NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation

NORTHERN VILLAGE OF PINEHOUSE, SASKATCHEWAN

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PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT

LINEAMENT INTERPRETATION

NORTHERN VILLAGE OF PINEHOUSE, SASKATCHEWAN

NWMO REPORT NUMBER:
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EXECUTIVE SUMMARY

In March 2012, the Northern Village of Pinehouse, 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 Pinehouse area for safely hosting a deep geological repository (Step 3). This request followed the successful completion of an initial screening conducted during Step 2 of the site selection process.

The preliminary assessment is a multidisciplinary 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 Pinehouse 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 completed as part of the desktop geoscientific preliminary assessment of the Pinehouse 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 Pinehouse 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 (ductile lineaments and brittle lineaments) 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 Pinehouse 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 northeastern part of the Pinehouse area where the thickness and extent of surficial cover is relatively low. The lowest density of lineaments was observed in the southern portion of the Pinehouse area around Pinehouse Lake and over low lying areas covered by overburden and wetlands.

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1 INTRODUCTION

In March 2012, the Northern Village of Pinehouse, 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 Pinehouse area 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 Pinehouse 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 Pinehouse area (Golder, 2013). The lineament interpretation 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 Pinehouse area in northern Saskatchewan. The assessment of interpreted lineaments in the context of identifying siting areas that are potentially suitable for hosting a repository is provided in the desktop preliminary geoscientific assessment report (Golder, 2013). The lineament interpretation area is referred to as the "Pinehouse area" in this report.

1.1 SCOPE OF WORK

The scope of work for this study includes the completion of a lineament interpretation of remotely-sensed datasets, including surficial (digital elevation data and satellite imagery) and geophysical (aeromagnetic) datasets for the Pinehouse area (approximately 2,913 km^2) in northern Saskatchewan (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);
- 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 orientation, length, reproducibility and coincidence.

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 in the Pinehouse area 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 Pinehouse area, no dyke lineaments were interpreted during this study. The two lineament categories employed in the analysis are described in more detail below in the context of their usage in this preliminary desktop study.

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

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

Lynden Penner, M.Sc., P.Eng., P.Geo. has undertaken the advancement of lineament research through the application of aerial and satellite imagery, DEMs, and GIS technology for a variety of projects including oil and gas exploration, potash mine development, groundwater exploration and contamination, CO_2 sequestration studies, and assessing gas leakage from oil and gas wells beginning in 1986 and continuing to present. Given his expertise in mapping and understanding lineaments, Mr. Penner advised project team members on lineament mapping approaches and assisted with mapping lineaments from remotely sensed imagery and worked with the project team to evaluate the significance of the mapped, coincident and linked lineaments.

Dr. Jason Cosford, Ph.D., P.Geo. has contributed to a wide range of terrain analysis studies conducted by JDMA, including routing studies (road, rail, pipeline, and transmission line), groundwater exploration, granular resource mapping, and environmental sensitivity analyses. Dr. Cosford, Mr. Penner and Dr. Jack Mollard were responsible for shallow groundwater studies for the Weyburn CO_2 sequestration research project. Dr. Cosford provided interpretation of the surficial lineaments and coordinated the evaluation of lineament attributes, and oversaw the preparation of integrated lineament datasets.

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

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

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 interpretation, 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 Pinehouse 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 Pinehouse 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 summaries of 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 interpretation (Section 5.0).

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

The Pinehouse area is mostly located within the Hearne craton (historically called Cree Lake zone) that comprises the eastern portion of the Western Churchill Province of the Canadian Shield (Figure 2). A small portion of the Pinehouse area extends into the adjacent Reindeer zone to the east. The Hearne craton (south of the Athabasca basin) is generally composed high grade Archean to Paleoproterozoic metamorphic rocks older than 1.8 billion years (Orrell et al., 1999; Card et al., 2008) that are overlain by sedimentary rocks of the Athabasca Group within the Athabasca Basin and Phanerozoic sedimentary rocks within the Western Canada Sedimentary Basin, north and south of the Pinehouse area, respectively. In the Canadian Shield, these rocks continue southward, with increasing depth beneath the sedimentary rocks of the Western Canada Sedimentary Basin, and northward outcropping again along the northern margin of the Athabasca Basin. The Hearne craton is bounded to the west by the Rae craton along the Snowbird tectonic zone and to the east side by the Reindeer zone along the Needle Falls shear zone (Figure 2). These shear zones are oriented in a north-northeast direction (azimuth of approximately 20°), and reflect the predominant alignment of major Precambrian structural features and lithologies in northern Saskatchewan (Munday, 1978a). The Hearne craton is further divided into three lithostructural domains (Lewry and Sibbald, 1980), from west to east, the Virgin River, Mudjatik, and Wollaston domains. A new proposed domain reclassification has been advanced where the Virgin River and Mudjatik domains are to be merged and renamed as Mudjatik domain (Card, 2012). For the purpose of simplicity, the old domain classification has been retained given that it is the one used by all sources utilized and because it does not have any impact in the objective of this assessment. The Pinehouse area is primarily located within the Wollaston domain, with two small portions lying on the Mudjatik domain and the Wathaman batholith, in the northwest corner and southeast corners of the Pinehouse area, respectively (Figure 2).

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

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

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

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

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

The Wathaman batholith is a very large megacrystic monzogranite-granodiorite intrusive body that extends for about 900 km along the eastern boundary of the Hearne craton and the Needle

Falls shear zone, separating the craton from the Reindeer zone. The batholith was emplaced during the Trans-Hudson Orogeny in a compressional tectonic regime (Fumerton et al., 1984).

Regional geophysical surveys were used to assist in mapping geologic structures within the Precambrian provinces and zones of northern Saskatchewan (Hajnal et al., 2005; White et al., 2005). A cross section through the Trans-Hudson Orogen in the Pinehouse area was constructed by White et al. (2005) based on geophysical surveys conducted as part of the Lithoprobe project (a multi-year continent-scale geophysical subsurface mapping initiative). Geophysical surveys conducted as part of this initiative included airborne magnetic, gravity, airborne radiometric, audio magnetotelluric and deep seismic surveys (Lucas et al., 1993; Lewry et al., 1994; Hajnal et al., 2005; White et al., 2005). Coupled geophysical modelling of Lithoprobe data for a west-east geophysical transect, located approximately 50 km south of the boundary between the Canadian Shield and the Western Canada Sedimentary Basin, estimates the Archean basement rocks of the Mudjatik domain to extend to depths from 5 to 10 km (White et al., 2005). The Archean basement rocks extend to similar depths in the Wollaston domain. Where present, the metasedimentary rocks of the Wollaston domain are expected to extend to depths ranging from approximately 5 to 8 km (White et al., 2005). Although the data was collected approximately 50 km to the south of the Pinehouse area, these estimates provide some insight with respect to the approximate thickness and continuity of major rock units proximal to the Pinehouse area.

2.1 PHYSICAL GEOGRAPHY

A detailed discussion of the physical geography of the Pinehouse area is provided in a separate terrain analysis report by JDMA (2013). The physical geography of the Pinehouse area exhibits topography and drainage that are characteristic of the Canadian Shield, a low-relief, dome-like, gently undulating land surface. The topography of the Pinehouse area generally ranges from about 521 m in the north, near Snake Rapids, to about 385 m on the shores of Pinehouse Lake (Figure 5).

Two major topographic highs are present within the Pinehouse area that are defined by the relative topographic lows of the Churchill River and Pinehouse Lake (Figure 5). North of the Churchill River, the topography is rugged with the highest elevations, greatest relief, and steepest slopes in the Pinehouse area. Incised valleys and depressions in this area appear to be dominantly oriented northeast-southwest and provide surficial expression to the underlying bedrock structures. South of the Churchill River, and to the east of Pinehouse Lake, the topography is similar to the area north of the Churchill River, with steep slopes and high relief, but the topography exhibits progressively lower relief and gentler slopes toward the south. Around Besnard Lake, in the very southeast of the Pinehouse area, the relief and slopes are very low. South of the Churchill River, and west of Pinehouse Lake, the topography is notably subdued, with lower elevations and relief, and gentler slopes. Noteworthy is that in the very southwest of the Pinehouse area, the topography shows slightly higher relief and steeper slopes that impart a topographic fabric trending northwest-southeast. The low relief in the southwest part of the Pinehouse area reflects the cover of Phanerozoic rocks over the Canadian Shield and more extensive Quaternary surficial materials.

Surface water covers a total area of 707 km^2, which represents a coverage of approximately 24% of the 2,914 km^2 Pinehouse area. The surficial hydrology is dominated by Pinehouse Lake, the largest in the Pinehouse area, and the Churchill River system, through which all of the surface flow within the Pinehouse area ultimately drains, eastward to Hudson Bay. The Haultain and Bélanger Rivers flow southward into the Churchill River from sub-basins to the north. The Massinahigan River drains the southwest corner of the Pinehouse area into Pinehouse Lake (Figure 5).

2.2 LOCAL BEDROCK GEOLOGY

The reader is directed to Golder (2013) for a detailed description and discussion of the bedrock and structural geology of the Pinehouse area. The main lithological units in the Pinehouse area include felsic gneiss in the Wollaston and Mudjatik domains, supracrustal rocks in the Wollaston domain, and megacrystic granitoid rocks of the Wathaman batholith in the Reindeer zone (Figures 2 and 3). Golder (2011) identifies the felsic gneiss in the Wollaston and Mudjatik domains, as well as the Wathaman batholith as being potentially suitable for hosting a deep geological repository in the Pinehouse area.

2.2.1 FELSIC GNEISS

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

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

2.2.2 METASEDIMENTARY AND METAVOLCANIC ROCKS

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

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

The metasedimentary and metavolcanic rocks also occur in relatively thin linear bands with a north-northeast strike through the center and towards the southeast corner of the Pinehouse area. These bands of rock are generally parallel to the Needle Falls shear zone and range in width from less than 1 km to over 5 km (Figure 3).

2.2.3 Wathaman Batholith

A small portion of the Pinehouse area extends onto the Wathaman batholith to the east of the Needle Falls shear zone (Figures 2 and 3). The geological characteristics of the Wathaman batholith are potentially favourable as a repository host rock type. However, the limited volume of this rock in the Pinehouse area and the proximity of the Needle Falls shear zone preclude any further consideration. The Wathaman batholith underlies a triangular shaped parcel of land at the southeast corner of the Pinehouse area measuring some 7 km along its base by 20 km toward the north. The Needle Falls shear zone forms the northwest side of this triangle of land.

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

2.2.4 Faults and Shear Zones

Structural features mapped in the Pinehouse area include major northeast- to north-northeast-trending ductile shear zones, and a predominant set of north- to north-northwest-trending brittle faults (Figures 2 and 3).

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

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

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

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

A series of steeply dipping north-northwest-trending brittle faults are noted at the east end of the Wollaston domain, close to the Needle Falls shear zone (Figures 2 and 3; White et al., 2005). The longest of these brittle structures is over 120 km in length and appears as prominent topographical lineament. These faults have been associated with brecciation, shearing, mylonitization and hydrothermal alteration (Byers, 1962). Sinistral horizontal displacement of up to 800 m is documented along the faults, and geophysical interpretations suggest near vertical dips for the fault planes. Some evidence suggests that reactivation and displacement has occurred along these faults as recent as the Cretaceous period (Byers, 1962). These steep faults were interpreted by Hajnal et al. (2005) to be part of the Tabbernor fault system (discussed below). Hajnal et al. (2005) further noted numerous east-dipping fracture zones within the upper portions of the Wollaston domain. These features were also noted along the east side of the Mudjatik domain, but are much less abundant to absent in the central to western portions of the Mudjatik.

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

2.2.5 Metamorphism

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

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

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

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

2.3 Geological History

Direct information on the geological and structural history of the Pinehouse area is limited. The geological and structural history summarized below integrates the results from studies undertaken elsewhere throughout and proximal to the area shown on Figure 3, drawing particularly on information from the Creighton, Saskatchewan area. 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 Pinehouse area, which may be modified after site-specific information has been collected, if the community is selected by the NWMO and remains interested in continuing with the site selection process.

The tectonic events that occurred ca. 2.1 to 1.9 billion years ago during the Trans-Hudson Orogeny imparted the predominant bedrock structure in the Pinehouse area. Based on studies undertaken throughout Northern Saskatchewan, five discernible stages of deformation (D1 to D5) have been distinguished which can provide a framework for understanding the structural history of the Pinehouse area. These important phases of the Trans-Hudson Orogeny, as well as events that both pre- and post-date the main orogenic event, are summarized in Table 1 below (Cumming and Scott, 1976; Stauffer and Lewry, 1993; Andsell, 2005; Corrigan et al., 2005; Hajnal et al., 2005; Corrigan et al., 2007; Whitmeyer and Karlstrom, 2007; Corrigan et al., 2009).

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

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

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

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

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

Time period (Ga)	Geological event
2.7	Approximate crystallization age of the felsic gneiss in the region that comprises the Hearne craton.
2.1 to 1.92	Initiation of rifting on the eastern margin of the Hearne craton and opening of the Manikewan ocean. Passive margin in the eastern margin of Hearne craton during rifting, with sedimentation of the Wollaston Supergroup.
1.92 to 1.88	Initiation of subduction underneath the eastern margin of Hearne craton leading to the beginning of both closure of the Manikewan Ocean and creation of the Rottenstone magmatic arc. Continued deposition of Wollaston Supergroup in a back-arc basin. This was followed by collisional compression of the rocks of the Wollaston Supergroup, Rottenstone and La Ronge domains. Collision resulted in D_1 ductile deformation that produced isoclinal folds and imparted the S_1 foliation to felsic gneiss.
1.88 to 1.865	Ongoing subduction resulted in the accretion of juvenile island arc terranes (La Ronge-Lynn Lake) to the southeastern margin of the expanded Rae-Hearne craton resulting in theformation of Rottenstone accretionary complex, while Wollaston back-arc basin shifted to foreland basin.
1.865 to 1.83	Closure of Wollaston basin at ca. 1.86 billion years with concomitant emplacement of Wathaman batholith between ca. 1.865-1.855 billion years along eastern margin of Rae-Hearne craton. Regional D_2 ductile deformation produced upright folds that overprinted the S_1 foliation. Ongoing subduction resulted in the accretion of the Glennie-Flin Flon complex to the Rae-Hearne craton. Collision of the Sask craton with the Rae-Hearne craton, which thrusted the accreted juvenile terranes over the Sask craton.
1.83 to 1.80	Terminal collision of Superior craton with the Rae-Hearne craton leading to final closure of the Manikewan ocean. Crustal shortening that occurred during this period resulted in movement along the Needle Falls shear zone. D_3 ductile deformation creates NE-striking upright folds dominant in the Wollaston domain. Activation (reactivation?) of the Needle Falls and Virgin River shear zones at ca. 1.83 billion years. Development of thick-skin imbrication in Mudjatik domain and thin-skin imbrication in Wollaston domain. D_4 ductile deformation creates NW-striking upright folds orthogonal to F_3 after movement on the Virgin River and Cable Bay shear zones.
1.80 to 1.72	Activation of the Tabbernor fault zone (ca. 1.8 billion years) and the D_5 steep-brittle faults observed within the Wollaston domain, extending into the Mudjatik domain.
1.72 - 1.5	Development of successor basins across parts of the Hearne craton, including formation of Athabasca basin.
< ca. 0.5	Deposition of Deadwood Formation in Phanerozoic Williston basin. Progressive infilling of Phanerozoic Western Canadian Sedimentary Basin in southern Saskatchewan and other regional areas.

2.4 Regional structural history

Five main stages of deformation (D1 to D5) associated with the Trans-Hudson Orogeny can be distinguished for the Pinehouse area, based on regional studies (e.g., Byers, 1962; Munday, 1978a; Tran and Smith, 1999; Annesley et al., 2005; Hajnal et al., 2005; White et al., 2005; Card and Bosman, 2007; Yeo and Delaney, 2007; Card et al., 2008). The following description is a summary of this previous work, primarily following the numbering system established by Card et al. (2008).

The earliest recognizable deformation event (D1) resulted in supracrustal and felsic rocks being isoclinally folded (F1). A prominent mineral foliation imparted by this phase, S1, 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 (D2) identified by Card et al. (2008) is marked by rare intrafolial folds with hinges defined by the S1 foliation. Card and Bosman (2007) indicate D2 involved the development of upright, northwest-trending F2 folds that re-oriented the S1 fabric in an area to the north of the Pinehouse area. Little information is available regarding this event, and it was not reported in earlier studies (e.g., Munday, 1978a). The third deformation event, D3, was characterized by the development of upright, north-northeast-trending folds that also reoriented the S1 foliation. The north-northeast-trending F3 fold limbs generally tighten towards the Virgin River and Cable Bay shear zones to the northwest of the Pinehouse area and towards the Needle Falls shear zone in the southeast corner of the Pinehouse area. The folds are more open within most of the Mudjatik domain away from the zones of higher strain.

The Virgin River, Cable Bay and Needle Falls shear zones developed during the latter stages of the D3 event or later as evidenced by the shear displacement along F3 fold limbs, but prior to the development of a second (weak) phase of northwest-trending folds (F4), during a localized D4 event in the westernmost part of the Mudjatik-Virgin River domains. The shear zone deformation is therefore ascribed to a D3 event. Card et al. (2008) noted that the F4 folds are generally orthogonal to the north-northeast-trending F3 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 S1 fabric in the westernmost part of the Mudjatik domain. Card and Bosman (2007) and Card et al. (2008) suggested that these F4 folds postdate the Virgin River and Cable Bay shear zones and are likely of Trans-Hudson age.

Brittle, D5, deformation resulted in a late series of dominantly north- to north-northwest-trending faults that bisect the Pinehouse area, and cross-cut the structures associated with the D1 to D4 events. These features have likely had a long history of re-activation consistent with the interpretation that they are related to the Tabbernor fault located about 200 km to the east of the Northern Village of Pinehouse. The Tabbernor fault initially formed during the Trans-Hudson Orogen approximately 1.83 Ga, likely with more recent periods of reactivation. Features in overlying sedimentary rocks and apatite fission track analyses indicate reactivation of the fault in the late Devonian and early Cretaceous Periods (Elliot, 1996; Davies, 1998; Hajnal et al., 2005).

2.5 QUATERNARY GEOLOGY

Quaternary geology of the Pinehouse area is described in detail in a separate terrain analysis report by JDMA (2013). During the Quaternary Period, several advances and retreats of continental glaciers occurred in the Pinehouse area. These glaciation periods eroded the bedrock and typically any surficial deposits associated with previous glacial events. The present conditions are a result of the latest Wisconsinan glaciation, during which the Laurentide Ice Sheet covered the entire Pinehouse area (Schreiner, 1984a).

Figure 4 illustrates the Quaternary geology of the Pinehouse area. Regionally, the main Quaternary deposits include morainal plains, and glaciofluvial plains, with sparse occurrences of glaciolacustrine plains. Ground moraines are the dominant glacial landform in northern Saskatchewan and vary from flat to hummocky (Schreiner, 1984a, b, c, d). 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. Thickness of the Quaternary strata over the Canadian Shield is variable and is generally thicker down ice (southwest) of the Athabasca Basin.

The most common bedrock surface cover in the Pinehouse area is morainal plain till, which extends along a northeast-trending band centred over Pinehouse. The composition is generally sandy to the northwest, and silty to the southeast. Sand deposits and some silt and clay deposits are noted in the larger lakes in the area, such as Pinehouse Lake, however the overall scarcity of lacustrine sediments indicates that Lake Agassiz may not have extended significantly over the Pinehouse area (Schreiner, 1984a, b). The morainal plain is flanked on both sides by glaciofluvial outwash deposits. A number of eskers have been mapped in the southeast corner of the Pinehouse area and organic bog plains occur to the east and southeast of Pinehouse Lake.

Areas dominated by rock outcrop are present in the east-northeast portion of the Pinehouse area, at about the same latitude as Knee Lake. This includes an area measuring approximately 20 by 20 km (Figure 4). Glacial evidence includes scouring, *roches moutonnées*, drumlinoids, wind flutings and striae (Schreiner, 1984a; Gilboy, 1985). Rugged local relief was enhanced as glaciers eroded low lying areas and polished resistant bedrock knobs. These features indicate that the ice flow direction was generally from northeast to southwest over the Pinehouse area. The direction of ice movement was almost parallel to the structural trend of the bedrock, thus enhancing the erosion of less resistant rock (Schreiner, 1984a).

Glaciofluvial deposits of sand and gravel are found along the Haultain, Bélanger and Massinahigan Rivers, which functioned as major meltwater channels (Schreiner et al., 1976). An extensive glaciofluvial outwash plain covers the Pinehouse area to the west and southwest of Sandy Lake. Glaciofluvial deposits also provide thin cover of the area between the Bélanger River in the northeast corner of the Pinehouse area and the eastern side of Bar Lake in the south-central portion of the Pinehouse area. Larger glaciofluvial deposits have the potential to represent significant regional aggregate or groundwater supplies. The good foundation conditions and abundance of suitable borrow and granular materials make these landforms ideal for transportation routes, building sites, and airport locations.

Estimates of overburden thickness within the Pinehouse area were extracted from descriptions in the available SGS reports. 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.

2.6 LAND USE

The Pinehouse area is located in a remote portion of northern Saskatchewan that is almost completely undeveloped. Pinehouse is the largest community in the area with a population of 978 recorded in the 2011 Census. This community is accessed by Highway 914 which runs generally north-south through the center of the Pinehouse area (Figure 1). The Churchill River represents a major traditional transportation corridor through the Provinces of Alberta, Saskatchewan and

Manitoba. It was used extensively during the fur trade with the Hudson's Bay Company in the early 1800s. Several outfitters are located along the Churchill River. The Pinehouse area is largely situated in an observation zone designated by the Saskatchewan Wildfire Management Plan. This observation zone extends north from the Churchill River to the northern provincial boundary. In such areas, wildfires are observed and generally not suppressed unless the cost of suppression is less than the value of the potential losses. These features do not negatively impact 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 Pinehouse 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 Pinehouse area (Figure 5). The digital elevation model (DEM) used for this interpretation, 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.

Table 2 Summary of source data information for the lineament interpretation of the Pinehouse area.

Dataset	Product	Source	Resolution	Coverage	Acquired	Additional Comments
DEM	Canadian Digital Elevation Data (CDED); 1:50,000 scale	Geobase	20 m	Entire area	1978 - 1995	Hillshaded and slope rasters used for mapping
Satellite Imagery	SPOT 4/5; Orthoimage, multispectral/ panchromatic	Geobase	10 m (panchromatic) 20 m (multispectral)	Entire area	2006 - 2009	Panchromatic mosaic used for mapping
Geophysics	Saskatchewan #8 (magnetic)	Geological Survey of Canada	1609 m line spacing Sensor height 305 m	West margin of Pinehouse area	1952	Lowest resolution dataset
	Saskatchewan #9 (magnetic)	Geological Survey of Canada	805 m line spacing Sensor height 305 m	Entire area	1969	Low resolution dataset

Hillshaded elevation maps were 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 Pinehouse area. The hillshade and slope rasters were most useful for mapping lineaments.

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

NTS Tiles:	Ground Resolution (arcsec.)
73O/10-16	0.75
73P/12-13	0.75
74A/04-05	0.75
74A/12-13	0.75
74B/01-16	0.75

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 an important information source for identifying surficial lineaments and exposed bedrock within the Pinehouse 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.

Five SPOT images (or 'scenes') provided complete coverage for the Pinehouse area (Table 4). The scenes are from the SPOT 4 and SPOT 5 satellites with images acquired in May 2006, June 2007, October 2007, September 2008, and September 2009. The imagery captured in May 2006 and September 2009 covers the majority of the Pinehouse area.

Table 4 Summary of SPOT imagery used for lineament interpretation.

Scene ID	Satellite	Date of image
S5_10541_5531_20071007	SPOT 5	October 7, 2007
S4_10600_5503_20070610	SPOT 4	June 10, 2007
S4_10712_5558_20080910	SPOT 4	September 10, 2008
S5_10639_5531_20090917	SPOT 5	September 17, 2009
S4_10626_5558_20060516	SPOT 4	May 16, 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 15º. 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, 2013). 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 Pinehouse area to allow for the mapping of continuous lineaments extending beyond the Pinehouse area.

3.1.2 GEOPHYSICAL DATA

The geophysical dataset incorporates aeromagnetic, gravity and radiometric data available across the entire Pinehouse 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 Pinehouse 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 Pinehouse 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 Pinehouse area.

The Pinehouse area has been covered by low-resolution magnetic data obtained from the Geological Survey of Canada (GSC), covers the entire Pinehouse area (GSC, 2012). Low-resolution magnetic data (805 m flight line spacing) obtained as Saskatchewan #9 survey from the GSC provides complete coverage of the entire Pinehouse area. Saskatchewan #8 survey provides lower resolution magnetic data (1,609 m flight line spacing) located along the western margin of the Pinehouse area and further west of the Pinehouse area.

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 coincidence (RA_2).

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

Each identified lineament feature was classified in an attribute table in ArcGIS. The description of the attribute fields used is included in Table 5. Fields 1 to 9 are populated during the first step. Fields 10 and 11 are populated during the second step. Fields 12 to 19 are populated in the third and final step.

A detailed description of the three workflow steps, as well as the way each associated attribute field is populated for each 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

3.2.2 STEP 2: REPRODUCIBILITY ASSESSMENT 1 (RA_1)

In step 2, 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.

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

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

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

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 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 datasets within which each feature has been identified is indicated in the appropriate attribute table field (Geophys, DEM, SAT).

4 FINDINGS

4.1 DESCRIPTION OF LINEAMENTS BY DATASET

4.1.1 SURFICIAL DATASETS (DEM 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 338 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 446 m to 45.4 km, with a geometric mean length of 3.3 km and a median length of 2.9 km. Thirteen percent (13%) of these lineaments, a total of 45, were assigned a certainty value of 3, reflecting a higher degree of confidence with the interpretations made from the CDED data as compared to the SPOT data discussed below. Certainty values of 2 and 1 were assigned to 222 (66%) and 71 (21%) lineaments, respectively. The reproducibility assessment shows coincidence for 105 lineaments (31%) (RA_1 = 2) and a lack of coincidence for 233 lineaments (69%) (RA_1 = 1). These findings for the CDED data appear to be very strongly influenced by the lack of coincidence among shorter lineaments.

Orientation data for the CDED lineaments, weighted by length, show a very dominant trend to the north-northeast to northeast (Figure 8). The rose diagram depicts a very strong north-northeast to northeasterly trend that corresponds well with the orientation of the regional foliation. A minor secondary trend is seen to the northwest to north-northwest that corresponds to the dominant orientation of the mapped brittle faults within and around the Pinehouse area (Figures 2 and 3).

The SPOT dataset compiled from the merger of lineaments identified by the two interpreters yielded a total of 472 lineaments (Figure 9). The length of the satellite lineaments range from 220 m to 44.4 km, with a geometric mean length of 2.1 km and a median length of 2.3 km. Of these satellite lineaments, a total of 42 (9%) were assigned the highest level of certainty (Certain = 3). Certainty values of 2 and 1 were assigned to 351 (74%) and 79 (17%) lineaments, respectively. The reproducibility assessment indicates that a total of 373 (79%) lineaments were identified by only one interpreter (RA_1 = 1), while the remaining 99 (21%) were identified by both interpreters (RA_1 = 2). This finding can be accounted for by the relatively poor coincidence among lineaments with shorter lengths. 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, the length of coincident lineaments is 40% of the total length of lineaments.

SPOT lineament orientations demonstrate a strong trend toward the northeast (Figure 9). There is also a less prominent trend to the north-northwest. These lineament orientations closely match those of the CDED data, which demonstrates that both of the surface-based datasets capture the same main lineament trends.

4.1.2 GEOPHYSICAL DATA

The airborne geophysical data interpretation was used to distinguish 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 323 lineaments were interpreted as ductile features. Such features are useful in identifying the internal foliation of the gneissic rock. In this report, the ductile lineaments are shown to provide context to our understanding of the tectonic history of the Pinehouse area, but 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.

There does not appear to be any bias in the geophysical lineament interpretation due to the east-west flight line orientation. There is no evidence of a flight line parallel lineament trend in either the SPOT or CDED lineament interpretations, while a weak westerly lineament trend is evident in the aeromagnetic interpretation.

Brittle lineaments interpreted from magnetic survey data total 338 in the Pinehouse area (Figure 10). The length of these lineaments range from 229 m to 51.2 km, with a geometric mean of 10.1 km and a median of 10.6 km. The geophysical lineaments exhibit prominent orientations to the north-northwest and to the north. There is also a notable trend to the east-northeast. Unlike the surficial lineaments, the geophysically-interpreted brittle lineaments do not display a dominant trend to the northeast.

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

A total of 304 (90%) of the geophysical lineaments were assigned the highest level of certainty (Certainty = 3), while 7% and 2% of the lineaments were given certainty values of two and one, respectively. The reproducibility assessment identified coincidence for 314 lineaments (93%) (RA_1 = 2) and a lack of coincidence for 24 of the interpreted lineaments (7%) (RA_1 = 1).

It should be noted that the disparity between the number of identified ductile features (n = 323) versus brittle features (n = 338) 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 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.

4.2 DESCRIPTION AND CLASSIFICATION OF INTEGRATED LINEAMENT COINCIDENCE (RA_2)

The integrated lineament dataset 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 Pinehouse area.

The merged lineament dataset (RA_2) contains a total of 889 lineaments that range in length from a minimum of 220 m to a maximum of 51.2 km. The geometric mean length of these lineaments is 4.5 km and the median length is 4.1 km. Lineaments in the >10 km and 5-10 km length bins represent 24% (216) and 22% (192) of the merged lineaments, respectively, while lineaments in the 1-5 km and <1 km length bins represent 48% (421) and 7% (60) 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 the trends in the aeromagnetic data. While the merged lineament dataset exhibits more scatter in lineament orientation, there remains the trend to the northeast that dominates the surficial lineaments. These orientations are consistent with the orientation of the regional shear zones. The rose diagram captures prominent north-northwesterly and northerly trends associated with regional brittle faults. These trends are defined primarily by the aeromagnetic lineaments, but also appear weakly expressed in the surficial lineament datasets.

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 (928) analyzed in the reproducibility assessment does not match the total number of lineaments in the integrated dataset (889). Results from the reproducibility assessment (RA_2) for this dataset show 730 lineament segments (79%) that lack a coincident lineament and thus were assigned a value of 1. A total of 180 lineament segments (19%) were coincident with a lineament from one other dataset (RA_2 = 2) and 17 lineament segments (1.8%) 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 longest lineaments were identified by multiple interpreters and thus showed the highest reproducibility values.

4.3 DESCRIPTION OF LINEAMENTS BY MAJOR GEOLOGICAL UNIT

The bedrock geology in the Wollaston domain of the Pinehouse area consists mostly of felsic gneiss and supracrustal rocks predominated by metasedimentary rocks of pelitic to psammitic composition. All of the rock units in the Pinehouse area are overprinted by a well-developed north-northeast-trending structural grain parallel to the regional shear zones (e.g., Figures 2 and 3). The northwestern portion of the Pinehouse area is underlain by felsic gneiss of the Mudjatik domain, while in the southeast there is a relatively small area underlain by megacrystic granitoid rocks of the Wathaman batholith domain. Collectively, these geological units cover 91% of the total Pinehouse area. The following discussion describes the dominant interpreted lineament orientations for each of these rock bodies.

Felsic gneiss of the Wollaston domain covers the largest portion of the Pinehouse area at about 1,500 km^2 and exhibits a total of 638 lineaments. This unit is relatively high in elevation and exhibits the highest relief and steepest slopes, particularly to the northeast of the Pinehouse area.

Unlike the other geological units, surficial cover is minimal, resulting in exposed bedrock from which lineaments are readily mapped. These gneissic rocks exhibit a strong foliation oriented toward the northeast. Many of the lineaments mapped in this unit reflect a surficial expression of this foliation and show the same orientation to the northeast (Figure 14). This prominent northeast-trending foliation is cut by long, brittle north-northwest-trending fractures that are mapped mostly in the northeast portion of the Pinehouse area, but that the aeromagnetic data, and previous mapping, suggest occur throughout the Pinehouse area.

The supracrustal rocks of the Wollaston domain host a total of 418 lineaments over an area of 589 km^2. The most extensive areas of this unit include: a reach along the Churchill River between Knee Lake and Sandfly Lake; the northern portion of Pinehouse Lake and McDonald Bay; and a section trending to the southwest from Sandfly Lake (Figure 3). Compared to the felsic gneiss, this unit is relatively low in elevation and exhibits lower relief and gentler slopes. As is common in the Shield, these relatively low areas are more extensively covered by surficial deposits and lakes and rivers. Nevertheless, the lineaments identified within this geological unit display strong trends to the north-northeast that appear to reflect the ductile layering in these metasedimentary rocks. This foliation trend is cross-cut by the north-northwest-trending lineaments that appear to represent brittle fractures associated with movement of the Tabbernor fault.

Felsic gneiss of the Mudjatik domain covers a relatively small portion of the Pinehouse area (26 km^2) to the northwest, around Knee Lake, and exhibits a total of 16 lineaments. The area near Knee Lake offers exposed bedrock, but to the west and south, this unit is covered extensively with surficial materials that limit the identification of bedrock features. Lineaments mapped in this geological unit appears to reflect both brittle and ductile features. These features exhibit orientations mostly to the north-northeast and to the northeast.

The Wathaman batholith covers 86 km^2 in the southeast corner of the Pinehouse area from which a total of 52 lineaments were mapped. All of the datasets captured an expression of the Needle Falls shear zone that bounds the Wathaman batholith to the west. Azimuths of the lineaments mapped from this unit display the same trends as the felsic gneiss from the Mudjatik and Wollaston domains in the Pinehouse area. The dominant orientation is to the northeast, consistent with the orientation of the regional foliation, with a secondary trend to the north-northwest that appears to reflect the regional pattern of brittle fracturing.

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, which refers to the length of lineaments per unit area, varies across the Pinehouse area. Since the resolution of the geophysical datasets does not change measurably across the Pinehouse area (Figure 7), the primary factor in the density variation is the extent of overburden cover. Lineament density was calculated using the line density method described in ESRI ArcGIS software, which determines the length of lineaments within a moving circular window (km/km^2). A radius of 1.25 km was used for the moving circular window, based on the repository footprint size and a 50 m cell size.

The lineament density is, in general, quite low across the entire Pinehouse area ranging between 1 and 4 km/km^2. The distribution of lineament density across the Pinehouse area primarily reflects bedrock exposure versus thicker and more extensive surficial cover. The highest lineament densities are observed in the northern portions of the Pinehouse area where there is well-exposed gneissic bedrock. In particular, high lineament densities were observed to the east of Gordon Lake, where there is little surficial cover and numerous well-expressed bedrock structures. The lowest lineament densities appear in the southwestern quadrant of the Pinehouse area where there are extensive surficial materials covering the Phanerozoic sedimentary rocks of the Western Canada Sedimentary Basin. The low lineament density here is also influenced by the southern reach of Pinehouse Lake, which, unlike the northern reach, lacks elongated islands and channels that represent a surficial expression of the underlying bedrock structure.

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 26% 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).

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 33%. 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 5% 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 northeast. Each of the datasets used in this interpretation expressed these features and both interpreters identified those with the longest lengths. This is a key finding of the interpretation as the north-northwest trending lineaments appear to be major bedrock structures associated with movement of the Tabbernor fault (Hajnal et al., 2005) and the northeast trending lineaments reflect foliation in the major geological units and structural domains.

5.3 LINEAMENT LENGTH

There is no information available on the depth extent into the bedrock of the lineaments interpreted for the Pinehouse 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 Pinehouse 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). Three prominent lineament orientation sets, north-northwest, north and northeast, and each with minor additional peaks, can be recognized in the length-weighted dataset. The northeast-trending set exhibits the broadest overall spread in orientation.

5.4 FAULT AND LINEAMENT RELATIONSHIPS

The known shear zones and mapped faults in the Pinehouse area include the northeast-trending Needle Falls shear zone, and the northwest trending brittle faults which are associated with movement on the Tabbernor 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. Interpreted lineaments exhibit a dominant northeast trend parallel to the regional northeast trending foliation defining the orientation of the Needle Falls shear zone. Secondary northwesterly and northerly orientations closely follow the trend of the known, and mapped, brittle fractures associated with movement on the Tabbernor fault.

The principal neotectonic stress orientation in central North America is generally oriented approximately east-northeasterly (63º ± 28º; Heidbach et al., 2009), although anomalous stress orientations have also been reported in the mid-continent that include a 90º change in azimuth of the maximum compressive stress axis (Brown et al., 1995) and a north-south maximum horizontal compressive stress (Haimson, 1990). 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 behaviour 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- and east- to east-northeast-oriented lineaments will likely reactivate in tension or as strike-slip faults, the north-northwest-oriented lineaments will likely reactivate as strike-slip to reverse faults, and the north-oriented lineaments likely as strike-slip 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 Pinehouse area. All of the lineaments identified in the Pinehouse 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 Pinehouse 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 (D1 to D4), or to new structures formed during the D5 event. The earliest fabric recognized by structural geologists in the field (Card and Bosman, 2007; Card et al., 2008), is the composite S1 fabric formed during D1. The D2 folding event was not assigned to any of the lineaments identified in this assessment. Interference between D3 and D4 orthogonal folding events produced the distinctive dome-and-basin pattern identified by the surface trace of the curviplanar S1 lithotectonic layering (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 ca. 1.80 billion years ago (Table 1). The brittle deformation of episode D5 produced the north-northwest and east- to northeast-trending 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 billion years, coincident with the timing of activation of the Tabbernor fault system (Table 1). The association between the brittle D5 structures and the Tabbernor fault suggests a long-lived history that may include Paleozoic and Mesozoic fault re-activation (e.g., Byers, 1962; Elliot, 1996). A long history of movement on the Tabbernor fault is consistent with the interpretation that surficial lineaments show similar orientations regardless of whether they are drawn over the area covered by Paleozoic sedimentary rocks or the area covered by the older Precambrian lithologies.

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 Pinehouse 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.

Lineaments were mapped from multiple, readily-available datasets that include digital elevation models (CDED), satellite imagery (SPOT), and geophysical data. The total number of lineaments interpreted from these data sources were 338, 472, and 323, respectively. The distribution of lineaments in the Pinehouse area reflects the bedrock structure, resolution of the datasets used, and surficial cover. Surface lineament density, as demonstrated in this interpretation, 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 northeastern part of the Pinehouse area, where thin surficial cover and exposed bedrock revealed numerous fractures in the crystalline rock. The lowest lineament densities were observed from low lying areas covered by overburden, lakes, and wetlands, particularly in the southwest where the bedrock is obscured by extensive drift cover and Pinehouse Lake.

Reproducibility (RA_1) and certainty of interpreted lineaments for each dataset appears highest for longer lineaments aligned with the prominent northeast structural trend, parallel to the Needle Falls shear zone, and the northwest trending brittle faults. These two lineament orientations 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 to northeast, north-northwest, and east-northeast to east. Ductile lineaments oriented to the northeast reflect the dominant regional structural trend and its attendant strong foliation associated with a likely D5 re-activation of the fabric developed during the D3 episode of regional shear zone deformation and those oriented to the northwest and north represent cross-cutting brittle fractures (D5) that appear to be associated with movement on the Tabbernor fault.

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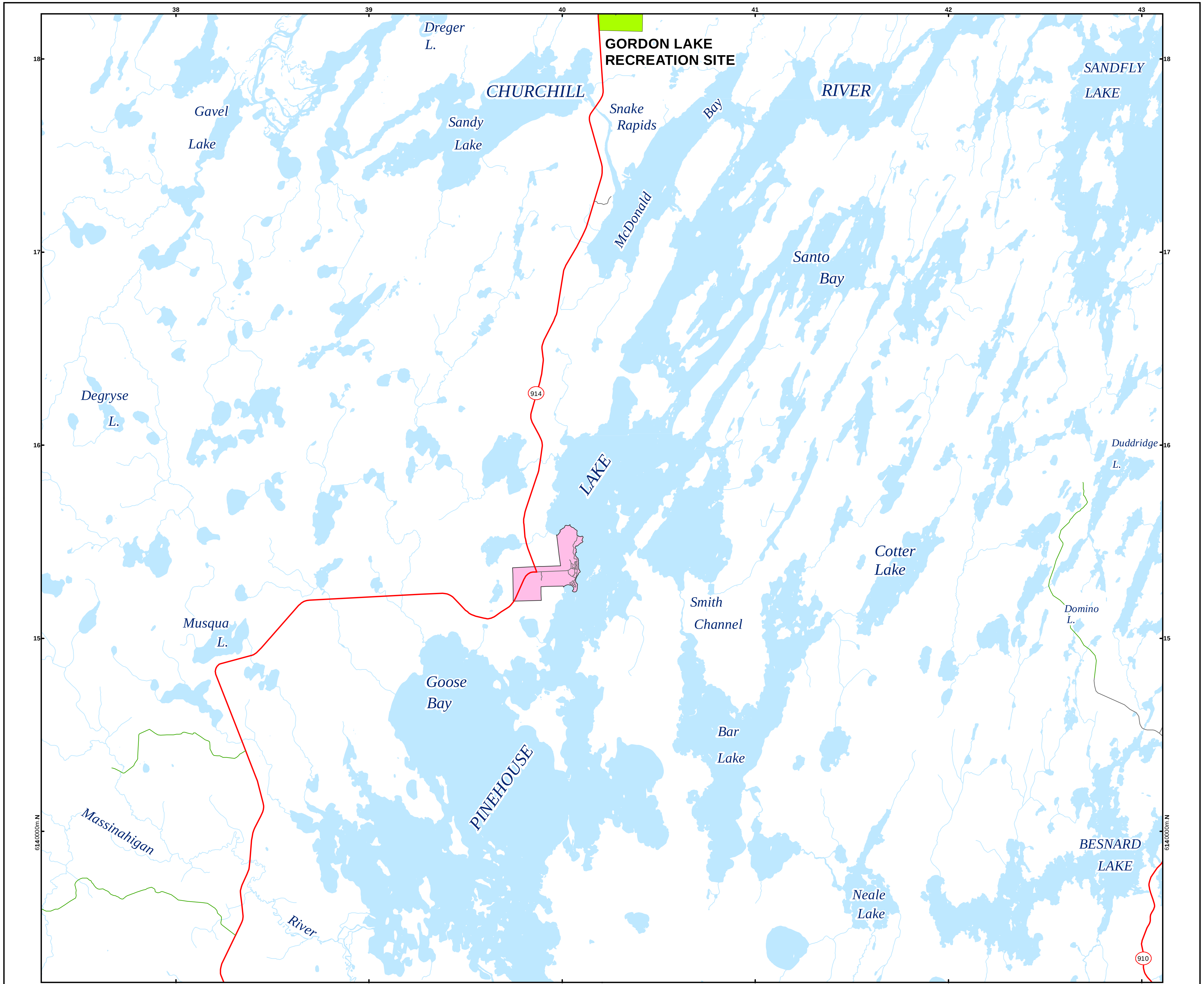
REPORT SIGNATURE PAGE

J.D. Mollard and Associates (2010) Limited

Jason Cosford, Ph.D., P.Geo. Lynden Penner, M.Sc., P.Eng., P.Geo.

FIGURES



LEGEND

Road (JDMA)

Road (SURN11)

Main road

Local road

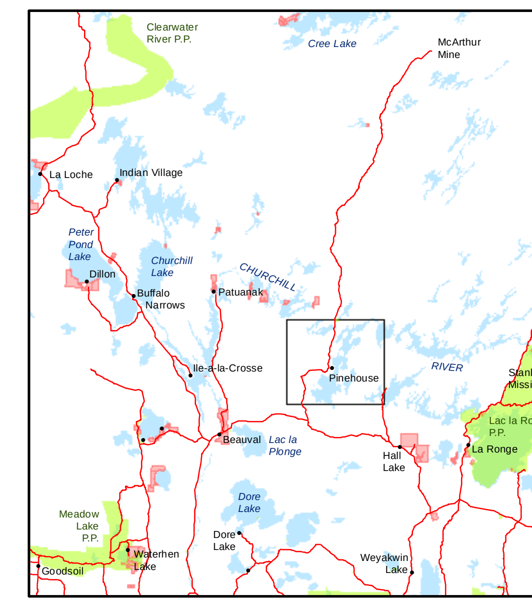
Village of Pinehouse

First Nation Reserve

Recreation site

Waterbody

Watercourse



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

NORTH

5 km

J D MOLLARD

PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, PINEHOUSE AREA, SASKATCHEWAN

TITLE

Northern Village of Pinehouse and surrounding area

DESIGN	DVZ	25 JUN 2012	FIGURE 1	REVISION 0
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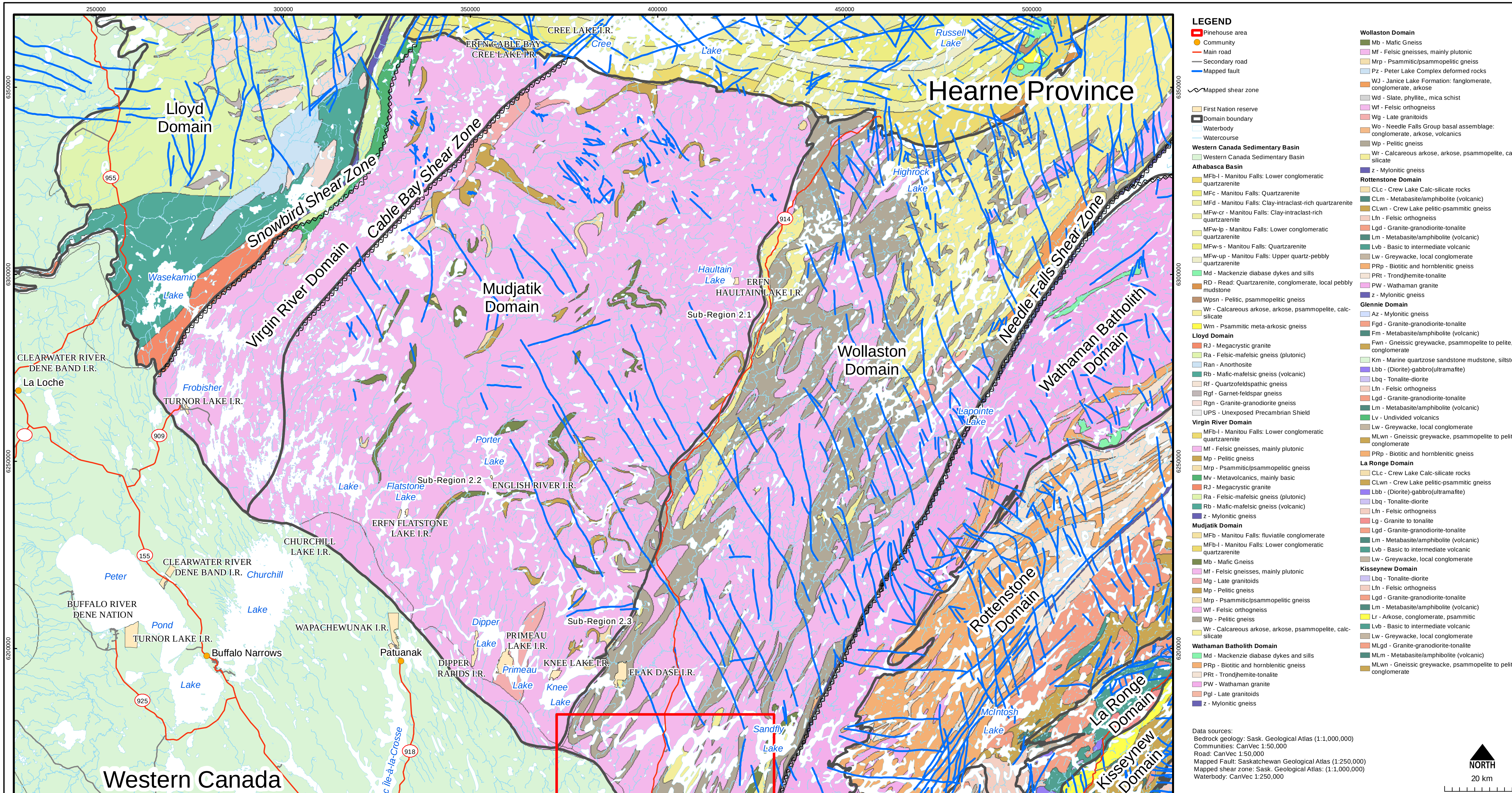
REVIEW	GS	08 NOV 2013		1:200,000



PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, PINEHOUSE AREA, SASKATCHEWAN

TITLE

Regional tectonic setting of the Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 2	REVISION 0
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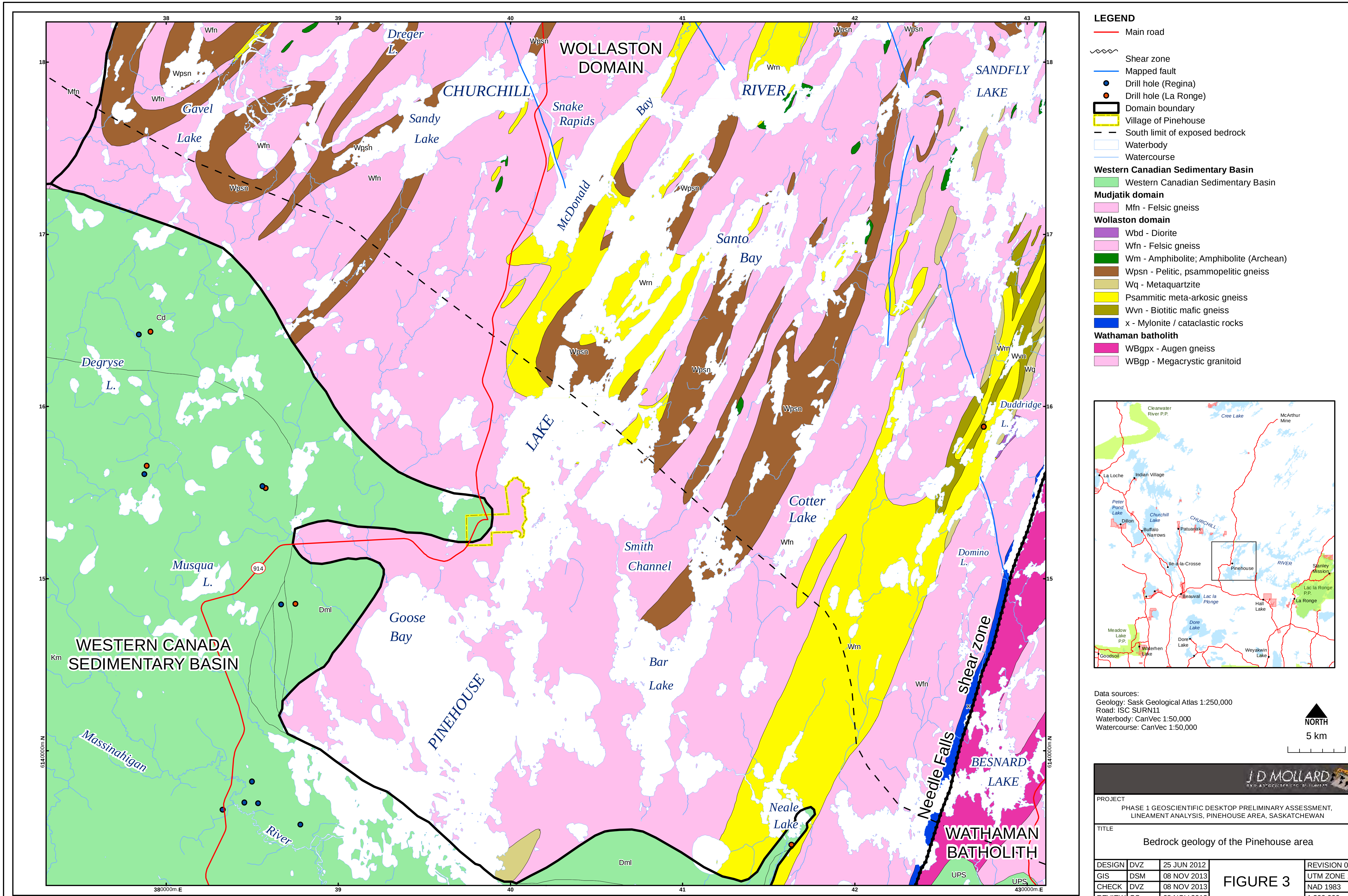

WOLLASTON DOMAIN
CHURCHILL
RIVER
SANDFLY LAKE
Dreger L.
Gavel Lake
Sandy Lake
Snake Rapids
McDonald Bay
Santo Bay
Cotter Lake
Smith Channel
Degryse L.
Musqua L.
Goose Bay
PINEHOUSE LAKE
Bar Lake
Massinahigan River
Neale Lake
Duddridge L.
Domino L.
Needle Falls shear zone
BESNARD LAKE
WATHAMAN BATHOLITH
WESTERN CANADA SEDIMENTARY BASIN
914
LEGEND
Main road
Shear zone
Mapped fault
Drill hole (Regina)
Drill hole (La Ronge)
Domain boundary
Village of Pinehouse
South limit of exposed bedrock
Waterbody
Watercourse
Western Canadian Sedimentary Basin
Western Canadian Sedimentary Basin
Mudjatik domain
Mfn - Felsic gneiss
Wollaston domain
Wbd - Diorite
Wfn - Felsic gneiss
Wm - Amphibolite; Amphibolite (Archean)
Wpsn - Pelitic, psammopelitic gneiss
Wq - Metaquartzite
Psammitic meta-arkosic gneiss
Wvn - Biotitic mafic gneiss
x - Mylonite / cataclastic rocks
Wathaman batholith
WBgpx - Augen gneiss
WBgp - Megacrystic granitoid
Data sources:
Geology: Sask Geological Atlas 1:250,000
Road: ISC SURN11
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
NORTH
5 km
J D MOLLARD
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, PINEHOUSE AREA, SASKATCHEWAN
TITLE
Bedrock geology of the Pinehouse area
DESIGN DVZ 25 JUN 2012
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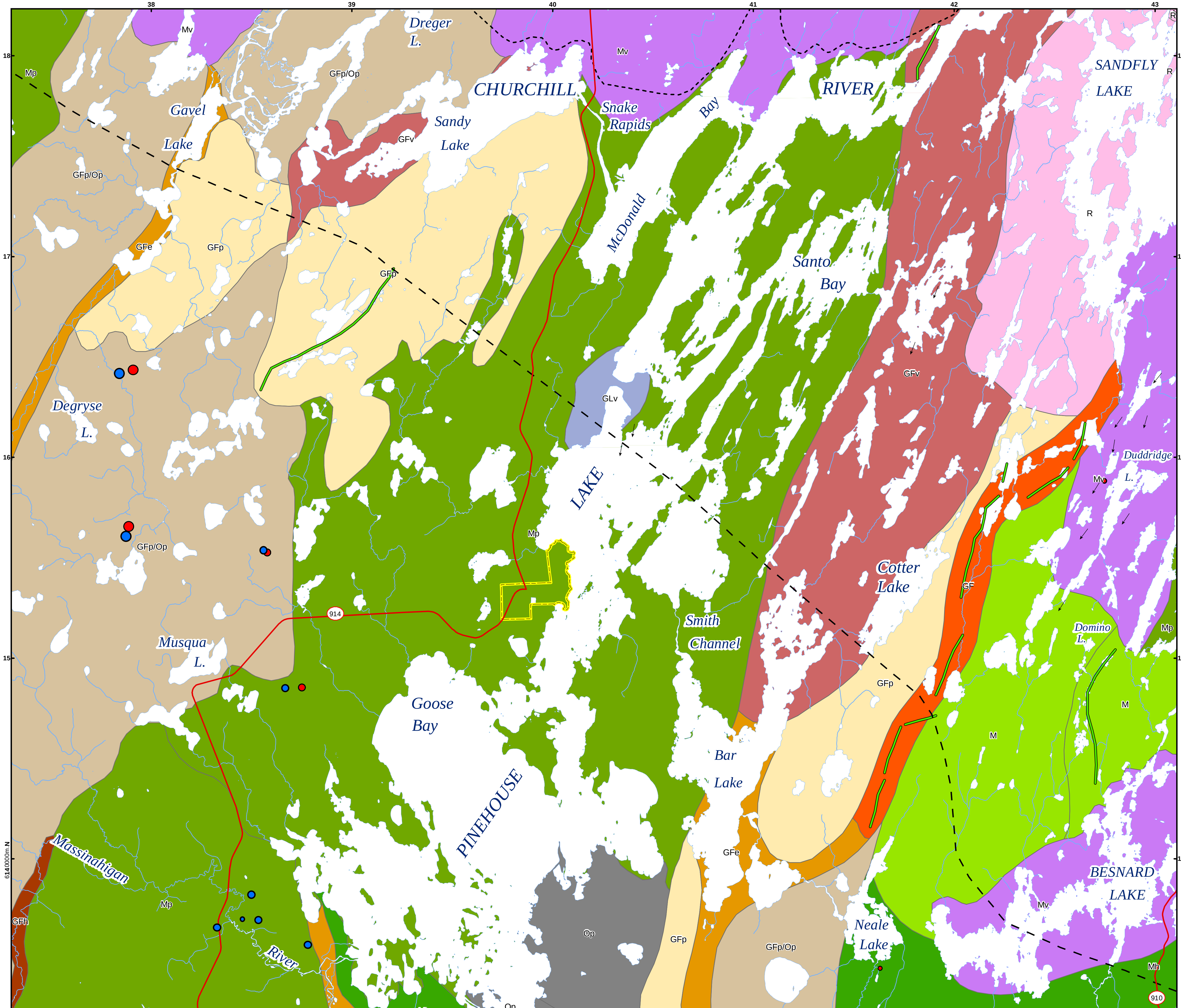


LEGEND

- Glacial striae
- Water well
- Main road
- Village of Pinehouse
- North limit of Churchill low
- South limit of exposed bedrock
- Esker
- Waterbody
- Watercourse

Surficial geology

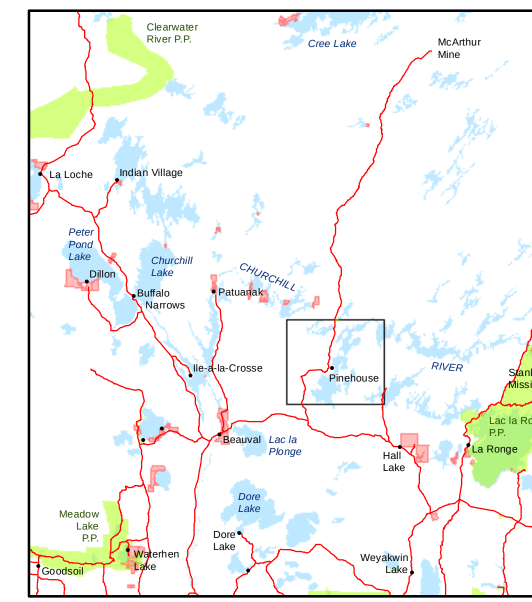
- Op - Organic plain
- GF - Glaciofluvial
- GFe - Glaciofluvial eroded
- GFh - Glaciofluvial hummocky
- GFp - Glaciofluvial plain
- GFp/Op - Glaciofluvial/organic plain
- GFv - Glaciofluvial veneer
- GLv - Glaiolacustrine veneer
- M - Morainal
- Mh - Morainal hummocky
- Mp - Morainal plain
- Mv - Morainal veneer
- R - Rock

Drill hole (Regina)
Depth to bedrock (m)

- 19.8 - 20.0
- 20.1 - 60.0
- 60.1 - 100.8

Drill hole (La Ronge)
Depth to bedrock (m)

- 1.4 - 20.0
- 20.1 - 60.0
- 60.1 - 91.7



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

NORTH

5 km

J D MOLLARD

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

TITLE
Surficial geology of the Pinehouse area

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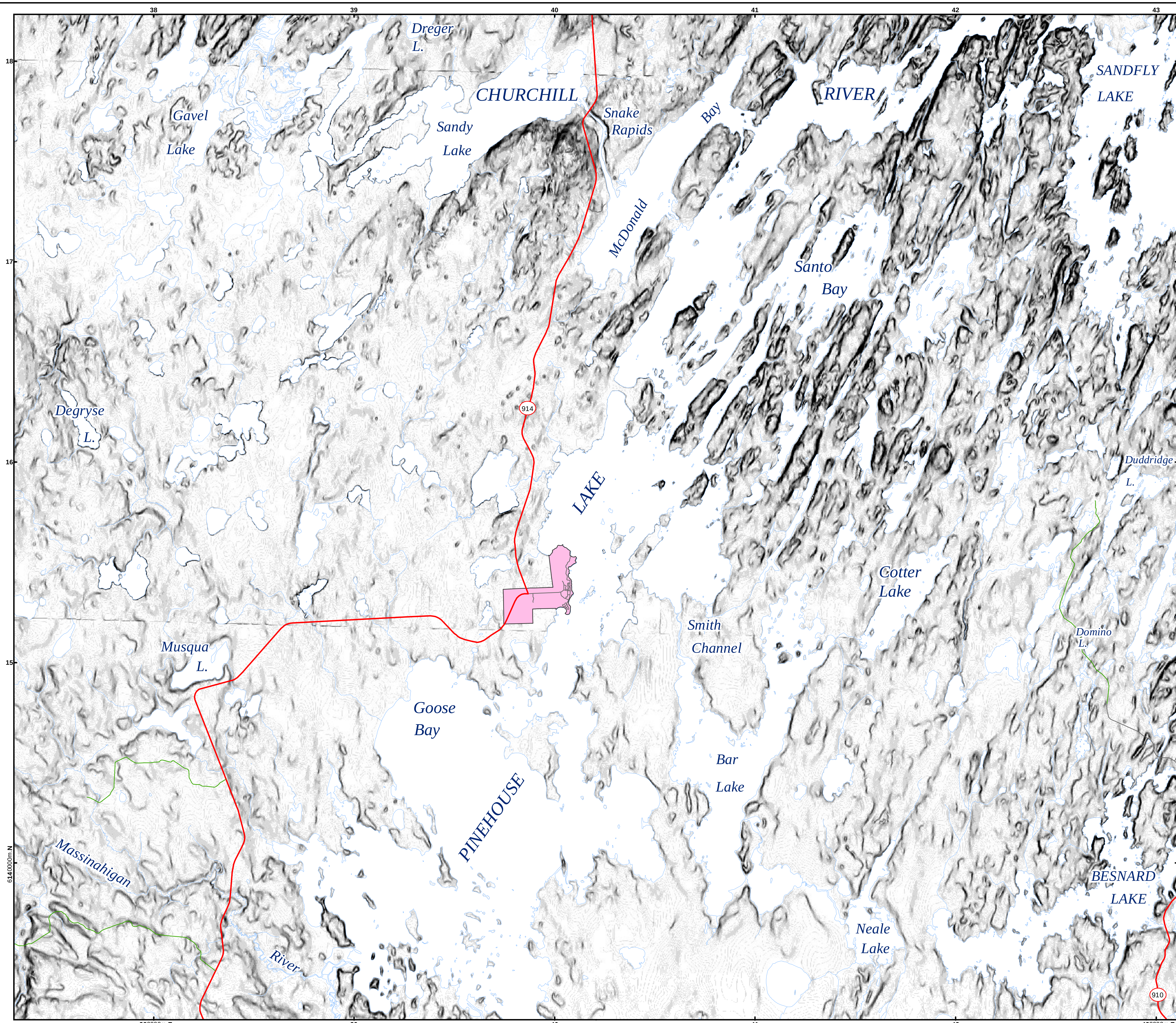


LEGEND

Road (JDMA)

Road (SURN11)

- Main road
- Local road

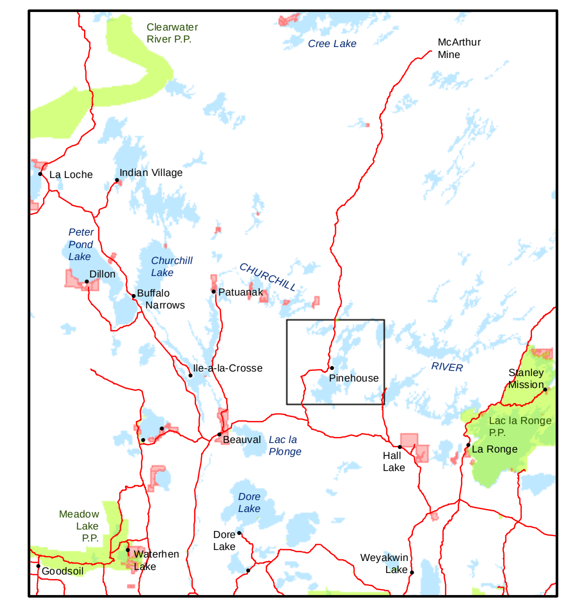
Village of Pinehouse

Waterbody

Watercourse

Slope (°)

- 0 - 1.3
- 1.4 - 2.7
- 2.8 - 4.1
- 4.2 - 5.5
- 5.6 - 6.9
- 7 - 8.3
- 8.4 - 9.7
- 9.8 - 32.8



Data sources:
DEM: CDED slope 1:50,000
Road (SURN11): ISC SURN11
Road (JDMA): Mapped from SPOT
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

5 km

J D MOLLARD

PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, PINEHOUSE AREA, SASKATCHEWAN

TITLE

CDED digital elevation data

DESIGN	DVZ	25 JUN 2012	FIGURE 5	REVISION 0
GIS	DSM	26 SEP 2013		UTM ZONE 13
CHECK	JIC	26 SEP 2013		NAD 1983
REVIEW	GS	26 SEP 2013		1:200,000

LEGEND

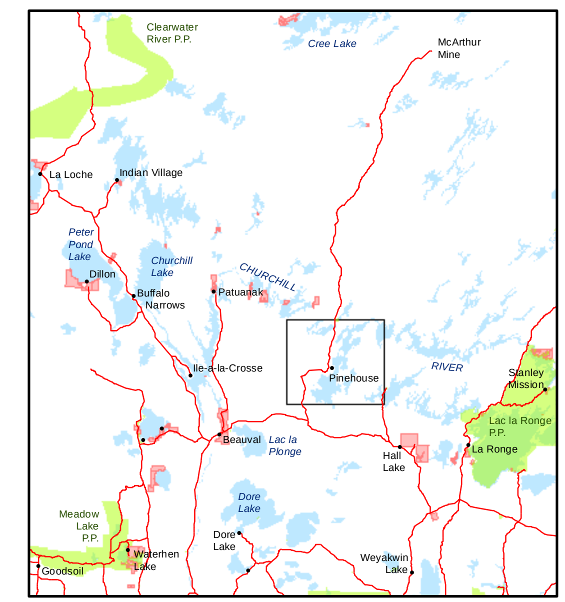
Road (JDMA)

Road (SURN11)

Main road

Local road

Village of Pinehouse



Data sources:
SPOT: geobase
Road (SURN11): ISC SURN11
Road (JDMA): Mapped from SPOT

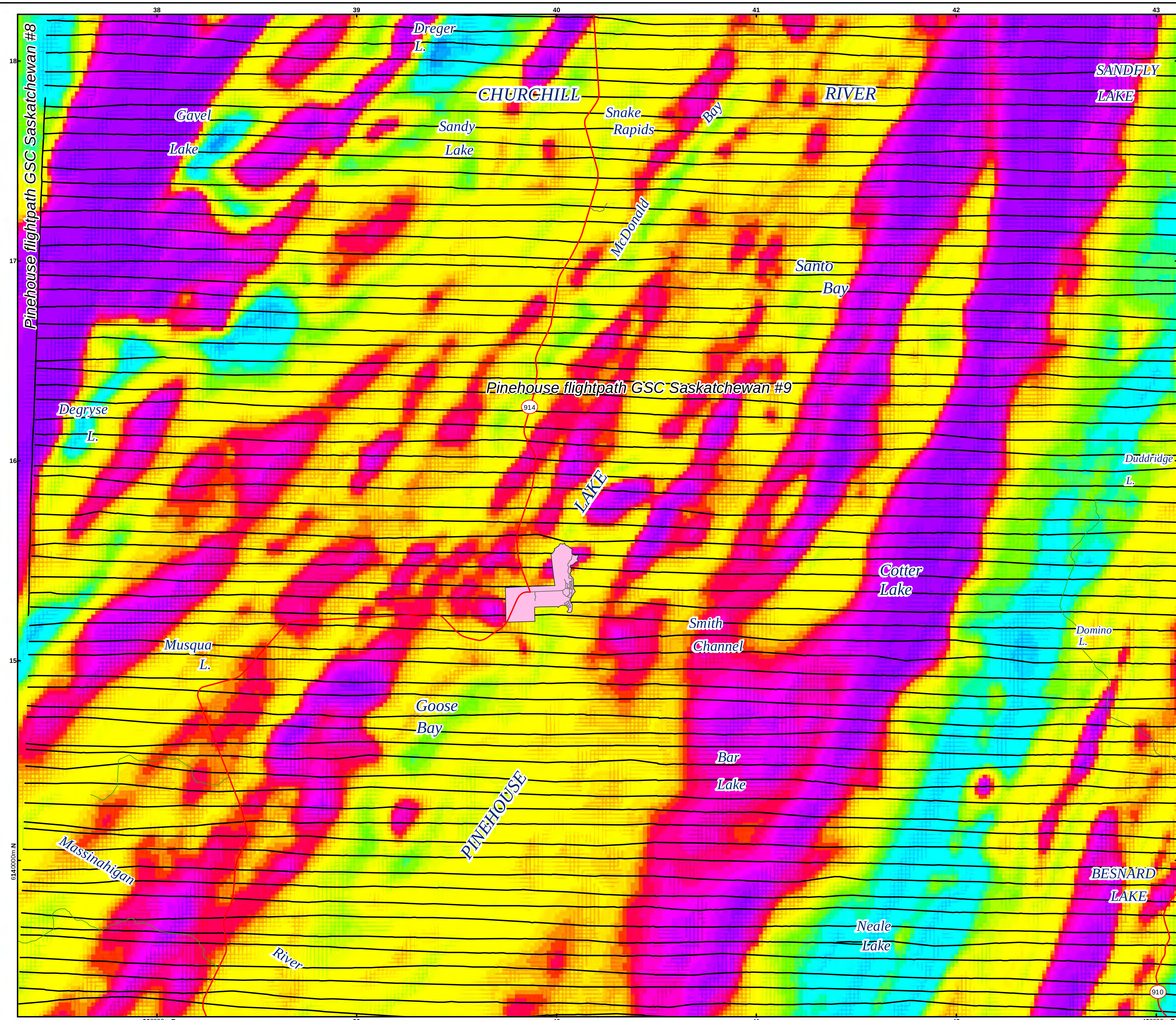
NORTH

5 km

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

TITLE
SPOT satellite data

DESIGN	DVZ	25 JUN 2012	FIGURE 6	REVISION 0
GIS	DSM	26 SEP 2013		UTM ZONE 13
CHECK	JIC	26 SEP 2013		NAD 1983
REVIEW	GS	26 SEP 2013		1:200,000



LEGEND

RTP (nT)

- 1,051 to 2,633
- 876 to 1,050
- 751 to 875
- 676 to 750
- 601 to 675
- 551 to 600
- 501 to 550
- 476 to 500
- 451 to 475
- 426 to 450
- 376 to 425
- 351 to 375
- 326 to 350
- 301 to 325
- 276 to 300
- 251 to 275
- 226 to 250
- 201 to 225
- 151 to 200
- 126 to 150
- 101 to 125
- 51 to 100
- 26 to 50
- 1 to 25
- -24 to 0
- -49 to -25
- -124 to -50
- -174 to -125
- -434 to -175

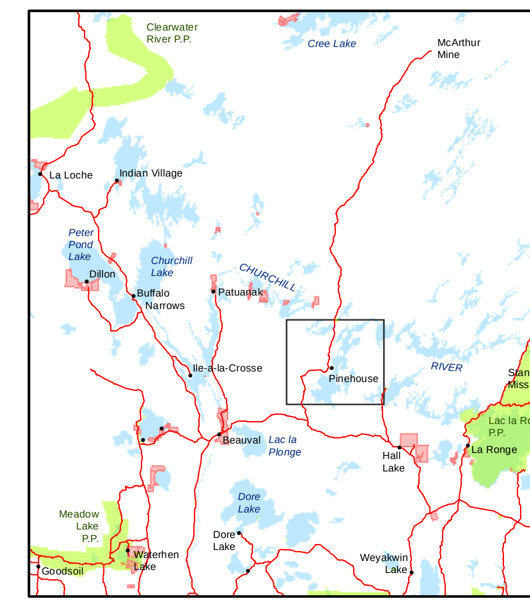
Road (JDMA)

Road (SURN11)

- Main road
- Local road

Village of Pinehouse

Pinehouse flightpath GSC Saskatchewan



Data sources:
Aeromagnetic pole reduced magnetic field: PGW (2012)
Road (SURN11): ISC SURN11
Road (JDMA): Mapped from SPOT

NORTH

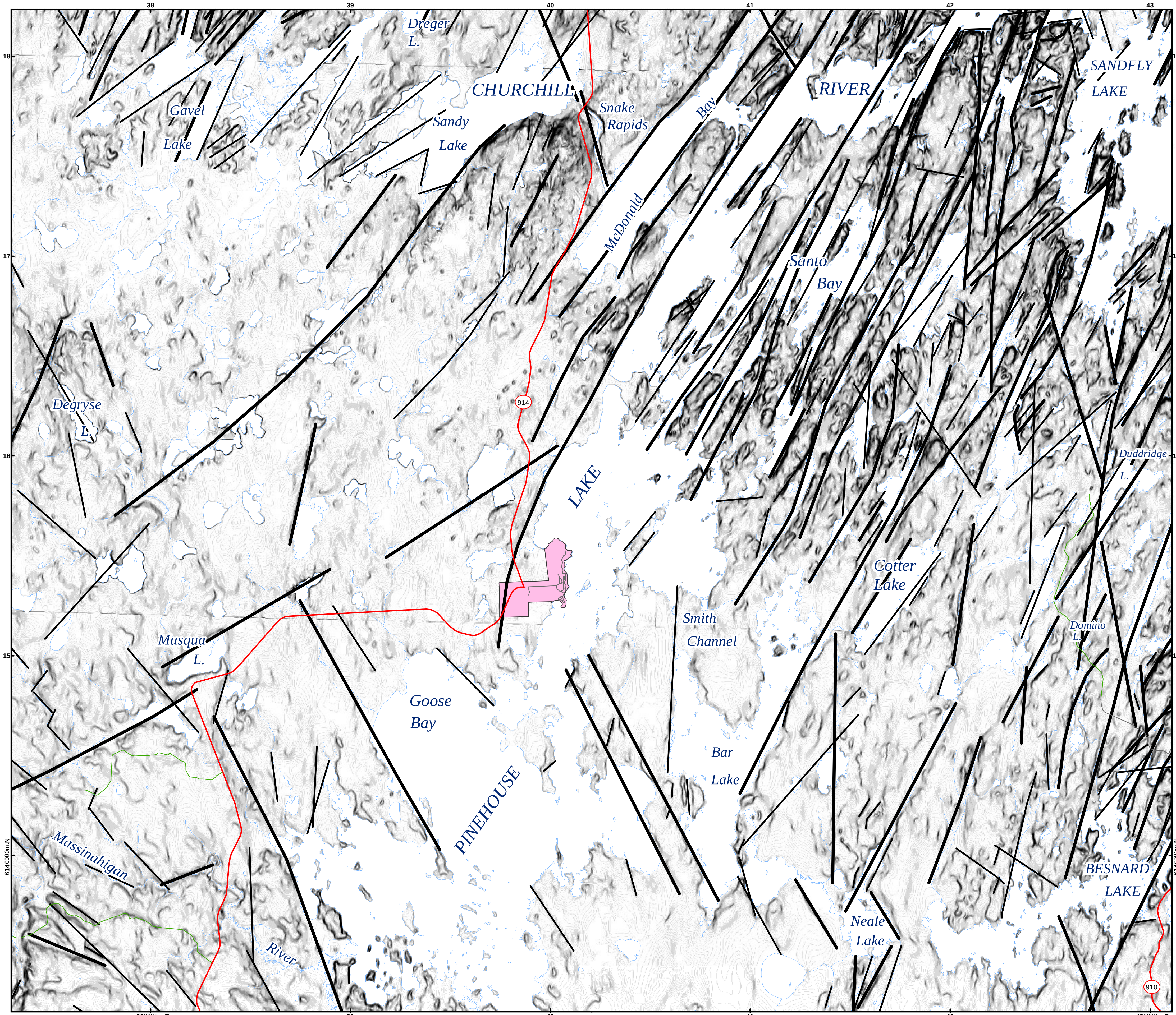
5 km

J D MOLLARD

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

TITLE
Pole reduced magnetic field for the Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 7	REVISION 0
GIS	DSM	26 SEP 2013		UTM ZONE 13
CHECK	JIC	26 SEP 2013		NAD 1983
REVIEW	GS	26 SEP 2013		1:200,000



LEGEND

- Road (JDMA)

Road (SURN11)

- Main road
- Local road

CDED lineament RA_1

- 1
- 2
- Village of Pinehouse
- Waterbody
- Watercourse

Slope (°)

- 0 - 1.3
- 1.4 - 2.7
- 2.8 - 4.1
- 4.2 - 5.5
- 5.6 - 6.9
- 7 - 8.3
- 8.4 - 9.7
- 9.8 - 32.8

Pinehouse CDED Data - Length Weighted Frequency Rose Plot

Data sources:
DEM: CDED slope 1:50,000
Road (SURN11): ISC SURN11
Road (JDMA): Mapped from SPOT
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000

NORTH

5 km

J D MOLLARD

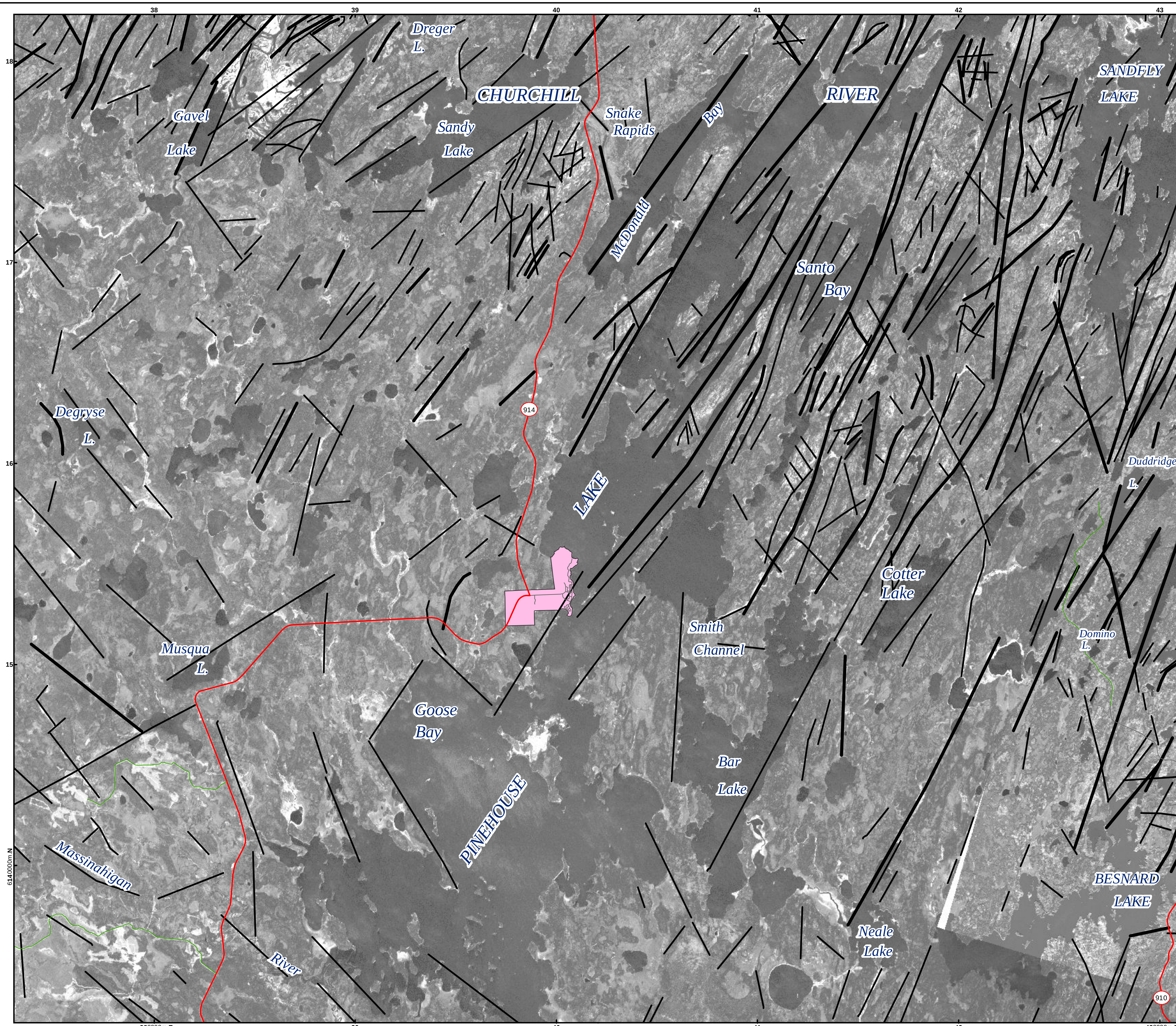
PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, PINEHOUSE AREA, SASKATCHEWAN

TITLE

CDED reproducibility assessment (RA_1)

DESIGN	DVZ	25 JUN 2012	FIGURE 8	REVISION 0
GIS	DSM	26 SEP 2013		UTM ZONE 13
CHECK	JIC	26 SEP 2013		NAD 1983
REVIEW	GS	26 SEP 2013		1:200,000



LEGEND

Road (JDMA)

Road (SURN11)

Main road

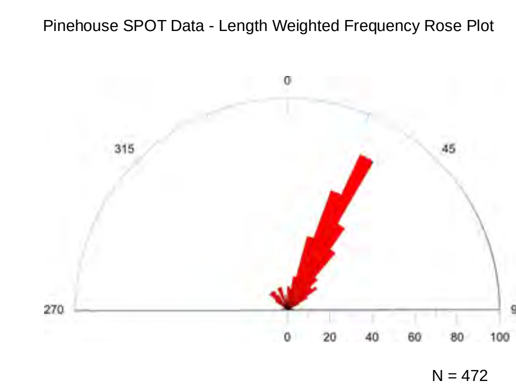
Local road

SPOT lineament RA_1

1

2

Village of Pinehouse



Data sources:
SPOT: geobase
Road (SURN11): ISC SURN11
Road (JDMA): Mapped from SPOT

NORTH

5 km

J D MOLLARD

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

TITLE
SPOT reproducibility assessment (RA_1)

DESIGN	DVZ	25 JUN 2012	FIGURE 9	REVISION 0
GIS	DSM	26 SEP 2013		UTM ZONE 13
CHECK	JIC	26 SEP 2013		NAD 1983
REVIEW	GS	26 SEP 2013		1:200,000

LEGEND

Road (JDMA)

Road (SURN11)

Main road

Local road

Aeromagnetic lineament RA_2

1

2

Village of Pinehouse

1,051 to 2,633

876 to 1,050

751 to 875

676 to 750

601 to 675

551 to 600

501 to 550

476 to 500

451 to 475

426 to 450

376 to 425

351 to 375

326 to 350

301 to 325

276 to 300

251 to 275

226 to 250

201 to 225

151 to 200

126 to 150

101 to 125

51 to 100

26 to 50

1 to 25

-24 to 0

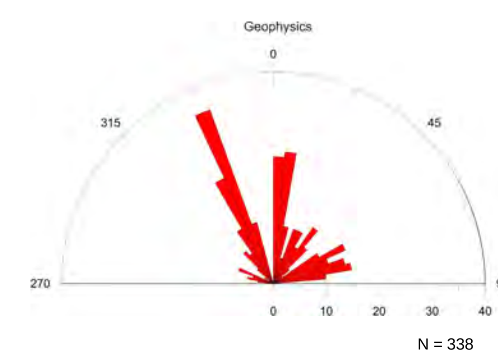
-49 to -25

-124 to -50

-174 to -125

-434 to -175

Pinehouse Geophysical Data - Length Weighted Frequency Rose Plot



Data sources:
Aeromagnetic pole reduced magnetic field: PGW (2012)
Road (SURN11): ISC SURN11
Road (JDMA): Mapped from SPOT

NORTH

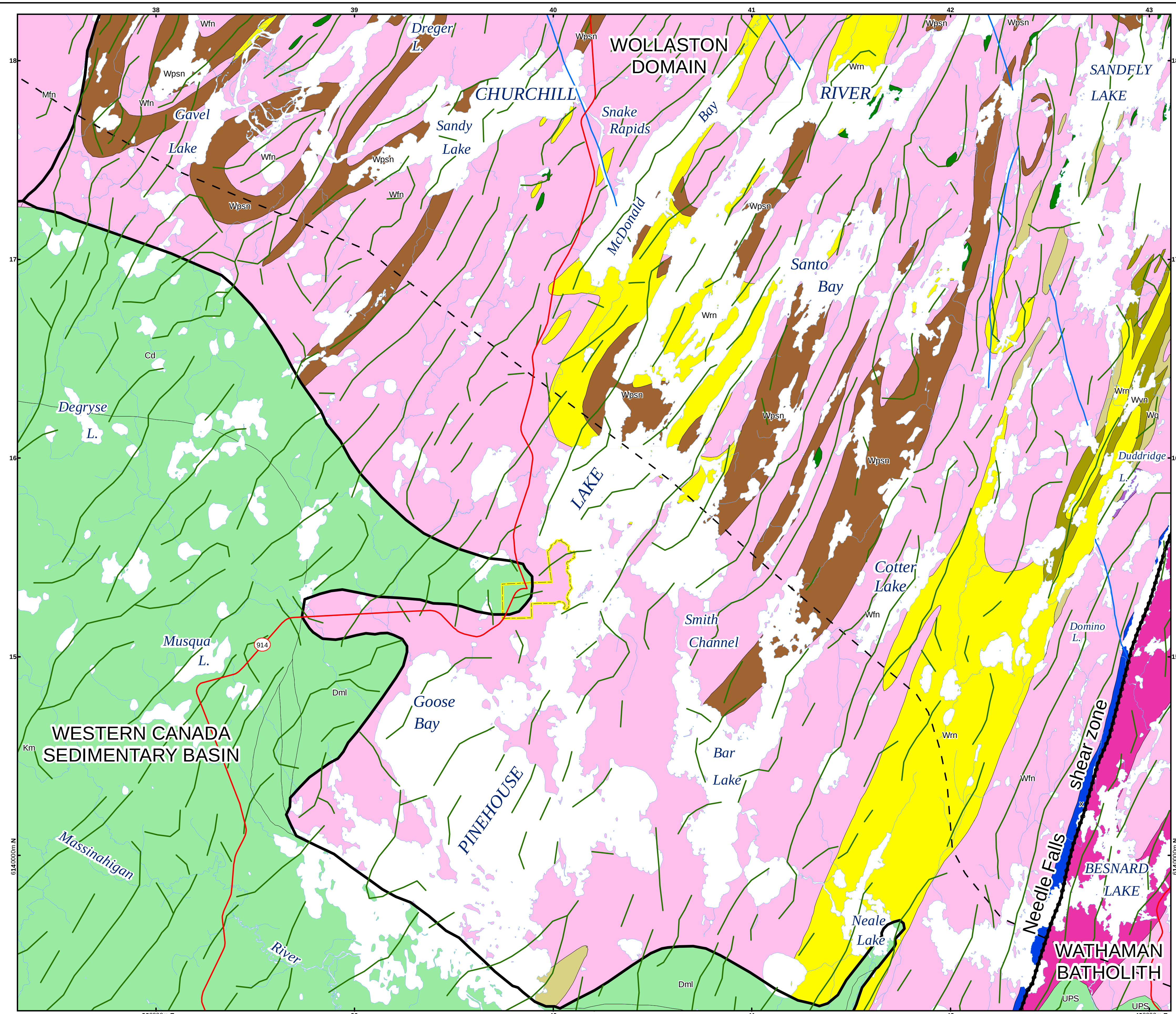
5 km

J D MOLLARD

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

TITLE
Aeromagnetic reproducibility assessment (RA_1)

DESIGN	DVZ	25 JUN 2012	FIGURE 10	REVISION 0
GIS	DSM	26 SEP 2013		UTM ZONE 13
CHECK	JIC	26 SEP 2013		NAD 1983
REVIEW	GS	26 SEP 2013		1:200,000



LEGEND

- Main road
- Shear zone
- Mapped fault
- Ductile lineament
- Domain boundary
- Village of Pinehouse
- South limit of exposed bedrock
- Waterbody
- Watercourse

Western Canadian Sedimentary Basin

- Western Canadian Sedimentary Basin

Mudjatik domain

- Mfn - Felsic gneiss

Wollaston domain

- Wbd - Diorite
- Wfn - Felsic gneiss
- Wm - Amphibolite; Amphibolite (Archean)
- Wpsn - Pelitic, psammopelitic gneiss
- Wq - Metaquartzite
- Psammitic meta-arkosic gneiss
- Wvn - Biotitic mafic gneiss
- x - Mylonite / cataclastic rocks

Wathaman batholith

- WBgpx - Augen gneiss
- WBgp - Megacrystic granitoid

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

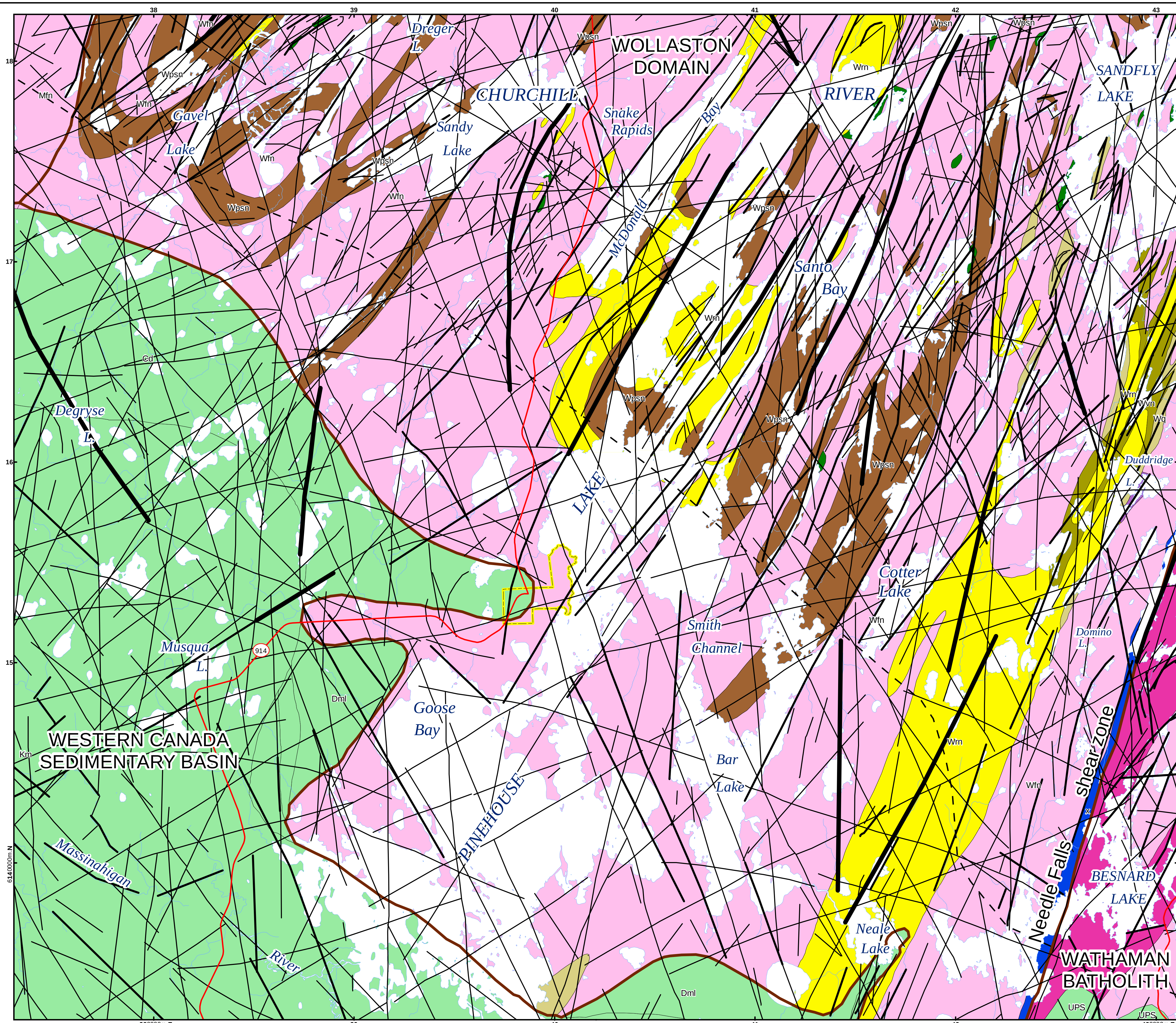
5 km

J D MOLLARD

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

TITLE
Ductile features of the Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 11	REVISION 0
GIS	DSM	26 SEP 2013		UTM ZONE 13
CHECK	DVZ	26 SEP 2013		NAD 1983
REVIEW	GS	26 SEP 2013		1:200,000



LEGEND

Main road

Lineament RA_2

1

2

3

Domain boundary

Village of Pinehouse

South limit of exposed bedrock

Waterbody

Watercourse

Western Canadian Sedimentary Basin

Western Canadian Sedimentary Basin

Mudjatik domain

Mfn - Felsic gneiss

Wollaston domain

Wbd - Diorite

Wfn - Felsic gneiss

Wm - Amphibolite; Amphibolite (Archean)

Wpsn - Pelitic, psammopelitic gneiss

Wq - Metaquartzite

Psammitic meta-arkosic gneiss

Wvn - Biotitic mafic gneiss

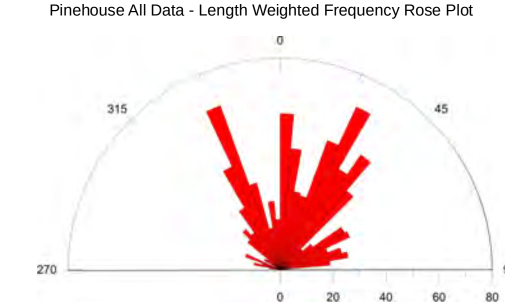
x - Mylonite / cataclastic rocks

Wathaman batholith

WBgpx - Augen gneiss

WBgp - Megacrystic granitoid

Pinehouse All Data - Length Weighted Frequency Rose Plot



N = 889

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

NORTH

5 km

J D MOLLARD

PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, PINEHOUSE AREA, SASKATCHEWAN

TITLE

Lineament classification by reproducibility assessment (RA_2)

DESIGN	DVZ	25 JUN 2012	FIGURE 12	REVISION 0
GIS	DSM	08 NOV 2013		UTM ZONE 13
CHECK	DVZ	08 NOV 2013		NAD 1983
REVIEW	GS	08 NOV 2013		1:200,000

LEGEND

- Main road

Lineament Length

- 0 - 1 km
- 1 - 5 km
- 5 - 10 km
- 10+ km
- Domain boundary
- Village of Pinehouse
- South limit of exposed bedrock
- Waterbody
- Watercourse

Western Canadian Sedimentary Basin

- Western Canadian Sedimentary Basin

Mudjatik domain

- Mfn - Felsic gneiss

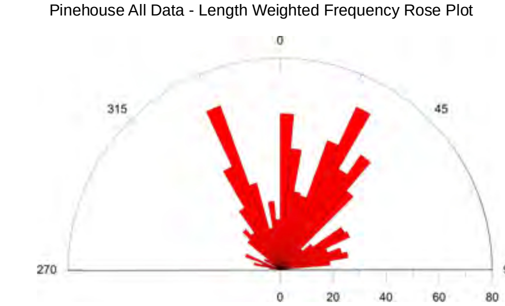
Wollaston domain

- Wbd - Diorite
- Wfn - Felsic gneiss
- Wm - Amphibolite; Amphibolite (Archean)
- Wpsn - Pelitic, psammopelitic gneiss
- Wq - Metaquartzite
- Psammitic meta-arkosic gneiss
- Wvn - Biotitic mafic gneiss
- x - Mylonite / cataclastic rocks

Wathaman batholith

- WBgpx - Augen gneiss
- WBgp - Megacrystic granitoid

Pinehouse All Data - Length Weighted Frequency Rose Plot



N = 889

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

NORTH

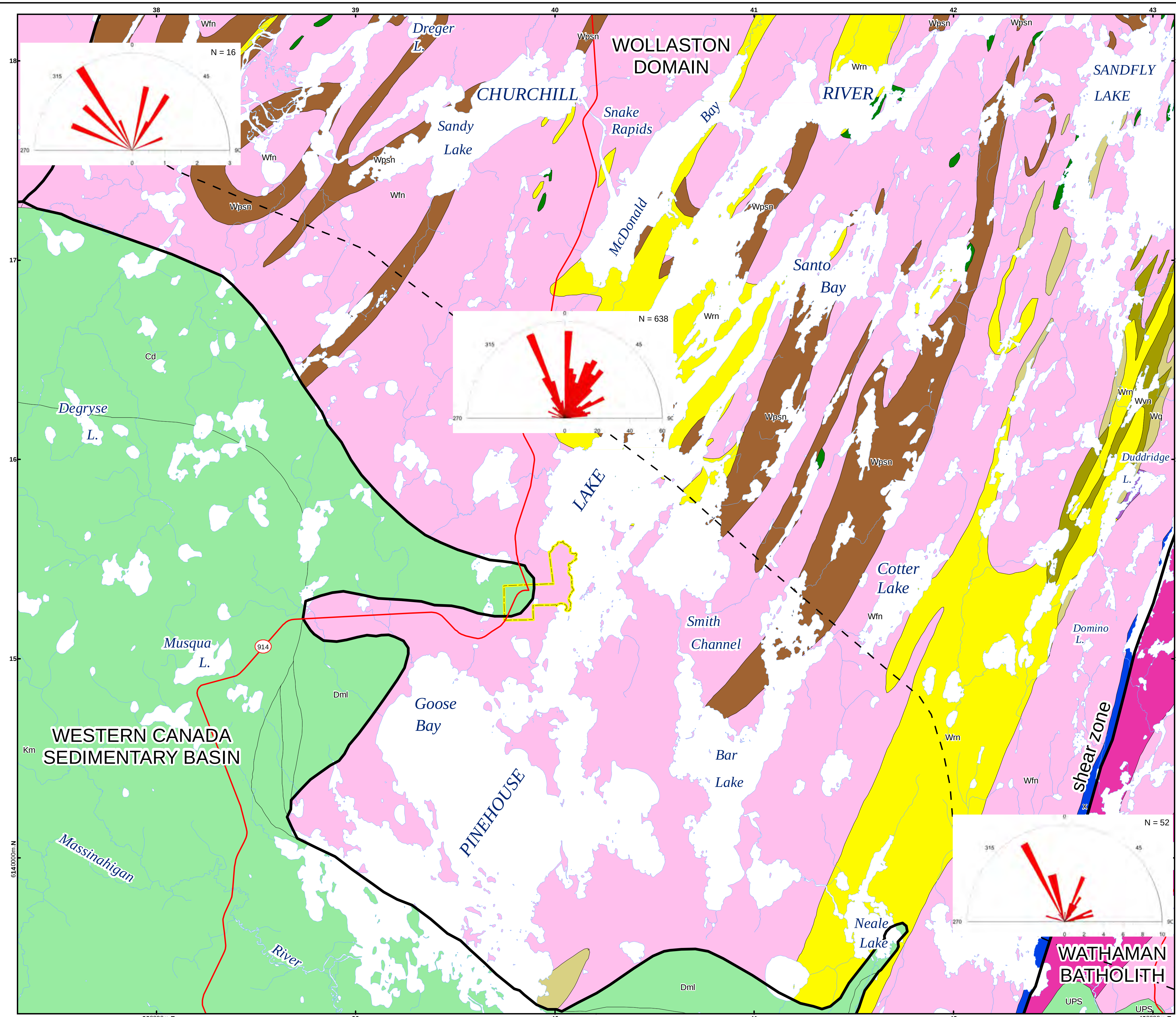
5 km

J D MOLLARD

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

TITLE
Lineament classification by length

DESIGN	DVZ	25 JUN 2012	FIGURE 13	REVISION 0
GIS	DSM	08 NOV 2013		UTM ZONE 13
CHECK	DVZ	08 NOV 2013		NAD 1983
REVIEW	GS	08 NOV 2013		1:200,000



LEGEND

- Main road
- Domain boundary
- Village of Pinehouse
- South limit of exposed bedrock
- Waterbody
- Watercourse

Western Canadian Sedimentary Basin

- Western Canadian Sedimentary Basin

Mudjatik domain

- Mfn - Felsic gneiss

Wollaston domain

- Wbd - Diorite
- Wfn - Felsic gneiss
- Wm - Amphibolite; Amphibolite (Archean)
- Wpsn - Pelitic, psammopelitic gneiss
- Wq - Metaquartzite
- Psammitic meta-arkosic gneiss
- Wvn - Biotitic mafic gneiss
- x - Mylonite / cataclastic rocks

Wathaman batholith

- WBgpx - Augen gneiss
- WBgp - Megacrystic granitoid

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

NORTH

5 km

J D MOLLARD

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

TITLE
Lineament orientation of the selected bedrock units in the Pinehouse area

DESIGN	DVZ	25 JUN 2012	FIGURE 14	REVISION 0
GIS	DSM	26 SEP 2013		UTM ZONE 13
CHECK	DVZ	26 SEP 2013		NAD 1983
REVIEW	GS	26 SEP 2013		1:200,000