopelite, calc-silicate

**Wathaman Batholith Domain**

- Md - Mackenzie diabase dykes and sills
- PRp - Biotitic and hornblentic gneiss
- PRt - Trondjhemite-tonalite
- PW - Wathaman granite
- Pgl - Late granitoids
- z - Mylonitic gneiss

**Wollaston Domain**

- Mb - Mafic Gneiss
- Mf - Felsic gneisses, mainly plutonic
- Mrp - Psammitic/psammopelitic gneiss
- Pz - Peter Lake Complex deformed rocks
- WJ - Janice Lake Formation: fanglomerate, conglomerate, arkose
- Wd - Slate, phyllite, mica schist
- Wf - Felsic orthogneiss
- Wlg - Late granitoids
- Wo - Needle Falls Group basal assemblage: conglomerate, arkose, volcanics
- Wp - Pelitic gneiss
- Wr - Calcareous arkose, arkose, psammopelite, calc-silicate
- z - Mylonitic gneiss

**Rottenstone Domain**

- CLc - Crew Lake Calc-silicate rocks
- CLm - Metabasite/amphibolite (volcanic)
- CLwn - Crew Lake pelitic-psammitic gneiss
- Ln - Felsic orthogneiss
- Lgd - Granite-granodiorite-tonalite
- Lm - Metabasite/amphibolite (volcanic)
- Lvb - Basic to intermediate volcanic
- Lw - Greywacke, local conglomerate
- PRp - Biotitic and hornblentic gneiss
- PRt - Trondjhemite-tonalite
- PW - Wathaman granite
- z - Mylonitic gneiss

**Glennie Domain**

- Az - Mylonitic gneiss
- Fgd - Granite-granodiorite-tonalite
- Fm - Metabasite/amphibolite (volcanic)
- Fwn - Gneissic greywacke, psammopelite to pelite, conglomerate
- Km - Marine quartzose sandstone mudstone, siltstone
- Lbb - (Diorite)-gabbro(ultramafite)
- Lbq - Tonalite-diorite
- Lfn - Felsic orthogneiss
- Lgd - Granite-granodiorite-tonalite
- Lm - Metabasite/amphibolite (volcanic)
- Lvb - Basic to intermediate volcanic
- Lw - Greywacke, local conglomerate
- MLwn - Gneissic greywacke, psammopelite to pelite, conglomerate
- PRp - Biotitic and hornblentic gneiss

**La Ronge Domain**

- CLc - Crew Lake Calc-silicate rocks
- CLwn - Crew Lake pelitic-psammitic gneiss
- Lbb - (Diorite)-gabbro(ultramafite)
- Lbq - Tonalite-diorite
- Lfn - Felsic orthogneiss
- Lgd - Granite-granodiorite-tonalite
- Lm - Metabasite/amphibolite (volcanic)
- Lvb - Basic to intermediate volcanic
- Lw - Greywacke, local conglomerate
- MLgd - Granite-granodiorite-tonalite
- MLm - Metabasite/amphibolite (volcanic)
- MLwn - Gneissic greywacke, psammopelite to pelite, conglomerate

**Kisseynew Domain**

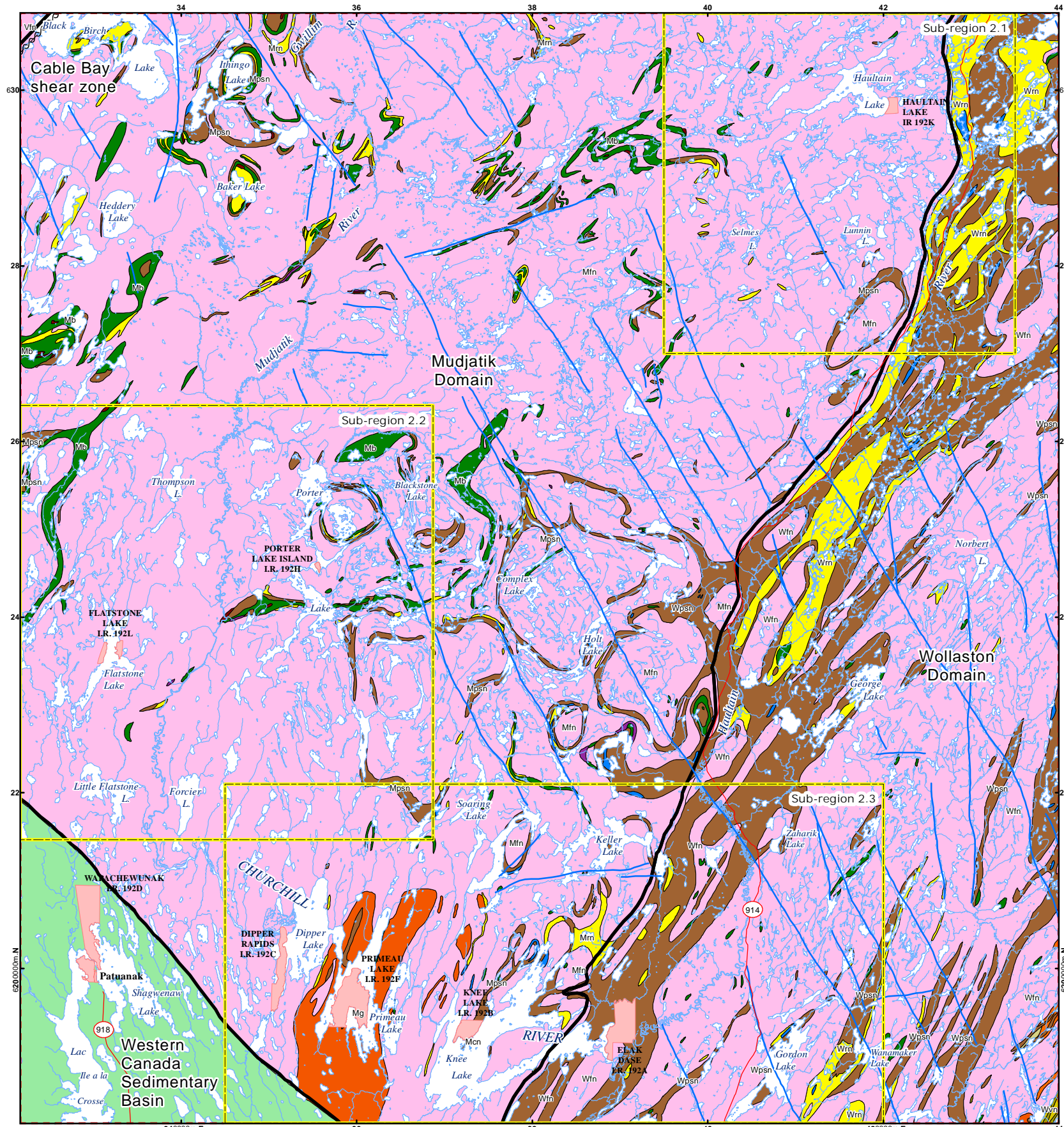
- Lbq - Tonalite-diorite
- Lfn - Felsic orthogneiss
- Lgd - Granite-granodiorite-tonalite
- Lm - Metabasite/amphibolite (volcanic)
- Lr - Arkose, conglomerate, psammitic gneiss
- Lvb - Basic to intermediate volcanic
- Lw - Greywacke, local conglomerate
- MLgd - Granite-granodiorite-tonalite
- MLm - Metabasite/amphibolite (volcanic)
- MLwn - Gneissic greywacke, psammopelite to pelite, conglomerate

Data sources:  
 Bedrock geology: Sask. Geological Atlas (1:1,000,000)  
 Communities: CanVec 1:50,000  
 Road: CanVec 1:50,000  
 Mapped Fault: Saskatchewan Geological Atlas (1:250,000)  
 Mapped shear zone: Sask. Geological Atlas (1:1,000,000)  
 Waterbody: CanVec 1:250,000

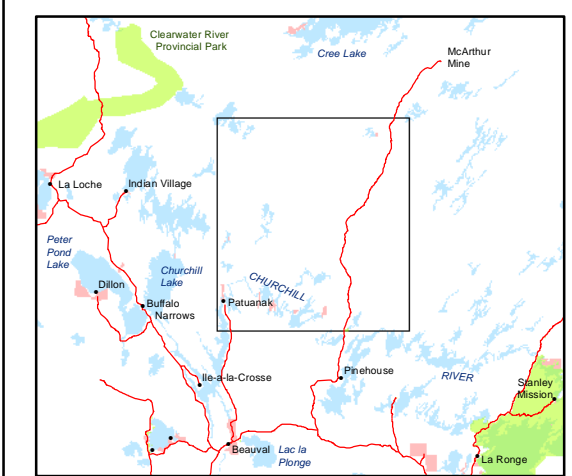
NORTH  
20 km

PROJECT		PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN, SASKATCHEWAN	
		TITLE	
DESIGN		DVZ	25 JUN 2012
GIS		DSM	19 SEP 2013
CHECK		JIC	19 SEP 2013
REVIEW		GS	19 SEP 2013
<b>FIGURE 2</b>			REVISION 0
			UTM ZONE 13 NAD 1983 1:1,000,000

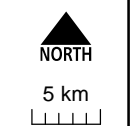




- LEGEND**
- Detailed area
  - ERFN area
  - Main road
  - Mapped fault
  - Cable Bay Shear Zone
  - Domain boundary
  - First Nation reserve
  - Waterbody
  - Watercourse
- Western Canada sedimentary basin**
- Western Canada Sedimentary Basin
- Mudjatik domain**
- Mcn - Calc-silicate rock, marble
  - 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
  - Wwn - Biotitic mafic gneiss



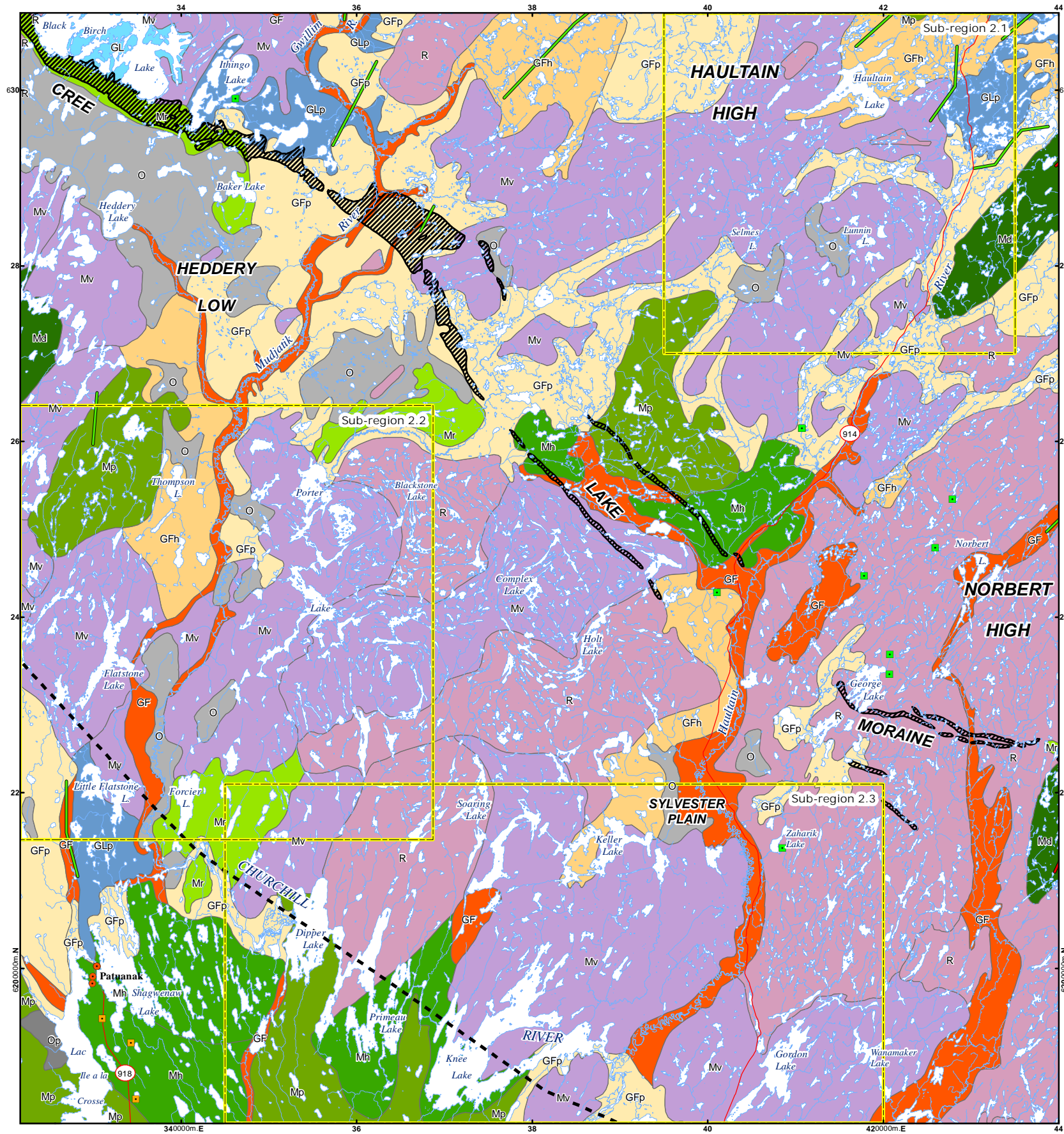
Data sources:  
 First Nation reserve: Sask Admin  
 Geology: Sask Geological Atlas 1:250,000  
 Road: ISC SURN11  
 Waterbody: CanVec 1:50,000  
 Watercourse: CanVec 1:50,000



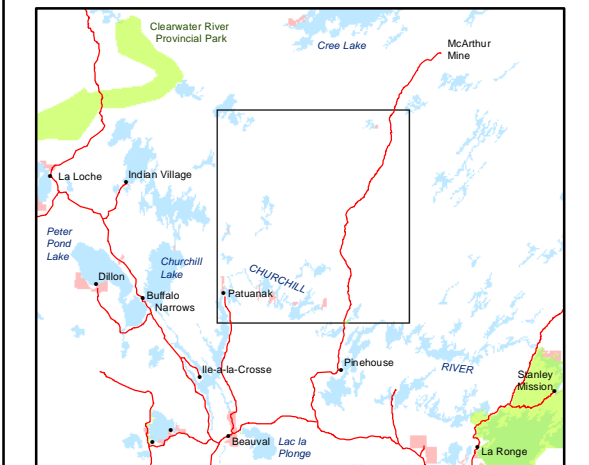
<b>J D MOLLARD</b> SINCE 1978			
PROJECT PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE Bedrock geology of the ERFN area			
DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	08 NOV 2013	UTM ZONE 13
CHECK	JIS	08 NOV 2013	NAD 1983
REVIEW	GS	08 NOV 2013	1:550,000

**FIGURE 3**





- 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



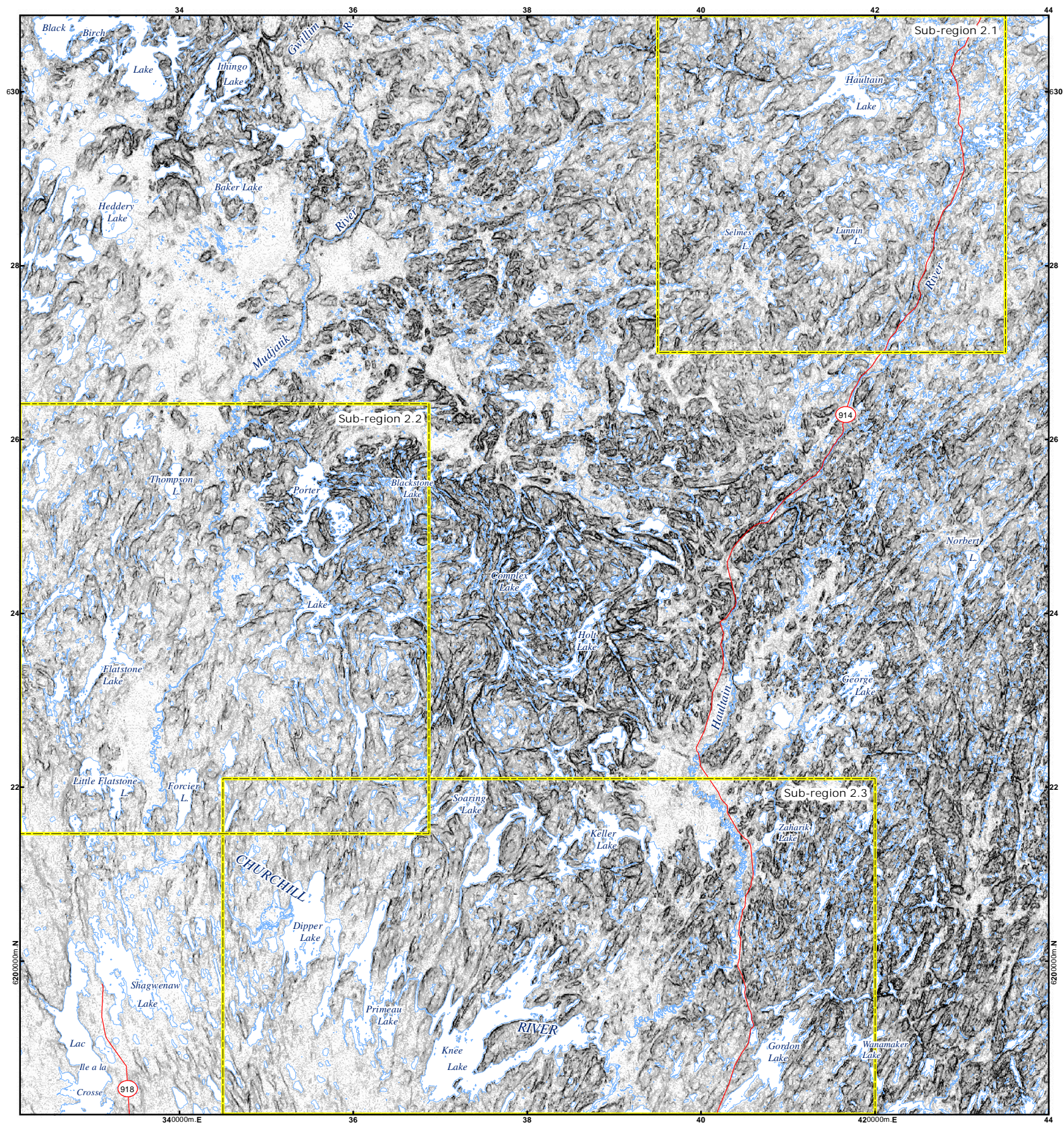
Data sources:  
 Geology: Sask Geological Atlas 1:250,000  
 Drill holes: Sask Geological Atlas  
 Water well: Water Well Information Database  
 Road: ISC SURN11  
 Waterbody: CanVec 1:50,000  
 Watercourse: CanVec 1:50,000



<b>J.D. MOLLARD</b> GEO. ASSOCIATES LTD. OF SASK.			
PROJECT PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE Surficial geology of the ERFN area			
DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	08 NOV 2013	UTM ZONE 13
CHECK	JIC	08 NOV 2013	NAD 1983
REVIEW	GS	08 NOV 2013	1:550,000

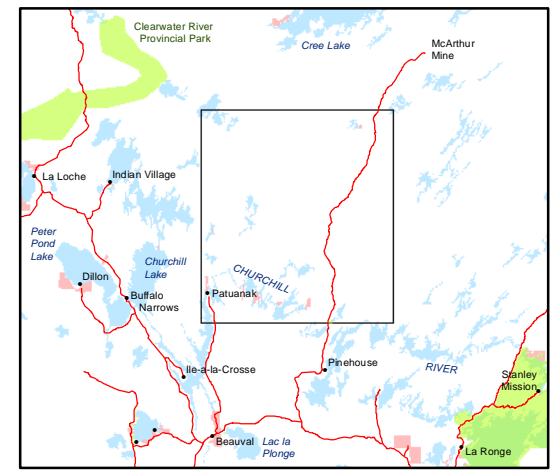
**FIGURE 4**





**LEGEND**

- Detailed area
- Main road
- Waterbody
- Slope (°)**
- 0 - 0.2
- 0.3 - 1.8
- 1.9 - 3.5
- 3.6 - 5.2
- 5.3 - 6.9
- 7 - 8.6
- 8.7 - 10.2
- 10.3 - 11.9
- 12 - 51.4



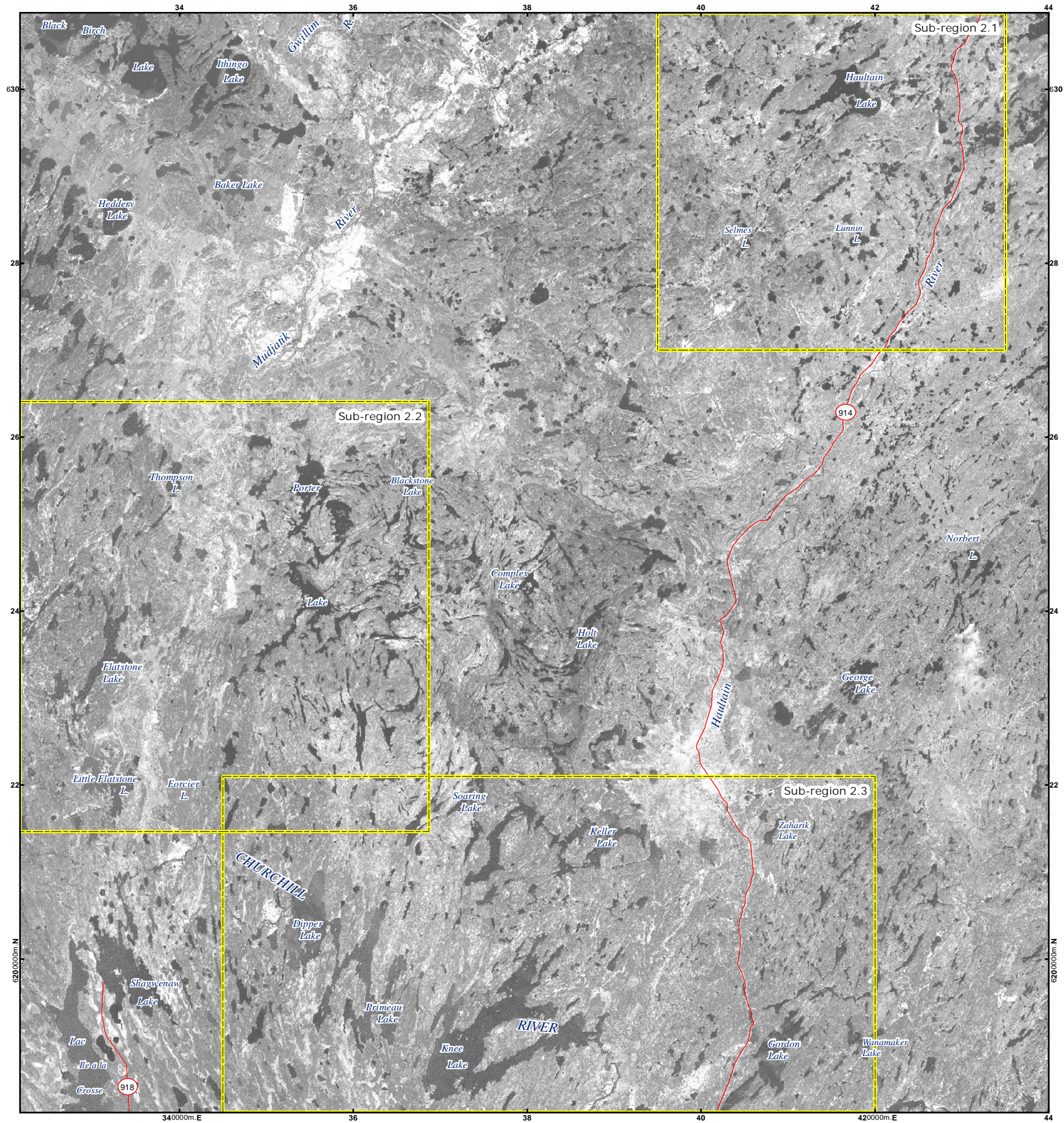
Data sources:  
 DEM: CDED slope 1:50,000  
 Main road: ISC SURN11  
 Waterbody: CanVec 1:50,000





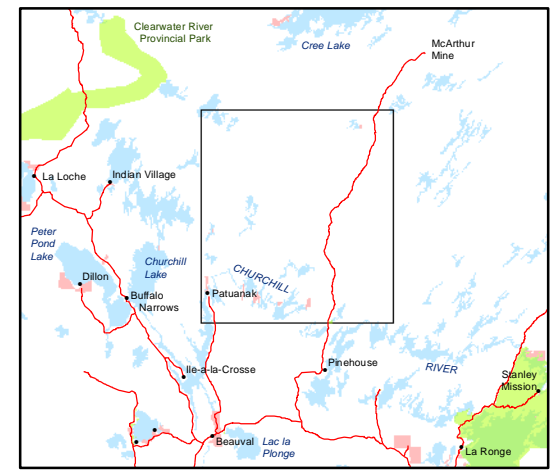
<b>J.D. MOLLARD</b> <small>Geo. &amp; Environmental Services Ltd.</small>			
PROJECT PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE CDED digital elevation data			
DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	17 SEP 2013	UTM ZONE 13
CHECK	JIC	17 SEP 2013	NAD 1983
REVIEW	GS	17 SEP 2013	1:550,000

**FIGURE 5**





**LEGEND**  
 Detailed area  
 Main road



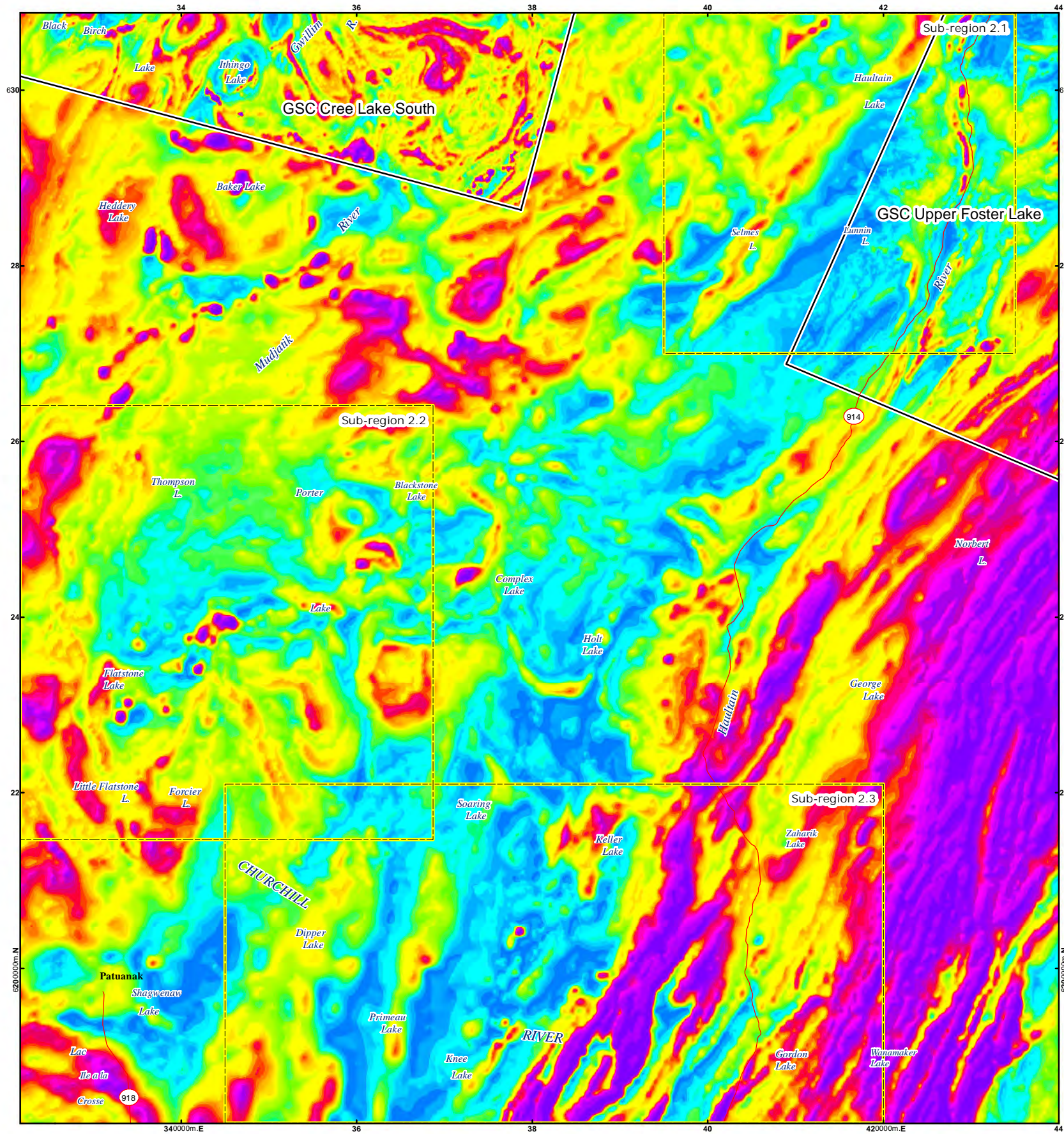
Data sources:  
 SPOT: Geobase  
 Main road: ISC SURN11  
 Waterbody: CanVec 1:50,000



<b>J.D. MOLLARD</b> GEO. ENGINEERING LTD.			
PROJECT PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE SPOT satellite data			
DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	17 SEP 2013	UTM ZONE 13
CHECK	JIC	17 SEP 2013	NAD 1983
REVIEW	GS	17 SEP 2013	1:550,000

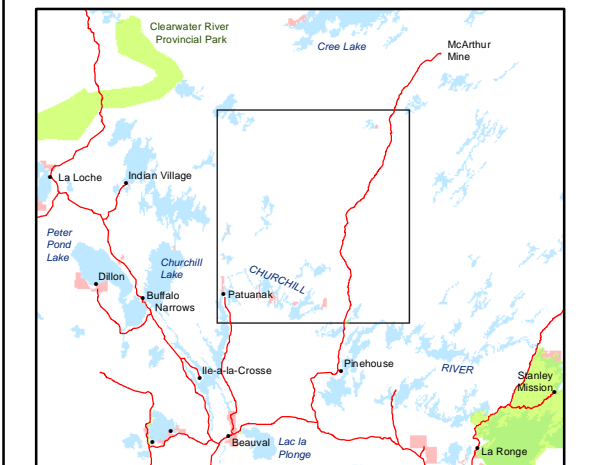
**FIGURE 6**





**LEGEND**

- Detailed area
- Main road
- ERFN geophysical survey outlines
- RTP (nT)**
- 681 to 4,892
- 521 to 680
- 401 to 520
- 321 to 400
- 261 to 320
- 201 to 260
- 161 to 200
- 121 to 160
- 81 to 120
- 61 to 80
- 21 to 60
- 1 to 20
- 39 to 0
- 59 to -40
- 79 to -60
- 99 to -80
- 119 to -100
- 159 to -120
- 179 to -160
- 199 to -180
- 219 to -200
- 259 to -220
- 279 to -260
- 319 to -280
- 339 to -320
- 379 to -340
- 439 to -380
- 2,435 to -440



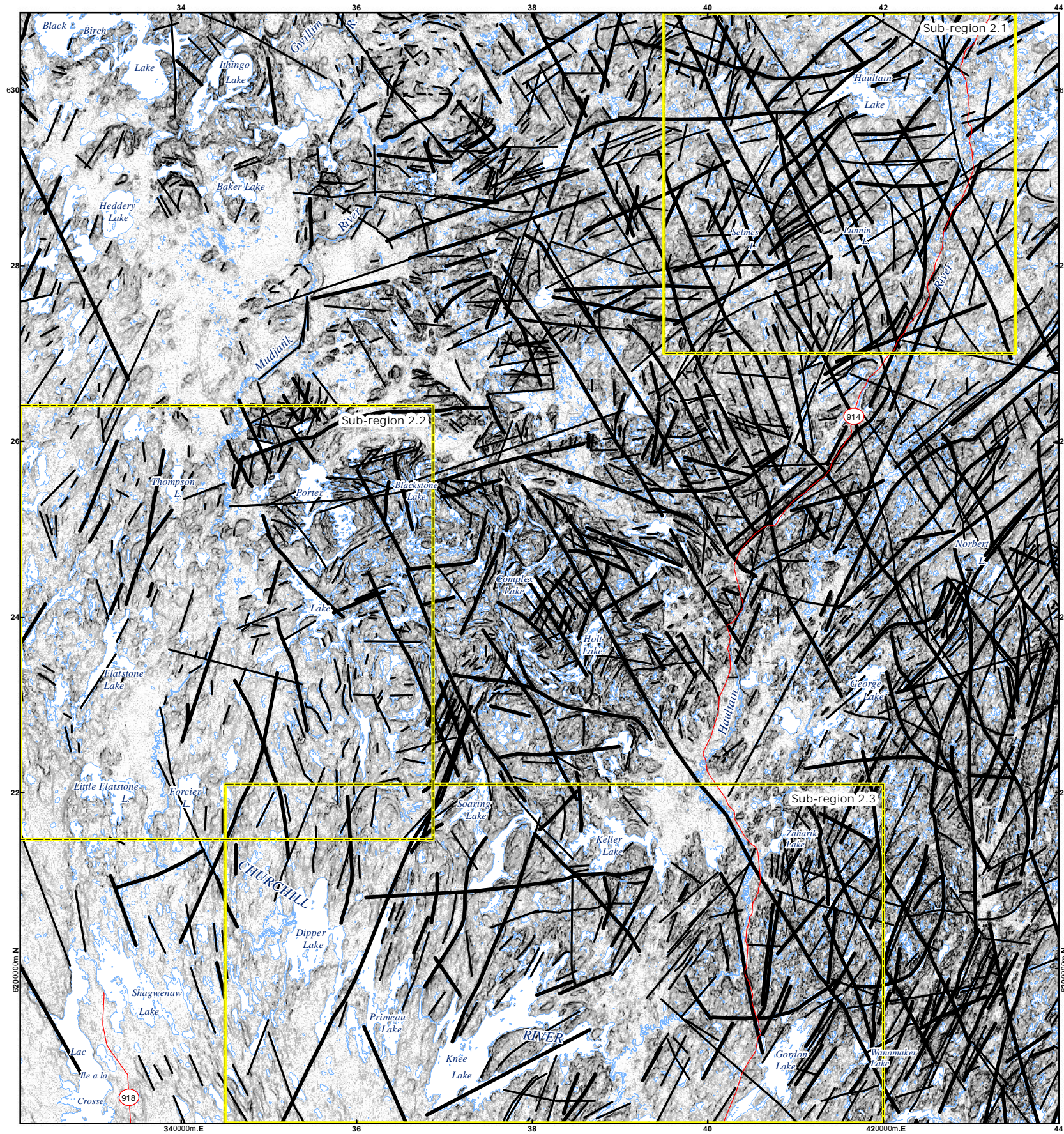
Data sources:  
 Aeromagnetic reduced magnetic field: PGW (2012)  
 Main road: ISC SURN11  
 Waterbody: CanVec 1:50,000



<b>PROJECT</b> PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
<b>TITLE</b> Pole reduced magnetic field for the ERFN area			
DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	17 SEP 2013	UTM ZONE 13
CHECK	JIC	17 SEP 2013	NAD 1983
REVIEW	GS	17 SEP 2013	1:550,000

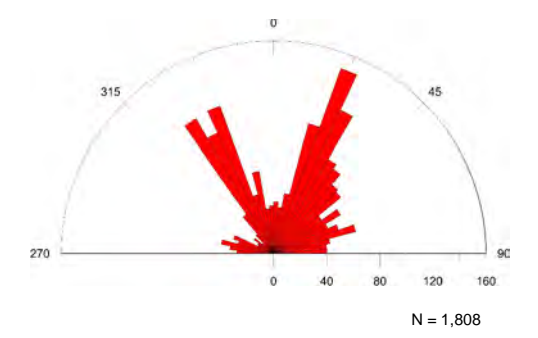
**FIGURE 7**



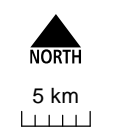



- LEGEND**
- Detailed area
  - Main road
- CDED Lineament RA\_1**
- 1
  - 2
- Waterbody**
- Waterbody
- Slope (°)**
- 0 - 0.2
  - 0.3 - 1.8
  - 1.9 - 3.5
  - 3.6 - 5.2
  - 5.3 - 6.9
  - 7 - 8.6
  - 8.7 - 10.2
  - 10.3 - 11.9
  - 12 - 51.4

ERFN CDED Data - Length Weighted Frequency Rose Plot



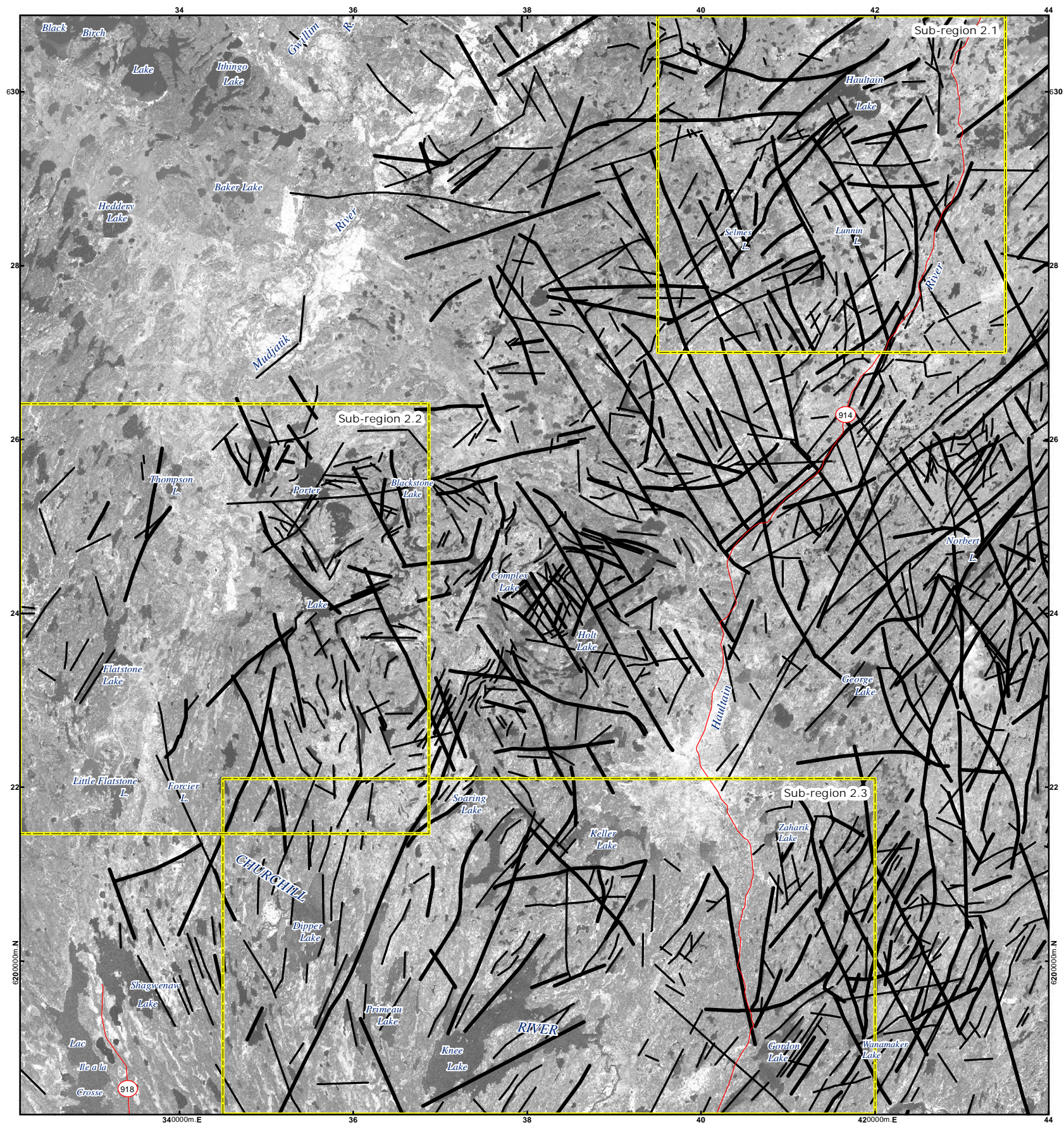
Data sources:  
 DEM: CDED slope 1:50,000  
 Main road: ISC SURN11  
 Waterbody: CanVec 1:50,000





PROJECT PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE CDED reproducibility assessment (RA_1)			
DESIGN	DVZ	25 JUN 2012	<b>FIGURE 8</b> REVISION 3 UTM ZONE 13 NAD 1983 1:550,000
GIS	DSM	17 SEP 2013	
CHECK	JIC	17 SEP 2013	
REVIEW	GS	17 SEP 2013	

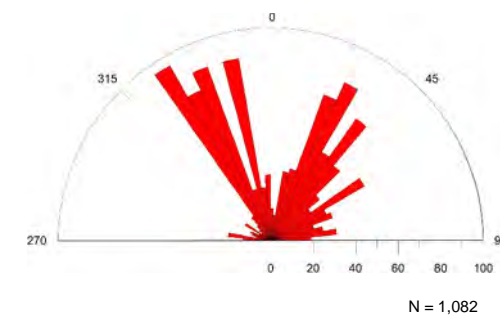




**LEGEND**

- Detailed area
- Main road
- SPOT Lineament RA\_1**
- 1
- 2

ERFN SPOT Data - Length Weighted Frequency Rose Plot



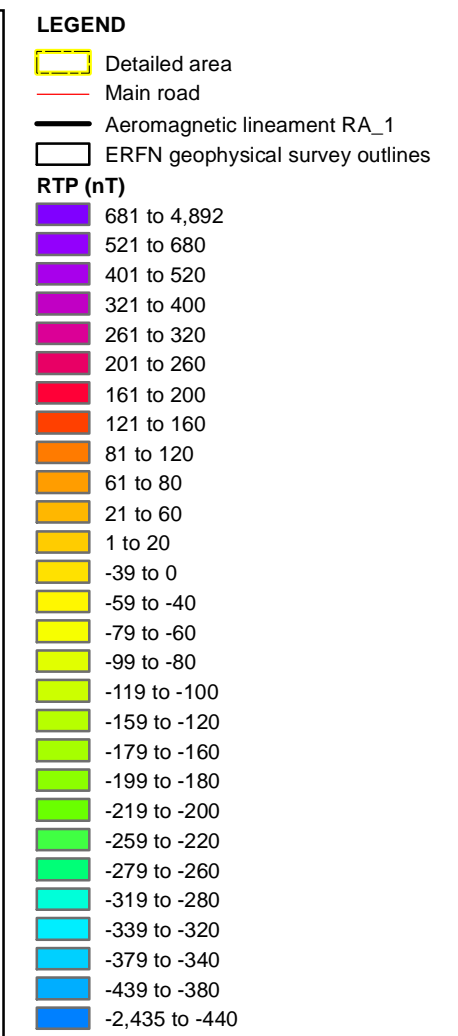
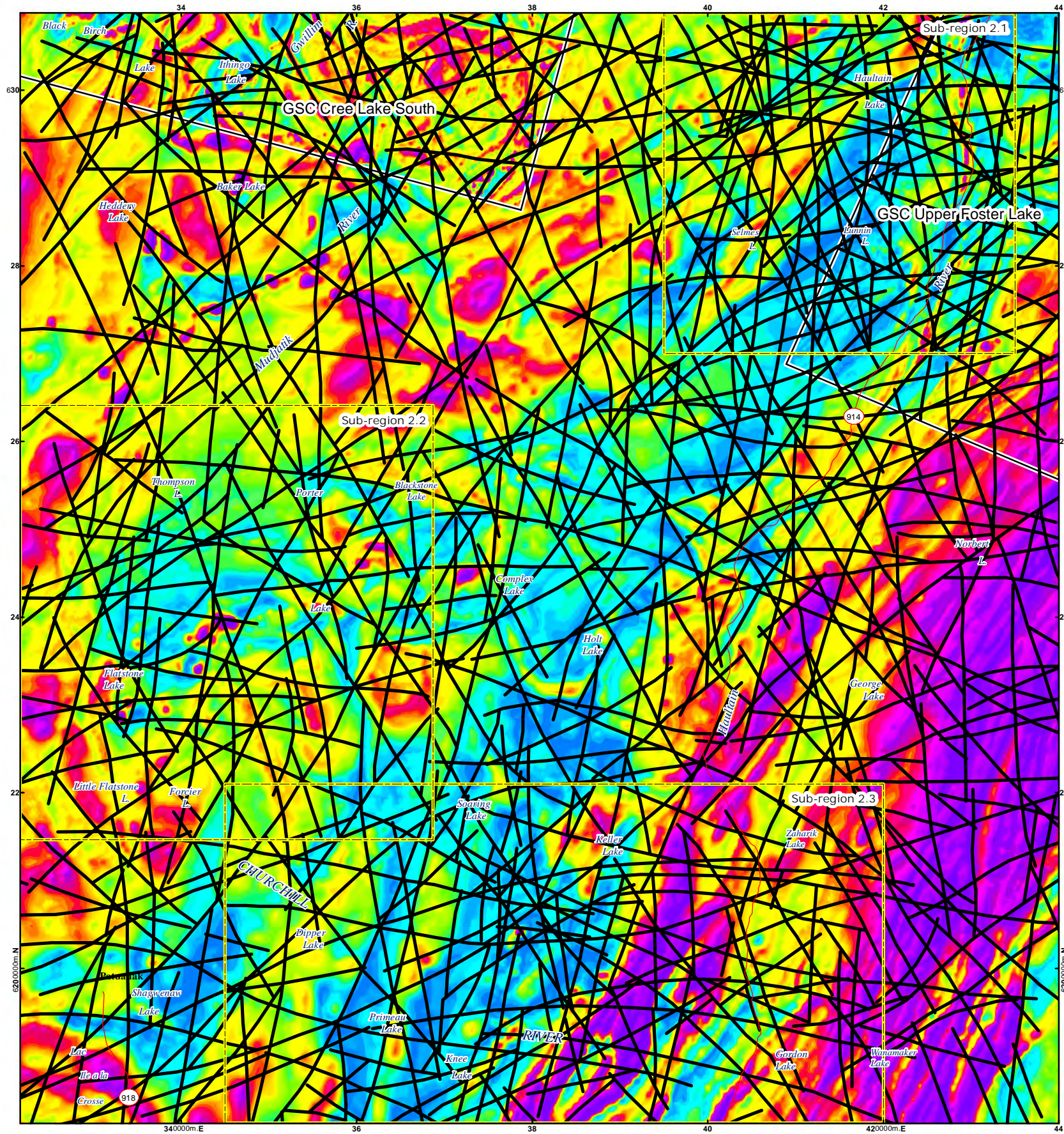
Data sources:  
 SPOT: Geobase  
 Main road: ISC SURN11  
 Waterbody: CanVec 1:50,000



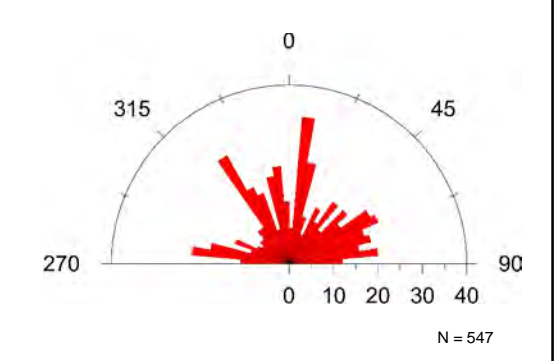
PROJECT			
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE			
SPOT reproducibility assessment (RA_1)			
DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	17 SEP 2013	UTM ZONE 13
CHECK	JIC	17 SEP 2013	NAD 1983
REVIEW	GS	17 SEP 2013	1:550,000

**FIGURE 9**





ERFN Aeromagnetic Data - Length Weighted Frequency Rose Plot

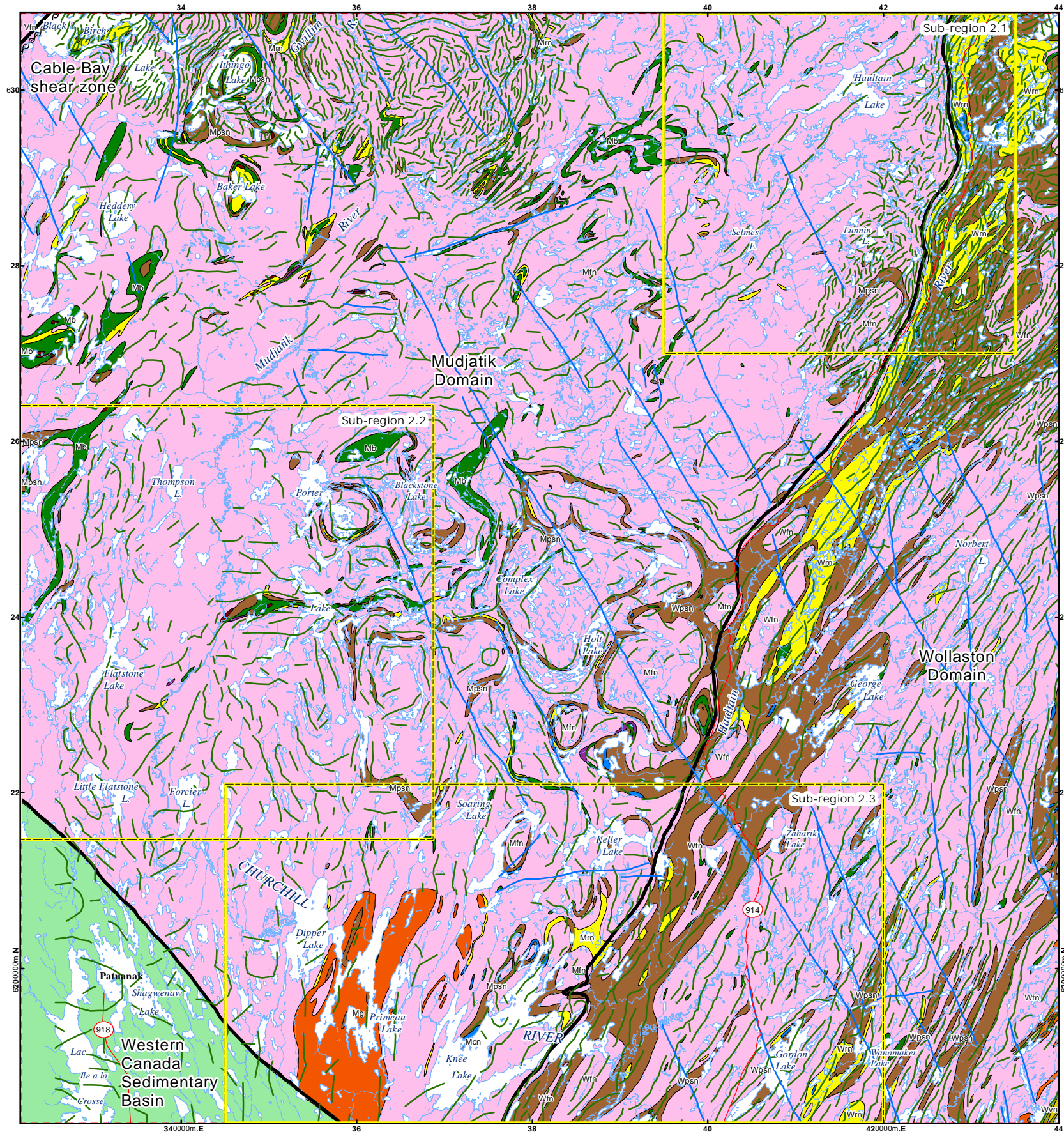


Data sources:  
 Aeromagnetic reduced magnetic field: PGW (2012)  
 Main road: ISC SURN11  
 Waterbody: CanVec 1:50,000



PROJECT			
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE			
Aeromagnetic reproducibility assessment (RA_1)			
DESIGN	DVZ	25 JUN 2012	<b>FIGURE 10</b> REVISION 3 UTM ZONE 13 NAD 1983 1:550,000
GIS	DSM	17 SEP 2013	
CHECK	JIC	17 SEP 2013	
REVIEW	GS	17 SEP 2013	





- LEGEND**
- Detailed area
  - ERFN area
  - Main road
  - Mapped fault
  - Mapped shear zone
  - Ductile feature
  - Domain boundary
  - Waterbody
  - Watercourse
- Western Canada sedimentary basin**
- Western Canada Sedimentary Basin
- 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

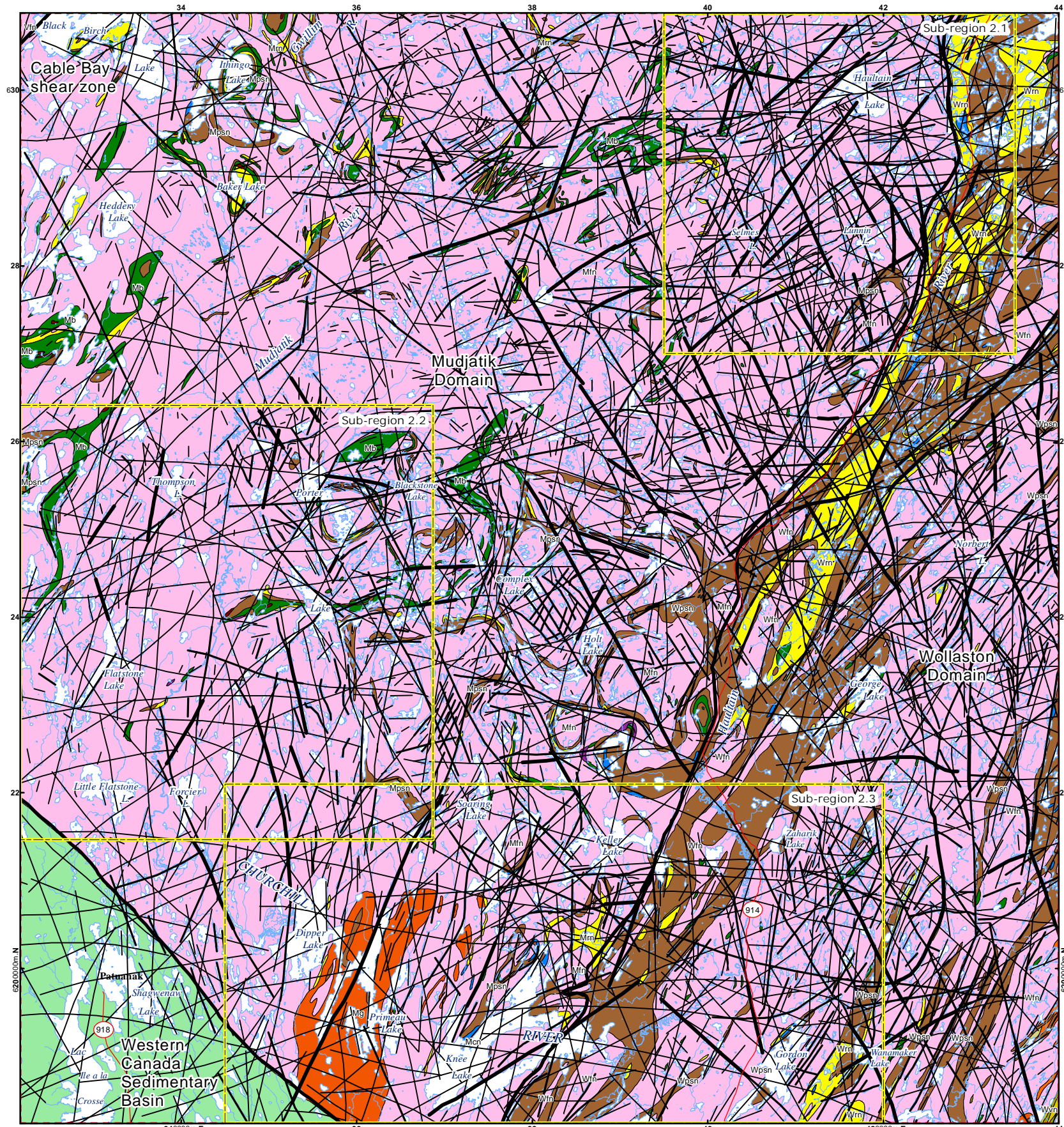
Data sources:  
 Geology: Sask Geological Atlas 1:250,000  
 Ductile feature: mapped by PGW from magnetostratigraphy  
 Road: ISC SURN11  
 Waterbody: CanVec 1:50,000  
 Watercourse: CanVec 1:50,000

NORTH  
 5 km

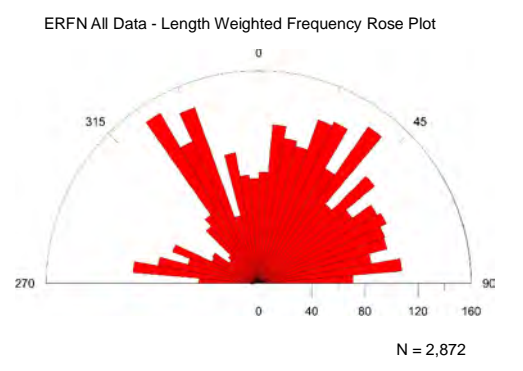
PROJECT PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN			
TITLE Ductile features of the ERFN area			
DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	20 SEP 2013	UTM ZONE 13
CHECK	JIS	20 SEP 2013	NAD 1983
REVIEW	GS	20 SEP 2013	1:550,000

FIGURE 11





- LEGEND**
- Detailed area
  - ERFN area
  - Main road
- Lineament RA\_2**
- 1
  - 2
  - 3
  - Domain boundary
  - Waterbody
  - Watercourse
- Western Canada sedimentary basin**
- Western Canada Sedimentary Basin
- 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 rock, marble
  - 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



PROJECT  
 PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT,  
 LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN

TITLE  
 Lineament classification by  
 reproducibility assessment (RA\_2)

DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	20 SEP 2013	UTM ZONE 13
CHECK	JIS	20 SEP 2013	NAD 1983
REVIEW	GS	20 SEP 2013	1:550,000

FIGURE 12





**LEGEND**

- Detailed area (Yellow dashed line)
- ERFN area (Red dashed line)
- Main road (Red line)

**Lineament length**

- 0 - 1 km (Thin black line)
- 1 - 5 km (Medium black line)
- 5 - 10 km (Thick black line)
- 10+ km (Very thick black line)

**Domain boundary**

- Waterbody (Blue outline)
- Watercourse (Blue line)

**Western Canada sedimentary basin**

- Western Canada Sedimentary Basin (Light green)

**Mudjatik domain**

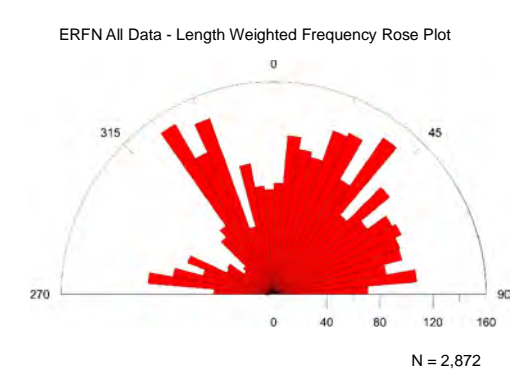
- Mcn - Calc-silicate rock, marble (Blue)
- Mfn - Felsic gneiss (Pink)
- Mg - Leucogranite (Orange)
- Mif - Banded iron formation (Dark red)
- Mb - Mafic gneiss (Green)
- Mpsn - Pelitic, psammopelitic and psammitic gneisses (Brown)
- Mm - Psammitic to meta-arkosic gneiss (Yellow)
- Mu - Ultramafic rock (Purple)

**Virgin River domain**

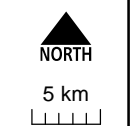
- Vfn - Felsic gneiss (Light pink)

**Wollaston domain**

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



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



**J D MOLLARD**  
 3RD FLOOR, 1000 - 10TH AVENUE, SASKATOON, SASKATCHEWAN, S4N 1A5

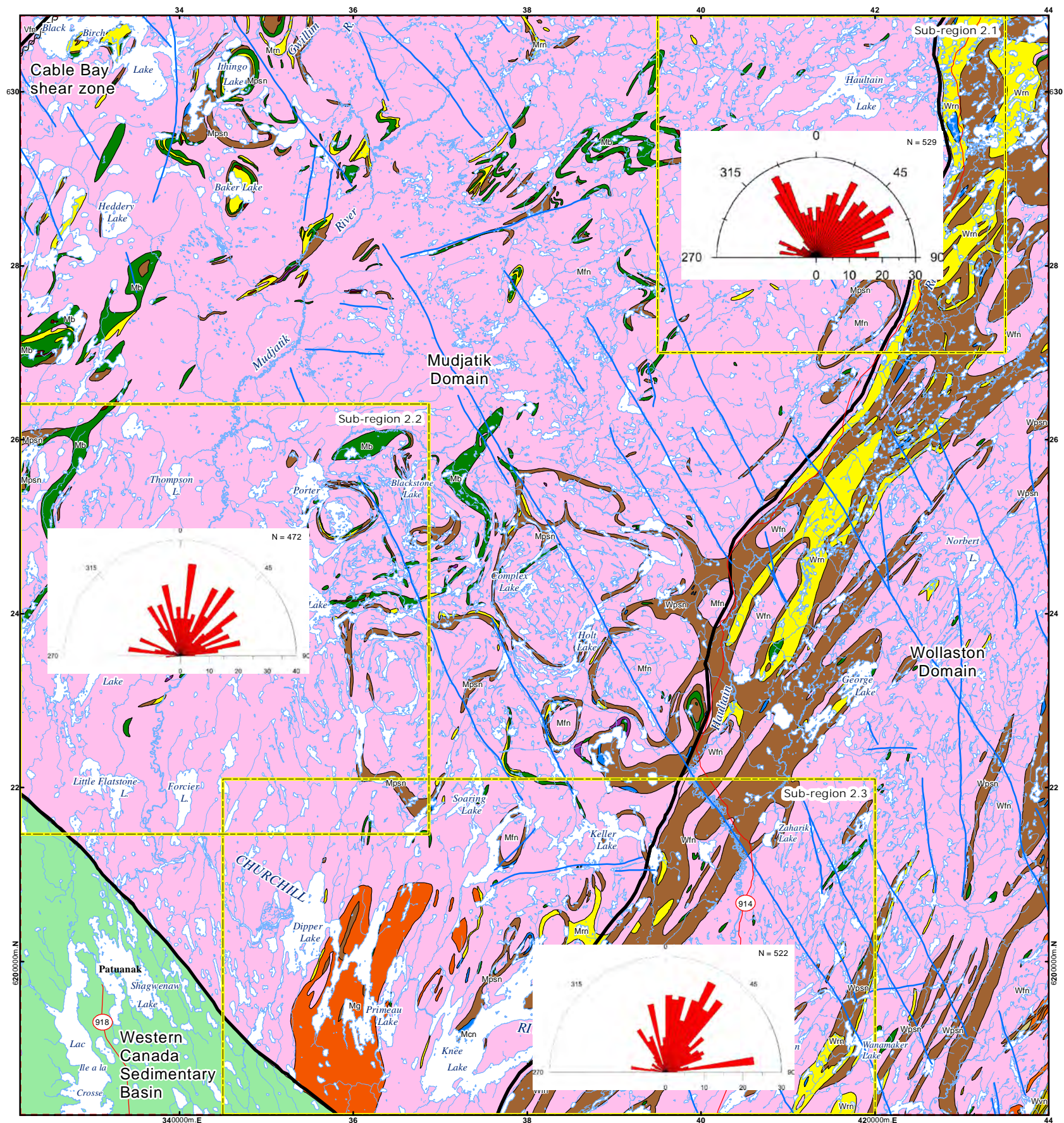
PROJECT  
 PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT,  
 LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN

TITLE  
 Lineament classification by length

DESIGN	DVZ	25 JUN 2012	REVISION 3
GIS	DSM	08 NOV 2013	UTM ZONE 13
CHECK	JIS	08 NOV 2013	NAD 1983
REVIEW	GS	08 NOV 2013	1:550,000

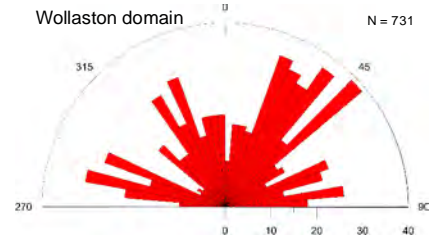
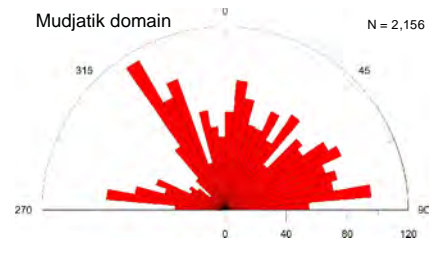
**FIGURE 13**





**LEGEND**

- Detailed area
  - ERFN area
  - Main road
  - Mapped fault
  - Mapped shear zone
  - Domain boundary
  - Waterbody
  - Watercourse
- Western Canada sedimentary basin**
- Western Canada Sedimentary Basin
- 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 -
  - Wma - Amphibolite (Archean)
  - Wpsn - Pelitic, psammopelitic gneiss
  - Wpx - Migmatized supracrustal rocks
  - 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



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PROJECT  
 PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT,  
 LINEAMENT ANALYSIS, ERFN AREA, SASKATCHEWAN

TITLE  
 Lineament orientations of detailed study areas  
 in the ERFN area

DESIGN	DVZ	25 JUN 2012	<b>FIGURE 14</b>	REVISION 3
GIS	DSM	08 NOV 2013		UTM ZONE 13
CHECK	JIS	08 NOV 2013		NAD 1983
REVIEW	GS	08 NOV 2013		1:550,000