NUCLEAR WASTE MANAGEMENT ORGANIZATION | SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment of Potential Suitability for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel

TOWN OF CREIGHTON, SASKATCHEWAN

APM-REP-06144-0051

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PHASE 1 DESKTOP GEOSCIENTIFIC PRELIMINARY ASSESSMENT OF POTENTIAL SUITABILITY FOR SITING A DEEP GEOLOGICAL REPOSITORY FOR CANADA'S USED NUCLEAR FUEL

Town of Creighton, Saskatchewan

REPORT

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Executive Summary

In December 2011, the Town of Creighton, 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 Creighton area for safely hosting a deep geological repository (Step 3). This request followed a successful completion of an initial screening conducted during Step 2 of the site selection process (Golder, 2011). The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. The findings of the overall preliminary assessment are reported in an integrated report (NWMO, 2013).

This report presents the results of a preliminary desktop geoscientific assessment to determine whether the Creighton area contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors. The assessment builds on the work previously conducted for the initial screening and focuses on the Town of Creighton and its periphery, which are referred to as the "Creighton area".

The geoscientific preliminary assessment was conducted using available geoscientific information and key geoscientific characteristics that can be realistically assessed at this early stage of the site evaluation process. These include: geology; structural geology; interpreted lineaments; distribution and thickness of overburden deposits; surface conditions; and the potential for economically exploitable natural resources. The desktop geoscientific preliminary assessment included the following review and interpretation activities:

- Detailed review of available geoscientific information such as geology, structural geology, natural resources, hydrogeology and overburden deposits;
- Interpretation of available geophysical surveys (magnetic, electromagnetic, gravity and radiometric);
- Lineament studies using available satellite imagery, topography and geophysical surveys to provide information on the characteristics such as location, orientation and length of interpreted structural bedrock features;
- Terrain analysis studies to help assess factors such as overburden type and distribution, bedrock exposures, accessibility constraints, watershed and subwatershed boundaries, groundwater discharge and recharge zones; and
- The identification and evaluation of general potentially suitable areas based on key geoscientific characteristics and the systematic application of NWMO's geoscientific site evaluation factors.

The desktop geoscientific preliminary assessment showed that the Creighton area contains at least two general areas that have the potential to satisfy NWMO's geoscientific site evaluation factors. One of the areas extends over most of the Annabel Lake pluton. The other area is in the south-central portion of the Reynard Lake pluton. The possibility for identifying additional potentially suitable areas is limited due the fairly small extent of the potentially suitable geological units within the Creighton area.

Both the Annabel Lake and Reynard Lake plutons appear to have a number of geoscientific characteristics that are favourable. They have sufficient depth and sufficient geographic extent. The bedrock within the two identified potentially suitable areas has good exposure and is mapped as fairly homogeneous. The two areas have low potential for natural resources, although they are in close proximity and surrounded by rock units with known mineral potential (e.g., greenstone belts). Both areas are generally accessible and have limited surface constraints, with the exception of some areas with large water bodies. The two areas have a complex orientation of interpreted lineaments, but remain generally amenable to site characterization.

While the identified general potentially suitable areas appear to have favourable geoscientific characteristics, there are inherent uncertainties that would need to be addressed during subsequent stages of the site evaluation process. Main uncertainties regarding the suitability of identified areas include the relatively small extent of the potentially suitable geological formations within the Creighton area, the proximity of major shear zones and mapped faults, and the high mineral potential of the surrounding greenstone belt.

Should the community of Creighton be selected by the NWMO to advance to Phase 2 of the study and remain interested in continuing with the site selection process, several years of progressively more detailed studies would be required to confirm and demonstrate whether the Creighton area contains sites that can safely contain and isolate used nuclear fuel. This would include the acquisition and interpretation of higher resolution airborne geophysical surveys, field geological mapping and the drilling of deep boreholes.

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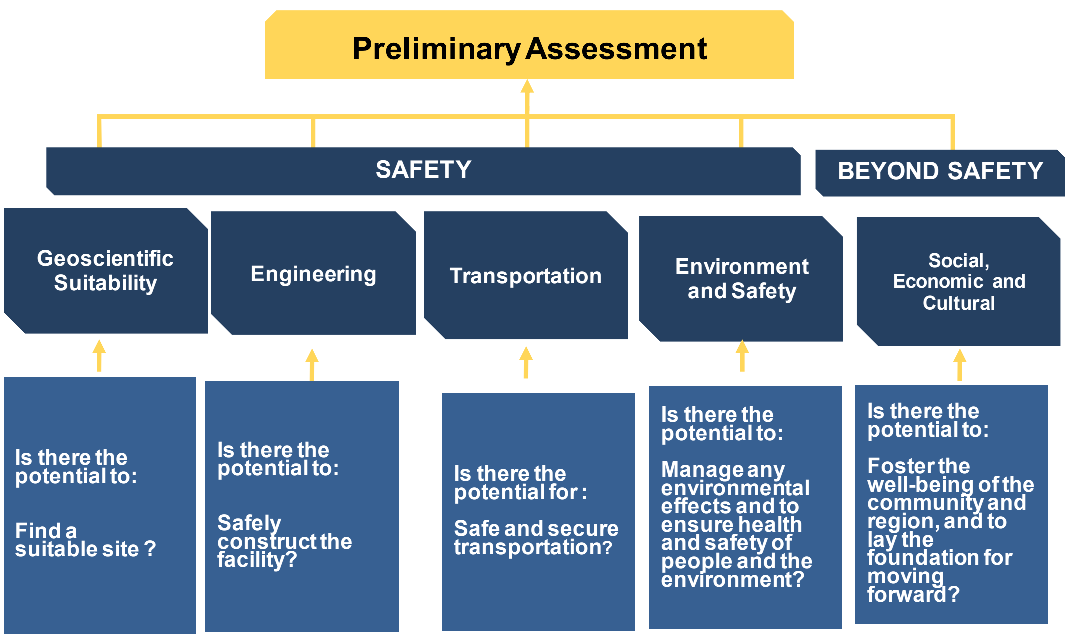
Lineament Interpretation, Town of Creighton, Saskatchewan (JDMA, 2013b)

1.0 INTRODUCTION

1.1 Background

In December 2011, the Town of Creighton, 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 Creighton area in Saskatchewan 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 (Golder, 2011).

The overall preliminary assessment is a multidisciplinary study integrating both technical and community well-being assessments as illustrated in the diagram below. The five components of the preliminary assessment address geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. A brief description of the project, the approach and the findings of the preliminary assessment are documented in an integrated preliminary assessment report (NWMO, 2013).



The objective of the preliminary assessment is to assess whether the Creighton area contains general areas that have the potential to meet NWMO's site evaluation factors. The preliminary assessment is conducted in two phases:

- ***Phase 1 - Desktop Study.*** For all communities electing to be the focus of a preliminary assessment. This phase involves desktop studies using available geoscientific information and a set of key geoscientific characteristics and factors that can be realistically assessed at the desktop phase of the preliminary assessment.

- ***Phase 2 - Preliminary Field Investigations.*** For a subset of communities selected by the NWMO, to further assess potential suitability. This phase involves preliminary field investigations that include high resolution geophysical surveys, geological mapping and the drilling of deep boreholes.

The subset of communities considered in Phase 2 of the preliminary assessment will be selected based on the findings of the overall desktop preliminary assessment, considering both technical and community well-being factors presented in the above diagram.

This report presents the results of a desktop geoscientific preliminary assessment of potential suitability (Phase 1), conducted by Golder Associates Ltd.

1.2 Desktop Geoscientific Preliminary Assessment Approach (Phase 1)

The objective of the Phase 1 desktop geoscientific preliminary assessment is to assess whether the Creighton area contains general siting areas that have the potential to satisfy the geoscientific evaluation factors outlined in the site selection process document (NWMO, 2010). The location and extent of identified potentially suitable areas would be confirmed during subsequent site evaluation stages.

The desktop preliminary geoscientific assessment built on the work previously conducted for the initial screening of the Creighton area (Golder, 2011) and focused on the Town of Creighton and its periphery, which are referred to as the "Creighton area" in this report (Figure 1.1). The boundaries of the Creighton area were defined to encompass the main geological features within the Town of Creighton and its surroundings. The Phase 1 Desktop Geoscientific Preliminary Assessment included the following review and interpretation activities:

- Detailed review of available geoscientific information such as geology, structural geology, natural resources, hydrogeology and overburden deposits;
- Interpretation of available geophysical surveys (magnetic, electromagnetic, gravity and radiometric);
- Lineament studies using available satellite imagery, topography and geophysical surveys to provide information on the characteristics such as location, orientation and length of interpreted structural bedrock features;
- Terrain analysis studies to help assess factors such as overburden type and distribution, bedrock exposures, accessibility constraints, watershed and subwatershed boundaries, groundwater discharge and recharge zones; and
- The identification and evaluation of potentially suitable siting areas based on key geoscientific characteristics and the systematic application of NWMO's geoscientific site evaluation factors.

The details of these various studies are documented in three supporting documents: Terrain Analysis (JDMA, 2013a); Geophysical Interpretation (PGW, 2013); and Lineament Interpretation (JDMA, 2013b). Key findings from these studies are summarized in this report.

1.3 Geoscientific Site Evaluation Factors

As discussed in the NWMO site selection process, the suitability of potential sites will be evaluated in a staged manner through a series of progressively more detailed scientific and technical assessments using a number of geoscientific site evaluation factors, organized under five safety functions that a site would need to ultimately satisfy in order to be considered suitable (NWMO, 2010):

- ***Safe containment and isolation of used nuclear fuel:*** Are the characteristics of the rock at the site appropriate to ensuring the long-term containment and isolation of used nuclear fuel from humans, the environment and surface disturbances caused by human activities and natural events?
- ***Long-term resilience to future geological processes and climate change:*** Is the rock formation at the siting area geologically stable and likely to remain stable over the very long term in a manner that will ensure the repository will not be substantially affected by geological and climate change process such as earthquakes and glacial cycles?
- ***Safe construction, operation and closure of the repository:*** Are conditions at the site suitable for the safe construction, operation and closure of the repository?
- ***Isolation of used fuel from future human activities:*** Is human intrusion at the site unlikely, for instance, through future exploration or mining?
- ***Amenable to site characterization and data interpretation activities:*** Can the geologic conditions at the site be practically studied and described on dimensions that are important for demonstrating long-term safety?

The list of site evaluation factors under each safety function is provided in Appendix A.

The assessment was conducted in two steps. The first step assessed the potential to find general potentially suitable areas within the Creighton area using key geoscientific characteristics that can realistically be assessed at this stage of the assessment based on available information (Section 7.2). The second step assessed whether identified potentially suitable areas have the potential to ultimately meet all of the safety functions outlined above (Section 7.3).

1.4 Available Geoscientific Information

Geoscientific information for the Creighton area was obtained from several data sources, including maps, reports, databases and technical papers. The review of existing information identified that there was sufficient geoscientific information available to conduct the Phase 1 geoscientific preliminary assessment studies and to identify potentially suitable general siting areas in the Creighton area. Key geoscientific information sources are summarized in this section, with a complete listing provided in Appendix B.

1.4.1 Satellite Imagery and Airborne Geophysics

High to low-resolution geophysical data, particularly magnetic, gravity, radiometric and very low frequency-electromagnetic (VLF-EM) data obtained from the Geological Survey of Canada (GSC, 2012) cover the entire Creighton area (Table 1.1 and shown on Figure 1.2).

Medium-resolution magnetic data from the GSC (Flin Flon Sherridon A, Flin Flon Sherridon B, and Flin Flon Queenair) provide complete coverage of the entire Creighton area. These surveys were flown at a terrain clearance of 150 m and flight line spacing of 300 m, providing these surveys with a medium spatial resolution. The Hanson Lake survey also provides complete coverage of the Creighton area, but at a slightly increased line spacing of 500 m. These datasets are locally superseded by higher resolution surveys provided by Hudson Bay

Exploration and Development Company Limited (Hudbay) through a Data Sharing Agreement (dated February 29, 2012).

Two additional magnetic/electromagnetic surveys obtained from the Hudbay provided higher resolution coverage over approximately 20% of the Creighton area to the east (Figure 1.2 and Table 1.1). The high resolution Hudbay surveys (Flin A, and Konuto) were flown at a lower terrain clearance compared to the GSC dataset with tighter flight line spacing providing these surveys with a relatively high spatial resolution. These surveys focused primarily on exploration in the greenstone belts, with moderate coverage of the plutonic rocks. These surveys provide the highest resolution magnetic data, as well as Versatile Time Domain Electromagnetic (VTEM) data.

Gravity data for the Creighton area were acquired from the GSC Gravity coverage database and downloaded from the Geological Survey of Canada (GSC, 2012). The data consists of an irregular distribution of 46 station measurements within or adjacent to the Creighton area, comprising roughly a station every 5 to 15 km, and every 1 km along Hwy 106. Despite the fact that data were of good quality, the sparseness of the measurement locations in the Creighton area can only be used to provide information about large scale geologic features.

The GSC radiometric data coverage and the Hanson Lake survey provide complete radiometric coverage of the Creighton area (GSC, 2012). The GSC radiometric data were flown at 5,000 m line spacing at a terrain clearance of 120 m above the surface. The limited resolution of GSC radiometric coverage was replaced with the Hanson Lake survey, which was flown at a much tighter line spacing of 500 m.

Additionally, approximately 19 km of Trans-Hudson Orogeny Transect seismic line 9, part of the Lithoprobe initiative, occurs within the Creighton area located along Highway 106, trending NW (Lucas et al., 1993; Lewry et al., 1994; White et al., 2005).

The digital elevation model data for the Creighton area is the Canadian Digital Elevation Data (CDED). The CDED is a 1:50,000 scale, 20 m resolution elevation model constructed by the Mapping Information Branch of NRCan. It was constructed using 1:50,000 scale source data from the National Topographic Data Base (NTDB) which was created from black and white aerial photographs (1:60,000 and 1:70,000 scale) acquired in the late 1960s and 1980s (Table 1.1; GeoBase, 2011a). A finer contour interval (25 foot) was used in the construction of the CDED over the western two-thirds of the Creighton area, whereas a lower resolution 50 foot contour interval was used in the east (Shuttle Radar Topography Mission, SRTM, based data).

Système Pour l'Observation de la Terre (SPOT) multispectral (20 m resolution) and panchromatic (10 m resolution) orthoimagery were available for the entire Creighton area (Table 1.1; GeoBase, 2011b). Four SPOT images (scenes) provided complete coverage for the Creighton area (Table 1.1). The scenes are from the SPOT 4 and 5 satellites with one image acquired in September 2005 and three in September 2006.

Table 1.1: Summary of Satellite and Geophysical Source Data for the Creighton Area

Dataset	Product	Source	Resolution	Coverage	Acquired	Additional Comments
DEM	Canadian Digital Elevation Data (CDED); 1:50,000 scale	Geobase	20 m	Entire Creighton area	1960s & 1980s	Source data provided 25 foot contour interval in the west 2/3rd, lower resolution 50 foot contour

Dataset	Product	Source	Resolution	Coverage	Acquired	Additional Comments
						interval in east
	Shuttle Radar Topography Mission (SRTM)	CGIAR	90 m	Entire area	2000	Hillshaded and slope rasters used for mapping
Satellite Imagery	SPOT 4/5; Orthoimage, multispectral/ panchromatic	Geobase	10 m (panchromatic) 20 m (multispectral)	Entire Creighton area	2005 & 2006	
Geophysics	Hanson Lake	GSC	500 m line spacing, Sensor height 120 m	Entire area	1993	Magnetic, radiometric and VLF-EM data. Lowest resolution dataset
	Flin A	Hudbay	200 m line spacing, Sensor height 40 m (VTEM), 60 m (mag.)	East-central	2007	Magnetic and VTEM data. Focused on greenstones
	Konuto	Hudbay	200 m line spacing, Sensor height 40 m (VTEM), 63 m (mag.)	South-central	2008	Magnetic and VTEM data. Focused on greenstones
	Flin Flon-Sherridon A	GSC	300 m line spacing, Sensor height 150 m	Entire area	1986	Magnetic and VLF-EM data. Poor quality VLF-EM data
	Flin Flon-Sherridon B	GSC	300 m line spacing, Sensor height 150 m	Adjacent to the southern margin of Creighton area	1986	Magnetic and VLF-EM data. Poor quality VLF-EM data
	Flin Flon (Queenair)	GSC	300 m line spacing, Sensor height 150 m	Adjacent to the eastern margin of Creighton area	1980	Magnetic and VLF-EM data. Poor quality VLF-EM data
	GSC National Gravity Compilation	GSC	5-15 km (1 km along Hwy 106), surface	Entire area	1950-1993	
Geophysics (Cont)	GSC National Radiometric Compilation	GSC	5000 m line spacing, Sensor Height 120 m	Southern margin of Creighton area	1978	

Dataset	Product	Source	Resolution	Coverage	Acquired	Additional Comments
	Lithoprobe THOT Line 9	GSC Lithoprobe	50m geophone spacing, 100 m vibroseis source interval	19 km along Hwy 106	1991-1992	Shallow subsurface poorly resolved

GSC – Geological Survey of Canada

VTEM – Versatile Time Domain Electromagnetic

VLF-EM – Very Low Frequency Electromagnetic

THOT – Trans-Hudson Orogen Transect

CGIAR – Consultative Group on International Agricultural Research

1.4.2 Geology

The bedrock geology of the Creighton area has been mapped extensively. Geological mapping coverage is good and generally up to date throughout most of the Creighton area. Most of this information is focused on the greenstone belts for their mining potential (McDougall, 1979; Gaskarth, 1981; MacDonald, 1981; Reilly 1990, 1991a, b, 1993, 1994; Thomas, 1990, 1991, 1992, 1993; Slimmon, 1993; MacDonald and Leclair, 1994; Gibson et al., 2001; Bailey, 2005; MacLachlan, 2006a, b; MacLachlan and Devine, 2007;). However, the plutons of interest to this assessment have also been mapped to some degree. Figure 1.2 shows the primary geological mapping coverage and geophysical data for the Creighton area that was used in this assessment. For clarity, many of the larger scale maps produced for the area that focus on the greenstones are not shown on Figure 1.2. These maps are largely compiled within more recent maps covering a larger extent (NATMAP, 1998; Saskatchewan Industry and Resources, 2010; Simard et al., 2010). For example, the most detailed publicly available maps produced for the area is a 1:10,000 scale map produced jointly by the Manitoba Geological Survey (Geoscientific Map MAP2010-1) and the Saskatchewan Ministry of Industry and Resources (Geoscience Map 2010-02) (Simard et al., 2010). The coverage of this map focuses on the areas with mining potential, but includes portions of the Annabel Lake pluton and the Phantom-Boot Lake pluton. Greater coverage of the Reynard Lake and Annabel Lake plutons was provided by the NATMAP Shield Margin Project, which included 1:100,000 scale synthesis mapping of the entire Creighton area (Lucas et al., 1999; NATMAP, 1998). Additionally, part of the Phantom-Boot Lake pluton was mapped by MacLachlan (2006a) at a scale of 1:3,000 and includes the bedrock geology of the Douglas Lake area.

A number of older maps provide some valuable structural information within the plutons of interest. Since the 1950s, the Saskatchewan Geological Survey (SGS) has produced several maps that include all or portions of the Annabel Lake pluton, the Reynard Lake pluton and Phantom-Boot Lake pluton. These maps include structural information that will assist with the development of a conceptual geological model of the Annabel Lake and Reynard Lake plutons (Byers and Dahlstrom, 1954; Byers et al., 1965; Simard et al., 2010). Some supplemental structural information was also available in various reports (Byers, 1954; Gendzwill, 1968).

Numerous peer reviewed articles have been written on the geology, geochronology and structural evolution of the Creighton area (e.g., Bailes and Syme, 1989; Fedorowich et al., 1993; Fedorowich et al., 1995; Syme et al., 1996; Bailey and Gibson, 2004; Simard and MacLachlan, 2009). These articles include some mapping information, ages of the various geological units and in some cases conceptual cross-sections (Parslow and Gaskarth, 1981; Bunker and Bush, 1982; Hajnal et al., 1983; Ansdell and Kyser, 1992; Ashton et al., 2005;

Simard et al., 2010). A number of peer reviewed articles describe the shear zones and brittle deformation features in the area (Bunker and Bush, 1982; Slimmon, 1995; Elliot, 1996; Davies, 1998). Research on the Trans-Hudson Orogen has provided further insight to the geological history of the area and large scale structures (Lucas et al., 1999; Corrigan et al., 2007; Morelli, 2009).

In the Creighton area, the Flin Flon greenstone belt has been the target of many drilling programs associated with mineral exploration and mining activities in the area. Rocks of the Flin Flon greenstone belt include mostly juvenile ocean arc and ocean floor assemblages. Recently these rocks have been collectively called the Flin Flon Arc assemblage (Lucas et al., 1999; Simard et al., 2010). However due to historical usage throughout the report the original terminology of Flin Flon greenstone belt, or simply greenstone belt has been retained throughout the remainder of the report when discussing the bedrock geology of the Creighton area.

The plutons of interest in this assessment have received very little attention due to their low mineral potential. However, a deep (>3,000 m) borehole was drilled in the 1960s into the Reynard Lake pluton. This hole was drilled for seismic monitoring purposes, and has provided some valuable information regarding the compositional characteristics at depth, rock properties and fracture conditions (Davis and Tammemagi, 1982).

Regional mapping of the surficial geology in the area was conducted in the 1970s and early 1980s by the Saskatchewan Research Council under contract to the Saskatchewan Geological Survey. The resulting information was compiled into a 1:250,000 scale map for northern Saskatchewan (Schreiner, 1984a,b). This regional information is available through the Saskatchewan Industry and Resources Atlas of Saskatchewan (2010). The Creighton area was mapped in greater detail during the late 1980s and 1990s (Campbell, 1987, 1988; Henderson and Campbell, 1992; Henderson 1995). Detailed surficial geological maps prepared from this work include a series of 1:50,000 scale Geological Survey of Canada maps covering the area (Campbell and Henderson, 1997; Henderson, 2002). Equivalent mapping was conducted to the east of the Manitoba border (Henderson and McMartin, 2008). A small portion of the Creighton area, including the southern portion of the Reynard Lake pluton, was mapped at a scale of 1:20,000 (Campbell 1987; 1988).

National seismicity data sources were reviewed to provide an indication of the seismicity in the Creighton area (Gendzwill and Unrau, 1996; NRCan, 2012).

1.4.3 Hydrogeology and Hydrogeochemistry

Limited site-specific information exists on the shallow hydrogeologic conditions in the Creighton area. Hydrogeological information was obtained from the Saskatchewan Watershed Authority (SWA) Water Well Record (WWR) database (SWA, 2009), as well as geological (SGS) and hydrological maps (NRCan) of the Creighton area. Combined with regional surface water drainage patterns and surficial geology maps, this information assists with the preliminary characterization of shallow groundwater.

No information is available regarding deep hydrogeochemistry within the Creighton area, so inferences have been made based on studies at similar geological settings elsewhere in the Canadian Shield. These studies have shown that the hydrogeochemical conditions at repository depth are similar across the Canadian Shield (Frape et al., 1984). Specific reports/studies include Frape et al. (1984); Frape and Fritz (1987); Gascoyne et al. (1987); Farvolden et al. (1988); Gascoyne (1994, 2000 and 2004); Everitt et al. (1996); and Rivard et al. (2009).

1.4.4 Natural Resources – Economic Geology

Due to the present and historical mining activities in the Creighton area, there is a significant amount of information available on the mineral resource (Byers and Dahlstrom, 1954; Byers et al., 1965; Pearse, 1990; Reilly, 1995; Corrigan et al., 2007; Morelli, 2009; Simard and MacLachlan, 2009; Saskatchewan Energy and Resources, 2012). The primary source of information on past and present mining activities is the Saskatchewan Energy and Resources Mineral Deposit Index (2012). Articles describing prospective areas have been prepared by Theyer and Heine (2002), Galley et al. (2007) and Morelli (2009).

The availability of information is good throughout the Creighton area with the most detailed information available for areas having some mineral potential, such as the Flin Flon greenstone belt and the margins of intrusive bodies. Limited data are available for the central portions of the intrusive bodies and the northern portion of the Creighton area, owing to a low mineral potential.

1.4.5 Geomechanical Properties

The geomechanical information available for the specific plutons of interest is limited. In the 1960s a deep (3,066 m) borehole was drilled into the Reynard Lake pluton for seismic monitoring purposes, and has provided some valuable information regarding the compositional characteristics at depth, rock properties and fracture conditions (Davis and Tammemagi, 1982). However, aside from density data and some seismic parameters, the geomechanical information is limited. As such, rock geomechanical properties have also been inferred from information obtained from other geological settings with similary types of rock elsewhere in the Canadian Shield. Much of this information is a result of the work done by Atomic Energy of Canada Limited (AECL) in the 1980s and 1990s as part of the Canadian Nuclear Fuel Waste Management Program.

Information on the geomechanical properties of granitic rocks is available from AECL's Underground Research Laboratory (URL) near Pinawa, Manitoba and the Atikokan research area in Ontario (Brown et al., 1989; Stone et al., 1989).

2.0 PHYSICAL GEOGRAPHY

2.1 Location

The Town of Creighton is located on the east-central edge of Saskatchewan adjacent to the Manitoba border, a few kilometres west of Flin Flon, Manitoba (Figure 1.1). The Northern Village of Denare Beach is located on the northeast shore of Amisk Lake, which is 18 km southwest of the settlement area of Creighton along Highway 167. The nearest large center is the City of Prince Albert, about 400 km to the southwest via Highway 106 (the Hanson Lake Road) and Highway 55. The Town of Creighton and its periphery is approximately 660 km^2 in size, as shown on Figure 1.1. Satellite imagery for the Creighton area (SPOT panchromatic, taken in 2005 and 2006) is presented on Figure 2.1.

2.2 Topography and Landforms

A detailed terrain analysis was completed as part of the preliminary assessment of potential suitability for the Creighton area (JDMA, 2013a). This section (and Section 2.3) presents a summary of this analysis.

The Creighton area is located in the Kazan Upland Physiographic Region of the western Precambrian Shield (Bostock, 1970). The Kazan Upland topography is typical of the Canadian Shield, with large areas of bedrock that form broad, smooth uplands and lowlands. First-order relief is smooth and gently rolling, while second-order relief is more complex. Second-order relief consists of ridges and valleys that are controlled by bedrock conditions. Much of this relief is the result of bedrock structure, and some is the result of differential erosion of different rock types by glacial ice. Ice movement smoothed and polished resistant bedrock hills and scoured out low-lying areas. Valleys and depressions between bedrock ridges and knolls are typically filled with lakes and bogs. Lakes and ridges in the Canadian Shield region are often aligned in a northeast-southwest direction, reflecting the direction of glacial ice advance (Schreiner, 1984a) as well as the structure of the underlying basement rocks.

The topography of the Creighton area is presented on Figure 2.2. Local relief is generally low with variations in elevation of less than 100 m. Ground surface elevation ranges from about 292 m at the shore of Schist Lake in the southeast to about 369 m in the north, immediately south of Ahrens Lake. The major gradients are from the north into Amisk Lake and into Schist Lake.

The large lakes and the surrounding rugged terrain represent the most distinct topographic features in the area, especially in light of the relatively flat-lying terrain in between. Amisk Lake and the uneven terrain around its margins form the main topographic feature in the central-west part of the area. The shape of Amisk Lake appears to reflect preferential erosion of metavolcanic rocks that are wrapped around a more erosion-resistant granodioritic core. Schist Lake, Embury Lake and the bordering ridges form the major topographic feature in the eastern part of the area. Virtually all of this relief is believed to be bedrock-controlled and associated with rock ridges.

Other distinctive topographic features in the Creighton area are the elevated, plateau-like surfaces which largely represent the surface expression of plutons. The plutons are characterized by areas of relatively low relief with relatively high relief margins (JDMA, 2013a), which is presumably due to differences in lithology between the plutons and the adjacent greenstone rocks. Examples include the Annabel Lake and Reynard Lake plutons. Of these plutons, a greater proportion of the Annabel Lake pluton is considered high ground (i.e., >10 m higher than average within a 20 km radius). The Annabel Lake pluton is continuously mapped as high ground except along the margin associated with the Annabel Lake shear zone (described in Section 3.1) and the Arner Lake trough within the pluton (JDMA, 2013a). The Arner Lake trough is an east-west oriented, linear depression (approximately 10 m deep compared to surrounding ground) with a topographic expression similar to that of the shear zones forming the margins of the pluton. The narrow, northern portion of the Reynard Lake pluton is mapped as high ground. Further southeast along the axis of the Reynard Lake pluton, the higher ground is composed of discontinuous patches, becoming low ground at and south of Patmore Lake and Reynard Lake at the south end of the pluton. The east-west trending ridge north of Johnson Lake is probably the best example in the area of the elevated, plateau-like surfaces associated with the plutons. Only the southeast portion of this ridge is visible on Figure 2.2. The higher points on this generally flat-topped, 5 to 8 km wide feature are at elevations of 360 to 370 m, which are generally 30 m above the lakes on either side of the ridge. The elevated aspect of these plateau-like intrusive bodies is generally provided by the low-lying nature of the shear zones and belts of metasedimentary and metavolcanic rocks around their margins. Generally, the greatest relief associated with these features occurs in a band around their margins.

The topographic lows are frequently associated with glaciofluvial and/or patches of glaciolacustrine deposits as shown on Figure 2.3. Henderson and Campbell (1992) suggested that some of the linear lows between bedrock ridges around Amisk Lake are associated with subglacial meltwater channels. Some of the linear depressions between bedrock ridges along the northwest shores of Amisk Lake are 200 to 500 m wide and 15 to 30 m deep. It is likely that meltwater erosion has exploited a lithological fabric in the bedrock. Perhaps competency contrasts in the bedrock are partly responsible for the high relief around the shores of Amisk Lake.

Bedrock knobs and ridges typically extend a maximum of 30 m above or below the surrounding terrain. The surface of the Reynard Lake pluton is somewhat more knobby than that of the Annabel Lake pluton, with the irregular shaped knobs on the former pluton typically about 0.5 to 2 km in extent.

Areas of steep slope form the margins of many of the rugged landforms in the Creighton area, such as ridges and knobs. In Precambrian shield terrain steep slopes are often associated with bedrock topography, with some notable exceptions (e.g., end moraines, kames, drumlins, melt water channels), and therefore it can be assumed that the presence of steep slopes in the landscape is most likely indicative of bedrock exposure. In the Creighton area, the plutons are expressed as low-relief surfaces with a low density of steep slopes. This observation can be interpreted as indicating that the bedrock surface itself is simply of low relief, or it can be interpreted as indicating that irregularities in the bedrock surface of similar amplitude to those around Amisk Lake have been filled with overburden. However, since abundant bedrock exposures are visible in the SPOT imagery over the pluton surfaces (Figure 2.1), and much of the exposed bedrock mapped in the area (Figure 2.3) also coincides with the plutons, these pluton surfaces may be less irregular than the bedrock units around Amisk Lake.

2.3 Watersheds and Surface Water Features

As part of the terrain study conducted for the preliminary assessment of potential suitability for the Creighton area, JDMA (2013a) carried out a drainage basin analysis in order to confirm and, where possible, partition the most detailed available mapping of watersheds by the Agriculture and Agri-Food Canada (AAFC) (formerly known as the Prairie Farm Rehabilitation Administration (PFRA)). The resulting mapping is shown on Figure 2.4 and was used to infer regional and local surface water and shallow groundwater flow directions. The colours on this figure represent different watershed boundaries.

Most of the Creighton area is contained within the Sturgeon-Weir River sub-sub basin (Figure 2.4), which is located within the primary Nelson River watershed that drains into Hudson Bay. The Sturgeon-Weir River drains through Amisk Lake and eventually empties into the Saskatchewan River at Cumberland House (approximately 100 km southwest of Creighton). The Saskatchewan River empties into Lake Winnipeg, which is drained by the Nelson River. In contrast, the north-central fringe of the Creighton area drains into the Churchill River, which flows towards Hudson Bay. This northern part of the area is located within the Central Churchill-Highrock Lake sub-sub basin.

Drainage within the Sturgeon-Weir portion of the Creighton area is either towards Athapapuskow Lake, located approximately 25 km southeast of Creighton or towards Amisk Lake located in the south-central portion of the area. The portion of the Creighton area that drains towards Athapapuskow Lake can be divided into three main watersheds (Figure 2.4). Flow on the northern part of Annabel Lake pluton is directed into Annabel Lake, where it flows eastward into Annabel Creek and then into Embury Lake, Big Island Lake, Schist Lake and finally Athapapuskow Lake. Drainage of the western margin of Annabel Lake pluton, around Creighton Lake, is directed through Creighton Creek and Flin Flon Creek into Ross Lake, which is drained by Ross Creek into Schist Lake. This watershed includes the Town of Creighton, Flin Flon and the active mining operations in the area.

The portion of the Creighton area that drains into Amisk Lake can be divided into five or more watersheds (Figure 2.4). The areas around Johnson Lake to the northwest drain into Neagle Lake, which is drained into the West Channel of Amisk Lake through Neagle Creek. The area around Welsh Lake to the southeast of the Annabel Lake pluton drains into the North Channel. The western portion of Reynard Lake pluton drains mainly into Wolverine Lake and into Comeback Bay of Amisk Lake, although a smaller part of this watershed drains into Magdalen Lake and into the North Channel. The south-central part of the Reynard Lake pluton drains into Mosher Lake before feeding into Comeback Bay. The northern and western margins of Reynard Lake pluton and the southern part of Annabel Lake pluton drain through Meridian Creek through Wekach Lake, Mystic Lake and Table Lake, before emptying into Amisk Lake.

A consequence of the elevated plateau-like terrain of many of the plutons in the Creighton area is the presence of drainage divides winding along the low relief surfaces of the plutons and creeks tracing along the pluton margins. Annabel Lake and Reynard Lake plutons are good examples of this phenomenon. The abundance of largely intact rock exposed on the elevated pluton surfaces might suggest that these features should be well drained. However, there is an abundance of narrow wetlands filling depressions on the pluton surfaces, which trap runoff for varying lengths of time before releasing it through evapotranspiration or into streams or lakes. A number of small lakes in the area are internal drainage systems with no outlets. Six of these are located along the southern margin of the Reynard Lake pluton. The abundance of wetlands is partly a function of the low relief terrain, but also a function of the irregularities in the bedrock surface. The organic deposits mapped in the surficial geology maps (Figure 2.3) represent peat and muck about 1 to 5 m thick located within poorly drained ground forming swamps, marshes, bogs and fens, typically associated with topographically enclosed basins or with extensive areas underlain by fine-grained, poorly drained glaciolacustrine deposits. The most extensive wetlands in the Creighton area are located in the southeast part of the area, particularly south and east of Spectral Lake and east of Mystic Lake. Smaller wetlands are distributed throughout the Creighton area. Approximately 18% of the Creighton area is covered by wetlands.

The Creighton area contains a large number of lakes of various sizes, four of which are larger than 10 km^2, with one of these being larger than 300 km^2 (Figure 2.4). These include: Annabel Lake (12 km^2), Embury Lake (13 km^2), Schist Lake (24 km^2), and Amisk Lake (308 km^2). There is a high density of small lakes on the Reynard Lake pluton in an area northwest of Highway 167. Surface water bodies cover approximately 16% of the Creighton area. The larger lakes are sufficiently large to conceal geological structures up to about ten kilometres in length (perhaps more in the case of Amisk Lake), and clusters of small lakes have additional potential to conceal structures, especially when the lakes are located in areas where geological structures are already largely concealed by overburden. Table 2.1 summarizes the areas and depths for some selected lakes in the Creighton area.

Table 2.1 Dimensional Characteristics of Selected Lakes in the Creighton area.

Lake	Area (km^2)	Maximum Recorded Depth (m)
Johnson Lake	7.2	3.7
Annabel Lake	12.4	4.9
Creighton Lake	1.2	5.9
Hamell Lake	2.2	6.7
Ross Lake[1]	0.6	9.0
Nesootao Lake	1.7	9.8
Phantom Lake[1]	4.7	10.0
Cliff Lake[1]	2.4	11.0
McRobbie Lake	0.4	13.0
Mosher Lake	2.6	27.0
Schist Lake[2]	23.9	30.0
Amisk Lake	307.7	40.1
Embury Lake[1]	12.8	45.0

[1]Approximate maximum depth after Van Loon and Beamish (1977)

[2]Approximate maximum depth after Franzin and McFarlane (1976)

Information on the depths of selected lakes in the Creighton area was obtained from depth surveys conducted by the Saskatchewan Fisheries Branch in the 1960s, 1970s and 1980s (Table 2.1) (Franzin and McFarlane, 1976; Van Loon and Beamish, 1977). Although it was not possible to obtain depth data on all of the lakes in the Creighton area, the variety in lake sizes and shapes included in the list of lakes in Table 2.1 is thought to capture much of the variability that exists within the area in terms of maximum lake depth. Many of the surveyed lakes appear to be less than 10 m deep in their deepest parts. The deepest lakes in the area reach approximate maximum depths of 30 to 45 m.

2.4 Land Use and Protected Areas

Figure 2.5 shows land disposition and ownership within the Creighton area including known protected areas. The following summarizes the status of current land use and protected areas within the Creighton area.

2.4.1 Land Use

The Creighton area is part of one of the most productive base metal regions in Canada (Reilly, 1995) and the Towns of Creighton and neighbouring Flin Flon, Manitoba, were established as communities to support mining operations. Prospecting began in the area in the early 1900s. In 1915, Thomas Creighton staked a claim on the Flin Flon Lake massive sulphide ore body, which became the original producing mine for the Hudson Bay Mining and Smelting Company. Base metal production in the Creighton area started in 1930 at the Flin Flon Mine, and continues today at the 777-Callinan Mine (located on the border of Saskatchewan and Manitoba) located 1 km and 3 km from the settlement area of Creighton, respectively. Currently, Hudbay employs almost 1,200 people in the area. The commercial centers that have grown around the mining activities have populations of approximately 1,500 people in Creighton and 6,800 people in Flin Flon.

The Town of Creighton includes residential and industrial infrastructure, with developments limited to roadways, the settlement area and a tailings management facility for the existing mining operations. The area surrounding the Town of Creighton is largely undeveloped with no major infrastructure other than the active mine. Several Crown Reserve areas, associated with Canadian Forces Station Flin Flon, are located between the towns of Creighton and Denare Beach (Figure 2.5).

2.4.2 Parks and Reserves

The Creighton area was screened for national, provincial and municipal parks, conservation areas, nature reserves and national wildlife areas. The only protected area within the Creighton area is the Amisk Lake Recreation Site located approximately 11 km southwest of the settlement area of Creighton along Highway 167 on the northeast shore of Amisk Lake and covers an area of about 350 ha (Figure 2.5). South of the recreation area, the Northern Village of Denare Beach is also located on the northeast shore of Amisk Lake. This community is 18 km southwest of the settlement area of Creighton along Highway 167.

A number of areas labelled as Crown Reserves are associated with a Department of National Defence Canadian Forces Station (Flin Flon) to the southwest of Creighton (Saskatchewan Industry and Resources, 2010). These include eight blocks of land located between the Town of Creighton and the Amisk Lake Recreation Site (Figure 2.5). These blocks of Crown Reserve land coincide with a deep borehole (borehole JXWS discussed below in Section 3) and an associated seismic monitoring array. Cut lines, likely associated with power and communications cables that connect the blocks of Crown Reserve land, are visible on Figure 2.1.

2.4.3 Heritage Sites

Heritage resources include all of Saskatchewan’s Historic and Precontact archaeological sites, architecturally significant structures, and palaeontological resources. Heritage resources are property of the Provincial Crown, and as such are protected under *The Heritage Property Act* (Government of Saskatchewan, 1980). The database for previously recorded heritage resources maintained by the Ministry of Tourism, Parks, Culture and Sport (TPCS, 2012) as well as the National Historic Sites Database (Parks Canada, 2012) was consulted to identify recorded heritage resources found within the Creighton area.

The results of the database search indicate that 18 archaeological sites have been recorded in the Creighton area. Fourteen sites are pre-contact Aboriginal artifact find and scatter sites; two sites are artifact/feature combination sites – one historic, the other unidentified, and two heritage resources have insufficient information to be given a site type designation.

The presence of local heritage sites would need to be confirmed in discussions with the community and Aboriginal peoples in the area.

3.0 GEOLOGY

3.1 Regional Bedrock Geology

3.1.1 Geological Setting

The lithostructural domains of northern Saskatchewan are presented on Figure 3.1. A geological cross section through northern Saskatchewan that passes along the southern boundary of the Creighton area is shown on Figure 3.2 (White et al., 2005). The Creighton area is located in the Flin Flon-Glennie complex, which is part of the Reindeer zone of the Canadian Shield in northern Saskatchewan. The Reindeer zone is part of the Paleoproterozoic Trans-Hudson Orogen within the Canadian Shield (Corrigan et al., 2007). The Creighton area is located just north of the contact with the Western Canada Sedimentary Basin, which is the Phanerozoic cover in the southern part of the province.

The Canadian Shield is a collage of Archean cratons, accreted juvenile terranes and sedimentary basins that were progressively amalgamated over a period of more than 2 billion years during the Proterozoic Eon (see Figure 3.1, and further discussed in Section 3.1.2 below). 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 Ga (Ansdell, 2005; Corrigan et al., 2005; Hajnal et al., 2005; Corrigan et al., 2007; Whitmeyer and Karlstrom, 2007; Corrigan et al., 2009). The resulting Trans-Hudson Orogen extends from South Dakota through Hudson Bay into Greenland and Labrador. Within Canada, the Trans-Hudson Orogen is a region approximately 500 km wide located between the Superior craton to the southeast and the Rae-Hearne craton to the north and northwest (Ferguson et al., 1999; Corrigan et al., 2007).

The Reindeer zone consists of a collage of Paleoproterozoic arc and oceanic volcanic rocks, plutons, and younger molasse and turbiditic sedimentary rocks (Corrigan et al., 2009; Morelli, 2009). Most of these rocks were formed in an oceanic to transitional subduction-related arc setting. The Reindeer zone structurally overlies approximately 3.2 to 2.4 Ga old Archean metaplutonic and paragneissic rocks of the Sask craton (Figure 3.2), which are exposed in the western portion of the Flin Flon Domain known as the Pelican window, approximately 70 km to 80 km to the west of the Town of Creighton (Lucas et al., 1999; Ashton et al., 2005). During collision of the Sask craton with the Rae-Hearne craton, these rocks of the Reindeer zone were thrust over the Sask craton along the Pelican thrust (Corrigan et al., 2005).

The Flin Flon-Glennie complex is situated within the southeastern portion of the Reindeer zone in Saskatchewan (Corrigan et al., 2009; Morelli, 2009). The geology of this region is shown on Figure 3.3. The Flin Flon domain (Figure 3.1) is an approximately 1.9 to 1.84 Ga old lithotectonic domain of the Trans-Hudson Orogen, and consists of a complex mixture of Paleoproterozoic volcano-plutonic rocks, representing arc, back arc, ocean plateau and mid ocean ridge environments, and molasse-type sedimentary rocks (Ansdell and Kyser, 1992; Corrigan et al., 2009; Morelli, 2009).

Regional geophysical surveys have been used to assist in mapping geologic structures within the Precambrian provinces and zones of northern Saskatchewan as part of the Lithoprobe project (a multi-year continent-scale geophysical subsurface mapping initiative) and the NATMAP Shield Margin project. Geophysical surveys conducted as part of this initiative include airborne magnetic, gravity, airborne radiometric, audio magnetotelluric and deep seismic reflection and refraction surveys (Lucas et al., 1993; Lewry et al., 1994; Hajnal et al., 2005; White et al., 2005). Figure 3.2 shows a cross section through northern Saskatchewan that includes the

Trans-Hudson Orogen in the Creighton area that 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).

3.1.2 Geological History

The chronology of tectonic events that occurred during the Trans-Hudson Orogeny provides a framework for understanding the geological history of the Creighton area. The important phases of the Trans-Hudson Orogeny that produced the present geological conditions observed in the rocks of the region are summarized in Table 3.1 below. The summary is based primarily on the picture of geodynamic evolution detailed in Fedorowich et al. (1995) but also includes information based on additional detailed work done in the area (Cumming and Scott, 1976; Fedorowich et al., 1993; Stauffer and Lewry, 1993; Ansdell, 2005; Ansdell et al., 2005; Corrigan et al., 2005; Hajnal et al., 2005; Corrigan et al., 2007; Whitmeyer and Karlstrom, 2007; Corrigan et al., 2009). In general, there is a characteristic pattern to the tectonic history that includes early stage brittle, to ductile, to brittle-ductile and finally to late brittle deformation over a period of almost 200 million years (Fedorowich et al., 1995), followed by a much more protracted history of localized brittle deformation that may have continued into the Mesozoic Era.

Table 3.1: Summary of the Geological and Structural History of the Creighton Area

Time Period (Ga)	Geological Event
ca. 2.075	Passive margin phase associated with initiation of deposition of the Wollaston Supergroup on the eastern margin of the Hearne craton. Manikewan ocean opens at the east of Hearne craton.
1.906 to 1.886	A series of volcanic assemblages, including the La Ronge-Lynn Lake arc and a series of arc oceanic assemblages (including Amisk Group/Flin Flon greenstone belt), coexisted in the Manikewan ocean.
1.886 to 1.86	Closure of Manikewan ocean produced accretion of various tectonic assemblages resulting in the formation of the Flin Flon-Glennie complex. Activation of earliest regional shear zones. [D_1]
1.86 to 1.834	Ongoing subduction and accretion during collision induces crustal thickening, thrust faulting and shear zone activation, and on-going folding. [D_2] Deposition of the Missi Group between ca. 1.847 and 1.842 Ga. Emplacement of successor arc intrusions between ca. 1.86 and 1.834 Ga (including the Annabel and Reynard Lake plutons).
1.83 to 1.79	Terminal collision of Trans-Hudson Orogen and final closure of the Manikewan ocean under conditions of peak metamorphism. Transpressional reactivation of regional shear zones, including Needle Falls shear zone and Tabbernor fault zone. [D_3]. Ductile shear zones form along the margins of the granitic intrusions.
1.79 to 1.76	Reactivation of regional shear zones as strike-slip fault zones and onset of retrograde metamorphic conditions. Development of NE-trending regional folds (i.e., the Embury Lake Flexure) and reactivation of regional shear zones. [D_4]
1.725 to 1.691	Brittle faulting and brittle reactivation of regional-scale faults and shear zones. [D_5]
post-1.691	Reactivation of regional scale brittle faults; e.g., Tabbernor fault system. [D_6]

Around 2.075 Ga, initial deposition of the Wollaston Supergroup took place in a passive to incipient rift setting on the eastern side of the Hearne craton. To the east of the Hearne craton, a series of arc oceanic assemblages, including the ca. 1.906 to 1.886 Ga volcanic rocks of the Amisk Group (Flin Flon greenstone belt) (Gordon et al.,

1990; Heaman et al., 1992) coexisted in the Manikewan ocean. During the period between approximately 1.886 and 1.865 Ga, the Manikewan ocean was closing and bringing together the various arc assemblages against each other and the Hearne craton, resulting in the formation of the Wollaston, Rottenstone and La Ronge domains, and the Flin Flon-Glennie complex.

A reversal of subduction polarity between approximately 1.865 and 1.85 Ga is associated with emplacement of the Wathaman batholith (Figure 3.1), as well as the oldest post-accretionary plutons recognized in the Flin Flon greenstone belt, such as the Annabel Lake pluton (ca. 1.86 Ga) and Reynard Lake pluton (ca. 1.853 Ga) (Ansdell and Kyser, 1990). These plutons are shown on Figure 3.4. Ongoing subduction between approximately 1.85 and 1.845 Ga resulted in the accretion of the Flin Flon-Glennie complex (including the Flin Flon greenstone belt) to the Hearne craton. Post-orogenic unconformable deposition of the sedimentary rocks of the Missi Group between ca. 1.847 and 1.842 Ga (Ansdell, 1993) upon the Flin Flon greenstone belt occurred during approximately the same timeframe. Northward migration of the Sask craton micro-continent close to the Flin Flon-Glennie complex may have also occurred during this period.

Between approximately 1.845 and 1.83 Ga, the Rae-Hearne craton was thrust upon the Sask craton along the Pelican thrust. This event also overprinted the Annabel Lake and Reynard Lake plutons, the Flin Flon greenstone belt and the rocks of the Missi Group (Figure 3.4). The Boot Lake and Phantom Lake plutons were emplaced at approximately 1.838 Ga (Heaman et al., 1992), or possibly as late as approximately 1.834 Ga (Ansdell and Kyser, 1990). Magmatism seems to have ended rather abruptly after this time, as no younger plutons have been recognized in the area.

Terminal collision with the Superior craton and final closure of the Manikewan ocean occurred between approximately 1.83 and 1.79 Ga (Fedorowich et al., 1995; Corrigan et al., 2005, 2009). Crustal shortening that occurred during this period resulted in the initiation of the Needle Falls shear zone (ca. 1.83 Ga), the Tabbernor fault zone (ca. 1.815 Ga) and the steeply-dipping brittle faults observed within the Wollaston Domain (Hajnal et al., 1996; Davies, 1998). Ductile shear zones mapped along the margins of the plutons in the Creighton area were also formed at this time. The shear zones record evidence of activation during peak metamorphic conditions that took place between approximately 1.82 and 1.79 Ga. The resultant greenschist to amphibolite facies metamorphic overprint is recognized throughout the Creighton area.

Later during (or after) the terminal collision, a regional northerly structural trend is folded into an east-trending orientation (e.g., the Embury Lake Flexure) and both local (e.g., Annabel Lake, West Arm and Mosher Lake) and regional scale (e.g., Needle Falls) shear zones were reactivated as strike-slip structures. Subsequent regional-scale brittle faulting, including brittle reactivation of regional scale faults and shear zones, occurred between approximately 1.725 and 1.695 Ga. Cooling ages of vein minerals within the reactivated shear zones constrain the minimum age for fault reactivation at ca. 1.691 Ga. Although poorly constrained in terms of actual timing, there is also evidence of localized, post-1.691 Ga, brittle faulting. This includes late movement along structures associated with the Tabbernor fault system that suggest a long history of reactivation that may have continued until the Mesozoic Era (e.g., Byers, 1962; Elliott, 1996).

Phanerozoic rocks (i.e., rocks younger than 541 million years old) of the Western Canada Sedimentary Basin unconformably 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 south of the Creighton 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 of Ordovician age (i.e., 485 to 443 million years old) unconformably overlie the Precambrian basement approximately 20 km south of Creighton. These rocks represent a remnant of the Cambrian to Devonian sedimentary succession that was deposited while much of the Churchill Province was inundated by shallow seas during the Paleozoic Era. The close proximity of the Western Canada Sedimentary Basin to the south and the apparent continuation of the sequence in the Hudson Bay area of Manitoba to the northeast suggests that the Creighton 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 just over 100 km to the west of Creighton, is characterized by sedimentary rocks of Cretaceous age. A few isolated outliers of Cretaceous sedimentary rocks are preserved in closer proximity to Creighton along the southern extension of the Tabbernor fault. The Mesozoic strata were deposited during a series of regressions and transgressions of the Cretaceous sea over the western interior of North America (Mossop and Shetsen, 1994). The prior extent of Mesozoic cover in the Creighton area, if any, is uncertain.

3.1.3 Regional Structural History

Fedorowich et al. (1995) described a structural history that is consistent with the regional geological events described above. This synthesis is based on the results from detailed structural and thermochronological analyses, primarily focused on the study of shear zones in the Flin Flon area. The structural history includes five main episodes of deformation (D_1 to D_5), and provides a relative temporal framework for the sequence of geological events described above. A later D_6 event is included herein to represent the protracted continuation of late brittle deformation until as recently as the Mesozoic Era.

D_1 deformation, attributed to north-south collision, is recognized by the development of vein arrays, thrust faulting and an early phase of folding within the ca. 1.906 to 1.886 Ga Amisk Group, but well prior to deposition of the 1.847 to 1.842 Ga Missi Group. Kinematic and geochronological evidence constrain D_1 to have occurred between ca. 1.886 and 1.860 Ga. D_2 is characterized by continued movement along thrust faults and associated fold development and is considered to have been synchronous with the peak episode of crustal thickening. D_2 is constrained to have occurred between ca. 1.860 and 1.840 Ga and therefore was on-going during deposition of the Missi Group. The crustal thickening resulted in a period of syntectonic granitic activity that also continued until ca. 1.840 Ga. D_3 produced folds and associated axial planar foliations, as well as a number of oblique-slip sinistral reverse shear zones and coincided with peak metamorphic conditions. Regional relationships indicate that the D_3 event was associated with a post-thickening period of east-southeast to west-northwest oriented transpression between ca. 1.820 and 1.790 Ga. D_4 represents the timing of reactivation of strike-slip shear zones and the reactivation of some pre-existing faults under retrograde metamorphic conditions. D_4 also produced the Embury Lake flexure, the dominant map-scale fold structure in the Creighton area. D_4 is constrained to have occurred between ca. 1.790 and 1.760 Ga. D_5 is characterized by late stage brittle oblique- and strike-slip movement under conditions of northwest to southeast compression at ca. 1.691 Ga. Protracted, post-1.691 Ga brittle reactivation of faults throughout the Creighton area is collectively attributed to a D_6 deformation event.

3.1.4 Mapped Regional Structure

Numerous named and unnamed faults and shear zones have been mapped in the Creighton area. For the purposes of this assessment, the general characteristics of the mapped structures shown on Figure 3.5 are summarized below.

The Annabel Lake, West Arm and Mosher Lake shear zones initially formed during D_2, likely with reactivation during the peak metamorphic conditions contemporaneous with D_3 deformation. Shearing during D_3 originally resulted in steeply dipping, north-trending ductile structures. Movement along these long shear zones was dominantly sinistral. Lineations are defined by stretched feldspar and quartz grains, as well as biotite and pyrite porphyroblasts. Later, post-peak metamorphic (D_4) reactivation reoriented these shear zones, under brittle-ductile conditions, into easterly trends in association with development of the Embury Lake flexure (Ansdell and Kyser, 1990; Fedorowich et al., 1993). Highly stretched cobbles of the Missi Group conglomerates are noted along the reactivated shear zones. Although reoriented by the (D_4) Embury Lake flexure, F_3 foliation remains parallel to the shear zone boundaries throughout the region (Fedorowich et al., 1993).

The Annabel Lake shear zone dips sub-vertically to the north and strikes east along Annabel Lake and Annabel Creek on the north side of the Annabel Lake pluton (Byers and Dahlstrom, 1954; Simard et al., 2010). The Annabel Lake shear zone is marked by a zone of intense shearing and mylonitization (Byers et al., 1965; Parslow and Gaskarth, 1981). The amount of movement within the Annabel Lake shear zone is unknown but evidence of sinistral movement has been noted by Ashton et al. (2005). The West Arm shear zone occurs between the Annabel Lake and Reynard Lake plutons, and strikes southeasterly through Wilson and Meridian lakes. The West Arm shear zone is also marked by a zone of intense shearing and mylonitization. The amount of movement along the West Arm shear zone is unknown, but it was sufficient to remove a portion of the south limb of a syncline which occurs in the vicinity of Wilson Lake (Byers et al., 1965). The Mosher Lake shear zone strikes southeast along the southern boundary of the Reynard Lake pluton. This shear zone converges with the West Arm shear zone at its western extent (Figures 3.4 and 3.5). The Mosher Lake shear zone includes numerous branching minor faults and zones of alteration (Byers and Dahlstrom, 1954). The Mosher Lake shear zone has a component of sinistral displacement, although the amount of displacement is unknown (Slimmon, 1995).

Brittle D_5 to D_6 deformation is noted along the southeast edge of the Reynard Lake pluton and within the southernmost portion of the pluton where some lithological zoning has been mapped (i.e., to the southeast of Patmore and Reynard Lakes). One set of faults is sub-parallel to the West Arm and Mosher Lake shear zones, with a north-northwesterly trend, and are likely a component of the faults with a similar orientation mentioned in Section 3.1.3. These faults have spacing ranging from approximately 500 m to 2.5 km. A roughly orthogonal set may be related to the Mystic Lake fault, which strikes northeast, and is located to the southeast and east of the pluton. The spacing of these faults locally ranges from approximately 200 m to 2 km (NATMAP, 1998).

The brittle fault structures include near vertical to steeply east-dipping, north-northeast and north-northwest-trending structures and attendant fault splays characterized by sinistral movement (Galley et al., 1991) (Figure 3.5). These faults appear to be a part of the D_5 deformation event (Fedorowich et al., 1995). Numerous north-northwest-trending fault splays extend through the greenstone rocks in the immediate area of Flin Flon (Byers, 1962). In addition, they extend well beyond the Creighton area to the north as a complex system of interconnecting and branching faults with thrusting and strike-slip movement displaying an en echelon pattern. These faults are also located to the east of the plutons of interest, near the Manitoba-Saskatchewan border. To the west, in the direction of the Annabel Lake and Reynard Lake plutons, several splays bend more towards the northwest, perhaps along planes of weakness resulting from the bounding older shear zones. A good example of this occurs to the north of Hamell Lake (adjacent to the east end of the Annabel Lake pluton) where a splay of the Ross Lake fault system bends into the Annabel Lake shear zone.

A second series of D_5 to D_6 faults in the Creighton area have northeast strikes and steep dips, and are characterized by dextral movement (Galley et al., 1991). Faults associated with this series are relatively short compared to the more north-south-trending faults, but have been noted to have widths up to 1 km to the east of the Creighton area. To the east of the Phantom-Boot Lake pluton, some of these relatively short faults are observed to cross-cut the Flin Flon Lake (thrust) fault. Examples of more prominent faults displaying orientations and movement consistent with these second series of faults include the Mystic Lake fault, which runs along the north portion of the Phantom-Boot Lake pluton (Figure 3.5). Byers (1962) interpreted this northeast-trending series of structures to also be a component of the Ross Lake fault system.

The Ross Lake fault system generally strikes in a north- to north-northwest direction through the Creighton area with a total length over 100 km (Byers, 1962; Fedorowich et al., 1993). The Ross Lake fault system consists of several sets of inter-related faults that occur between Schist Lake to the south of the Creighton area (located within Manitoba), and Precipice Lake, approximately 13 km to the north of the Creighton area (Figure 3.5) (Byers, 1962). This fault system cross-cuts the Embury Lake flexure and the Annabel Lake shear zone (Ansdell and Kyser, 1990; Fedorowich et al., 1993; NATMAP, 1998; Saskatchewan Industry and Resources, 2010) confirming a post-D_4 timing of development. In the northeast portion of the Creighton area, approximately 1,250 m of sinistral oblique reverse displacement has occurred along the Ross Lake fault system (Byers et al., 1965).

In the Creighton area, the brittle faults related to the Ross Lake fault system are characterized by brecciation, gouge, and some mylonitization of acidic wall rocks or shearing with partial chloritization of basic rocks. Stringers and veins of quartz-calcite and quartz-epidote are common, often with these materials forming the matrix of fault breccias. In quartzo-feldspathic rocks, finely disseminated hematite imparts a reddish colour on the wall rocks (Byers, 1962). Seismic reflection profiles (Lithoprobe) through the area suggest that this fault and its attendant splays extend at high angles through the arc volcanic rocks to depths greater than 12 km (Lucas et al., 1994; Hajnal et al., 1996). Several smaller parallel faults, also interpreted as D_5 to D_6 structures, are located within the pluton near Arthur Lake at the north end of the Phantom-Boot Lake pluton. These faults are cut by the Douglas Lake fault, which extends into the northwest lobe of the pluton with a north strike (Simard et al., 2010). Approximately 200 m (in plan view) of sinistral movement has occurred along the Douglas Lake fault. At least two other north-striking faults cut through the northern portion of the pluton with a maximum spacing of approximately 1 km. The Dion Lake fault strikes in a northeast direction and largely separates the Phantom Lake granite to the east from a portion of the Boot Lake intrusions to the west. Less structural information is available in the southern portion of the pluton due to less detailed mapping. Byers et al. (1965) mapped one fault in the south-central portion of the pluton (southeast of Boot Lake), with a west-northwest strike. It is possible that this feature cuts through the south end of Boot Lake and may be related to the Mystic Lake fault to the southwest.

It is possible that the faults in the Creighton area interpreted to be a part of the Ross Lake fault system are in fact related to the much larger Tabbernor fault system (Byers, 1962). The Tabbernor fault is a deep rooted, splayed fault system that extends from the Northwest Territories to the states of North and South Dakota (Giroux, 1995).

The fault is a topographic, geophysical and geological lineament that extends a distance greater than 1,500 km. In Saskatchewan, the fault has a northerly strike and displays sinistral movement. Creighton is located approximately 80 km east of the Tabbernor fault (Corrigan et al., 2009; Morelli, 2009). This fault initially formed during the Trans-Hudson Orogeny approximately 1.815 Ga (Davies, 1998), but likely experienced more recent periods of reactivation (Elliot, 1996). Several researchers have discussed evidence that the Tabbernor fault zone was active as recently as the Phanerozoic based on apparent disturbance of overlying Ordovician rocks (Byers, 1962; Elliot, 1996; Davies, 1998; Kreis et al., 2004). As such, evidence of neotectonics may be preserved in younger units overlying the fault zone. However, there is no marked topographic lineament apparent in the Ordovician rocks near the Creighton area, suggesting that movement in the area had ceased by Ordovician time (Byers, 1962).

3.1.5 Metamorphism

Studies on metamorphism in Precambrian rocks across the Canadian Shield have been summarized in several publications since the 1970s, including a symposium proceedings (Fraser and Heywood 1978), and issues of The Canadian Mineralogist in 1997 and 2000 (e.g., Kraus and Menard, 1997; Menard and Gordon, 1997; Berman et al., 2000; Easton, 2000a,b; Berman et al., 2005). The thermochronologic record for major parts of the Canadian Shield are given in a number of studies supported by government surveys and represented by Berman et al. (2005), Bleeker and Hall (2007), Corrigan et al. (2007) and Pease et al. (2008).

In general, there is limited local preservation of pre-Neoarchean metamorphism within the Canadian Shield (e.g., Breaks and Bartlett, 1991; Percival and Skulski, 2000). Regionally, the Superior Province largely preserves low pressure and low to high temperature Neoarchean metamorphism, approximately 2.710 to 2.640 Ga, but there is a widespread tectonothermal overprint of Archean crust by Paleoproterozoic deformation and typically amphibolite facies metamorphism across the Churchill Province through northernmost Ontario under the northern Hudson Bay Lowland, western Manitoba, northern Saskatchewan and Nunavut (e.g., Skulski et al., 2002; Berman et al., 2005). The Paleoproterozoic volcanism, sedimentation and plutonism of the Trans-Hudson Orogen involved moderate to high temperature and low to moderate pressure metamorphic conditions beginning approximately 1.84 to 1.8 Ga and culminating with the collisional convergence of the bounding Archean Hearne Province and Superior Province (Kraus and Menard, 1997; Menard and Gordon, 1997; Corrigan et al., 2007).

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

Locally, two periods of metamorphic mineral growth appear to have occurred in the Creighton area (Fedorowich et al., 1993). These periods correspond to the D_2 and D_3 deformation events described in Section 3.1.3 and the two most distinct foliations in the region are defined by phyllosilicates that grew during these periods. The earliest period of metamorphism appears to be related to the intrusion of the major felsic plutons in the area (including the Reynard Lake and Annabel Lake plutons), and consists of alteration due to the slow cooling of magmatic rocks after crystallization resulting in contact aureoles around the plutons (Byers et al., 1965;

Fedorowich et al., 1993). This first period of low-grade metamorphism was initiated during D_2 and likely continued during D_3 (Bailes and Syme, 1989). Locally, an amphibolite grade halo has been noted around the Reynard Lake pluton as a result of this first phase of metamorphism (Ansdell and Kyser, 1990). The contact aureole is up to 1 km wide, with hornblende being the dominant amphibole (Galley et al., 1991).

The second stage of metamorphism is related to the D_3 collisional stage of the Trans-Hudson Orogen, where metamorphic conditions peaked between approximately 1.815 and 1.796 Ga (Corrigan et al., 2007). This resulted in peak metamorphism from greenschist to amphibolite facies within the Creighton area (Parslow and Gaskarth, 1981; Ferguson et al., 1999), allowing for preservation of primary textures and structures (Simard and MacLachlan, 2009). This regional metamorphism is shown as locally over-printed chlorite-actinolite over the earlier contact aureoles surrounding the plutons. Lower greenschist mineral assemblages are characterized by chlorite, tremolite-actinolite, albite, epidote, sericite and quartz (Galley et al., 1991). During this period, a certain amount of hydrothermal alteration occurred around faults and shear zones in the Creighton area (Byers et al., 1965).

Regionally, metamorphic grade generally decreases from the north to the south. To the north of the Creighton area (approximately 10 km towards the Kisseynew metasedimentary gneissic belt), the grade of metamorphism increases to upper amphibolite facies (Galley et al., 1991; Fedorowich et al., 1993). In this higher grade area to the north, retrograde lower greenschist mineral assemblages are reported in D_5 faults (Byers et al., 1965). Further south, metamorphic grade decreases from middle greenschist (biotite) in the Ross Lake (Flin Flon) area, to sub-greenschist (prehnite-pumpellite) in the White Lake area approximately 8 km southeast of Creighton (Bailes and Syme, 1989; Galley et al., 1991).

3.1.6 Erosion

There is no site-specific information on erosion rates for the Creighton area. Gordon (1989) estimated an uplift rate of 60 to 110 m/million years for the Kisseynew Domain to the north of Creighton. This rate applied to a period between 1.815 to 1.705 Ga, following peak metamorphism. Past studies reported by Hallet (2011) and McMurry et al. (2003) provide general information on erosion rates for the Canadian Shield during the last glaciation period. The average erosion rate from wind and water on the Canadian Shield is reported to be about 2 m per 100,000 years (Merrett and Gillespie 1983). Higher erosion rates are associated with glaciation. The depth of glacial erosion depends on several regionally specific factors, such as the ice geometry, topography, and local geological conditions, such as overburden thickness, rock type and pre-existing weathering.

Flint (1947) made one of the first efforts to map and determine the volume of all the terrestrial glacial sediment in North America, and concluded that all of the Plio-Pleistocene advances of the Laurentide ice-sheet had accomplished only a few tens of feet of erosion of the Canadian Shield. White (1972) pointed out that this ignored the much larger quantity of sediment deposited in the oceans, and revised the estimate upward by about an order of magnitude. Subsequently, Laine (1980; 1982) used North Atlantic deposits, and Bell and Laine (1985) used all the marine sediment repositories of the Laurentide ice-sheet (excluding the Cordilleran ice-sheet) to arrive at an average erosion of 120 m over 3 million years. Bell and Laine (1985) considered this to be a minimum value, although they made no allowance for non-glacial erosion or the role of rock weathering on erosion rates during the initial glacial advances in the late Pliocene Epoch. Hay et al. (1989), contending that in the Gulf of Mexico the depth of sediment of Laurentide provenance is greatly overestimated by Bell and Laine (1985), reduced this estimate of regional erosion to 80 m over the same time period.

3.2 Local Bedrock and Quaternary Geology

Information on the local bedrock and Quaternary geology for the Creighton area was obtained from the various published reports for the area, geological maps (Section 1.5.1), and the geophysical interpretation of the area conducted as part of this preliminary assessment (PGW, 2013). Findings from the geophysical, lineament and terrain analysis studies carried out as part of the preliminary assessment of the Creighton area (JDMA, 2013a; JDMA, 2013b, and PGW, 2013) are integrated in this assessment to provide insight on the lithological variability, structures and extent of the overburden cover for each of the intrusions being considered in the Creighton area.

3.2.1 Bedrock Geology

The bedrock geology of the Creighton area is shown on Figure 3.4. The geological boundaries shown on this figure, and all subsequent figures, are from the Geological Atlas of Saskatchewan (Saskatchewan Industry and Resources, 2010). In addition, Figure 3.5 shows the local geology map supplemented with structural measurements based on the detailed work of Byers and Dahlstrom (1954), Byers et al. (1965), Gendzwill (1968) and Simard (2010).

The geology of the Creighton area is dominated by large granitic intrusions and associated tonalitic units, including the Annabel Lake, Reynard Lake and Phantom-Boot Lake plutons. These Proterozoic intrusions were emplaced into the older supracrustal rocks of the Flin Flon greenstone belt and the overlying succession of sedimentary rocks, the Missi Group. A description of the granitic intrusions, the Flin Flon greenstone belt and the Missi Group is provided in the following subsections.

3.2.1.1 Reynard Lake Pluton

The Reynard Lake pluton is located approximately 5 km southwest of the Town of Creighton, and extends approximately 25 km to the northwest. As can be seen on Figure 3.4, the pluton is tear-drop shaped, with its lobe situated at the southeast end of the pluton. The lobe is approximately 6 km wide at its widest point.

The Reynard Lake pluton is inferred to have intruded the older Flin Flon greenstone belt during the Trans-Hudson Orogeny. The pluton is estimated to be approximately 1.853 Ga old, based on dating using the single-zircon Pb-evaporation technique (Ansdell and Kyser, 1990 and 1992).

Surface mapping of the Reynard Lake pluton (Figure 3.4) indicates that the pluton consists of a central core of coarse-grained porphyritic microcline granodiorite. The large microcline phenocrysts have a pink to buff colour and are surrounded by a medium- to coarse-grained light pink to grey groundmass. The central core of the pluton is surrounded by a shell of discontinuous non-porphyritic biotite granodiorite. This biotite granodiorite is medium-grained with a white to pinkish colour. In some cases, the margins of the pluton are noted to be marked by sharp contacts with metavolcanic rocks (Bunker and Bush, 1982). In other cases, Lucas et al. (1996) stated that Reynard Lake intrusion (as well as the Kaminis intrusion to the south, and intrusive sheets of the Mystic Lake assemblage) display weakly to moderately developed tectonic fabrics paralleling the shear zones as well as abundant deformed layer-parallel intrusive sheets within the shear zones themselves. Two distinct foliations have been observed in the pluton (Figure 3.5), the first of which has a northerly trend, followed by a younger set conforming to the boundaries of the intrusive bodies (Byers et al., 1965).

The granodiorite plutons in the Creighton area correspond to generally low magnetic field strength anomalies (Figures 3.6 and 3.7). Within the eastern portion of the Creighton area airborne geophysical data are available on 200 m line spacings, and covers the eastern portions of the Annabel Lake and Reynard Lake plutons. For the balance of the Creighton area, the geophysical data are on 300 to 500 m line spacings. The Reynard Lake pluton is well-defined magnetically by the flat response and exhibits a moderate-to-low magnetic background relative to the linear magnetic high anomalies of the adjacent mafic metavolcanics and the more mafic intrusions to the southeast. A number of widely spaced low amplitude magnetic anomalies are observed towards the outer edges may reflect the more granodioritic phase and/or remnants of the metavolcanics into which it intruded. These anomalies are highly coincident with detailed field mapping described as a border zone of contaminated granodiorite units with inclusions of metavolcanic rock units (Byers, 1954; Byers et al., 1965). The most magnetically homogeneous and inactive part of the Reynard Lake pluton appears to be away from the margin of the pluton, in the area neighbouring Reynard and Patmore lakes at its southeast end (PGW, 2013). This area is also highlighted by a different radiometric response compared to the remainder of the pluton, which is more potassium-dominant. The magnetic interpretation suggests the presence of small 500 m to 2 km diameter gabbro-diorite intrusions (two beneath Annabel Lake to the north of the pluton, one adjacent to Hamell Lake to the northeast, and one to the west of Creighton Lake), characterized by disruptions in the long, curvilinear anomalies that reflect the foliation in the pluton and shearing along its boundary (shown on Figure 16 of PGW, 2013). These possibly later intrusions do not appear in the southeastern portion of the Reynard Lake pluton. With the exception of the intrusion near Hamell Lake, previous mapping in the area did not note any such intrusions (NATMAP, 1998). However, the lateral extent of the Reynard Lake pluton is consistent between the available mapping and the current geophysical interpretation (NATMAP, 1998; PGW, 2013).

The variation in gravity response is in part a result of the density differences between rock types observed at surface, but is also in part related to the thickness of these rock units and deeper structures, including crustal roots (White et al., 2005). The gravity response (Figure 3.8) is generally low throughout most of the Creighton area, with the exception of metavolcanic greenstone assemblages of the eastern Amisk Lake area, which form a gravity high. The gravity coverage over the Reynard Lake pluton is too sparse to draw any conclusions. In general, the gravity field over the area is typical of a granite-greenstone domain, consisting of a mosaic of highs and lows of generally limited extent. The gravity response increases to the south and east within the Creighton area, indicating the presence of the Flin Flon greenstone belt and possibly a thinner extent for the Reynard Lake pluton relative to the Annabel Lake pluton (PGW, 2013).

Foliation within the pluton is generally parallel to the foliations present in adjacent metavolcanic rocks, and is prominent within the pluton, except in the central part of the large mass. Jointing is common at the surface and occurs as defined sets common to both plutonic and surrounding metavolcanic rocks (Byers and Dahlstrom, 1954; Byers et al., 1965).

In 1965 to 1966, a 3,066 m deep borehole was drilled vertically into the Reynard Lake pluton at a location within the larger southeastern lobe of the pluton (collar location at 54° 43.48' N, 101° 58.68' W as shown on Figure 3.4). The hole was drilled by Defence Construction Ltd. as part of a “Joint Experimental Weather Station” (JXWS) for the Royal Canadian Air Force (Gendzwill, 1968). It is therefore referred to as borehole JXWS in this report. The project was supported by the Geological Survey of Canada (GSC) and the U.S. Geological Survey (USGS). During this investigation, borehole JXWS was drilled to a depth of 3,066 m into the pluton and subsequent well logging was performed by Schlumberger of Canada Ltd. (Gendzwill, 1968; Davis and Tammemagi, 1982). The borehole was reportedly used for a seismic monitoring station and currently appears in the USGS's Advanced National Seismic System.

Core samples (1 to 2 m in length) were obtained from borehole JXWS at approximately 300 m intervals, while cutting samples were collected at 10 m intervals (Bunker and Bush, 1982; Davis and Tammemagi, 1982). The generalized lithology encountered within this drill hole consisted of pink to grey, medium-grained granodiorite to mafic granodiorite to approximately 450 m depth, followed by grey to light grey quartz diorite to approximately 2,250 m depth, in turn underlain by very dark, fine-grained mafic quartz diorite to the termination of the drill hole. The contacts between these three lithologic zones are broadly transitional (Davis and Tammemagi, 1982). Minor granitic dykes and zones with evidence of greenschist alteration were also encountered. Generally, mafic and plagioclase content increases with depth while quartz and potassium feldspar content decreases with depth. Small granitic or aplitic dykes are common, as are chlorite-rich fragments of schist (Gendzwill, 1968).

The majority of the structures identified from core samples collected from borehole JXWS and through thin section analysis appear as sub-horizontal foliations and banding with a dip ranging from 20º to 25º. However, the quality of the structural dataset from this drill hole and the effect of drill hole orientation bias are unknown. Generally, structures infer syntectonic deformation, which is consistent with the regional interpretation of the plutonic bodies within the Creighton area (Davis and Tammemagi, 1982; Hajnal et al., 1983). Microfracture frequencies were logged using the available core samples, and ranged from 0 to less than 20 fractures per metre (Davis and Tammemagi, 1982). Most of the fractures do not extend greater than 5 to 10 mm in length. Fracture filling materials include: muscovite, chlorite, quartz, calcite, epidote and opaque (mostly pyrite) minerals (Davis and Tammemagi, 1982). Further, a narrow range of radioelement concentrations at depths of 225 to 1,000 m and 2,300 to 3,054 m, as measured by Bunker and Bush (1982), suggests to these authors that the rock within these intervals consists of homogenous rock, essentially unaffected by fracturing and alteration.

A P-wave velocity profile of borehole JXWS prepared by Gendzwill (1968) indicates low velocities over the top 30 m of bedrock. Given that alteration of the granodiorite is not observed at the surface, the low velocities are likely the result of fracturing in the upper 30 m of rock. Below this depth, the velocity is in the order of 6 km/s indicating more intact conditions. At a depth of approximately 2.3 km, velocities increase and generally correspond to a gradational change in lithology from leuco-quartz diorite to denser quartz diorite. Gendzwill (1968) suggested that the quartz diorite below a depth of 2.3 km is similar to the border zone of the Reynard Lake pluton mapped at ground surface, possibly indicating the base of the pluton.

There was good correlation between downhole geophysical surveys (caliper, sonic, gamma and dipmeter) that were conducted within borehole JXWS, which indicated an apparent increase in fractures between 2,000 m and 2,700 m. However, there was insufficient core available over this interval to support the differentiation between fractures and responses due to mineralogical changes in the geophysical logs (Davis and Tammemagi, 1982). A prominent and closely spaced fracture set was noted perpendicular to the core axis at a depth of 1,917 m, and may be the result of stress relief disking and not representative of *in situ* conditions. Paucity of core samples did not allow a comparison of geophysical log responses with fractures observed in the core.

Based on borehole JXWS, the pluton extends to a depth of at least 3 km (Gendzwill, 1968). Seismic investigations suggest it extends to a depth of about 5 to 5.5 km (Bunker and Bush, 1982; Hajnal et al., 1983).

In summary, the Reynard Lake pluton is a 1.853 Ga old body of rock composed of granitoid rocks ranging from granodiorite to tonalite-quartz diorite (along the southern margin) at surface to quartz diorite below 2,000 m. It is well-defined magnetically by the flat response and exhibits a moderate-to-low magnetic background. Rock property data obtained from the JXWS borehole indicates that there is massive, homogeneous, competent, rock at typical repository depths.

3.2.1.2 Annabel Lake Pluton

The Annabel Lake pluton is located approximately 3 km to the northwest of the Town of Creighton, extending 25 km further to the west. This pluton is elongated parallel to regional shear zones in the east-west to southeast-northwest direction (see Figure 3.4), generally widening (to approximately 5 km) towards the southeast end of the pluton.

The Annabel Lake pluton was formed approximately 1.86 Ga, based on dating by Ansdell and Kyser (1990). The pluton consists of medium- to coarse-grained, foliated granodiorite, containing quartz, feldspar, biotite and hornblende. It is one of the relatively large plutons in the area emplaced in the Flin Flon greenstone belt. No specific information is available regarding the compositional homogeneity of the pluton. However, given its similar geological history to the Reynard Lake pluton, the Annabel Lake pluton is expected to have generally similar compositional zoning. The Annabel Lake pluton shows a potassium-dominant radiometric response, very similar to the northern two-thirds of the Reynard Lake pluton (PGW, 2013).

The magnetic response over Annabel Lake pluton is fairly similar to that of the Reynard Lake pluton (Figures 3.6 and 3.7). However, the Annabel Lake pluton exhibits a more active magnetic pattern than the Reynard Lake pluton that may be a reflection of a more dioritic composition. It also has two fairly distinct zones including an oval-shaped magnetically quiet area to the northwest, similar to the southeast portion of the Reynard Lake pluton, and a more magnetic area to the southeast, where foliation that conforms to the bounding shear zones and neighbouring greenstone belts is evident. Although no specific information is available regarding the compositional homogeneity of the pluton, the oval-shaped magnetically quiet area displays a distinct change in response towards the east. This change in magnetic response is coincident with the mapped change in bedrock units from granodiorite dominated in the northwest to a biotite granodiorite along the eastern portion of the pluton (Byers, 1954; Byers et al., 1965). In addition, structural lineation measurements suggest the magnetically quiescent area may represent the central portion of an elongated dome structure, whereby the axial trace runs through the center of the pluton and plunges to the west-southwest, parallel to the long axis of the pluton (Byers and Dahlstrom, 1954).

Whereas the overall background of the pluton is subdued, zones of disrupted magnetic lineaments (mainly east-west-striking) are evident throughout the pluton and are particularly strong between Amer Lake and Creighton Lake. In this area, there may be more mixing of metavolcanic and plutonic rocks compared to what has been mapped (Simard et al., 2010). Similar to the Reynard Lake pluton, the magnetic interpretation suggests the presence of small 500 m to 2 km diameter gabbro-diorite intrusions (i.e., four west-centrally located features), characterized by disruptions in the long, curvilinear anomalies that reflect the foliation in the plutons and shearing along their boundaries (PGW, 2013). Agreement with available mapping with respect to these features shows some inconsistencies although the magnetic signatures might be reflecting (unexposed) rocks at depth. For example, the available geophysical interpretation suggests that the pluton extends further to the northeast towards Black Lake and Hamell Lake (NATMAP, 1998; PGW, 2013). However, the lateral extent of the remainder of the pluton is generally consistent between the available mapping and the current geophysical interpretation.

As mentioned above in Section 3.2.1.1, the gravity response (Figure 3.8) is generally low throughout most of the Creighton area. The bulk of the gravity stations were located along Highway 106 (Figure 3.8). This survey line therefore crossed the northern edge of the Annabel Lake pluton, and the resultant Bouguer anomaly map reveals a >20 mGal negative anomaly across the pluton. This suggests that the Annabel Lake pluton may extend to depths in the range of 5 to 5.5 km (Hajnal et al., 1983).

Mineral foliation within the pluton appears to define an elongated domal shape. The axial trace of this elongated dome runs through the center of the pluton and plunges to the west-southwest, parallel to the long axis of the pluton (Byers and Dahlstrom, 1954). Foliation within the Annabel Lake pluton is generally parallel to foliations present in adjacent metavolcanic rocks, and is prominent within the pluton, except in the central part of pluton.

Jointing is common at ground surface and occurs as defined sets common to both plutonic and surrounding metavolcanic rocks (Byers and Dahlstrom, 1954; Byers et al., 1965).

No specific information at depth within the Annabel Lake pluton was found through available sources.

In summary, the Annabel Lake pluton is a 1.86 Ga old body of rock that is composed of granodiorite near surface and may have lithological zoning, as observed in the Reynard Lake pluton. The Annabel Lake pluton exhibits a more active magnetic pattern than the Reynard Lake pluton, which may be a reflection of a more dioritic composition. It also has two fairly distinct zones including an oval-shaped magnetically quiet area to the northwest. Given its similar geological history to the Reynard Lake pluton, the Annabel Lake pluton is expected to be generally similar in thickness and have similar rock characteristics.

3.2.1.3 Phantom-Boot Lake Pluton

The Boot Lake and Phantom Lake plutons have been traditionally assumed to be different phases of a same magmatic episode (e.g., Galley and Franklin, 1987; Thomas, 1989). However, Ansdell and Kyser (1992) pointed out that they are not petrogenetically linked as evidenced from their respective geochemistry. While the Boot Lake pluton (as well as the Annabel and Reynard Lake plutons) may have originated from partial melting of crustal rocks, the Phantom Lake pluton could not have originated from partial melting of a depleted mantle source or of typical volcanic Amisk rocks based on geochemical signatures; its magma in turn derived from another distinct source (Ansdell and Kyser, 1992). However, due to the collective size and close proximity of these plutons, they are discussed together in this report and referred to as the Phantom-Boot Lake pluton.

The Phantom-Boot Lake pluton is located approximately 2 km to the south of the settlement area of Creighton. Compared to Reynard Lake and Annabel Lake plutons, the Phantom-Boot Lake pluton is a relatively small intrusive body, measuring approximately 6 km long (in the north-south direction) by 2 km wide (in the east-west direction) (see Figure 3.4).

Detailed 1:10,000 scale mapping by Simard et al. (2010) provides lithological and structural information for the northern third of the Phantom-Boot Lake pluton. A small portion of the northern tip of the pluton was mapped at a scale of 1:3,000 by MacLachlan (2006a). To the south of Bootleg Lake, less detailed information is available for this pluton, and coarser scale maps have been relied upon (Byers et al., 1965; NATMAP, 1998; Saskatchewan Industry and Resources, 2010).

The Phantom-Boot Lake pluton is considered a successor-arc intrusion that was emplaced later in the tectonic evolution of the area and at shallower depths than the Reynard Lake and Annabel Lake plutons (Ansdell and Kyser, 1990; NATMAP, 1998; and Simard et al., 2010). The pluton consists of two intrusions that are considered coeval. Ansdell and Kyser (1990) dated a granodiorite phase of the Boot Lake pluton at approximately 1.842 Ga and a granite phase of the Phantom Lake pluton at approximately 1.840 Ga, respectively. They also obtained an age of approximately 1.834 Ga for the associated granite dykes of the Phantom Lake pluton. Heaman et al.

(1992) in turn obtained an age of approximately 1.838 Ga for both a monzogranodiorite phase of the Boot Lake pluton and a granodiorite phase of the Phantom Lake pluton.

The Phantom Lake intrusion is composed of fine- to medium-grained porphyritic granodiorite-tonalite with a massive to banded texture (Guliov, 1989; Simard et al., 2010). This intrusion occurs along the southwest shore of Phantom Lake (Figure 3.4). Surface mapping of fractures within the Phantom Lake granite has been conducted for building stone purposes (Guliov, 1989). However, the generated maps do not provide sufficient information for spatial correlation with other maps. The mapping does indicate that surface fracturing is common, with a vertical to sub-vertical orientation. Guliov (1989) suggested that the observed surface fractures may not extend to great depth, but no information has been collected at depth.

The Boot Lake intrusion wraps around the Phantom Lake intrusion to the west, southwest, and through to the south (Figure 3.4). This intrusion is zoned and has been further subdivided into two general rock types including a granodiorite to quartz diorite, and quartz-diorite to gabbro (Simard et al., 2010). The second unit constitutes part of a lobe of rock along the northwest side of the pluton. Simard et al. (2010) considered this unit to be part of the pluton, whereas the Geological Atlas of Saskatchewan (Saskatchewan Industry and Resources, 2010) maped this as a separate unit. For the purposes of this assessment, the entire lobe of quartz-diorite to gabbro is included as part of the pluton, given that Thomas (1990) mapped the area at a finer scale (1:10,000) than the Geological Atlas of Saskatchewan (1:100,000).

The Phantom-Boot Lake pluton is complex from both a geological and geophysical perspective. The geological mapping in this area shows a complicated distribution of intrusive phases adjacent to the metavolcanic rocks. The magnetic amplitudes over this pluton are the strongest and more variable compared to any of the other intrusive rocks in the area (Figure 3.6). This could suggest a more dioritic-gabbroic composition than the Reynard Lake and Annabel Lake plutons. Multiple phases are evident in both the magnetic and radiometric data, at scales of a kilometre or less. The phases have been subdivided in the magnetic interpretation according to variations in anomaly amplitudes, widths and orientations (PGW, 2013). The core of the Phantom Lake pluton shows northeast-oriented foliations whereas to the southwest in the vicinity of Boot Lake, the foliations run north-northwest as they do in the adjacent greenstones. Ultramafic and/or gabbro-diorite units likely occur under the swampy region east of Mystic Lake. The gravity coverage over the pluton is too sparse to draw any conclusions about the thickness of the pluton.

Brittle structures have been mapped around the perimeter of the pluton (see Figure 3.4), with the exception of the south, which is predominantly covered by wetlands. The Rio fault is located along the northwest edge of the pluton (Simard and MacLachlan, 2009; Simard et al., 2010). This fault separates the northern lobe of quartz-diorite and gabbro from the surrounding greenstones (Simard et al., 2010).

Mineral foliation within the Phantom-Boot Lake pluton appears to strike predominantly in a northward direction, generally parallel with the long axis of the pluton. Lineations trend southward and plunge at approximately 40º to 50º (Byers and Dahlstrom, 1954; Byers, et al., 1965; Simard et al., 2010).

There are several boreholes near the perimeter of the Phantom-Boot Lake pluton, specifically near the Rio fault along the northwest edge of the pluton. However, these boreholes targeted the surrounding greenstones and no specific information at depth within the Phantom-Boot Lake pluton was found through available information sources.

In summary, the Phantom-Boot Lake pluton is a zoned granitic to gabbroic body which is younger than the Reynard Lake and Annabel Lake plutons. The Phantom-Boot Lake pluton was probably emplaced at shallower depths than the other nearby plutons and is of unknown thickness. It is proximal to a number of faults that are of interest from a mineral exploration perspective (see Section 5.0). Major faults are located along the northwest side of the pluton as well as within the pluton. The approximate spacing between these mapped faults is in the order of 100 m to 1 km (Simard et al., 2010).

3.2.1.4 Flin Flon Greenstone Belt

The greenstone belt rocks in the Creighton area were not considered as potentially suitable for hosting a deep geological repository in the initial screening due to their composition, structural complexity and resource potential (Golder, 2011). However, they are described here for completeness and context.

The majority of the Town of Creighton itself is underlain by metavolcanic rocks of the Flin Flon greenstone belt. These rocks extend to the north, east, southeast and southwest of the Town. Four tectonostratigraphic assemblages have been recognized within the Flin Flon greenstone belt. These include: juvenile oceanic arc (ca. 1.9 to 1.88 Ga), oceanic floor (ca. 1.9 Ga), oceanic plateau/ocean island (undated), and evolved arc (ca. 1.92 to 1.9 Ga). These rocks are the oldest in the Creighton area, and they consist of basic original volcanic flows, pyroclastic rocks, and lesser amounts of acidic to intermediate volcanic rocks and clastic rocks (Bailes and Syme, 1989; Syme et al., 1996; Lucas et al., 1999; Bailey and Gibson, 2004; Simard et al., 2010). This assemblage also includes dykes, sills, and small intrusive porphyritic bodies (Simard et al., 2010). Rocks of the Flin Flon greenstone belt are heterogeneous and variable in type, and are arranged in layers of variable thickness and lithological compositions (Byers and Dahlstrom, 1954). Due to the complex structure (folding and faulting) within the Flin Flon greenstone belt, thickness of individual lithologies and stratigraphic interpretation within the assemblage can be difficult (NATMAP, 1998; Simard et al., 2010). It has been estimated that these rocks are approximately 4 to 6 km thick in the Creighton-Amisk Lake area (Byers and Dahlstrom, 1954; Byers et al., 1965). More recent estimates suggest they are in the order of 10 to 20 km thick (Lucas et al., 1994; Hajnal et al., 1996; White et al., 2005).

3.2.1.5 Metasedimentary Rocks of the Missi Group

The metasedimentary rocks of the Missi Group in the Creighton area were also not considered as potentially suitable for hosting a deep geological repository in the initial screening due to their composition (sandstone, conglomerate and metagreywacke) (Golder, 2011). However, they are described here for completeness and context.

The Flin Flon greenstone belt is unconformably overlain by interlayered metasedimentary conglomerates, wackes and arkoses of the Missi Group, which is a sequence of synorogenic fluvial molasse deposits (Byers et al., 1965; Davis and Tammemagi, 1982; Ansdell and Kyser, 1990; Simard et al., 2010). Rocks of the Missi Group are found to the north and east of the Creighton area. These rocks are interpreted to have been deposited during regional uplift in a collisional tectonic environment, and are approximately 1.847 to 1.842 Ga old (Fedorowich et al., 1993; Simard et al., 2010). The thickness of the rocks of the Missi Group is estimated to be approximately 1 to 2.75 km (Byers and Dahlstrom, 1954; Byers et al., 1965).

3.2.2 Quaternary Geology

Overburden deposits within the Creighton area were mapped as part of a regional surficial mapping program covering the Precambrian shield of Saskatchewan and undertaken between 1974 and 1984 by the

Saskatchewan Research Council under contract to the Saskatchewan Geological Survey (Schreiner, 1984a). Field investigations were preceded by interpretation of aerial photographs at a scale of about 1:60,000 and photo-mosaics at a scale of about 1:50,000. Much of the field campaign consisted of shoreline mapping around lakes sufficiently large to accommodate float-equipped aircraft, with additional field investigations conducted along roads where exposures and borrow pits provided valuable sections. Schreiner et al. (1975) summarized the field investigations that form the basis of the 1:250,000 scale surficial geology map sheet covering the Creighton area (Schreiner, 1984b); these involve 92 sites of which 17 were auger holes. Four of the 17 auger holes in the map sheet were completed within the Creighton area along Highway 106 (auger holes EC-101 to 104), with lithologic strip logs presented in the map margin.

Surficial geology mapping in the late 1980s (Campbell, 1987; 1988) and in the 1990s (Henderson and Campbell, 1992; Henderson, 1995) in support of gold and base metal exploration resulted in two 1:50,000 scale surficial geology maps covering the Saskatchewan portion of the Creighton area (Figure 2.3) including GSC Map 1919A (Campbell and Henderson, 1997) and GSC Map 2010A (Henderson, 2002). These maps include an estimate of overburden thickness. Two additional maps cover the Manitoba portion of the Creighton area (McMartin, 1997; Henderson and McMartin, 2008).

With reference to Figure 2.3, Quaternary deposits in the Creighton area comprise glaciolacustrine and glaciofluvial sediments, till, and organic plains, with generally thin and discontinuous drift cover. Where glacial deposits cover topographic highs in the bedrock surface, sediments are generally thin (veneer like) and less than 1 m thick (Davis and Tammemagi, 1982; Hajnal et al., 1983; Schreiner, 1984a; Henderson and Campbell, 1992; Henderson, 2002). Bedrock and thin veneer (<1 m) comprise 38% of the Creighton area. Thicker overburden deposits tend to occur in low lying areas. For example, borehole records from the Saskatchewan Industry and Resources Geological Atlas of Saskatchewan (2010) indicate that the Quaternary deposits can be up to 70 m thick in discrete areas between Douglas and Phantom lakes, and around Amisk Lake.

The Quaternary units originated from the Wisconsinan glaciations as a result of the interplay between the retreat of the ice sheet and the inundation of the area by Glacial Lake Agassiz, which covered the entire Creighton area approximately 10,000 to 9,000 years ago. Two till units have been recognized in the area (Henderson and Campbell, 1992). A lower till unit consists of grayish brown sandy and silty material, which was deposited subglacially. This lower till underlies glaciolacustrine deposits. It is fairly widely distributed east of Amisk Lake, whereas it has not been recognized north of Annabel Lake. The upper till unit overlies glaciolacustrine sediments as a thin veneer in places throughout the Creighton area. East of Amisk Lake, this unit is brown, massive to laminated, with a silty sand matrix, typically less than 1 m thick. North of Annabel Lake, it occurs within or overlying the glaciolacustrine sequence.

Glaciofluvial and glaciolacustrine deposits comprise the most prominent surficial sediments in the Creighton area. They are primarily ice proximal and near shore sediments of well sorted, horizontally bedded sand and gravel, as well as deep water deposits of massive to bedded fine sand, silt and clay. North of Annabel Lake, they reach more than 20 m of thickness extending in a 3 to 5 km wide west-east-trending belt, whereas east of the Amisk Lake they form north-south, long discontinuous linear features (Henderson and Campbell, 1992).

The following sections describe the Quaternary geological conditions above the Reynard Lake, Annabel Lake and Phantom-Boot Lake plutons.

3.2.2.1 Reynard Lake Pluton

Approximately 31% of the surface of the Reynard Lake pluton consists of exposed bedrock (Figure 3 in JDMA, 2013a). Another 33% of the surface of this pluton is covered by only a thin veneer (<1 m) of till or glaciolacustrine sediments. As such, approximately 64% of the Reynard Lake pluton is relatively exposed. The area within the pluton displaying the greatest bedrock exposure is located in the east-central portion of the pluton (to the north of Highway 106 and near Reynard and Patmore lakes). This generally coincides with the wider lobe of the pluton. The surface of the pluton is interspersed with peat bog and discontinuous patches of silt and clay. These patches of overburden are sporadic and fill low-lying areas on the pluton that have poor drainage.

Thicker overburden deposits are mapped within the valleys associated with the shear zones on the north and south sides of the pluton (Campbell and Henderson, 1997; Henderson, 2002). These deposits include till, silt, clay and organic deposits. To the north, narrow bands of sand and gravel deposits are up to approximately 20 m thick in the valleys associated with Wilson and Meridian Lakes. Similar sand and gravel deposits with greater lateral extent occur between the pluton and Amisk Lake to the south (Henderson, 2002). These units may form local aquifers (see Section 4.0).

3.2.2.2 Annabel Lake Pluton

The Annabel Lake pluton is mapped with a similar degree of bedrock exposure as the Reynard Lake pluton (Figure 2.3). Approximately 32% of the Annabel Lake pluton has been mapped as exposed bedrock, and another 28% has been mapped as having a thin (<1 m) till or glaciolacustrine veneer, for a total of 60% of the pluton being relatively exposed. Exposed bedrock dominates the eastern half of the Annabel Lake pluton, over the wider portion of the pluton located near Creighton Lake. The proximity of this outcrop area to the former Hudson Bay Mining and Smelting (Hudbay) activities has resulted in very low coverage by vegetation (Figures 2.1 and 2.3). Within this area of exposed bedrock, patches of peat bog, fens, swamp or marsh fill low lying areas with poor drainage. Further west, a band of thin till veneer generally less than 1 m thick covers the central portion of the pluton. Patches of organics, glaciolacustrine silts and clays are associated with this band of till. Bedrock exposure improves toward the west, centered on the pluton's wider lobe in the west (Campbell and Henderson, 1997).

Thicker overburden deposits are mapped within the valleys associated with the shear zones on the north and south sides of the pluton (Campbell and Henderson, 1997). These deposits include till, silt, clay and organic deposits. Narrow bands of sand and gravel deposits up to approximately 20 m thick occur in the valleys associated with Wilson and Meridian lakes to the south of the pluton. A similar narrow band of sand and gravel occurs to the north of the pluton near Hamell Lake. These deposits extend west toward Annabel Lake and may be related to a relatively large glaciofluvial deposit to the north of Annabel and Johnson lakes.

3.2.2.3 Phantom-Boot Lake Pluton

Significant amounts of peat bog (27%) and water (20%) cover the Phantom-Boot Lake pluton (Campbell and Henderson, 1997; JDMA, 2013a). Till veneer with some glaciofluvial deposits are found immediately north and west of Boot Lake (Figure 2.3). Larger patches of sand and gravel deposits cover eastern portions of the pluton. Approximately 26% of the pluton is covered by relatively thick overburden. The remaining 27% of the Phantom-Boot Lake pluton has been mapped as exposed bedrock or as having a thin glaciolacustrine veneer.

3.2.3 Lineament Investigation

A detailed lineament investigation was conducted for the Creighton area using multiple datasets that included satellite imagery (SPOT), digital elevation model data (CDED), and geophysical (aeromagnetic) survey data (JDMA, 2013b). Lineaments are linear features that can be observed on remote sensing and geophysical data and which may represent geological structures (e.g. fractures). However, at this stage of the assessment, it is uncertain if interpreted lineaments are a reflection of real geological structures, and whether such structures extend to depth. The assessment of these uncertainties would require detailed geological mapping and borehole drilling.

The lineament investigation identified interpreted brittle structures and ductile lineaments in the Creighton area, and evaluated their relative timing relationships within the context of the local and regional geological setting. A detailed analysis of interpreted lineaments is provided by JDMA (2013b) and key aspects of the lineament investigation are summarized in this section.

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

- ***Ductile lineaments:*** Features which were interpreted as being associated with the internal fabric of the rock units (including sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation) were classified as ductile lineaments. This category also includes recognizable penetrative shear zone fabric. These features are included to provide context to our understanding of the tectonic history of the Creighton area, but were not included in the merged lineament sets or statistical analyses.
- ***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 reactivation parallel to the ductile fabric, including shear zones. 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 the area; expert judgement; and to a certain extent, the quality of the pre-existing knowledge of the bedrock geology of the Creighton 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.

For each dataset, brittle lineaments were interpreted by two independent expert interpreters using a number of attributes, including certainty and reproducibility (JDMA, 2013b). The certainty attribute describes the clarity of the lineament within each dataset based on the judgement of the interpreter (i.e., with what certainty a feature is interpreted as a lineament). Reproducibility was assessed in two stages (RA_1 and RA_2). Reproducibility assessment RA_1 reflects the coincidence between lineaments interpreted by the two expert interpreters. Reproducibility assessment RA_2 reflects the coincidence of interpreted lineaments between the different datasets used.

In addition, ductile geophysical lineaments, including all interpreted features which conform to the penetrative rock fabric in the Creighton area, such as stratigraphic and 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 (PGW, 2013). These ductile lineaments are included to provide context to the tectonic history of the Creighton area, but were not included in the merged lineament sets or statistical analyses.

The SPOT and CDED datasets (Figures 2.1 and 2.2, respectively) were used to identify surficial lineaments expressed in the topography, drainage and vegetation. The SPOT dataset has a uniform resolution of 10 m (panchromatic) and 20 m (multispectral) over the entire Creighton area (JDMA, 2013b). The CDED dataset is at a 1:50,000 scale, with a uniform 20 m resolution over the entire Creighton area (JDMA, 2013b). A finer contour interval (25 foot) was used in the construction of the CDED over the western two-thirds of the Creighton area, whereas a lower resolution 50 foot contour interval was used in the east (from SRTM data). 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.

Aeromagnetic datasets (Figures 3.6 and 3.7) were used to identify linear geophysical anomalies indicative of bedrock structures. Regional intermediate to low resolution data (at 300 to 500 m line spacing) is available for the entire Creighton area. Two additional magnetic/electromagnetic surveys obtained from Hudbay provided higher resolution (200 m line spacing) coverage over approximately 20% of the Creighton area to the east (Figure 1.2). The available geophysical coverage allowed for the identification of geophysical lineaments in the order of 1 km or longer in length.

Figure 3.9 shows the combined surficial lineaments (SPOT and CDED). The lineaments shown on Figure 3.9 consist of a merged dataset from two different interpreters. That is, they are the results of reproducibility assessment 1 (RA_1) described by JDMA (2013b). The results shown in Figure 3.9 depict the results from the RA_1 analysis, binned into four length categories (<1 km, 1 to 5 km, 5 to 10 km, >10 km). The SPOT dataset yielded a total of 693 surficial lineaments, ranging from 131 m to 34.1 km in length, with a geometric mean length of 1.1 km, while the CDED dataset yielded a total of 429 lineaments, ranging from 229 m to 31.7 km long, with a geometric mean length of 1.6 km. The frequency and distribution of surficial lineaments (especially shorter <1 km lineaments) was seen to be influenced by overburden coverage in the area (Figure 3.9). However, drift cover in the Creighton area is generally thin (less than 1 m) over the two larger plutons (i.e., Annabel Lake and Reynard Lake plutons) with thicker overburden deposits confined to topographic lows. Thicker overburden is noted over a greater proportion of the Phantom-Boot Lake pluton toward the southeast. 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 dataset yielded a total of 927 lineaments, 280 interpreted as brittle faults and 647 interpreted as ductile features (Figures 3.10 and 3.11, respectively). Again, the lineaments are categorized according to the length bins mentioned above. As described above, Figure 3.10 consists of a merged dataset from two different interpreters (i.e., RA_1 described by JDMA (2013b)). The ductile lineaments in Figure 3.11 were interpreted by an automated picking routine and confirmed by a single specialist observer (PGW, 2013). The length of the brittle geophysical lineaments ranged from 1 km to 41.3 km, with a geometric mean length of 6.2 km. The density and distribution of geophysical lineaments is influenced by the resolution of the geophysical coverage.

The frequency of geophysical lineaments is higher in areas of high data resolution such as in the eastern third of the Creighton area which includes the eastern lobes of the Annabel Lake and Reynard Lake plutons. This observation suggests that the western portions of these plutons may have shown a similar geophysical lineament density if higher resolution aeromagnetic data was available. The frequency of shorter lineaments could be similar in areas not covered by high resolution aeromagnetic data, but remain undetectable due to the low resolution aeromagnetic coverage.

Aeromagnetic features interpreted as ductile structures have been mapped separately and are shown on Figure 3.11. Such features are particularly useful in identifying the degree of deformation within the greenstone belts. For example, the D_4 Embury Lake flexure is evident in this dataset to the northeast of Hamell Lake. They also reveal some ductile deformation that occurred along the margins of the plutons which are interpreted as D_3 features related to the major shear zones. It should be noted that the density of these features is also influenced by the resolution of the geophysical coverage.

The geophysical lineament data has advantages over surficial lineament data in that it is minimally affected by overburden cover, which may partially or completely mask surficial lineaments. Importantly, aeromagnetic data allows interpretation of lineaments from the surface to potentially great depths.

Figure 3.12 shows the distribution of brittle lineaments from the merged surficial and geophysical datasets, classified by length. The merged lineament dataset yielded a total of 1,107 lineaments, ranging from 131 m to 41.3 km in length, with a geometric mean length of 1.7 km.

JDMA (2013b) noted the following trends in the final merged lineament dataset.

- Longer lineaments generally have a higher certainty and reproducibility.
- Areas defined by higher lineament density tend to correspond to areas with better bedrock exposure and higher resolution geophysical data.
- There is a greater coincidence between surficial lineaments (14% coincidence between CDED and SPOT) than between geophysical lineaments and surficial lineaments (9% of geophysical lineaments are observed in surficial datasets), presumably since surficial lineaments interpreted from CDED and SPOT are expressions of the same bedrock surficial feature.
- The low coincidence between surficial and geophysical lineaments is presumably due to a variety of factors. For example, the structures identified in the aeromagnetic data 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 infilling or overburden; and the geometry of the feature (e.g., dipping versus vertical). These factors are also constrained by the resolution of the differing datasets. At 500 m flight line spacing, small features or features in the aeromagnetic dataset oriented at a low angle to the flight lines may not be as recognizable as in the available surveys with 200 m line spacing.

A rose diagram of length-weighted orientations of brittle lineaments is provided on Figure 3.12. There are several broad lineament trends in the merged lineament dataset based on length-weighted frequency. The most prominent trend is toward the north, with a wide range from north-northwest to north-northeast. There is also a prominent east- to east-southeast trend. Another notable trend is to the northeast. The above trends are all evident in the aeromagnetic lineaments except that the north-northeast and north-northwest trends are individually more distinguished (see rose diagram on Figure 3.10). The northerly trend was especially prominent in the CDED dataset, while the SPOT dataset highlights the east-west trend (Figures 9 and 10 in JDMA, 2013b). The reason for this may be due to the low relief on the plutons, combined with some features not resolved with the elevation data, but are visible in the SPOT data. An example of this occurs at the east end of the Annabel Lake pluton where numerous east-trending lineaments are visible in the SPOT image, but are unresolved in the CDED data. Lineament orientation trends for the individual plutons in the Creighton area (i.e., Annabel Lake pluton, Reynard Lake pluton and Phantom-Boot Lake pluton) are presented on Figure 3.13 and further discussed in the geologic formation-specific subsections below.

Figures 3.14 to 3.17 were produced in order to provide some insight into the influence of lineament length on the distribution of lineament density across the Creighton area. This set of figures shows the progressive filtering (removing) of lineaments corresponding to the same length bins used above (<1 km, 1 to 5 km, 5 to 10 km, >10 km), and with the remaining lineaments plotted on top of the density gradient. In other words, Figure 3.14 includes all lineaments as shown in Figure 3.12 and with a background showing the same information as a density gradient map (in km/km^2). Figure 3.15 filters out the <1 km long lineaments and so the underlying density gradient map represents only those lineaments 1 km in length or greater. The same is done, in a step-wise manner, for Figure 3.16 (filtering all lineaments <5 km) and for Figure 3.17 (filtering all lineaments <10 km). In general, the figures show that filtering out the shorter lineaments greatly increases the spacing between lineaments, including within areas having more exposed bedrock and higher resolution aeromagnetic surveys. For example, Figure 3.17 shows that there are areas within the Annabel Lake and Reynard Lake plutons that contain relatively few lineaments that are longer than 10 km, leaving large volumes of rock between interpreted long lineaments. Also, filtering out the shorter lineaments appears to reduce the effects of both variable overburden cover (in the case of surficial lineaments) and low resolution aeromagnetic surveys on lineament density. For example, the Annabel Lake pluton, with well-exposed bedrock and high resolution aeromagnetic surveys in the east, exhibits very high lineament densities when all lineaments are shown but when the shorter lineaments are filtered out the lineament density is greatly reduced and becomes more comparable to the west end of the pluton (with greater overburden cover and lower geophysical resolution).

Figure 3.18 shows the combined datasets (i.e., mapped regional faults, brittle lineaments, major shear zones and ductile lineaments) which helps provide a structural understanding of the Creighton area. As discussed in Section 3.1.3, the major shear zones in the area include the Annabel Lake shear zone, the West Arm shear zone and the Mosher Lake shear zone. These ductile-brittle shear zones largely bound the Annabel Lake and Reynard Lake plutons (Figures 3.4 and 3.5) and are interpreted to have originated as ductile D_2 structures with later D_3 and D_4 (and likely D_5 to D_6) reactivation along these planes of weakness (Section 3.1.3). The most reliable parameter in identifying these shear zones through the lineament analysis appears to be coincidence amongst datasets (RA_2 value). These mapped features were observed in all three datasets (RA_2 = 3) used to identify lineaments over a significant portion of their mapped length (Figure 3.18). Lineament length also assists in the identification of these features. All of the major shear zones are represented by lineaments greater than 10 km long over most of their mapped length. This increases the confidence in the ability of the lineament analysis to identify important structures that likely extend to repository depth. A number of (D_3) structures that are bent by the (D_4) Embury Lake flexure were mapped in both the SPOT and CDED datasets (RA_2 = 2). Examples to the east of the Creighton area include several long (>10 km) faults that wrap around Embury Lake including the Manistikwan fault that runs along the south side of the lake.

The most notable mapped brittle structure in the area is the Ross Lake fault system which also includes a mosaic of brittle fault splays throughout the Creighton area. This fault system is matched by segments of coincident (RA_2 = 3) geophysical and surficial lineaments. Coincidence between all three datasets occurs for short (1 to 5 km) segments of this fault system. In this case, coincidence appears more important than length for identifying these splays. However, the spatial positioning of these shorter RA_2 = 3 lineaments suggests that they could be combined into one long feature. Further, coincidence between two independent datasets was noted for a number of long faults that are likely part of the Ross Lake fault system (RA_2 = 2). For example, the Cliff Lake fault located approximately 4 km to the east of Creighton was mapped using the SPOT and CDED datasets.

The following subsections describe the characteristics of the interpreted lineaments for each of the main intrusive bodies in the area, as well as the relative age of the lineaments identified in the Creighton area.

3.2.3.1 Reynard Lake Pluton

A total of 205 lineaments were mapped over the Reynard Lake pluton (Figure 3.12), which covers an area of 90 km^2. Many of the long interpreted lineaments extend beyond the pluton into the metavolcanic rocks of the greenstone belt and adjacent plutons. Lineaments over the Reynard Lake pluton range in length from <100 m to 9.6 km and have a geometric mean length of 2.6 km. Orientations of these lineaments were weighted by length and plotted on a rose diagram (Figure 3.13), which shows three dominant orientations within the pluton including one widely distributed group from the north-northwest to north-northeast, to the northeast and an east- to east-southeast group.

Interpreted surficial lineaments (Figure 3.9) range in length from approximately 100 m to 4.2 km over the Reynard Lake pluton. The surficial lineament density is variable across the pluton. This is likely due to the lower overburden cover present in the northeastern portion of the pluton associated with the former Hudbay smelting activities.

Interpreted geophysical lineaments (Figure 3.10) range in length from approximately 200 m to 11.4 km over the Creighton area. Notably, the longer east- to east-southeast-trending lineaments are present in, and unique to, this dataset. The geophysical lineament density based on the available data is generally low towards the west. Lineament density shows an increase toward the east where the higher resolution datasets overlap the eastern lobe of the Reynard Lake pluton. The density variation is primarily a result of the variable aeromagnetic data resolution and it is therefore likely that a similar density of lineaments exists across the entire pluton.

The highest degree of coincidence between the interpreted lineaments and mapped structures is observed for the West Arm shear zone and the Mosher Lake shear zone to the north and south of the Reynard Lake pluton, respectively. The West Arm shear zone is greater than 30 km long, and was mapped using all three datasets (RA_2 = 3) over almost its entire length. Based on this comparison, it is perhaps the most prominent feature in the Creighton area that likely extends to repository depth. Another prominent feature of similar magnitude is a long (>10 km, RA_2 = 3) lineament in the western third of the pluton. This lineament cuts through the Reynard Lake pluton and the Annabel Lake pluton to the north. To the south, it bends into the mapped Mosher Lake shear zone. This lineament and the Mosher Lake shear zone both have the potential to extend to repository depth.

3.2.3.2 Annabel Lake Pluton

A total of 321 lineaments were mapped over the Annabel Lake pluton (Figure 3.12), which covers an area of 89 km^2. As shown on Figure 3.12, brittle lineaments interpreted in the Annabel Lake pluton (JDMA, 2013b) extend beyond the pluton into the metavolcanic rocks of the greenstone belt, as well as the adjacent plutons. The Annabel Lake pluton has good bedrock exposure and high resolution aeromagnetic survey coverage over the eastern lobe of the pluton. Within the Annabel Lake pluton, the mapped lineaments range in length from 400 m to 7.8 km and have a geometric mean length of 1.6 km. Azimuths of the lineaments mapped over the Annabel Lake pluton were weighted by length and plotted on a rose diagram (Figure 3.13). The results show a somewhat uniform distribution of orientations, with slightly more prominent east, northeast and northwest trends.

Figure 3.9 shows the surficial lineament distribution over the Annabel Lake pluton. These lineaments range in length from approximately 400 m to 6.1 km. The surficial lineament density shows a higher density over the eastern half of the pluton than the west part of the pluton. This may be due to less overburden cover over the Annabel Lake pluton in the east. The curvilinear lineaments have been interpreted as brittle-ductile and may be associated with internal foliation or compositional variations. Further, vegetation cover is particularly low at the east end of the pluton due to the proximity of the nearby smelter’s smoke stack, and so the variation in interpreted surficial lineament density is likely due to greater visibility of surface features.

Figure 3.10 shows the geophysical lineament distribution over the Annabel Lake pluton. These lineaments range in length from approximately 1.1 km to 7.8 km. The geophysical lineament density across the Annabel Lake pluton is relatively uniform compared to the surficial lineaments, with a slightly higher density in the east due to the high resolution aeromagnetic data coverage over the eastern portion of the pluton.

As noted above for the Reynard Lake pluton, the highest degree of coincidence between the interpreted lineaments and mapped structures is observed for the major shear zones including the Annabel Lake shear zone and the West Arm shear zone which was discussed above. The Annabel Lake shear zone is greater than 20 km long, and was mapped using all three datasets (RA_2 = 3) over at least half of its entire length. The same prominent (>10 km long, RA_2 = 3) lineament discussed in Section 3.2.3.1 cuts through the Annabel Lake pluton just west of its center.

3.2.3.3 Phantom-Boot Lake Pluton

A total of 60 lineaments were identified within the Phantom-Boot Lake pluton which covers an area of 14 km^2 (Figure 3.12). Some of these lineaments extend beyond the pluton into the metavolcanic rocks of the greenstone belt, as well as the adjacent plutons. Lineament orientations for the Phantom-Boot Lake pluton (Figure 3.13) show main trends to the northeast, north, northwest and east. The northeastern trend is the most dominant trend observed. As with the other intrusions, the density of lineaments identified in the Phantom-Boot Lake pluton appears to be closely related to the extent of overburden cover and the low resolution of the available aeromagnetic data.

Figure 3.9 shows the surficial lineament distribution over the Phantom-Boot Lake pluton. These lineaments range in length from approximately 400 m to 2.8 km and have a geometric mean length of 1.0 km. The surficial lineament density is low across the pluton, due to the greater proportion of overburden and lake cover on this pluton relative to the others.

Only small patches of higher resolution aeromagnetic data are available in the north and south ends of the pluton. Figure 3.10 shows the geophysical lineament distribution over the Phantom-Boot Lake pluton. These lineaments range in length from 500 m to 4.1 km. The geophysical lineament density across the Phantom-Boot Lake pluton is relatively high, despite the low resolution aeromagnetic data available for the pluton.

The highest degree of coincidence between the interpreted lineaments and mapped structures is observed for the Dion Lake fault which borders the pluton to the north (Figure 3.18). This fault was mapped as an RA_2 =2 lineament to the southwest of the pluton. Some of the mapped faults to the east of the pluton appear to correspond with the geophysical lineaments, with some offset. The offset may be the result of the geophysical data detecting the feature at depth.

3.2.3.4 Relative Age Relationships of Lineaments

As discussed in Section 3.1.3, there are a number of mapped structural features in the Creighton area with established relative age relationships. This section integrates the observed lineaments with the structural history of the area, based on the available information. This interpretation, which may be refined as more information becomes available, was used at this stage to assist with the understanding of the relative importance of lineament sets.

The major shear zones in the Creighton area were initially developed during the regional D_2 deformation event, reactivated during the D_3 event, and subsequently modified during the D_4 event. They are curvilinear features, reflecting their ductile to brittle-ductile nature and have orientations that generally range from east-west to southeast. As mentioned above, coincident lineaments from all three independent datasets (geophysical and surficial lineaments with RA_2 = 3) are noted for all of the major shear zones over significant portions of their mapped length. As such, these lineaments can be classified, with some degree of confidence, as D_5-D_6 structures formed by reactivation of the composite D_2-D_4 structures (Figure 3.18).

Numerous short lineaments within the plutons can be correlated to the shear zones based on a similar orientation. The visibility of these features is strongly influenced by overburden cover. They are responsible for the high lineament density in areas with very good bedrock exposure. They also have a low degree of coincidence between the SPOT, CDED and aeromagnetic datasets. These short lineaments may be related to D_2-D_4 but are not interpreted to be features that extend to repository depth. These short, curvilinear lineaments have been interpreted as brittle-ductile and may be associated with internal foliation, compositional variations or possibly the surface expression of the shallow (<100 m deep) fracture system typical of the Canadian Shield (see Section 6).

The major D_2-D_4 shear zones are also crosscut by younger D_5-D_6 faults. This is best shown in the area by the Ross Lake fault which is interpreted to have formed during the fifth deformation stage (D_5) (Ansdell and Kyser, 1990; Fedorowich et al., 1993, 1995; NATMAP, 1998; Saskatchewan Industry and Resources, 2010) and, as a part of the Tabbernor fault system to have been reactivated during D_6. This cross-cutting relationship is evident to the northeast of the Annabel Lake pluton, near Hamell Lake, where the Ross Lake fault offsets Annabel Lake shear zone and the Embury Lake flexure. The Ross Lake fault is matched by a lineament with coincidence between all three datasets (RA_2= 3). The Embury Lake flexure and the north-northeast- to north-northwest-trending splays related to the Ross Lake fault are all identified by surficial and geophysical lineaments that have coincidence between at least two datasets (RA_2 =2) and are all longer than 10 km. A number of long north-northeast- to north-northwest-oriented lineaments have the same orientation as mapped brittle faults.

The northeast-trending lineaments are primarily concentrated in the Flin Flon greenstone belt and are coincident with mapped faults in the Creighton area. Complex faulting in the Creighton area makes the relative age of these fault structures uncertain, although this series belongs to the D_5 event (Galley et al., 1991; Fedorowich et al., 1995), as well as reactivation during the protracted D_6 event. Byers (1962) interpreted the northeast-trending faults to also be a component of the Ross Lake fault system. Within the greenstone belt, for example immediately east of the Phantom-Boot Lake pluton, some of these relatively short faults are coincident with surficial lineaments observed to cross-cut the Flin Flon Lake fault, suggesting that they are the youngest mapped faults in the area.

Prominent north-northwest to north-northeast and northeast lineament trends noted in the aeromagnetic dataset correspond to the D_5-D_6 faults (Figure 3.18). In the northern portion of the Creighton area, east-west lineament trends noted in the aeromagnetic dataset correspond to the D_2-D_3 shear zones (Figure 3.18). The north-northwest- to north-northeast-trending faults are the most widespread and appear to coincide with the southern parts of the Comeback Bay and Mosher Lake shear zones which bend to a more north-south orientation in the southern portion of the Creighton area. These lineaments are well represented in the plutons of interest, although no faults have been noted to extend significantly into these units in the available mapping. A number of long geophysical lineaments have a similar orientation as the northeast-trending faults. These features do not coincide with any of the surficial lineaments and coincidence between these lineaments with mapped faults of the same orientation appears low. Several long northeast-trending geophysical lineaments traverse the plutons; however these features have not been noted in the available mapping of the plutons. As such, the importance of these long geophysical lineaments is less certain.

The surficial lineaments display three strong trends that correspond to the mapped D_5-D_6 faults and major shear zones in the area (Figure 3.18). The rose diagram for the SPOT data shows two strong orientations to the northeast and the general east-west trend, while the rose diagram for the CDED data shows a dominant trend to the north-northwest through north-northeast (JDMA, 2013b). The north-northwest- to north-northeast-trending lineaments are interpreted to correspond to the similarly oriented sinistral faults. The northeast-oriented lineaments are interpreted to correspond to similarly oriented dextral faults. The dominant east- to east-southeast trend displayed by the SPOT dataset largely corresponds to the D_2-D_3 shear zones adjacent to the Annabel and Reynard Lake plutons as well as many of the short lineaments observed in the plutons.

In summary, the most important mapped features, with established age relationships, have been identified through the lineament analysis. They are defined by longer >10 km lineaments with greater coincidence amongst datasets. This allows the known age relationships to be extended to the other identified lineaments with similar orientations. These mapped features are well characterized at surface and likely extend to repository depth. All three datasets used to map lineaments identified these features (RA_2 = 3). Furthermore, longer (>10 km) lineaments corresponding to the mapped faults are considered important and may also extend to repository depth.

3.3 Seismicity and Neotectonics

3.3.1 Seismicity

Saskatchewan is one of the most seismically stable regions in North America (NRCan, 2012). Historically, very few earthquakes of magnitude greater than 3 (Nuttli magnitude) have occurred within Saskatchewan and none in the Creighton area, as shown on Figure 3.19. The largest earthquake ever recorded in Saskatchewan occurred in 1909 in the southern portion of the province near the USA border (650 km from Creighton), and measured a magnitude of 5.5 (NRCan, 2012). Due to limited information available for Saskatchewan, the focal depths of these events are unknown. It should be noted that the low seismicity may be the result of sparse monitoring stations. Weaker events are difficult to detect using the existing seismograph network that provides a magnitude of completion (lowest detectable limit) of about m_N 2.5. Further, the database includes only about 30 years of instrumental recording for Saskatchewan.

A significant portion of the seismicity measured in Saskatchewan is due to mining activities near Wollaston Lake, Esterhazy and Saskatoon (Gendzwill and Unrau, 1996). Of the 43 seismic events with a magnitude greater than M 1.8 in the period between 1985 and 2008 in Saskatchewan, 30 of those are identified as anthropogenic (man-made). The remaining 13 have been documented by Natural Resources Canada as natural earthquakes (NRCan, 2012). The majority of these events are the result of the collapse of eroded salt domes and formations located within Saskatchewan's sedimentary rock cover. A query of the Geological Survey of Canada's National Earthquake Database found no earthquakes in the Creighton area for their period of active monitoring, 1985 to the present.

In summary, the available literature and recorded seismic events indicate that Saskatchewan is located within an area of very low seismicity. Atkinson and Martens (2007) calculated the annual earthquake probability for the stable Canadian craton to be in the order of 10^{-4} to 10^{-3}. There have been no earthquakes recorded near the Creighton area.

3.3.2 Neotectonic Activity

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

The movement and interaction of tectonic plates creates horizontal stresses that result in the compression of crustal rocks. The mean of the current major horizontal principal stress orientation in central North America, based on the World Stress Map (Heidbach et al., 2009), is NE (63° ± 28°). This orientation coincides roughly with both the absolute and relative plate motions of North America (Baird and McKinnon, 2007; Heidbach et al., 2009), and is controlled by the present tectonic configuration of the North Atlantic spreading ridge (Sbar and Sykes, 1973) which has likely persisted since the most recent Paleocene-Eocene plate reorganization (Rona and Richardson, 1978; Gordon and Jurdy, 1986).

Possible evidence of neotectonics preserved in Paleozoic rocks above the major north-south oriented Tabbernor fault has been noted by a number of researchers (Elliot, 1996; Davies, 1998; Kreis et al., 2004). The Tabbernor fault is located approximately 80 km west of Creighton, but might be related to north-south-trending faults located to the east of the plutons of interest, such as the Ross Lake fault. Any neotectonic activity might be expected to occur as reactivation of such faults, since these features are planes of weakness around the plutonic rocks. However, no cases of neotectonic evidence have been documented for the immediate area surrounding Creighton. The current average major principal stress orientation is at a high angle to the Tabbernor and Ross Lake fault systems, which is favourable in terms of conditions that would minimize movement along these and related features. There are, however, a number of features such as the northeast-oriented (Section 3.1.4) series of faults and the western portions of the shear zones that are at relatively low angles to the major principal stress orientation, therefore creating more favourable conditions for potential movement. Given that 90° rotations have been observed in similar Canadian Shield locations, site-specific testing is required to characterize the current stress state in the Creighton area.

The geology of the Creighton area is typical of many areas of the Canadian Shield, which has been subjected to numerous glacial cycles during the last million years. The tectonic fabric of the continent is therefore overprinted by post-glacial isostatic rebound in the northern portion of the North America plate. During the last glaciations (Wisconsinan), most of Saskatchewan was covered by the Laurentide ice sheet that flowed from Hudson Bay, located to the northeast. The thickness of the Laurentide ice sheet across Saskatchewan is unknown, although it likely thinned to the southwest at the edges of the flow. At the maximum extent of the Wisconsinan glaciation, approximately 21,000 years ago (Barnett, 1992), the Earth's crust was depressed by more than 340 m in the Minnesota/North Dakota area (Brevic and Reid, 1999), due to the weight of glacial ice. The amount of crustal depression in the Creighton area would be of a somewhat greater magnitude, due to its closer proximity to the main center of glaciation located over Hudson's Bay.

The Creighton area has been ice free since 8,000 to 9,000 years before the present. Since the regression of the Laurentide ice sheet at that time, isostatic rebound has been occurring. The amount of depression of the Earth's crust in the Creighton area and the rate of rebound are unknown due to lack of data from the continental interior, but generally both are thought to diminish with distance from Hudson Bay (Lambert et al., 1998). Crustal uplift models suggest that the rate of rebound across the Prairie Provinces may be as much as 5 mm/year (Lambert et al., 1998). As a result of the glacial unloading, horizontal stresses are created locally in shallow bedrock. Natural stress release features include elongated compressional ridges or pop-ups such as those described by White et al. (1973) and McFall (1993). Further analysis would also be required to assess the potential for movement to occur along any faults in the area as a result of isostatic rebound.

No neotectonic structural features are known to occur within the Creighton area. It is therefore useful to review the findings of previous field studies involving fracture characterization and evolution as it pertains to glacial unloading. McMurry et al. (2003) summarized several studies conducted in a number of plutons in the Canadian Shield and in the crystalline basement rocks in western Ontario. These various studies found that fractures below a depth of several hundred metres in the plutonic rock were ancient features. Early-formed fractures have tended to act as stress domain boundaries. Subsequent stresses, such as those caused by plate movement or by continental glaciation, generally have been relieved by reactivation along the existing zones of weakness rather than by the formation of large new fracture zones.

Under the appropriate conditions, glaciolacustrine deposits may preserve neotectonic features indicative of paleo-seismic activity (JDMA, 2013a). Existence of such features can be used to extend the seismic record for a region well into the past. As shown on Figure 2.3, glaciolacustrine terrain in the Creighton area is generally located to the north of the Creighton area, with some patches of glaciolacustrine veneer within the western portions of the Annabel Lake and Reynard Lake plutons. A number of these patches of glaciolacustrine deposits are located above the Annabel Lake shear zone. These locations may allow for the investigation of the presence of neotectonic features.

4.0 HYDROGEOLOGY AND HYDROGEOCHEMISTRY

4.1 Groundwater Use

Information regarding groundwater use in the Creighton area was obtained from the Saskatchewan Watershed Authority (SWA) Water Well Record (WWR) database. The location of known water wells is shown on Figure 4.1. The Town of Creighton obtains its potable water source from Douglas Lake via the Creighton Water Treatment Plant (Podaima, 2011), so groundwater use in the area is limited. There are 16 water well records relating to three locations in the Creighton area (see Figure 4.1). Details of these wells are summarized in Table 4.1. Of the 16 records noted in the table, there were ten withdrawal wells, three observation wells and three test holes.

All of the wells were completed in glacial deposits. There are no bedrock wells in the Creighton area. One well just outside of the Town of Creighton was completed to a depth of 15 mbgs and has a static water level approximately 12 mbgs. The remaining water wells were all drilled in the Denare Beach area and have completion depths that range from 6 to 62 mbgs and the recorded water levels range from 2 to 6 mbgs. Withdrawal rates were recorded for four wells with pumping rates ranging from 4 to 11 L/min. These well yields reflect the purpose of the wells and do not necessarily reflect the maximum sustained yield that might be possible from the aquifer.

Table 4.1: Water Well Records for the Crieghton Area

Water Well Type	Water Well Use	Location	Total Well Depth (m)	Static Water Level (mbgs)	Tested Well Yield (L/min)	Depth to Top of Bedrock (m)	Completion Strata
Domestic	Withdrawal	Denare Beach	19	6	6	N/A	Glacial
Domestic	Withdrawal	Denare Beach	21	3	4	N/A	Glacial
Domestic	Withdrawal	Creighton	15	12	N/A	N/A	Glacial
Domestic	Withdrawal	Denare Beach	6	4	N/A	N/A	Glacial
Municipal	Withdrawal	Denare Beach	28	3	N/A	N/A	Glacial
Municipal	Withdrawal	Denare Beach	24	3	N/A	N/A	Glacial
Municipal	Withdrawal	Denare Beach	24	3	8	N/A	Glacial
Municipal	Withdrawal	Denare Beach	28	3	11	N/A	Glacial
Municipal	Water Test Hole	Denare Beach	N/A	N/A	N/A	N/A	Glacial
Municipal	Water Test Hole	Denare Beach	N/A	N/A	N/A	N/A	Glacial
Municipal	Water Test Hole	Denare Beach	N/A	N/A	N/A	N/A	Glacial
Municipal	Observation	Denare Beach	24	N/A	N/A	N/A	Glacial
Municipal	Observation	Denare Beach	62	3	N/A	N/A	Glacial
Municipal	Observation	Denare Beach	27	2	N/A	N/A	Glacial
Municipal	Withdrawal	Denare Beach	32	2	N/A	N/A	Glacial
Municipal	Withdrawal	Denare Beach	31	2	N/A	N/A	Glacial

N/A = not available

4.2 Overburden Aquifers

The wells listed in Table 4.1 are reported (where information is available) to be installed into glacial deposits but stratigraphic details are not available with the water well records. However, mapping of intertill aquifers in the area indicates the presence of three overburden units (Henderson and Campbell, 1992) including an upper till, glaciolacustrine deposits and a lower till. The lower till primarily occurs east of Amisk Lake and, based on well depths, is likely the unit into which the wells in the Denare Beach area are installed. This till unit commonly overlies bedrock and is itself generally overlain by glaciolacustrine deposits of varying thickness. Generally the lower till is a grey to grey brown sandy to silt diamicton. The younger till overlies glaciolacustrine sediments in the Creighton area and is composed of a silty sandy matrix (Henderson and Campbell, 1992). The lateral and vertical extent of this aquifer has not been investigated. Based on the surficial geology of the area, it is interpreted that the aquifer is located in a depression in upper bedrock surface (Campbell and Henderson, 1997). It is estimated that the aquifer extends approximately 3 km in the north-south direction by 1 to 2 km in the east-west direction. Other similar deposits extend to the north; however, there are no wells installed in that area and the presence of any hydraulic connection between these overburden deposits is unknown.

The one well installed outside of the Denare Beach area is located immediately west of the Town of Creighton. Based on the surficial geology near this well, it appears to be installed in a small drift-filled bedrock depression typical of the area. There are many similar locations throughout the area that may be capable of supporting small amounts of localized groundwater development. However, they tend to be small, and any hydraulic connection to neighbouring units is likely to be limited.

In summary, the overburden aquifers in the Creighton area are minimal in extent and currently not used significantly. There is little interest in developing these small aquifers as a significant groundwater resource given the abundance of surface water in the area.

4.3 Bedrock Aquifers

There are no known shallow or deep bedrock aquifers that are being utilized in the Creighton area. The deepest well in the Creighton area is 62 m deep and water well records do not indicate whether it is installed in overburden or bedrock. Given its location, this well, which is an observation well only, is likely installed in glacial deposits. If bedrock was encountered in this well, it would be considered a part of the shallow groundwater system.

Precambrian rock of the Canadian Shield is not commonly developed as a significant aquifer, primarily due to the low frequency of fractures that are capable of producing sufficient quantities of water. Water wells drilled into Precambrian rock for water supply purposes are not likely to extend deeper than 100 m in most cases. At greater depths, water quality generally decreases (becomes saline) to conditions that preclude potable water use (Frape and Fritz, 1987).

One borehole was drilled to a depth greater than 3 km into the Reynard Lake pluton (borehole JXWS) (Davis and Tammemagi, 1982). While the borehole was not drilled for hydrogeological characterization purposes, the available information did not indicate the presence of any significant water bearing zones in the upper 2 km of the pluton. No further information regarding groundwater at depth was available for the Creighton area.

In summary, the bedrock at typical repository depths in the Creighton area is not considered to be a significant groundwater resource. There are currently no known bedrock wells in the area, and the bedrock is unlikely to be used for such purposes in the future.

4.4 Regional Groundwater Flow

In many shallow groundwater flow systems the water table is generally a subdued replica of the topography. The variation of the water table elevation across an area reflects the changes in hydraulic head and therefore driving force within the flow system. However, the pattern of groundwater flow will also be influenced by horizontal and vertical variations in the hydraulic properties of the medium; for example, associated with interbedding of sand and clay layers in overburden sediments and the presence of fracture networks in bedrock. However, as a general concept, shallow groundwater flow in Canadian Shield terrain will tend to be directed from areas of higher hydraulic head, such as highlands, towards areas of lower hydraulic head such as adjacent or nearby valleys and depressions. The extent of these localized flow systems is defined by local, topography-controlled, drainage divides across which flow will not readily occur. However, the geometry of shallow flow systems can be more complex in the presence of permeable fracture zones and more complex topography.

With this general concept in mind and with reference to the drainage features in the Creighton area shown on Figure 2.4, it is inferred that shallow groundwater flow in the overburden and shallow bedrock (e.g., upper 50 to 100 m of bedrock) will mimic the surface water flow systems. The Creighton area includes the Churchill River Basin in the north and the Saskatchewan River Basin in the south. The boundary between these two major watersheds is located to the north of the string of lakes including Johnson Lake, Annabel Lake, and Embury Lake. On the north side of this divide, the regional shallow groundwater flow direction is inferred to be generally northeast, away from the Creighton area.

The majority of the Creighton area is located to the south of the divide, in the Saskatchewan River basin. The Saskatchewan River basin can be divided into a number of sub-basins that will control groundwater flow directions. Groundwater in the valley containing Annabel Lake and water on the northernmost part of the Annabel Lake pluton flows toward the east, through the Annabel Creek area and into Embury Lake. Further east on the Annabel Lake pluton, including Creighton Lake, the flow direction is southeast through the Flin Flon area and towards Phantom and Schist Lakes.

The largest sub-basin in the Creighton area is the Amisk Lake sub-basin. Shallow groundwater flow will tend to be south to southwest towards Amisk Lake in the area including the southernmost portion of the Annabel Lake pluton, and the Reynard Lake pluton. On the east side of Amisk Lake, shallow groundwater flow will be west toward the lake in an area that includes the west side of the Phantom-Boot Lake pluton (i.e., Boot Lake), Mystic Lake and Table Lake. This area includes Denare Beach, which is the location of fifteen of the registered water wells, nine of which are used for withdrawal. Similarly, the shallow groundwater flow direction in the proximity of these wells is expected to be west towards Amisk Lake.

Shallow groundwater flow on the eastern half the Phantom-Boot Lake pluton is expected to be east towards Phantom Lake in the north and Schist Lake in the south.

No information was found in the available literature regarding groundwater recharge rates and temporal patterns in the Creighton area. However, it is expected to be typical for the Canadian Shield region with elevated recharge in spring and fall, reduced recharge in late summer, and essentially no recharge during frozen winter conditions. Recharge patterns will be a function of local conditions with the highest rates generally occurring in elevated areas underlain by permeable sand or gravel deposits or by fractured bedrock in areas where it is exposed or covered by thin overburden. Lowland areas, especially muskeg, store substantial amounts of water and may act simultaneously as discharge and recharge areas according to seasonal variations. On the surfaces of the plateau-like plutons, it is expected that groundwater recharge will occur through the small lakes and wetlands situated on top of these topographic highs. Where there is exposed bedrock, a portion of this may flow towards topographic lows as runoff. Where thin layers of overburden cover the rock, discharge to the topographic lows may occur via interflow through the overburden or the shallow bedrock groundwater system itself.

Deeper into the bedrock, fracture frequency in a mass of rock will tend to decline, and eventually, the movement of ions will be diffusion-dominated. However, fracture networks associated with deep faults and shear zones will influence advective groundwater flow around bodies of rock characterized by diffusion limited conditions. As such, in the Creighton area, it can be expected that features such as the long regional faults and shear zones will be important in the deep groundwater flow system.

There is little known about the hydrogeologic properties of the deep bedrock in the Creighton area, as no deep boreholes have been advanced for this purpose. Experience from other areas in the Canadian Shield has shown that active groundwater flow in bedrock is generally confined to shallow fractured localized systems, and is dependent on the secondary permeability associated with the fracture networks. For example, in Manitoba's Lac du Bonnet batholith, groundwater movement is largely controlled by a fractured zone down to about 200 m depth (Everitt et al., 1996). The low topographic relief of the Canadian Shield tends to result in low hydraulic gradients for groundwater movement in the shallow active region (McMurry et al., 2003). In deeper regions, hydraulic conductivity tends to decrease as fractures become less common and less interconnected (Stevenson et al., 1996; McMurry et al., 2003). Increased vertical and horizontal stresses at depth tend to close or prevent fractures thereby reducing permeability and resulting in diffusion-dominated groundwater movement (Stevenson et al., 1996; McMurry et al., 2003). Hydraulic conductivity values measured at typical repository depths (500 m or greater) at the Whiteshell Research Area and Atikokan range from approximately 10^{-15} to 10^{-10} m/s (Ophori and Chan, 1996; Stevenson et al., 1996). Data reported by Raven et al. (1985) show that the hydraulic conductivity of the East Bull Lake pluton east of Elliot Lake, Ontario, decreases from an average near surface value of 10^{-8} m/s to less than 10^{-12} m/s below a depth of 400 to 500 m.

Many of the faults and shear zones in the Creighton area coincide with topographic lows. These topographic lows are often the location of wetlands and lakes. Major faults and shear zones can extend to depths that are likely greater than repository depth. As such, it can be expected that features such as the Annabel Lake shear zone, the West Arm shear zone, the Mosher Lake shear zone and the fault systems near the east ends of the Annabel Lake pluton and Reynard Lake pluton could form important pathways for groundwater movement at depth. Further, the hydraulic properties along these flow paths can be expected to vary over several orders of magnitude depending on site-specific conditions.

The orientation of fracture networks relative to the orientation of the maximum horizontal compressive stress may also influence permeability. A lower effective hydraulic conductivity would be predicted for fractures oriented at a high angle to the maximum compressive stress axis compared to otherwise identical low angle fractures. Horizontal stress measurements from various locations in the Canadian Shield (Kaiser and Maloney, 2005; Maloney et al., 2006) indicate that the axis of maximum horizontal stress is oriented predominantly in the west-southwest direction. This is generally consistent with the World Stress Map; however, anomalous stress orientations are known to exist in the Churchill and Superior Provinces. A 90° change in azimuth of the maximum compressive stress axis was identified in the near surface in the Whiteshell area and Ruttan Mine of Manitoba (Brown et al., 1995; Kaiser and Maloney, 2005) while a roughly north-south orientation of maximum horizontal compressive stress was found for the Sioux Falls Quartzite in South Dakota (Haimson, 1990). In view of the general paucity of data and the anomalous stress orientations in mid-continent, caution is warranted in extrapolating a west-southwest stress orientation to the Creighton area without site-specific data. The exact nature of deep groundwater flow systems in the Creighton area will need to be evaluated at later stages of the site evaluation process, through the collection of site-specific information.

4.5 Hydrogeochemistry

No information on hydrogeochemistry was found for the Creighton area. Existing literature, however, has shown that groundwater within the Canadian Shield can be subdivided into two main hydrogeochemical regimes: a shallow, generally fresh water flow system, and a deep, saline water flow system (Gascoyne et al., 1987; Gascoyne, 2000; 2004).

Gascoyne et al. (1987) investigated the saline brines within Precambrian plutons and identified a chemical transition at around 300 m depth marked by a uniform and rapid rise in total dissolved solids (TDS) and chloride. This was attributed to advective mixing occurring above 300 m with a shift to diffusion-controlled flow below that depth. It was noted that major fracture zones within the bedrock can, where present, extend the influence of advective processes to greater depths and hence lower the transition to the more saline conditions characteristic of deeper, diffusion-controlled conditions.

In the deeper regions, where groundwater transport in unfractured or sparsely fractured rock tends to be very slow, long residence times in the order of a million years or more have been reported (Gascoyne, 2000 and 2004). Groundwater research carried out in AECL's Whiteshell Underground Research Laboratory (URL) in Manitoba found that crystalline rocks from depths of 300 to 1,000 m have TDS values ranging from 3 to 90 g/L (Gascoyne et al., 1987; Gascoyne, 1994; 2000 and 2004). TDS values exceeding 250 g/L, however, have been reported in some regions of the Canadian Shield at depths below 500 m (Frape et al., 1984).

Site-specific conditions will influence the depth of transition from advective to diffusion-dominated flow, which may occur at a depth other than the typical 300 m reported by Gascoyne et al. (1987). Such conditions would need to be evaluated during subsequent site evaluation stages.

5.0 NATURAL RESOURCES – ECONOMIC GEOLOGY

Information regarding the mineral resource potential for the Creighton area has been obtained from a variety of sources including a number of historical and recent studies conducted in the Creighton area (Byers and Dahlstrom, 1954; Byers et al., 1965; Pearse, 1990; Reilly, 1995; Corrigan et al., 2007; Morelli, 2009; Simard and MacLachlan, 2009; Saskatchewan Energy and Resources, 2012). Most of this attention has been focused on the Flin Flon greenstone belt, compared to the intrusive plutons with lower mineral potential. The primary source of information on past and present mining activities is the Saskatchewan Energy and Resources (2012) Mineral Deposit Index. Articles describing prospective areas have been prepared by Theyer and Heine (2002), Galley et al. (2007) and Morelli (2009).

Resource development and ongoing exploration in the Creighton area is focussed on minerals associated with the greenstone belt and regional shear zones bounding the plutonic rocks. The economic mineral potential is considered low within the core regions of the major felsic plutonic bodies in the Creighton area. Figure 5.1 shows the active exploration interests in the Creighton area as evidenced by active mining claims, as well as known mineral occurrences identified in the Saskatchewan Energy and Resources (2012) Mineral Deposit Index. Large portions of all the plutons in the Creighton area are covered by active mining claims. In December 2012, Saskatchewan initiated an online claim staking system (Mineral Administration Registry Saskatchewan) and many of these claims are the result of recent staking.

5.1 Metallic Mineral Resources

Several mines have produced copper and gold in the Creighton area including one operating mine and twelve past producing mines. The majority of the metallic mineral occurrences identified within the Creighton area are associated with the rocks of the Flin Flon greenstone belt. Three major metallogenetic periods have been identified in the Flin Flon greenstone belt (Galley et al., 2007). These are: pre-accretion mineralization formed during submarine oceanic arc and extension arc settings (volcanic massive sulphide [VMS] deposits), arc compression (Cu-Mo and Ni-Cu- platinum group elements [PGE] mineralization), and terrain collision and crustal thickening with associated faulting (Au deposits). The most prospective areas are those of tholeiitic volcanic/volcaniclastic assemblages (Morelli, 2009). As of 2007, a total of 27 deposits have been mined in the Flin Flon greenstone belt (Galley et al., 2007).

In the case of the Annabel Lake and Reynard Lake plutons, the large volumes toward the center of the intrusions seem devoid of metallic mineralization. It is possible that gold-hosting shears that formed along heterogeneities exist within the plutons. However, none are currently known in the Creighton area. With reference to Figure 5.1, all mines and the vast majority of mineral occurrences are found within metavolcanic rocks of the Flin Flon greenstone belt or near the margins of the granodioritic plutons. Numerous metallic mineral occurrences have been identified in the Creighton area and their exploration continues today.

Gold and Base Metals

In total, there is one producing mine, six past producing properties and two developed prospects within the Creighton area (Figure 5.1). The active mine (777 Mine, located in part within the Callinan mine claim property) is producing copper with minor amounts of gold, silver, zinc, and lead. Of the past producing properties (including the Henning Maloney Mine, Bootleg Mine/Rio Deposit, Newcor Mine, Flin Flon Mine) and developed prospects, six produced copper, and six produced gold. All of these properties have some amounts of sulphide minerals, and commonly have minor amounts of gold and silver associated with them (Saskatchewan Energy and Resources, 2012). In addition, several other past producing or developed prospects with similar mineral potential have been identified within the Flin Flon greenstone belt but outside the immediate Creighton area.

The Creighton area is part of one of the most productive base metal regions in Canada (Reilly, 1995). Large VMS deposits are found within the Creighton area. VMS deposits in the Creighton area have a wide range of ore compositions, volcanic host lithologies and deposition styles (Reilly, 1995; Corrigan et al., 2007). This includes VMS deposits that can range in size from approximately 10 to 20 m wide by 30 to 90 m long to 20 m wide by 275 m long (e.g., the Flin Flon Mine deposit) (Byers et al., 1965). Sulphide minerals (pyrite and pyrrhotite), as well as gold deposits, have also been associated with quartz veining. The Birch Lake assemblage is considered to be a favourable exploration site for VMS deposits (Morelli, 2009). The West Amisk assemblage is considered to have potential for Flin Flon type VMS mineralization, while the Sandy Bay assemblage is considered to have lower economic potential.

Base metal production in the Creighton area started in 1930 at the Flin Flon Mine, and continues today at the 777-Callinan Mine (located on the border of Saskatchewan and Manitoba) located 1 km and 3 km from the settlement area of Creighton, respectively. There are two demolished head frames associated with the Flin Flon Mine; the North Main and South Main, and one existing headframe currently associated with the 777-Callinan Mine. The Millrock member of the Flin Flon Formation plays host to both the Flin Flon and 777-Callinan Mine deposits. The Phantom Lake and Green Lake peninsulas have recently been reclassified as belonging to the Millrock Member (Simard and MacLachlan, 2009).

Minor amounts of gold have been historically produced from gold-only deposits in the Creighton area, and gold has been produced in association with the base metals at the Flin Flon and 777-Callinan Mines, among other VMS deposits (Saskatchewan Energy and Resources, 2012). The majority of the ‘gold only’ occurrences within the Creighton area are related to mesothermal mineralization, similar to shear hosted lode gold mineralization within Archean rocks. The known gold occurrences are generally small and marginally economical (Reilly, 1995). Gold is associated with quartz veining, and is generally erratically distributed throughout them. Gold occurrences of this style in the Creighton area are located within metavolcanic rocks of the Flin Flon greenstone belt, as well as along the margins of or within quartz diorite and granodiorite rocks, such as the Reynard Lake pluton (Figure 5.1). According to the Saskatchewan Mineral Deposits Index (SMDI Nos. 2259, 2562, 2596 and 2597), the occurrences noted within the Reynard Lake pluton consist of a series of three small occurrences referred to as the Don, DB, and JH showings. They were originally discovered by Cameco in approximately 1990 and consist of possible silicified shear zones within the pluton. The gold showing just northeast of Patmore Lake is known as the Angelski Patmore occurrence, another minor shear-hosted showing that was discovered in 1957 (SMDI No. 0008). The economic viability of such occurrences is currently considered low. West of the Creighton area, in the northern portion of Amisk Lake on Missi Island, numerous gold showings and deposits have been identified (SRK, 2011), and Claude Resources recently released a significant gold resource. There is potential for continued exploration in this area.

Tungsten occurrences have been found within quartz-scheelite veining between Douglas and Phantom lakes within the Flin Flon greenstone belt, and along the margin of the Phantom-Boot Lake pluton. It is generally associated with molybdenum (Byers et al., 1965). There are no known economic tungsten deposits within the Creighton area.

Rare Metals and Rare Earths

There are no known rare earth metal occurrences within the Creighton area.

Uranium

There are no known uranium occurrences within the Creighton area; although, a few radioactive pegmatite dykes have been located on the south shore of Wildnest Lake, approximately 38 km northwest of the Town of Creighton. These are small and none are known to be economic (Byers and Dahlstrom, 1954). There is currently no known uranium exploration underway in the Creighton area.

Platinum Group Elements (PGE)

PGE occurrences are also known in the Flin Flon greenstone belt in the Creighton area. The McBratney Lake PGE and gold occurrence is situated approximately 10 km east of the Town of Creighton, within the Flin Flon greenstone belt. The concentrations of PGE and gold are exceptionally high (Theyer and Heine, 2002) and indicate a potential for economic PGE deposits within the Flin Flon greenstone belt.

5.2 Non-Metallic Mineral Resources

Known non-metallic mineral resources within the Creighton area include building stone, sand and gravel, asbestos, talc and magnesite.

Sand, Stone and Gravel

Sand and gravel deposits found in the Creighton area consist of deposits related to the most recent glaciations. These resources are generally scarce and small in size in the Creighton area. Small deposits have been developed south of Denare Beach, and along the road between Denare Beach and Creighton. Large sand and gravel deposits have been identified north of Annabel Lake. However, access to these deposits is difficult due to their remote location from roads (Byers and Dahlstrom, 1954).

Some resource potential for building stone has been identified within the Creighton area. Rocks suitable for this purpose include granite, marble, granodiorite, quartz-eye diorite and dolomite (Byers and Dahlstrom, 1954; Byers et al., 1965; Pearse, 1990). The area also has metagabbro rock, at times classified as a marble in the building stone industry (Guliov, 1989). These occurrences of potential building stone are located approximately 6 to 15 km south of the settlement area of Creighton, between Phantom and Mystic Lakes, within metavolcanic rocks of the Flin Flon greenstone belt, and plutonic rocks of the Kaminis Lake pluton (Pearse, 1990).

Currently, there are no building stone quarries within the Creighton area; although, the potential development of this resource in the future may take place, but would not occur at or near repository depths.

Peat

The major peatlands of Saskatchewan occur on the northern margin of the Western Canada Sedimentary Basin (SGS, 2003). Peatlands occur within the Creighton area, however, it is unknown if these deposits have any economic potential. Only one peat producer operates within Saskatchewan, near Carrot River, approximately 200 km to the southwest of Creighton (SGS, 2003).

Diamonds

No kimberlites or lamproites that could be diamond bearing have been identified in the Creighton area, although the potential for the Canadian Shield to host economic diamond deposits has been demonstrated by a number of mines in the Northwest Territories, Nunavut and Ontario.

Asbestos

Chrysotile asbestos is associated with serpentinized ultrabasic intrusive rock to the east of Amisk Lake, approximately 15 to 25 km south of the settlement area of Creighton. The largest of these occurrences is located near the south end of Birch Lake, and extends to the south of Table Lake, over a length of approximately 10 km and a width of approximately 100 to 300 m. A smaller asbestos occurrence is located under Mosher Lake, south of the Reynard Lake pluton (Byers and Dahlstrom, 1954), approximately 18 km southwest of the settlement area of Creighton. It is unknown whether any of these occurrences are currently economical.

Talc and Magnesite

A large body containing talc and magnesite occurrences is located in the Mosher Lake area approximately 18 km to the southwest of the settlement area of Creighton, and has a strike length of approximately 275 m (Byers and Dahlstrom, 1954). Selective development and separation of the talc and magnesite may make these occurrences feasible; however, it is unknown if these occurrences are currently economical.

5.3 Petroleum Resources

The Creighton area is located in a crystalline geological setting where the potential for petroleum resources is negligible and where no hydrocarbon production or exploration activities are known to occur.

6.0 ROCK GEOMECHANICAL AND THERMAL PROPERTIES

Geomechanical information including intact rock properties, rock mass properties and *in situ* stresses are needed to design stable underground openings, predict the subsequent behaviour of the rock mass around these openings, and predict the response of the groundwater flow system. As such, geomechanical information associated with a potential host rock can be used when addressing several geoscientific, safety-related factors defined in the site selection process document (NWMO, 2010). There is limited geomechanical information on the granodioritic intrusions in the Creighton area. Table 6.1 summarizes all available geomechanical information from the intrusions in the Creighton area and from sites elsewhere in the Canadian Shield with rock types similar to those of interest. These sites are the Lac du Bonnet granite at AECL's Underground Research Laboratory (URL) in Manitoba and the Eye-Dashwa granite near Atikokan, Ontario. The majority of the geomechanical characterization work for the URL in Pinawa, Manitoba, was conducted on these rocks as part of AECL's Nuclear Fuel Waste Management Program in the 1990s.

6.1 Intact Rock Properties

Intact rock properties tabulated in Table 6.1 are based on laboratory testing of rock core specimens from boreholes (Annor et al., 1979; Hajnal et al., 1983; Stone et al., 1989; Fowler et al., 2005). The table also includes basic rock properties such as density, porosity, uniaxial compressive strength and tensile strength for use in engineering design and structural analyses. These parameters feed into the rock mass classification schemes, and *in situ* stress determination.

No specific information is available regarding the intact rock properties of the Annabel Lake pluton and the Phantom-Boot Lake pluton. The felsic plutonic rocks of the Creighton area share a similar mineralogical composition to the comparatively well-studied Lac du Bonnet batholith and Eye-Dashwa pluton (Annor et al., 1979; Hajnal et al., 1983; Stone et al., 1989; Fowler et al., 2005). At this early stage of the site evaluation process, it is reasonable to assume that the geomechanical properties of intact rock in the Creighton area may resemble those of the Lac du Bonnet batholith and Eye-Dashwa pluton.

The drilling of the 3,066 m deep borehole (JXWS) and associated seismic research has provided some geomechanical information for the Reynard Lake pluton (Bunker and Bush, 1982; Davis and Tammemagi, 1982). Table 6.1 summarizes the available rock properties data available for the Reynard Lake pluton, compared to information available from other Canadian Shield sites. In general, the limited available information is typical of similar property values for other comparable to other Canadian Shield rocks. Note that some important geomechanical parameters are not available for the pluton. A site-specific geotechnical assessment involving a drilling and testing program would need to be conducted during later stages of site evaluation. The rock property values presented in Table 6.1 are consistent with the values selected for numerical modeling studies conducted to evaluate the performance of hypothetical repository designs in a similar crystalline rock environment (SNC-Lavalin Nuclear Inc., 2011; Golder Associates, 2012a,b).

Table 6.1: Summary of Intact Rock Properties Available for Selected Canadian Shield Rocks

Property	Reynard Granodiorite	Lac du Bonnet Granite	Eye-Dashwa Granite
Uniaxial compressive strength (MPa)	N/A	185 ±24[c]	212 ±26[c]
Split Tension (Brazilian) Strength (MPa)	N/A	4 to 9[d]	N/A
Porosity (%)	0.26[a,b]	0.35[c]	0.33[c]
P-wave velocity (km/s)	5.5 to 6[a,b]		
S-wave velocity (km/s)	3.3 to 3.6[a,b]		
Density (kg/m^3)	2,680 upper 60 m[b] increasing to 2,900 at EOH[a]	2,650[c]	2,650[c]
Young's Modulus (GPa)	80[e]	66.8[c]	73.9[c]
Poisson's Ratio	0.21[b]	0.27[c]	0.26[c]
Thermal Conductivity (W/(m°K))	NA	3.4[c]	3.3[c]
Coef. Thermal Expansion (x10^{-6}/ºC)	NA	6.6	15

EOH = End of Hole
N/A = Not Available

[a]Fowler et al., 2005

[b]Hajnal et al., 1983

[c]Stone et al., 1989

[d]Annor et al., 1979

[e]Calculated from elastic equations knowing P- and S- wave velocity and Poisson's Ratio

6.2 Rock Mass Properties

Fracture spacing, orientation and condition (width or aperture, mineral fill, evidence of relative displacement, etc.) of the fractures tend to dominate the overall mechanical response of the rock mass. There is little information available on rock mass properties of the plutons in the Creighton area.

In general, there will be a downward decreasing fracture density from highly fractured rocks in shallow horizons (approximately <300 mbgs) to sparsely fractured intact rock at greater depths as experienced at other Canadian Shield sites (e.g., Everitt, 2002). Fractures observed on surface bedrock exposures may occur as well-defined sets of geological discontinuities, or as randomly oriented and variably-dipping features. Based on observations from other Canadian Shield sites (e.g., Everitt, 2002) and stress measurement data (e.g., Maloney et al., 2006), one could infer that a shallowly-dipping to sub-horizontal fracture set may exist as a result of either strain releasing during the rebound from the last glacial cycle or the presence of pre-existing fabric anisotropy (e.g., bedding, tectonic foliation) in the rock structure.

The Reynard Lake pluton was the subject of a study to determine the seismic characteristics of a Precambrian pluton and its adjacent rocks (Hajnal et al., 1983). The seismic study involved drilling of a 3,066 m borehole (JXWS) along with several nearby shallow boreholes (60 m deep). The average fracture frequency from these boreholes was only about four fractures per metre in the upper 60 m of rock. This is a relatively low degree of fracturing compared to what has been observed at similar depths and in similar rocks of the Canadian Shield (Stone et al., 1989). Excluding faults, fracture frequency is generally expected to decrease with depth (Brown et al., 1989). The upper 60 m of the Reynard Lake pluton may be representative of the highest fracture frequency within the rock mass between large discontinuities. Fracture frequency in the pluton was found to correlate well with seismic velocity, with increased fracturing corresponding to slower velocities. The results showed a small low velocity zone over the upper 5 to 10 m of rock, which is attributed to the presence of open fractures in an upper weathered zone (Gendzwill, 1968). Downhole geophysical surveys (caliper, sonic, gamma and dipmeter) that were conducted within borehole JXWS indicated an apparent increase in fractures between 2,000 m and 2,700 m; however, there was insufficient core available over this interval to support the differentiation between fractures and responses due to mineralogical changes in the geophysical logs (Davis and Tammemagi, 1982). Rock mass properties for the Creighton area will need to be determined at later stages of the assessment, through the collection of site-specific information.

6.3 *In situ* Stresses

Knowledge of the *in situ* stresses at a site is required to model the stress concentrations around underground excavation designs. These stress concentrations are ultimately compared to the strength of a rock mass to determine if conditions are stable or if the excavation design needs to be modified. This is particularly important in a repository design scenario, where minimization of excavation-induced rock damage is required.

No site-specific information is available regarding the *in situ* stress conditions within the Creighton area. A large set of such stress measurements (263 measurements) is available from various locations in the Canadian Shield (Kaiser and Maloney, 2005; Maloney et al., 2006). The nearest *in situ* stress measurements were taken at the Ruttan Mine (Churchill Province/Lynn Lake Sub-province) located approximately 240 km to the northeast of Creighton. At a depth of 661 m in the Ruttan Mine, the minimum principal stress ranges from 14 MPa to 27.5 MPa (with an average value of 22 MPa) and dips at an angle of 59°. As a check, vertical *in situ* stresses may also be estimated using the unit weight of the rock measured on intact core specimens. Assuming a rock density of 2.8 Mg/m^3, and a corresponding unit weight of 27.5 kN/m^3, the approximate magnitude of the *in situ* vertical stress at a depth of 500 m at the Ruttan Mine would be 14 MPa.

Horizontal stress conditions are more difficult to estimate. However, overcoring or hydraulic fracturing methods can be used to determine the stresses on a plane at depth and resolve the horizontal *in situ* stress conditions (or resolve inclined principal stresses). The horizontal stress information from the dataset mentioned above is presented on Figure 6.1 (Kaiser and Maloney, 2005; Maloney et al., 2006). A review of the data available for the Ruttan Mine area indicates that the maximum principal stress in that area is 52 MPa (at a depth of 661 m) and oriented in the north-northwest to south-southeast direction (Kaiser and Maloney, 2005). This magnitude is within the expected range shown on Figure 6.1, and approximately 10 MPa higher than the average for that depth. It should be noted that this maximum principal stress direction was provided for only one measurement taken using an overcoring method. The World Stress Map which indicates a dominant west-southwest direction of the maximum principal stress within the central portion of the Canadian Shield (Heidbach et al., 2009). However, a significant number of measurements in the database (e.g., at Thompson Manitoba approximately 280 km northeast of the site, the URL in southeastern Manitoba, and the Campbell Mine in northwestern Ontario) indicated a maximum principal stress direction approximately 90° to the dominant trend which would agree with the measurement taken at the Ruttan Mine.

The observation that the stress state is neither constant nor linear (Maloney et al., 2006) suggests that variability should be expected in the Canadian Shield. Based on the available stress measurement data, Maloney et al. (2006) developed a conceptual model that describes the variable stress state in the upper 1,500 m of the Canadian Shield. The conceptual model identifies a shallow stress released zone from surface to a depth of 250 m, a transition zone from 250 to 600 m and an undisturbed stress zone below 600 m. The undisturbed stress zone can be expected to be representative of far-field boundary stress conditions whereas stresses within the shallow zone tend to be lower as they have been disturbed through exhumation and influenced by local structural weaknesses such as faults (Maloney et al., 2006). Typical repository depths of approximately 500 m fall within the transition zone, where the maximum principal stress may range from approximately 20 to 50 MPa.

Local stress relief features such as faults and shear zones can be expected to locally affect stress regime. For example, thrust faults at AECL's URL were shown to be boundaries between significant changes in the magnitude and orientation of the principal stresses. Above a major thrust fault, located at depth of 270 m (referred to as Fracture Zone 2, or FZ2 at the site), the magnitude was close to the average value for the Canadian Shield and the orientation of the maximum horizontal stress was consistent with the average predicted by the World Stress Map (i.e., southwest). Below the same thrust fault, the stress magnitudes are much higher than the average data for the Canadian Shield, and the maximum principal stress rotates approximately 90° to a southeast orientation (Martino et al., 1997). The principal maximum horizontal stress magnitude below the Fracture Zone 2 thrust fault remains relatively constant around 55-60 MPa, which is more typical of the values found at greater depths. The southeast orientation of the maximum principal horizontal stress is consistent with the data presented by Herget (1980) for the area which indicates maximum compression clustered in the southwest and southeast for the Canadian Shield.

In addition to loading history and geologic structure, *in situ* stress conditions are further influenced by rock mass complexity (i.e., jointing, heterogeneities and mineral fabric). As such, local stresses may not resemble the average stress state for a region (Maloney et al., 2006). The conceptual model presented by Maloney et al. (2006) is considered appropriate for sub-regional modelling activities. Due to wide scatter in the data (Figure 6.1), site-specific measurements will be required during detailed site investigations for application to more detailed design activities.

6.4 Thermal Conductivity

Thermal conductivity values for potential host rocks provide information on how effectively the rock will transfer heat from the repository and dissipate it into the surrounding rock. The thermal conductivity of a rock is in part dependent on its mineral composition, with rocks composed of higher quartz content generally having higher thermal conductivities. The thermal conductivity of quartz (7.7 W/(m˚K)) is greater than that of other common rock-forming minerals such as feldspars (1.5 to 2.5 W/(m˚K)) or mafic minerals (2.5 to 5 W/(m˚K)) (Clauser and Huenges, 1995).

There are no site-specific thermal conductivity values or detailed quantitative mineral compositions for the Creighton area. However, the mineralogy of the Annabel Lake pluton, Reynard Lake pluton and Phantom-Boot Lake pluton are described in Section 3.2.1. Available information indicates that the compositions of these plutons range from granite to granodiorite to tonalite/quartz diorite. The quartz mineral content of these rock types can range from approximately 15% to 60% by volume (Streckeisen, 1976). The range of measured thermal conductivity values for these rock types found in the literature are presented in Table 6.2.

Table 6.2: Thermal Conductivity Values for Granite, Granodiorite and Tonalite

Rock type	Average thermal conductivity (W/(m˚K))	Minimum thermal conductivity (W/(m˚K))	Maximum thermal conductivity (W/(m˚K))
Granite[a,b,c,d,e,f,g]	3.15	2.60	3.63
Granodiorite[a,f,g]	2.69	2.44	2.86
Tonalite[h,i]	3.01	2.95	3.14

[a]Petrov et al., 2005; [b]Kukkonen et al., 2011, [c]Stone et al., 1989; [d]Back et al., 2007; [e]Liebel et al., 2010; [f]Fountain et al., 1987; [g]Fernández et al., 1986; [h]de Lima Gomes and Mannathal Hamza, 2005; [i]Kukkonen et al., 2007

Although no thermal conductivity values are available for the Creighton area, some useful comparisons are provided by Stone et al. (1989) in their summary of thermal conductivity values for two late Archean granitic intrusions of the Superior Province of the Canadian Shield, the Lac du Bonnet batholith and the Eye-Dashwa pluton (Table 6.1). Both intrusions were described as having similar mineralogical compositions, with quartz content generally varying between 23 and 27%. The average thermal conductivity for the Eye-Dashwa pluton was 3.3 W/(m˚K) based on 35 samples. The average thermal conductivity for the Lac du Bonnet batholith was 3.4 W/(m˚K) based on 227 samples. For comparison, a value of 3 W/(m˚K) was selected for numerical modeling studies conducted to evaluate the thermo-mechanical performance of hypothetical repository designs in a similar crystalline rock environment (Golder Associates, 2012a,b).

The above literature values for thermal conductivity are considered useful for comparison purposes as part of this preliminary assessment. However, actual values will need to be determined at later stages of the assessment, during the collection of site-specific information.

7.0 POTENTIAL GEOSCIENTIFIC SUITABILITY OF THE CREIGHTON AREA

7.1 Approach

The objective of the Phase 1 desktop geoscientific preliminary assessment is to assess whether the Creighton area contains general areas that have the potential to satisfy the geoscientific evaluation factors and safety functions defined in the site selection process document (NWMO, 2010). The location and extent of general potentially suitable siting areas would be refined during the second phase of the preliminary assessment through more detailed assessments and field evaluations.

The repository is expected to be constructed at a depth of about 500 mbgs. The surface facilities will require a dedicated surface area of about 600 by 550 m for the main buildings and about 100 by 100 m for the ventilation exhaust shaft (NWMO, 2013). The actual underground footprint at any particular site would depend on a number of factors, including the characteristics of the rock, the final design of the repository and the inventory of used fuel to be managed. For the purpose of this preliminary assessment, it is assumed that the repository would require a footprint in the order of 2 by 3 km.

The geoscientific assessment of suitability was carried out in two steps. The first step (Section 7.2) was to identify general potentially suitable areas using the key geoscientific characteristics described below. The second step (Section 7.3) was to verify that identified general areas have the potential to meet all NWMO's geoscientific site evaluation factors (NWMO, 2010). The potential for finding general potentially suitable areas was assessed using the following key geoscientific characteristics:

- ***Geological Setting:*** Areas of unfavourable geology identified during the initial screening (Golder 2011) were not considered. Both the rocks of Flin Flon greenstone belt and the Missi Group are considered unfavourable (Figures 3.4 and 7.1). The Flin Flon greenstone belt consists primarily of mafic metavolcanic rocks (greenstones) and the Missi Group consists primarily of metasandstones, metaconglomerates and metagreywackes. These groups of rock are highly heterogeneous and intensely deformed. The Flin Flon greenstone belt in particular has the highest mapped fault density in the area. The exclusion of the Flin Flon greenstone belt and the Missi Group from the Creighton leaves three felsic plutons that are potentially suitable for hosting a deep geologic repository. These include the Annabel Lake pluton, the Reynard Lake pluton and the Phantom-Boot Lake pluton (Golder, 2011).

  The Annabel pluton is about 25 km long with a fairly constant width of about 5 km in most areas, which limits the width of potential areas to less than 4 km. This is to allow for an offset distance from the bounding shear zones and possible lithological heterogeneity at the outer edges of the pluton.

  The Reynard Lake Pluton is about 25 km long with a maximum width of about 6 km at its eastern edge. The pluton narrows significantly towards its western margin where the width becomes less than 3 km over almost half of the pluton. Similar to the above, an offset distance from the bounding shear zones and possible lithological heterogeneity at the outer edges of the pluton is required. As such, the eastern half of the pluton was preferred for the selection of general potentially suitable areas.

  Most of the Phantom-Boot Lake pluton is considered too small to accommodate the 2 by 3 km general siting area requirement. The Phantom-Boot Lake pluton is also complex from both a geological and geophysical perspective (Section 3.2.1.3). The geological mapping in this area shows a complicated distribution of intrusive phases adjacent to the metavolcanic rocks. The magnetic amplitudes over this pluton are the strongest and more variable compared to any of the other intrusive rocks in the area. Multiple phases are evident in both the magnetic and radiometric data, at scales of a kilometre or less. For these reasons, and others discussed below, the Phantom-Boot Lake pluton was excluded from further consideration.

- ***Structural Geology:*** Areas within or immediately adjacent to regional faults and shear zones were considered unfavourable. The main structural features in the Creighton area include major ductile shear zones, such as the Annabel Lake, West Arm and Mosher Lake shear zones which are located at the perimeter of the Annabel Lake and Reynard Lake plutons. There are also several mapped brittle faults occurring mainly in the greenstone belt with some occurring within the limited portions of the plutons (Figure 3.5). From a siting perspective, the margins of the plutons were avoided due to their close proximity to these major ductile shear zones. As well, the southern portion of the Reynard Lake pluton was avoided because of the proximity of several mapped faults.

- ***Lineament Analysis:*** In the search for general potentially suitable areas, there is a preference to select areas that have a relatively low density of lineaments, particularly a low density of longer lineaments, as they are more likely to extend to greater depth than shorter lineaments. However, as discussed in Section 7.2, the distribution of lineaments across the Creighton area is not a significant differentiating factor when identifying general potentially suitable areas. The density of lineament is fairly uniform across the Annabel Lake and Reynard Lake plutons with only subtle differences. The desktop interpretation of remotely-sensed datasets necessarily includes a component of uncertainty as a result of data quality, scale of the Creighton area, expert judgement, and to a certain extent, the quality of the pre-existing knowledge of the bedrock geology of the Creighton 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.

- ***Overburden:*** The distribution and thickness of overburden cover is an important site characteristic to consider when assessing amenability to site characterization of an area. For practical reasons, it is considered that areas covered by more than 2 m of overburden deposits would not be amenable to trenching for the purpose of structural mapping. This consideration is consistent with international practices related to site characterization in areas covered by overburden deposits (e.g., in Finland; Andersson et al., 2007). At this stage of the assessment, preference was given to areas with greater mapped bedrock exposures.

  The thickness and distribution of overburden within the Creighton area is relatively well defined (Figure 2.3). Approximately 60% of the Annabel Lake and 64% of the Reynard Lake plutons are mapped as exposed bedrock or having a thin till veneer. With such a high percentage of bedrock exposure and the relatively small extent of the potentially suitable areas considered for the Annabel Lake and Reynard Lake plutons, overburden cover is not a significant differentiating factor for delineating general potential areas. The Phantom-Boot Lake pluton is covered by a larger percentage of relatively thicker overburden, which is another reason for this area not being preferred. The overburden thickness and distribution in potentially suitable siting areas will be refined during Phase 2 of the preliminary assessment, provided the community is selected by the NWMO, and remains interested in continuing with the site selection process.

- ***Protected Areas:*** All provincial and national parks within the Creighton area were excluded from consideration in the selection of potentially suitable areas. There are no park areas on the Annabel Lake pluton or the Reynard Lake pluton. The only protected area is the Amisk Lake Recreation Site located approximately 11 km southwest of the settlement area of Creighton on the northeast shore of Amisk Lake, about 2 km west of the Reynard Lake pluton's southern lobe (Figures 1.1 and 7.1).

- ***Natural Resources:*** Areas with known potential for exploitable natural resources were excluded from further consideration. These include the Flin Flon greenstone belt which was already excluded during the initial screening stage (Golder, 2011a). The small Phantom-Boot Lake pluton has also been excluded from further consideration because of its higher economic mineral potential compared to the Annabel Lake and Reynard Lake plutons (Morelli, 2012). The boundaries of this pluton have been the target of mineral exploration and it is entirely covered by mineral claims (Figure 5.1).

  Active mining and ongoing exploration in the Creighton area is mainly focussed on minerals associated with the Flin Flon greenstone belt and the shear zones bounding the plutons. Figure 5.1 illustrates the density of mineral claim activity that surrounds and encroaches onto large areas of the Annabel Lake and the Reynard Lake plutons. The economic mineral potential of the Annabel Lake and Reynard Lake plutons is considered low and no known economic metallic mineralization has been exploited. The claims along the margins of the plutons and some that encroach toward the center of the plutons are generally focused on gold mineralization showings which are generally small and marginally economical (Reilly, 1995; Morelli, 2012). No rare earth elements have been identified in the Reynard and Annabel Lake plutons.

  At this stage of the assessment, areas covered by active mining claims were not systematically excluded if the claims were located in geological environments judged to have low mineral resource potential, particularly where the claims were of short tenure. These areas will be assessed in more detail during subsequent site evaluation stages.

- ***Surface Constraints:*** Areas of obvious topographic constraint (density of steep slopes), and large water bodies (wetlands, lakes) and accessibility were considered for the identification of potentially suitable areas. The majority of the Creighton area is accessible by existing roads and logging roads. While areas with such constraints were not explicitly excluded at this stage of the assessment, they are considered less preferable, all other factors being equal. There are some small patches of poorly drained wetland areas over the Annabel Lake and Reynard Lake plutons but their small size and scattered occurrence makes them not a significant differentiating factor when identifying potentially suitable areas on these plutons. There are no significant topographic features on the surfaces of these larger plutons that would make site investigation or construction exceptionally difficult. The Phantom-Boot Lake pluton is largely covered by wetlands and small lakes (47%), which is another reason for excluding it from further consideration.

7.2 Potential for Finding General Potentially Suitable Areas

The consideration of the above geoscientific evaluation factors and constraints revealed that the Creighton area contains general siting areas where there is a potential to find suitable sites for hosting a deep geological repository. These general areas are in the Annabel Lake and Reynard Lake plutons. Figure 7.1 shows features illustrating some of the key characteristics and constraints used to identify general potentially suitable areas including: bedrock geology, protected areas, areas of thick overburden cover, all lineaments, the existing road network, the potential for natural resources and mining claims. The legend of this figure includes a 2 by 3 km box to illustrate the approximate surface area of potentially suitable rock that would be needed to host a repository.

The following sections describe how the key geoscientific factors and constraints discussed above were applied to the various geological units within the Creighton area to assess whether they contain general areas that have the potential to satisfy the NWMO's geoscientific site evaluation factors. At this stage of the assessment, the boundaries of these general areas are not yet defined. The location and extent of potentially suitable siting areas will be refined during Phase 2 of the preliminary assessment.

7.2.1 Annabel Lake Pluton

As discussed in Section 3.2.1, the Annabel Lake pluton consists of 1.86 Ga old granodiorite, with a probable thickness of approximately 5 to 5.5 km (Figures 3.2 and 3.4). The pluton is somewhat limited in size, with a total area of approximately 89 km^2.

A large portion (approximately 60%) of the Annabel pluton is either exposed or covered by a thin till or glaciolacustrine veneer (generally less than 1 m). With such a high portion of bedrock exposure and the relatively small size of the pluton, overburden cover was not a differentiating factor for identifying general potential areas. The presence of natural resources was also not a large differentiating factor as the mineral potential of the Annabel Lake pluton is low with no mineral showings, although the entire pluton is covered by mining claims (Figure 5.1) apparently associated with the bounding shear zones. Therefore, the main constraining factors used for finding potentially suitable areas within the Annabel Lake pluton were geology, structural geology and to a certain extent, lineament density.

The Annabel Lake pluton appears to have a number of favourable geoscientific characteristics for hosting a repository, with localized constraints based to a small extent on rock type, structural geology and lineaments. The margins of the Annabel Lake pluton were avoided because of their proximity to the Annabel Lake and West Arm shear zones. These shear zones converge at the west end of the pluton, implying increased structural complexity in that area. In addition, the lithological heterogeneity on the eastern end of the Annabel pluton (east of Creighton Lake) that was interpreted by the geophysical study (PGW, 2013) and shown on Figure 3.6 was avoided. The magnetic response over Annabel Lake pluton is fairly similar to that of the Reynard Lake pluton (Figures 3.6 and 3.7). However, the Annabel Lake pluton exhibits a more active magnetic pattern than the Reynard Lake pluton that may be a reflection of a more dioritic composition. Based on the current geophysical interpretation, the northern and southern boundaries of the Annabel Lake pluton are located further north (<1 km) compared to the position based on the bedrock geology map (PGW, 2013). This interpretation may correspond to the position of the pluton at depth and would need to be verified during subsequent stages of investigation. The eastern end of the Annabel Lake pluton also has several mapped faults, several of which appear to originate within the Flin Flon greenstone belt. Other mapped faults in the Creighton area may be related to the regional Tabbernor fault zone, located approximately 80 km to the west.

The density of interpreted surficial lineaments is high but fairly uniform across the Creighton area except for where a large number of short surficial lineaments were identified on the Annabel Lake pluton between Arner Lake and Flin Flon Lake in the satellite image (Figure 3.9). This higher frequency may be due to less overburden cover over the Annabel Lake pluton and low vegetation cover at the east end of the pluton. The frequency of surficial lineaments identified is expected to be similar across the plutons if overburden and vegetative cover was not obscuring them. The orientation of surficial lineaments in the Annabel Lake pluton (Figures 3.9 and 3.13) is very complex with many directions indicated. At the desktop stage of the assessment it is uncertain if surficial lineaments represent real bedrock structures and how far they extend to depth, particularly the shorter lineaments.

As described in Section 1.5.2, there are two slightly different resolutions of geophysical data (Figure 3.7) in the Creighton area (200 m and 300 m). The difference in resolution does not appear to greatly affect the lineament density (i.e., the higher resolution areas do not appear to have significantly more lineaments than the lower resolution areas). The overall density of interpreted geophysical lineaments over the Annabel Lake pluton is high but relatively uniform (Figure 3.10), with subtle differences showing what appears to be slightly more geophysical lineaments on the eastern edges of the pluton. The orientation of geophysical lineaments in the Annabel Lake pluton (Figures 3.10 and 3.13) is very complex with many directions indicated. Therefore, the frequency of geophysical lineaments was not deemed to be a large differentiating factor other than not favoring the eastern edge of the pluton. As shown on Figure 7.1, there is a northerly geophysical lineament set with spacing between 0.75 and 1.5 km and a generally easterly to north-easterly set of geophysical lineaments with spacing between 1.5 and 4 km. This suggests the presence of a number of areas with few interpreted lineaments. These areas warrant further consideration for identifying general potentially suitable volumes of rock for hosting a deep geological repository.

The lineament filtering process by length, as described in Section 3.2.3 and presented on Figures 3.14 to 3.17, was also examined to guide the selection of general potential areas. When lineaments longer than 5 km and 10 km are filtered (Figures 3.16 and 3.17), the density of lineaments over the Annabel Lake pluton becomes relatively uniform except for a slightly higher density area south of Creighton Lake. The figures also show that when the 5 km and 10 km filtering are applied, the majority of surface lineaments are removed and the density of lineaments over the pluton becomes dominated by the distribution of geophysical lineaments. The area within the Annabel Lake pluton with the highest density of lineaments (south of Creighton Lake on Figure 3.17) was avoided. Lineaments on the Annabel Lake pluton longer than 5 km and 10 km are typically spaced in the order of 0.75 and 1.5 km and between 1 and 4 km, respectively.

The Annabel Lake pluton (Figure 7.1) comprises Crown Land. Mining claims cover the entire pluton but are associated with the adjacent greenstone belt and shear zones. No economic mineralization occurs within the pluton but the mineral resource potential of the surrounding greenstone belt is high. Access is good throughout the area via Highway 106 which parallels the northern side of the pluton. There are no significant topographic features on the surfaces of this pluton that would make site investigation or construction exceptionally difficult. The pluton is generally well drained with discontinuous areas of wetland. The pluton is high ground with low relief. The total lake cover of the Annabel lake pluton is approximately 15%, with another 19% covered by wetlands. The majority of lake cover occurs at the northwest margin of the pluton (Figure 7.1). Quaternary mapping (see Figure 2.3) shows that exposed or thinly covered bedrock comprises approximately 60% of the pluton.

In summary, while the Annabel Lake pluton is relatively small, most of the pluton was identified as potentially suitable based mainly on its favourable geology and structural geology. The geological setting consists of an early granodioritic intrusion, good bedrock exposure with interpreted acceptable lineament spacing, and low potential for economically exploitable natural resources. It is also outside of protected areas and is accessible via the existing road network. The density and predictability of both surficial and geophysical lineaments would need to be further assessed during subsequent stages of the site evaluation process through the acquisition of higher resolution geophysical surveys and detailed geological mapping.

7.2.2 South-Central Portion of the Reynard Lake Pluton

The south-central portion of the Reynard Lake pluton is located approximately 8 km southwest of the settlement area of Creighton (Figure 7.1). As discussed in Section 3.2.1, the Reynard Lake pluton consists of 1.853 Ga old granodiorite (Figure 3.4). With depth, the pluton grades to quartz diorite below 450 m, with mafic content increasing. The pluton is somewhat limited in size, with a total area of approximately 90 km^2.

Similarly to the Annabel Lake pluton, overburden cover and potential for natural resources in the Reynard Lake pluton were not considered as significant differentiating factors. Approximately 64% of the Reynard Lake pluton is either exposed or covered by a thin till or glaciolacustrine veneer (Figure 2.3). The mineral potential of the Reynard Lake pluton is low with only localized mineral showings (Figure 5.1). As such, overburden cover and mineral potential were not differentiating factors for identifying potential areas.

Most of the south-central portion of the Reynard Lake pluton appears to have a number of favourable geoscientific characteristics for hosting a repository, with localized constraints based, to a small extent, on rock type, structural geology and lineaments. The south-central portion of the Reynard Lake pluton encompasses the wider portion of the pluton but avoids the margins with their proximity to the West Arm and Mosher Lake shear zones and associated structural complexity. As with the Annabel lake pluton, these shear zones converge towards the west, implying increased structural complexity. In addition, the south-central portion avoids the lithological heterogeneity and mapped faults at the southern end of the pluton, shown on the Figure 3.4 (geological mapping) and Figure 3.6 (geophysical magnetic data). Other mapped faults in the Creighton area may be related to the regional Tabbernor fault zone, located approximately 80 km to the west. The magnetic signature over the south-central portion of the pluton is the most inactive and homogeneous of the identified areas (Figure 3.6). These characteristics may suggest lateral lithological homogeneity; although, deep drilling shows a gradational change in lithology with depth.

The density of interpreted surficial lineaments is high but fairly uniform across the Reynard Lake pluton (Figure 3.9). The orientation of surficial lineaments in the Reynard Lake pluton (Figures 3.9 and 3.13) is very complex with many directions indicated. At the desktop stage of the assessment it is uncertain if surficial lineaments represent real bedrock structures and how far they extend to depth, particularly the shorter lineaments.

The density of geophysical lineaments across the Reynard Lake pluton also is high but relatively uniform, with some subtle differences showing slightly more geophysical lineaments on the eastern side of the Reynard Lake pluton (Figure 3.10). The orientation of geophysical lineaments in the Reynard Lake pluton (Figures 3.10 and 3.13) is very complex with many directions indicated. Therefore, the lineament density was not a differentiating factor when choosing general areas on the Reynard Lake pluton. As shown on Figure 7.1, there is a northerly geophysical lineament set with spacing between 0.75 and 1.5 km and a generally easterly to north-easterly set of geophysical lineaments with spacing between 0.75 and 1.5 km. This suggests the presence of a number of areas with few interpreted lineaments. These areas warrant further consideration for identifying potentially suitable volumes of rock for hosting a deep geological repository.

The lineament filtering process by length, as described in Section 3.2.3 and presented on Figures 3.14 to 3.17, was also examined to guide the selection of general potential areas. When lineaments longer than 5 km and 10 km are filtered (Figures 3.16 and 3.17), the density of lineaments over the Reynard Lake pluton becomes relatively uniform except for a slightly higher density area northeast of Patmore Lake. The figures also show that when the 5 km and 10 km filtering are applied, the majority of surface lineaments are removed and the density of lineaments over the pluton becomes dominated by the distribution of geophysical lineaments. The area within the Reynard Lake pluton with the highest density of lineaments (northeast of Patmore Lake on Figure 3.17) was avoided. Lineaments in the south-central portion of the Reynard Lake pluton longer than 5 km and 10 km are typically spaced in the order of 0.75 and 1.5 km and between 1 and 4 km, respectively.

A large portion (51%) of the south-central portion of the Reynard Lake pluton (Figure 7.1) comprises land classified as Crown Reserve and is on Canadian Forces Station Flin Flon. The remaining land is Crown Land. Mining claims cover the area but are associated with the adjacent greenstone belt and shear zones. No economic mineralization occurs within the area but the mineral resource potential in the surrounding greenstone belt is considered high. Access is good throughout the area via Highway 167 which passes through the south-central portion of the Reynard Lake pluton. There are no significant topographic features on the surfaces of this pluton that would make site investigation or construction exceptionally difficult. The area is generally well drained with only small, discontinuous areas of wetland. The area is high ground with low to moderate relief. Several small lakes occur within the area (Figure 7.1). The total lake and wetland cover on the Reynard Lake pluton is approximately 10% and 20%, respectively. Quaternary mapping (see Figure 2.3) shows that exposed or thinly covered bedrock comprises approximately 64% of the area.

In summary, the south-central portion of the Reynard Lake pluton was identified based on its favourable geology and structural geology. The geological setting consists of an early granodiorite (grading to quartz diorite at depth) intrusion; excellent bedrock exposure with interpreted acceptable lineament spacing, and low potential for economically exploitable natural resources. The area is also outside of protected areas and is accessible via the existing road network. The density and predictability of both surficial and geophysical lineaments would need to be further assessed during subsequent stages of the site evaluation process through the acquisition of higher resolution geophysical surveys and detailed geological mapping.

7.2.3 Other Areas

Most of the Annabel Lake pluton was chosen as a general potential siting area (Figure 7.1). The extreme western portion of the pluton was not chosen because of a large body of water (Annabel Lake) and more extensive overburden deposits. In this area the Annabel Lake and West Arm shear zones converge closer together which could imply an added structural complexity of the rock mass. The extreme eastern end of the pluton was not chosen because of the lithological complexity in this area. Tonalite-quartz diorite intrusions and slivers of greenstone and ultramafic rocks are present in this area. These surficial and geological characteristics make the extreme western and eastern portions of the Annabel Lake pluton less preferred as a potential area.

No prospective areas were identified on the western half of the Reynard Lake pluton due to the limited lateral extent of the pluton. The pluton width narrows to the west and the West Arm and Mosher Lake shear zones converge. There is physically not enough area to identify a 2 by 3 km block in this region. In addition, there is some lithological complexity (tonalite-quartz diorite and ultramafic rocks) and some mineral showings along the southern boundary in the central portion of the pluton. No prospective areas were identified on the southern portion of the Reynard Lake pluton because of mineralogical complexity, where a mixture of tonalite-quartz diorite, gabbro-diorite and ultramafic intrusions occur.

No prospective areas were identified with the Phantom-Boot Lake pluton because of bodies of water (Phantom and Boot Lakes) and extensive overburden deposits. In addition, there is lithological complexity (granite, granodiorite-quartz diorite and quartz diorite-gabbro). Several mineral showings and two past producing mines occur on or immediately adjacent to the pluton.

Given the above considerations, the potential for identifying additional general potentially suitable siting areas is limited. The location and extent of potentially suitable areas will be refined during Phase 2 of the preliminary assessment through more detailed site evaluations.

7.2.4 Summary of Characteristics the Annabel Lake and Reynard Lake Plutons

Table 7.1 provides a summary of the key geoscientific descriptive characteristics of the two identified general potential siting areas in the Creighton area. At this stage in the site evaluation process, it is not possible to objectively rank the relative suitability of the areas because of the lack of information at repository depth and the variability in the resolution of available aeromagnetic surveys, which can provide an insight into the distribution of subsurface structures.

Table 7.1: Summary of Characteristics of the Annabel Lake and Reynard Lake Plutons - Creighton

Geoscientific Descriptive Characteristic	Annabel Lake Pluton	South-central Reynard Lake Pluton
Rock Type	Predominantly granodiorite	Predominantly granodiorite, grading to quartz diorite below 450 m
Age	c. 1.86 Ga	c. 1.853 Ga
Inferred host rock thickness	5 to 5.5 km	2.3 km confirmed, 5 to 5.5 km inferred
Extent of rock unit within the Creighton area	Annabel Lake pluton: 84 km^2	Reynard Lake pluton: 88 km^2
Relative proximity to mapped regional geological features (fault zones, shear zones, geological sub-province boundaries, etc.)	Tabbernor fault zone – approximately 80 km	Tabbernor fault zone – approximately 80 km
Structure: faults, foliation, dykes, joints	Annabel Lake shear zone (N); West Arm shear zone (S); Foliation parallel to shear zones; High apparent surface lineament density; High apparent geophysical lineament density	West Arm shear zone (N); Mosher Lake shear zone (S); Mapped faults to the SE; Foliation parallel to shear zones; High apparent surface lineament density; High apparent geophysical lineament density
Aeromagnetic characteristics and resolution	Quiescent to moderately noisy, moderate to high resolution	Quiescent, moderate to high resolution
Terrain: topography, vegetation	Low relief, most vegetation in west, least vegetation in east	Low to moderate relief, intermediate vegetation
Access	Hwy 106 parallels the north boundary of the area	Hwy 167 runs through the area and additional access roads are present
Resource Potential	Low	Low

Geoscientific Descriptive Characteristic	Annabel Lake Pluton	South-central Reynard Lake Pluton
Bedrock Exposure	Moderate	Moderate
Drainage	Generally good with small discontinuous wetland areas; Contains a local surface water divide between Annabel Lake and Amisk Lake	Generally good; Draining to Amisk Lake

7.3 Evaluation of the General Potentially Suitable Areas in the Creighton Area

This section provides a brief description of how the identified potentially suitable areas were evaluated to verify whether they have the potential to satisfy the geoscientific safety functions outlined in NWMO's site selection process (NWMO 2010). At this early stage of the site evaluation process, where limited geoscientific information is available, the intent is to assess whether there are any obvious conditions within the identified potentially suitable areas that would fail to satisfy the geoscientific safety functions. These include:

- ***Safe containment and isolation of used nuclear fuel:*** Are the characteristics of the rock at the site appropriate to ensuring the long-term containment and isolation of used nuclear fuel from humans, the environment and surface disturbances caused by human activities and natural events?
- ***Long-term resilience to future geological processes and climate change:*** Are the rock formation at the siting area geologically stable and likely to remain stable over the very long term in a manner that will ensure the repository will not be substantially affected by geological and climate change process such as earthquakes and glacial cycles?
- ***Safe construction, operation and closure of the repository:*** Are conditions at the site suitable for the safe construction, operation and closure of the repository?
- ***Isolation of used fuel from future human activities:*** Is human intrusion at the site unlikely, for instance, through future exploration or mining?
- ***Amenable to site characterization and data interpretation activities:*** Can the geologic conditions at the site be practically studied and described on dimensions that are important for demonstrating long-term safety?

The evaluation factors under each safety function are listed in Appendix A. At this early stage of the site evaluation process, where limited data at repository depth exist, the intent is to assess whether there are any obvious conditions indicate that the identified siting areas would fail to satisfy the safety functions.

An evaluation of the two identified general potentially suitable areas is provided in the following subsections.

7.3.1 Safe Containment and Isolation of Used Nuclear Fuel

The geological, hydrogeological, chemical and mechanical characteristics of a suitable site should promote long-term isolation of used nuclear fuel from humans, the environment and surface disturbances; promote long-term containment of used nuclear fuel within the repository; and restrict groundwater movement and retard the movement of any released radioactive material.

This requires that:

- The depth of the host rock formation should be sufficient for isolating the repository from surface disturbances and changes caused by human activities and natural events;
- The volume of available competent rock at repository depth should be sufficient to host the repository and provide sufficient distance from active geological features such as zones of deformation or faults and unfavourable heterogeneities;
- The hydrogeological regime within the host rock should exhibit low groundwater velocities;
- The mineralogy of the rock, the geochemical composition of the groundwater and rock porewater at repository depth should not adversely impact the expected performance of the repository multiple-barrier system;
- The mineralogy of the host rock, the geochemical composition of the groundwater and rock porewater should be favourable to retarding radionuclide movement; and
- The host rock should be capable of withstanding natural stresses and thermal stresses induced by the repository without significant structural deformations or fracturing that could compromise the containment and isolation functions of the repository.

The above factors are interrelated as they contribute to more than one safety function. The remainder of this section provides an integrated assessment of the above factors based on information that is available at the desktop stage of the evaluation.

As discussed in Section 3 and summarized in Table 7.1, available geophysical information indicates that the estimated thicknesses of the Annabel Lake and Reynard Lake plutons are between 5 and 5.5 km. A deep borehole drilled into the Reynard Lake pluton has confirmed that this pluton is at least 3 km thick. Based on this, the thicknesses of the rock in the two general areas identified in these plutons (Section 7.2) are likely to extend well below typical repository depths (approximately 500 m), which would contribute to the isolation of the repository from human activities and natural surface events. This would need to be confirmed during subsequent site evaluation stages, provided the community remains interested and is selected by the NWMO to advance in the site selection process.

Analysis of existing information and of lineaments interpreted during this preliminary assessment (Section 3.2.3) indicate that the two general areas in the Creighton area have the potential to contain structurally bounded rock volumes of sufficient size to host a deep geological repository. The distribution of lineament density as a function of lineament length over the potentially suitable host rock units shows that the variable density and spacing of shorter brittle lineaments is influenced by the amount of exposed bedrock and lack of vegetative cover near the smelter. By classifying the lineaments according to length, this local bias is reduced in both general areas. Spacing between geophysical lineaments is between generally 0.75 and 1.5 km and between 1 and 4 km for all lineaments longer than 5 km and 10 km, suggesting there is potential for there to be sufficient volumes of structurally favourable rock at typical repository depth. Both general areas are located away from mapped deformation zones or faults.

The hydrogeological regime at repository depth should exhibit low groundwater velocities and retard the movement of any potentially released radioactive material. It is difficult to predict the exact nature of the groundwater regime at repository depth as no site-specific information was found on deep bedrock groundwater conditions in the two areas, or anywhere in the Creighton area. The potential for groundwater movement at repository depth is in part controlled by the fracture frequency, the degree of interconnection and the extent to which the fractures are sealed due to higher stress levels and the presence of mineral infilling. Experience from other areas in the Canadian Shield indicates that ancient faults, similar to those in the Creighton area, have been subjected to extensive periods of rock-water interaction resulting in the long-term deposition of infilling materials that contribute to sealing and a much reduced potential for groundwater flow at depth. Site-specific conditions that can influence the nature of deep groundwater flow systems need to be investigated at later stages in the site evaluation process through site characterization activities that include drilling and testing of deep boreholes.

As discussed in Section 4.4, available information for other granitic intrusions (plutons and batholiths) within the Canadian Shield, indicates that active groundwater flow within structurally-bounded blocks tends to be generally limited to shallow fracture systems, typically less than 300 m. In deeper regions, hydraulic conductivity tends to decrease as fractures become less common and less interconnected (Stevenson et al., 1996; McMurry et al., 2003). Increased vertical and horizontal stresses at depth tend to close or prevent fractures thereby reducing permeability and resulting in diffusion-dominated groundwater movement (Stevenson et al., 1996; McMurry et al., 2003). Hydraulic conductivity values measured at typical repository depths (500 m or greater) at the Whiteshell Research Area and Atikokan range from approximately 10^{-15} to 10^{-10} m/s (Ophori and Chan, 1996; Stevenson et al., 1996). Data reported by Raven et al. (1985) show that the hydraulic conductivity of the East Bull Lake pluton decreases from an average near-surface value of 10^{-8} m/s to less than 10^{-12} m/s below a depth of 400-500 m.

Information on other geoscientific characteristics relevant to the containment and isolation functions of a deep geological repository, such as the mineralogy of the rock, the geochemical composition of the groundwater and rock porewater, the thermal and geomechanical properties of the rock are not available at this stage of the site selection process. The review of available information from other locations with similar geological settings did not reveal any obvious conditions that would suggest unfavourable mineralogical or hydrogeochemical characteristics for the granodioritic plutonic rocks characterizing the two general potentially suitable areas identified within the Creighton area. Site-specific mineralogical and hydrogeochemical characteristics, including pH, Eh and salinity, would need to be assessed during subsequent site evaluation stages. Based on experience at locations having similar types of rock, it is expected that the granodioritic plutonic rocks characterizing the two areas will have suitable mineralogy, porewater geochemistry and thermal and geomechanical properties with respect to containment and isolation functions. These properties would need to be assessed during subsequent site evaluation stages.

In summary, the review of available information, including completion of a lineament analysis and geophysical interpretation of the area, did not reveal any geological or hydrogeological conditions that would indicate that the two identified general areas would be unable to satisfy the containment and isolation function. Potential suitability of these areas would have to be further assessed during subsequent site evaluation stages.

7.3.2 Long-term Resilience to Future Geological Process and Climate Change

The containment and isolation functions of the repository should not be unacceptably affected by future geological processes and climate changes, including earthquakes and glacial cycles.

The assessment of the long-term stability of a suitable site would require that:

- Current and future seismic activity at the repository site should not adversely impact the integrity and safety of the repository system during operation and in the very long term;
- The expected rates of land uplift, subsidence and erosion at the repository site should not adversely impact the containment and isolation functions of the repository;
- The evolution of the geomechanical, hydrogeological and geochemical conditions at repository depth during future climate change scenarios such as glacial cycles should not have a detrimental impact on the long-term safety of the repository; and
- The repository should be located at a sufficient distance from geological features such as zones of deformation or faults that could be potentially reactivated in the future.

A full assessment of the above factors requires detailed site-specific data that would be typically collected and analyzed through detailed field investigations. The assessment would include understanding how the site has responded to past glaciations and geological processes and would entail a wide range of detailed studies involving disciplines such as seismology, hydrogeology, hydrogeochemistry, paleohydrogeology and climate change. At this desktop preliminary assessment stage of the site evaluation process, the long-term stability factor is evaluated by assessing whether there is any evidence that would raise concerns about the long-term stability of the two general potentially suitable areas identified in the Creighton area. The remainder of this section provides assessment summary of the factors listed above.

The Creighton area is located within the Churchill Province of the Canadian Shield, where large portions of land have remained tectonically stable for more than 1.6 Ga. Historically, very few earthquakes of magnitude greater than 3 on the Richter scale have been recorded within Saskatchewan and none in the Creighton area in the past. As discussed in Section 3.2, fault zones have been identified in the Creighton area. These brittle features were created in the area approximately 1.7 Ga as part of the last significant deformation event known to have occurred in the area (D_5). There is some evidence suggesting periods of reactivation along a fault system (Tabbernor fault) approximately 80 km to the west of Creighton as recent as the Phanerozoic (i.e., more recent than 541 million years old) (Elliot, 1996; Davies, 1998; Kreis et al., 2004). However, there is no available evidence of recent movement in the Creighton area and the majority of the movement along any related faults is inferred to have occurred during the Precambrian (1.6 to 1.8 Ga).

The geology of the Creighton area is typical of many areas of the Canadian Shield, which has been subjected to numerous glacial cycles during the last million years. Glaciation is a significant past perturbation that could occur in the future. However, findings from studies conducted in other areas of the Canadian Shield suggest that deep crystalline rocks, particularly plutonic intrusions, have remained largely unaffected by past perturbations such as glaciation. Findings of a comprehensive paleohydrogeological study of the fractured crystalline rock at the Whiteshell Research Area, located within the Manitoba portion of the Canadian Shield (Gascoyne, 2004) indicated that the evolution of the groundwater flow system was characterized by periods of long-term hydrogeological and hydrogeochemical stability. Furthermore, there is evidence that only the upper approximately 300 m have been affected by glaciations within the last million years. McMurry et al. (2003) summarized several studies conducted in a number of plutons in the Canadian Shield and in the crystalline basement rocks of Western Ontario. These various studies found that fractures below a depth of several hundred metres in the plutonic rock were typically ancient features. Subsequent geological processes such as plate movement and continental glaciations have caused reactivation of existing zones of weakness rather than the formation of large new zones of fractures.

Land in the Creighton area is still experiencing isostatic rebound following the end of the Wisconsinan glaciations (Section 3.3.2). Vertical velocities show present-day uplift of about 10 mm/yr near Hudson Bay, the location of thickest ice at the last glacial maximum (Sella et al., 2007). The uplift rates generally decrease with distance from Hudson Bay and change to subsidence (1 to 2 mm/yr) south of the Great Lakes. Present day rebound rates in the Prairie Provinces should be in the order of 5 mm/yr (Lambert et al., 1998). There is no site-specific information on erosion rates for the Creighton area. However, as discussed in section 3.1.6, the erosion rates from wind, water and past glaciations on the Canadian Shield are reported to be low.

In summary, available information indicates that the identified general areas in the Creighton area have the potential to meet the long-term stability factor. The review did not identify any obvious geological or hydrogeological conditions that would cause the performance of a repository to be substantially altered by future geological and climate change processes, or prevent the identified areas from remaining stable over the long term. The long-term stability factor would need to be further assessed through detailed multidisciplinary geoscientific and climate change site investigations.

7.3.3 Safe Construction, Operation and Closure of the Repository

The characteristics of a suitable site should be favourable for the safe construction, operation, closure and long term performance of the repository.

This requires that:

- The available surface area should be sufficient to accommodate surface facilities and associated infrastructure;
- The strength of the host rock and *in situ* stress at repository depth should be such that the repository could be safely excavated, operated and closed without unacceptable rock instabilities; and
- The soil cover depth over the host rock should not adversely impact repository construction activities.

There are few surface constraints that would limit the construction of surface facilities in the two general potentially suitable areas identified in the Creighton area. The areas are characterized by low to moderate relief and each contains enough surface land outside protected areas and major water bodies to accommodate the required repository surface facilities.

From a constructability perspective, limited site-specific information is available on the local rock strength characteristics and *in situ* stresses for the plutons in the Creighton area. However, there is abundant information at other locations of the Canadian Shield with similar types of rock that could provide insight into what should be expected for the Creighton area in general. As discussed in Section 6, available information suggests that granitic crystalline rock units within the Canadian Shield generally possess good geomechanical characteristics that are amenable to the type of excavation activities involved in the development of a deep geological repository for used nuclear fuel (Arjang and Herget, 1997; Everitt, 1999; McMurry et al., 2003; Chandler et al., 2004). The conceptual model developed by Kaiser and Maloney (2005), based on available stress measurement data, describe the variable stress state in the upper 1,500 m of the Canadian Shield. Although this model can be used as an early indicator of average stress changes with depth, significant variations such as the principal horizontal stress rotation and the higher than average stress magnitudes found at typical repository depth (500 m) at AECL's URL (Martino et al., 1997) could occur as a result of local variations in geological structure and rock mass complexity.

The general areas on the Annabel Lake pluton and the south-central portion of the Reynard Lake pluton are situated in areas having good outcrop exposure. Overall, bedrock exposure on the Annabel and Reynard Lake plutons is high (approximately 60% or greater with exposed bedrock or only a thin till veneer), and bedrock exposure within the two areas is therefore also high. At this stage of the site evaluation process, it is not possible to determine the exact thickness of the overburden deposits in these areas. Figure 2.3 shows these areas to be dominated by exposed bedrock and a thin (<1 m) till veneer. These conditions are geotechnically suitable in terms of bearing capacity and stability for the construction of surface infrastructure associated with a repository.

In summary, the two identified general areas in the Creighton area have good potential to meet the safe construction, operation and closure factor.

7.3.4 Isolation of Used Fuel from Future Human Activities

A suitable site should not be located in areas where the containment and isolation functions of the repository are likely to be disrupted by future human activities.

This requires that:

- The repository should not be located within rock units containing economically exploitable natural resources such as gas/oil, coal, minerals and other valuable commodities as known today; and
- The repository should not be located within geological units containing groundwater resources at repository depth that could be used for drinking, agriculture or industrial uses.

The mineral potential in the Creighton area (Section 5) is concentrated in the Flin Flon greenstone belt. Numerous metallic mineral occurrences have been identified in the Creighton area and their mining and exploration continues today. No known economic mineralization has been identified to date within the Annabel Lake and Reynard Lake plutons. Active mining claims that are focused on the adjacent shear zones extend some distance onto the plutons, and two minor gold showings are located on the eastern side of the Reynard Lake pluton. However, no exploration activity related to these claims and showings has been reported in the Saskatchewan Energy and Resources Saskatchewan Mineral Deposit Index (2012).

The review of available information did not identify any groundwater resources at repository depth for the Creighton area. As discussed in Section 4.3, the Saskatchewan Watershed Authority (SWA) Water Well Record database shows that all water wells known in the Creighton area obtain water from overburden sources ranging from 6 to 62 m. Experience from other areas in the Canadian Shield has shown that active groundwater flow in crystalline rocks is generally confined to shallow fractured localized systems (Gascoyne et al., 1987; Gascoyne, 1994, 2000 and 2004). SWA Water Well Records indicate that no potable water supply wells are known to exploit aquifers at typical repository depths in the Creighton area or anywhere else in northern Saskatchewan.

Groundwater at such depths is generally saline and very low groundwater recharge at such depths limits potential yield, even if suitable water quality were to be found.

In summary, the potential for groundwater resources and economically exploitable natural resources at repository depth is considered low in the two identified general areas within the Creighton area although this conclusion will be subject to further confirmation.

7.3.5 Amenability to Site Characterization and Data Interpretation Activities

In order to support the case for demonstrating long-term safety, the geologic conditions at a potential site must be amenable to site characterization and data interpretation.

Factors affecting the amenability to site characterization include geological heterogeneity, structural and hydrogeological complexity, accessibility, and the presence of lakes or overburden with thickness or composition that could mask important geological or structural features.

As described in Section 3, the Annabel Lake and Reynard Lake plutons are interpreted as relatively homogeneous granodioritic bodies that have experienced several episodes of both ductile and brittle deformation. Deep drilling into the Reynard Lake pluton indicated gradational changes in compositional zoning and similar conditions could be expected for the Annabel Lake pluton. Geological mapping in the area has focussed on the greenstone belt. As such, some lithological refinement would likely occur if detailed mapping of the plutons occurs. The apparent homogeneity of the Reynard Lake and Annabel Lake plutons may in part reflect less detailed mapping.

As discussed in Section 7.1, interpreted lineaments represent the observable two-dimensional expression of three-dimensional features. The ability to detect and map such lineaments is influenced by topography, the character of the lineaments (e.g., their width, orientation, age, etc.), and the underlying resolution of the data used for the mapping. The eastern portion of the Annabel Lake and Reynard Lake plutons has slightly higher apparent lineament densities than towards the west, which may be due to the greater bedrock exposure and less vegetation coverage, but could also be an actual difference in lineament density. The orientation of lineament features in three dimensions represents another degree of structural complexity that will require assessment through detailed site investigations in future phases of the site selection process.

The identification and mapping of geology and structure is strongly influenced by the extent and thickness of overburden cover and the presence of large lakes. The Creighton area is characterized by good bedrock exposure over the plateau-like surfaces of the Annabel Lake and Reynard Lake plutons. These areas are dominated by exposed bedrock or a thin (<1 m) till veneer. Thicker overburden deposits are concentrated in relatively small topographic depressions, wetlands and lakes on the plutons. As mentioned in section 7.2.1, the majority of lake cover occurs at the northwest margin of the pluton, which may have an impact on the ability to characterize the rock in that area.

Provincial Highway 106 provides general access to the Annabel Lake pluton and runs approximately 2 km to 3 km from the northern boundary of the pluton. Provincial Highway 167 provides direct access to south-central portion of the Reynard Lake pluton.

The review of available information did not indicate any obvious conditions which would make the rock mass in the identified general siting areas unusually difficult to characterize. Access and outcrop locations are available for site characterization purposes at both identified general areas.

8.0 GEOSCIENTIFIC PRELIMINARY ASSESSMENT FINDINGS

The objective of the Phase 1 geoscientific preliminary assessment was to assess whether the Creighton area contains general areas that have the potential to satisfy the geoscientific site evaluation factors outlined in NWMO's site selection process document (NWMO, 2010).

The preliminary geoscientific assessment built on the work previously conducted for the initial screening (Golder, 2011) and focused on the Town of Creighton and its periphery, which are referred to as the "Creighton area" (Figure 1.1). The assessment was conducted using available geoscientific information and key geoscientific characteristics that can be realistically assessed at this early stage of the site evaluation process. The key evaluation factors used relate to: geology; structural geology and distribution of lineaments; distribution and thickness of overburden deposits; surface conditions; and the potential for economically exploitable natural resources. Where information for the Creighton area was limited or not available, the assessment drew on information and experience from other areas with similar types of rock on the Canadian Shield. The desktop geoscientific preliminary assessment included the following review and interpretation activities:

- Detailed review of available geoscientific information such as geology, structural geology, natural resources, hydrogeology, overburden deposits;
- Interpretation of available geophysical surveys (magnetic, electromagnetic, gravity and radiometric);
- Lineament studies using available satellite imagery, topography and geophysical surveys to provide information on the characteristics such as location, orientation and length of interpreted structural bedrock features;
- Terrain analysis studies to help assess factors such as overburden type and distribution, bedrock exposures, accessibility constraints, watershed and subwatershed boundaries, groundwater discharge and recharge zones; and
- The identification of general potentially suitable areas based on key geoscientific characteristics and the systematic application of NWMO's geoscientific site evaluation factors.

The desktop geoscientific preliminary assessment showed that the Creighton area contains at least two general areas that have the potential to satisfy NWMO's geoscientific site evaluation factors. One of these areas extends over most of the Annabel Lake pluton. The other area is in the south-central portion of the Reynard Lake pluton.

Both the Annabel Lake and Reynard Lake plutons appear to have a number of geoscientific characteristics that are favourable. They have sufficient depth and sufficient geographic extent. The bedrock within the two identified potentially suitable areas has good exposure and is mapped as relatively homogeneous. The two areas have low potential for natural resources, although they are in close proximity and surrounded by rock units with known mineral potential (e.g., greenstone belts). Both areas are generally accessible and have limited surface constraints, with the exception of some areas with large water bodies. The two areas have a complex orientation of interpreted lineament, but remain generally amenable to site characterization.

While the Creighton area appears to have favourable geoscientific characteristics, there are inherent uncertainties that would need to be addressed during subsequent stages of the site evaluation process. Main uncertainties regarding the suitability of identified areas include the relatively small extent of the potentially suitable geological units within the Creighton area, the proximity of major shear zones and mapped faults, and the high mineral potential of the surrounding greenstone belt.

Interpreted lineaments suggest that both identified potentially suitable areas have the potential to contain structurally bounded rock volumes of sufficient size to host a deep geological repository. However, the potential impact of the shear zones and mapped faults in the vicinity of the two identified potentially suitable areas would need to be further assessed during subsequent site evaluation stages.

Should the community of Creighton be selected by the NWMO to advance to Phase 2 of the study and remain interested in continuing with the site selection process, several years of progressively more detailed studies would be required to confirm and demonstrate whether the Creighton area contains sites that can safely contain and isolate used nuclear fuel. This would include the acquisition and interpretation of higher resolution airborne geophysical surveys, field geological mapping and the drilling of deep boreholes.

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Report Signature Page

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AM/GWS/wlm

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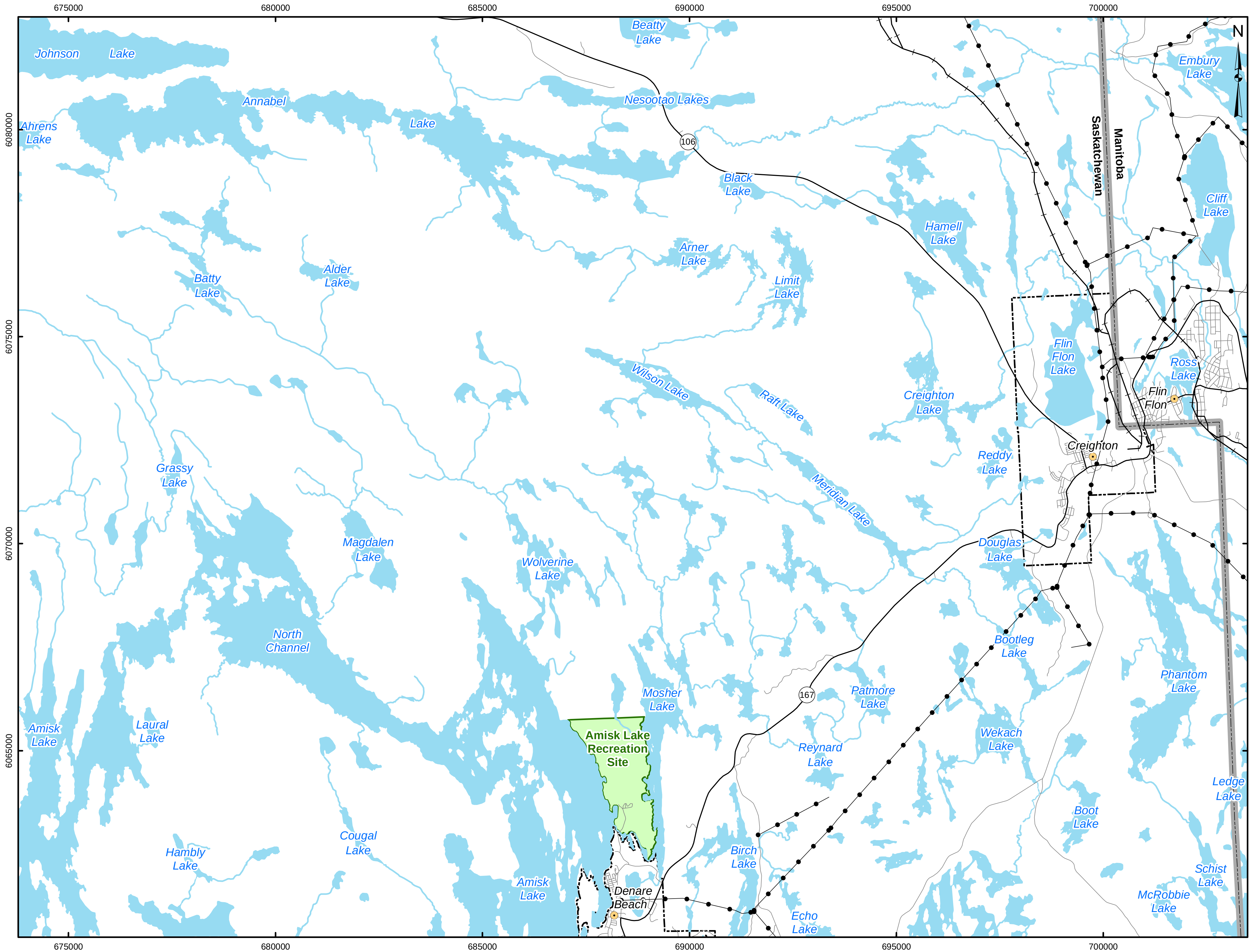
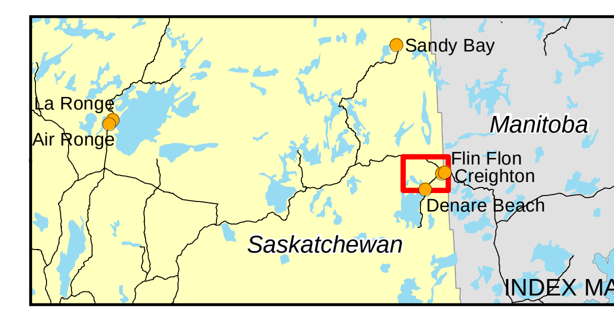
FIGURES



LEGEND

- Municipality Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Transmission Line
- Watercourse
- Waterbody
- Park and Recreation Area



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Town of Creighton and Surrounding Area

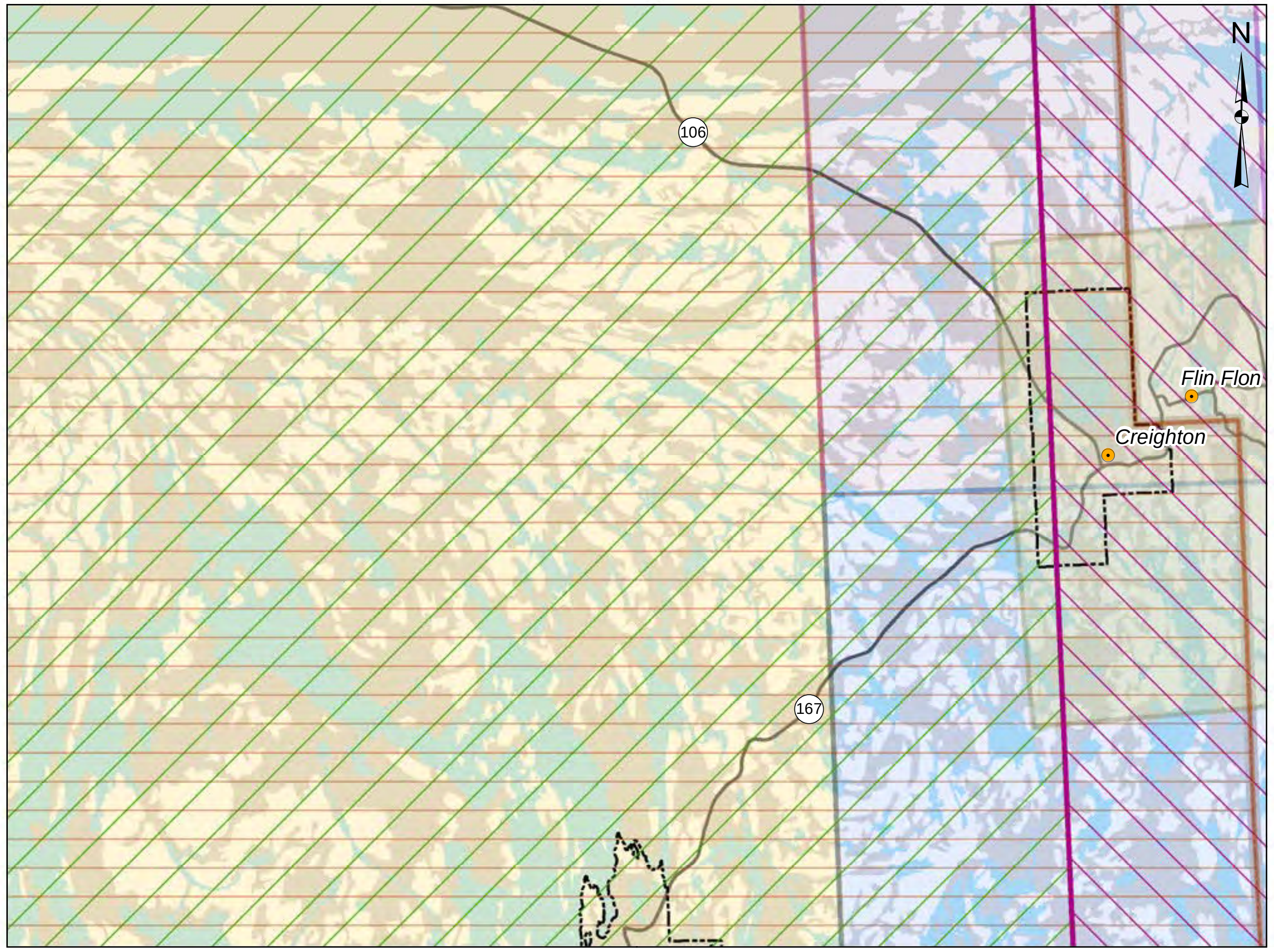
Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012		
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

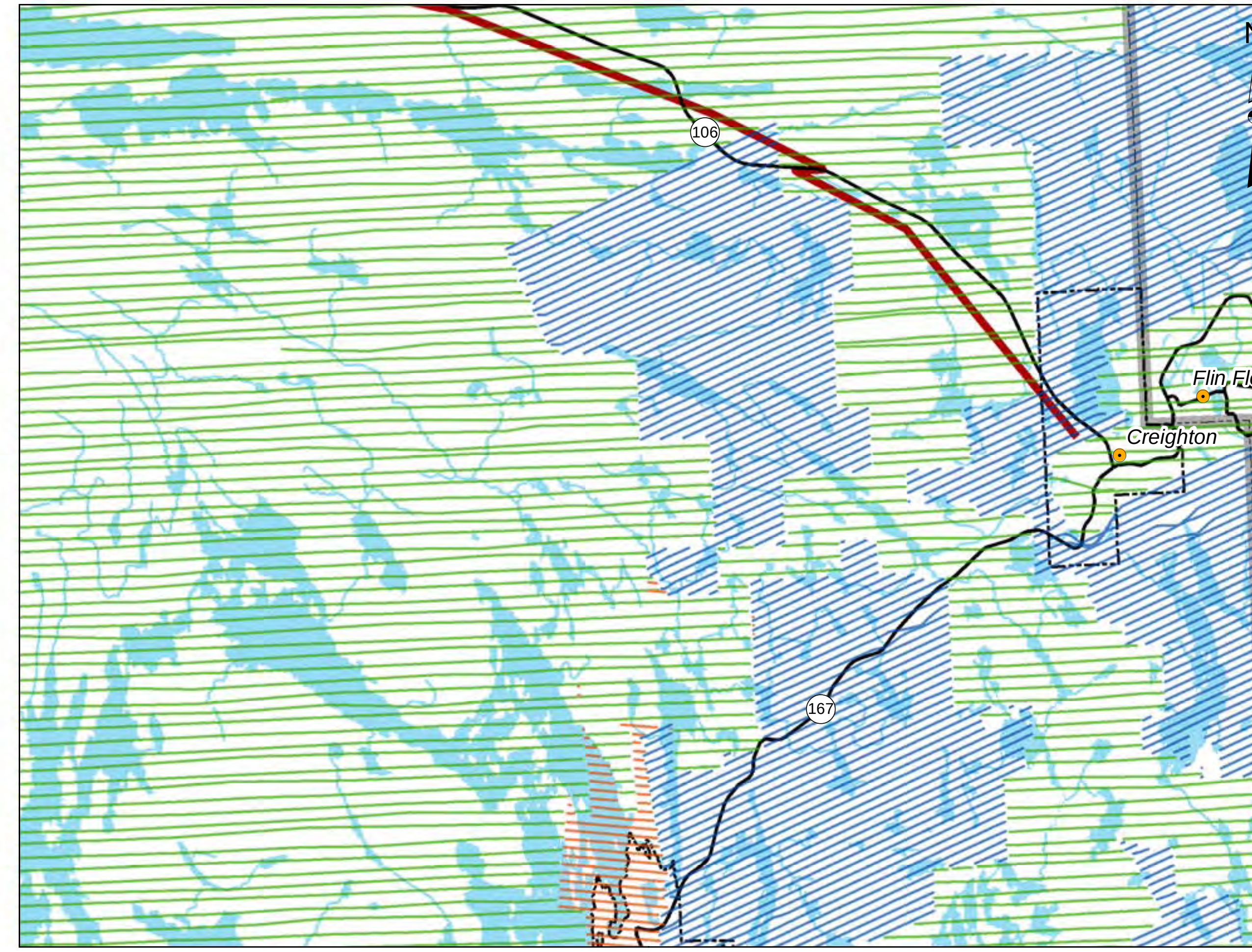
FIGURE: 1.1

G:\Projects\2012\12-1152-0026_NWMO_PhaseI_Feasibility\GIS\MXDs\Reporting\Creighton\Draft_Integrated_Report\CreightonAndSurroundingLands.mxd

Geology Mapping Coverage



Geophysics Mapping Coverage



LEGEND

- Municipal Boundary
- Community
- Main Road
- Watercourse
- Waterbody
- Overburden Cover

Detailed Bedrock Geology Extent

- Byers and Dahlstrom Map 1954 (14c)
- Byers et al 1965 Map No. 62b
- Byers et al 1965 Map No. 62c
- NATMAP1998 258A Sheet1 Boundary
- NATMAP1998 Map258A Sheet2 Boundary
- Saskatchewan Energy and Resources, 2010
- Simard et al., 2012 Map 2010-1

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

LEGEND

- Municipal Boundary
- Community
- Main Road
- Watercourse
- Waterbody
- Lithoprobe Line

Geophysical Survey Flightpaths

- Geophysics Flight Paths Hudbay FlinA
- Geophysics Flight Paths Hudbay Konuto
- Geophysics Flight Paths GSC Flin Flon Sherridon A

4 2 0 4 8 12
SCALE 1:175,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Bedrock Mapping and
Geophysical Coverage of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 1.0
DESIGN	PM/JB	19 Nov. 2012	FIGURE: 1.2	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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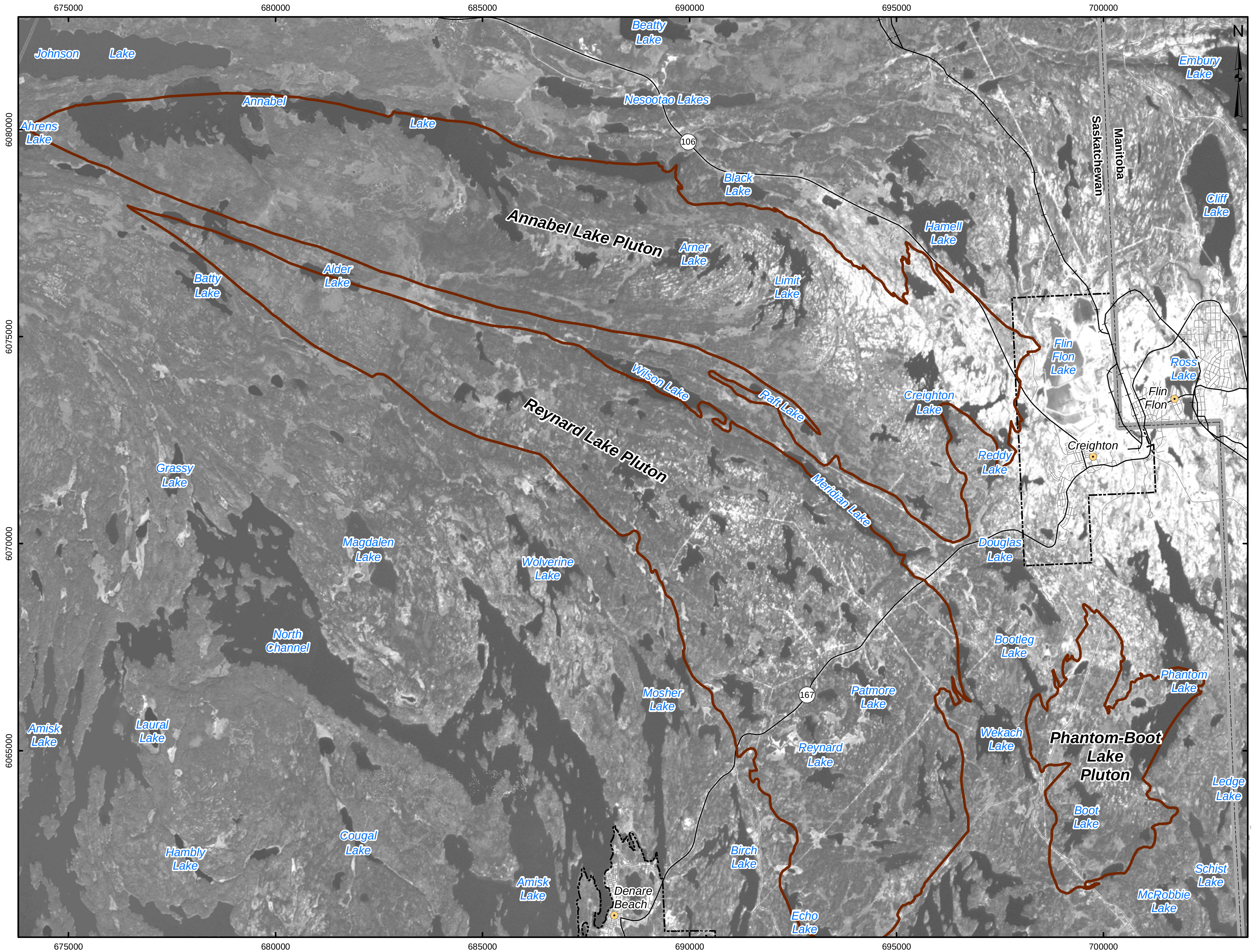
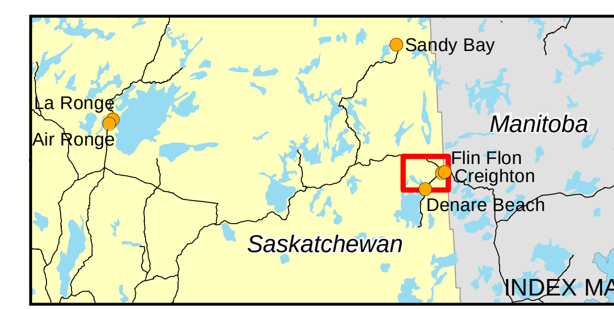


G:\Projects\2012\12-1152-0026_NWMO_PhaseI_Feasibility\GIS\MXDs\Reporting\Creighton\Draft_Integrated_Report\SatelliteImageryCreightonArea.mxd

LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Outline of Major Pluton



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Imagery - SPOT obtained from GeoBase (2005, 10m resolution)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

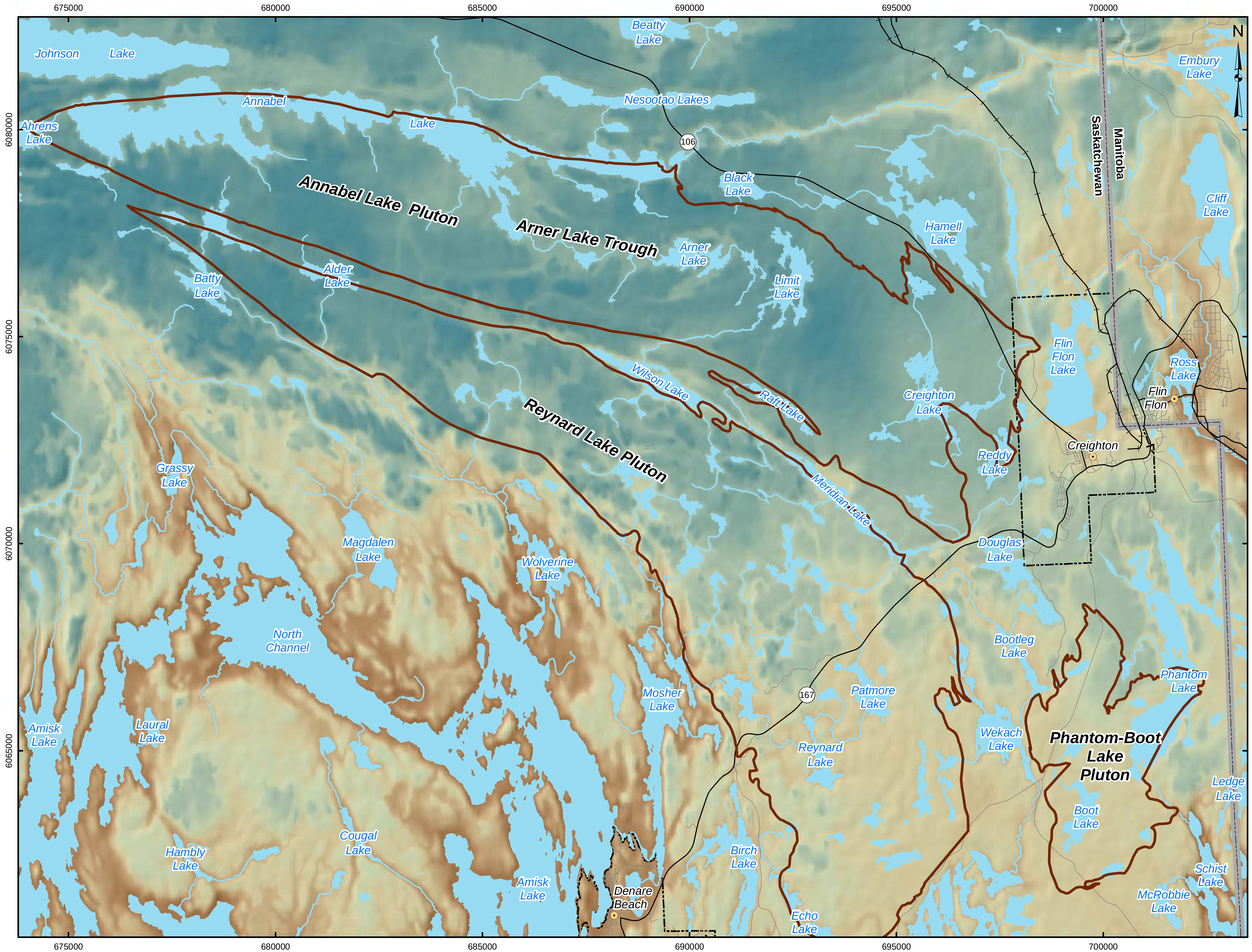
2 1 0 2 4 6
SCALE 1:100,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Satellite Imagery of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012	FIGURE: 2.1	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

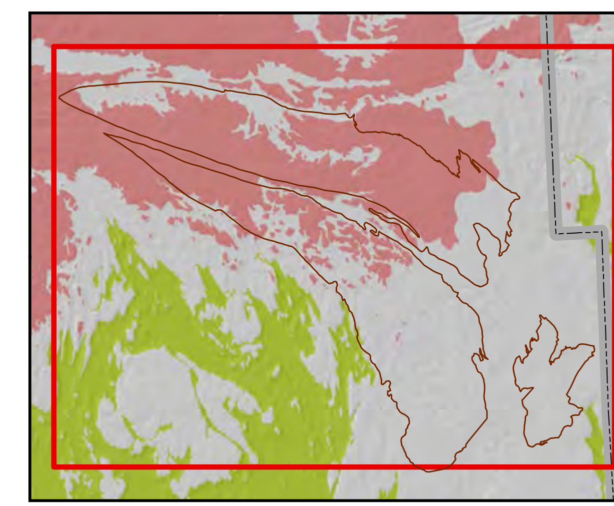


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Outline of Major Pluton

Elevation (masl)
377
370
360
350
340
330
320
310
300
290

KEY TOPOGRAPHIC HIGHS AND LOWS



Elevation (masl)
290 - 310 311 - 342 343 - 377

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Digital Elevation Model - CDED slope and elevation raster: Geobase.ca (1:50,000)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6
SCALE 1:100,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

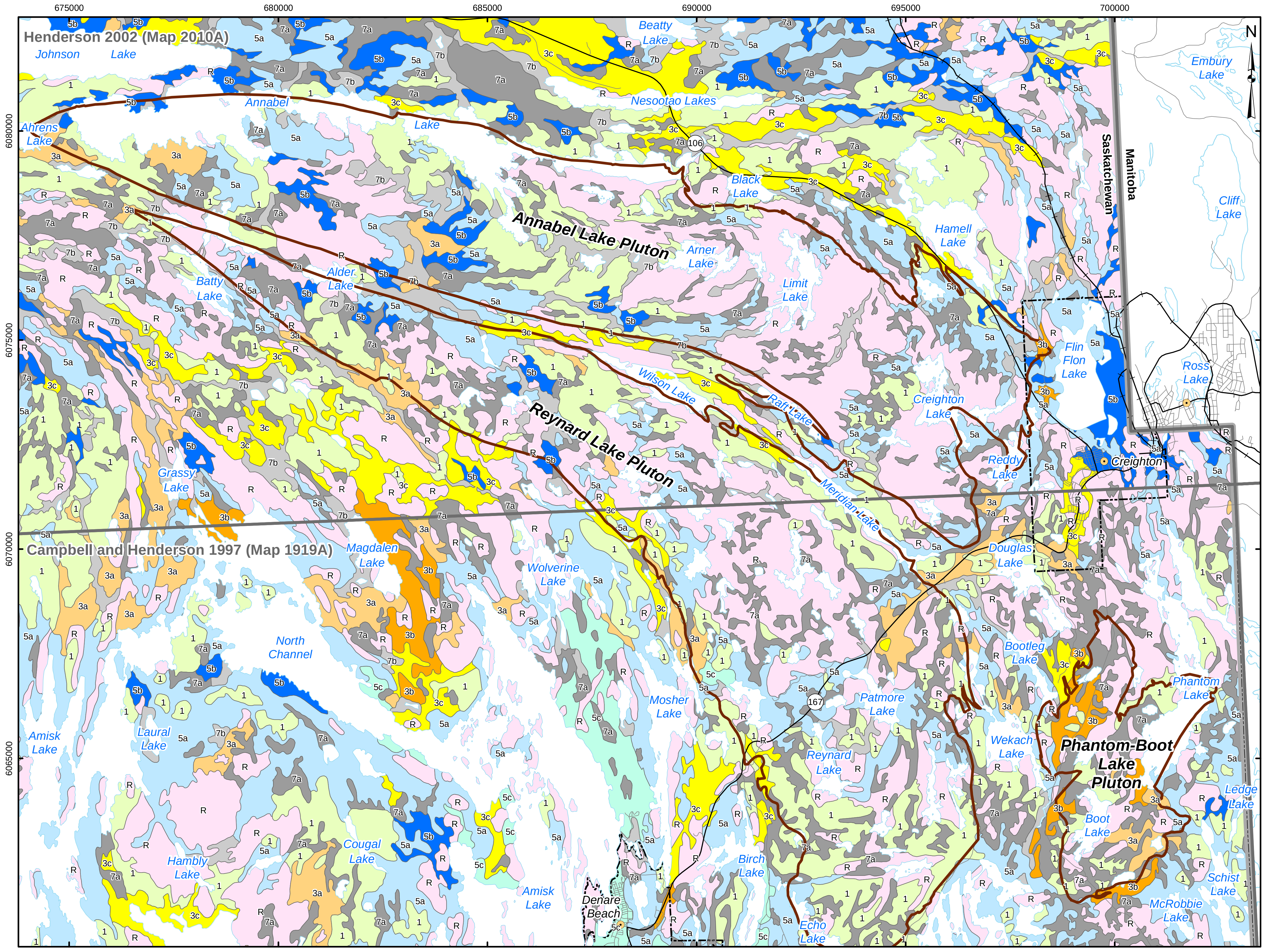
TITLE
Elevation and Major Topographic Features of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012		
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

FIGURE: 2.2

G:\Projects\2012\12-1152-0026_NWMO_PhaseI_Feasibility\GIS\MXDs\Reporting\Creighton\Draft_Integrated_Report\ElevationMajorTopographicFeaturesCreightonArea.mxd

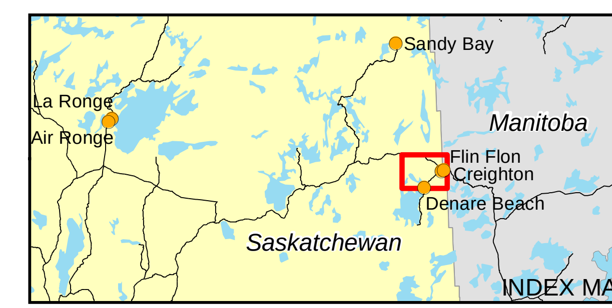


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Waterbody
- Outline of Major Pluton

Landform

- 7b - Fen peat
- 7a - Bog peat
- 5c - Glaciolacustrine nearshore
- 5b - Glaciolacustrine offshore blanket
- 5a - Glaciolacustrine offshore veneer
- 3c - Glaciofluvial subaqueous outwash
- 3b - Glaciofluvial ice-contact
- 3a - Sand and gravel of undetermined origin
- 1 - Till veneer
- R - Bedrock



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Wells - Saskatchewan Watershed Authority Water Well Database
Landform - Surficial Geology, Saskatchewan (1:50,000)
Campbell, J.E. and P.J. Henderson, 1997. Surficial geology, Denare Beach-Schist Lake, Saskatchewan-Manitoba, Natural Resources Canada (NRC) Map 1919A (1:50:000)
Henderson, P.J., 2002. Surficial geology, Annabel Lake-Flin Flon, Saskatchewan. Geological Survey of Canada, Natural Resources Canada (NRC) Map 2010A, 1:50,000 scale.
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSEMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Terrain Features of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012		
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

FIGURE: 2.3

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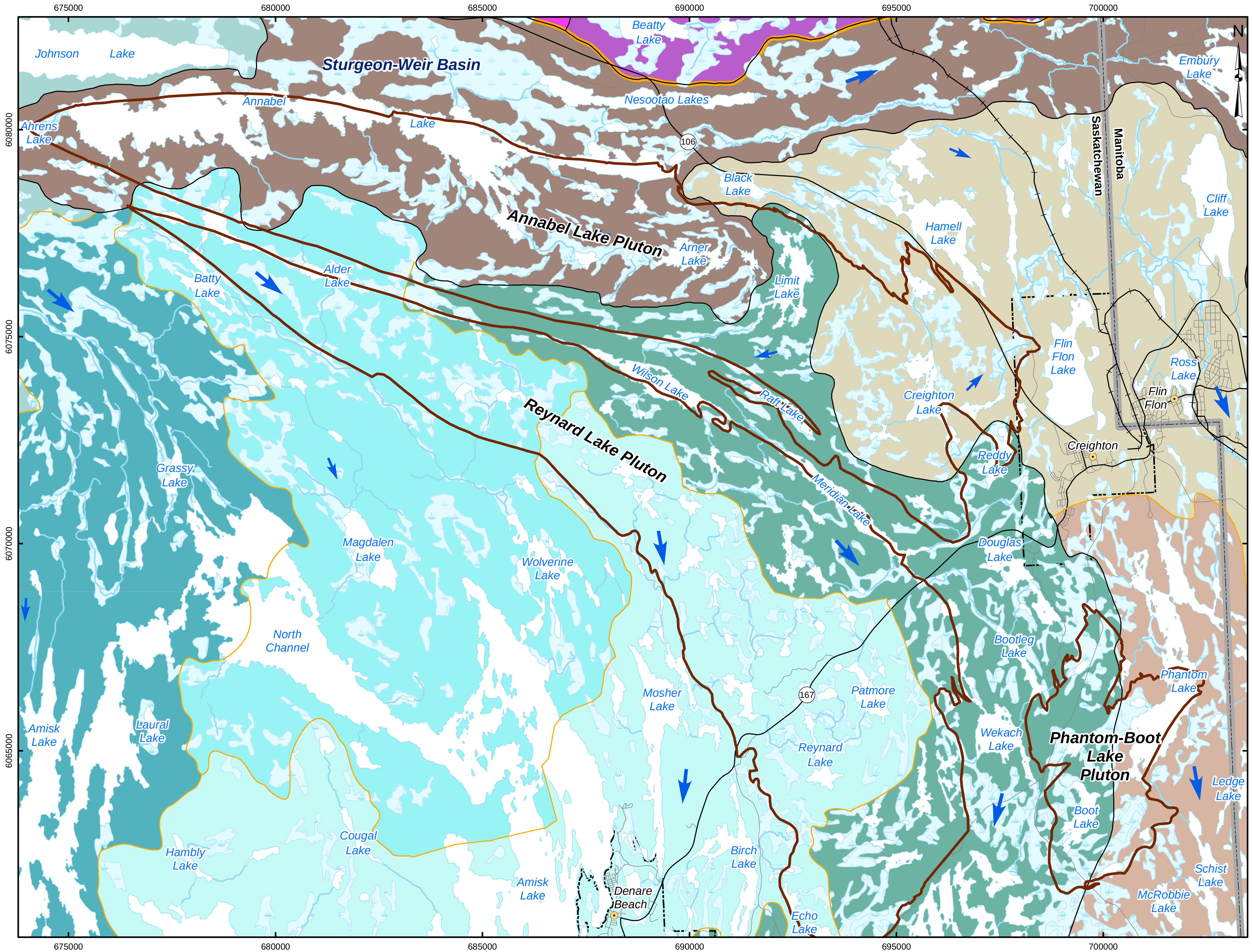


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Outline of Major Pluton

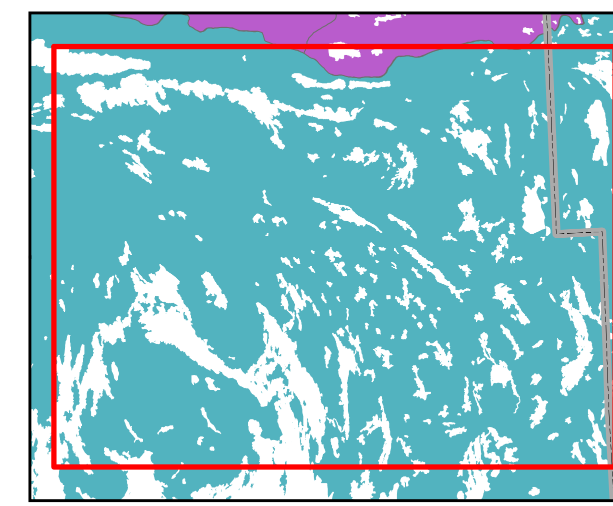
Flow Direction

- Minor Flow
- Major Flow

Watershed Boundary

- Delineated by PFRA (Confirmed by JDMA)
- Delineated by JDMA
- Watercourse
- Waterbody
- Wetland
- Environment Canada Sub-basin

MAP OF TERTIARY WATERSHEDS



Nelson River Drainage Area
Western & Northern Hudson Bay Drainage Area

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Drainage Divide - PFRA sub-basin (updated by JDMA)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Drainage Features of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012	FIGURE: 2.4	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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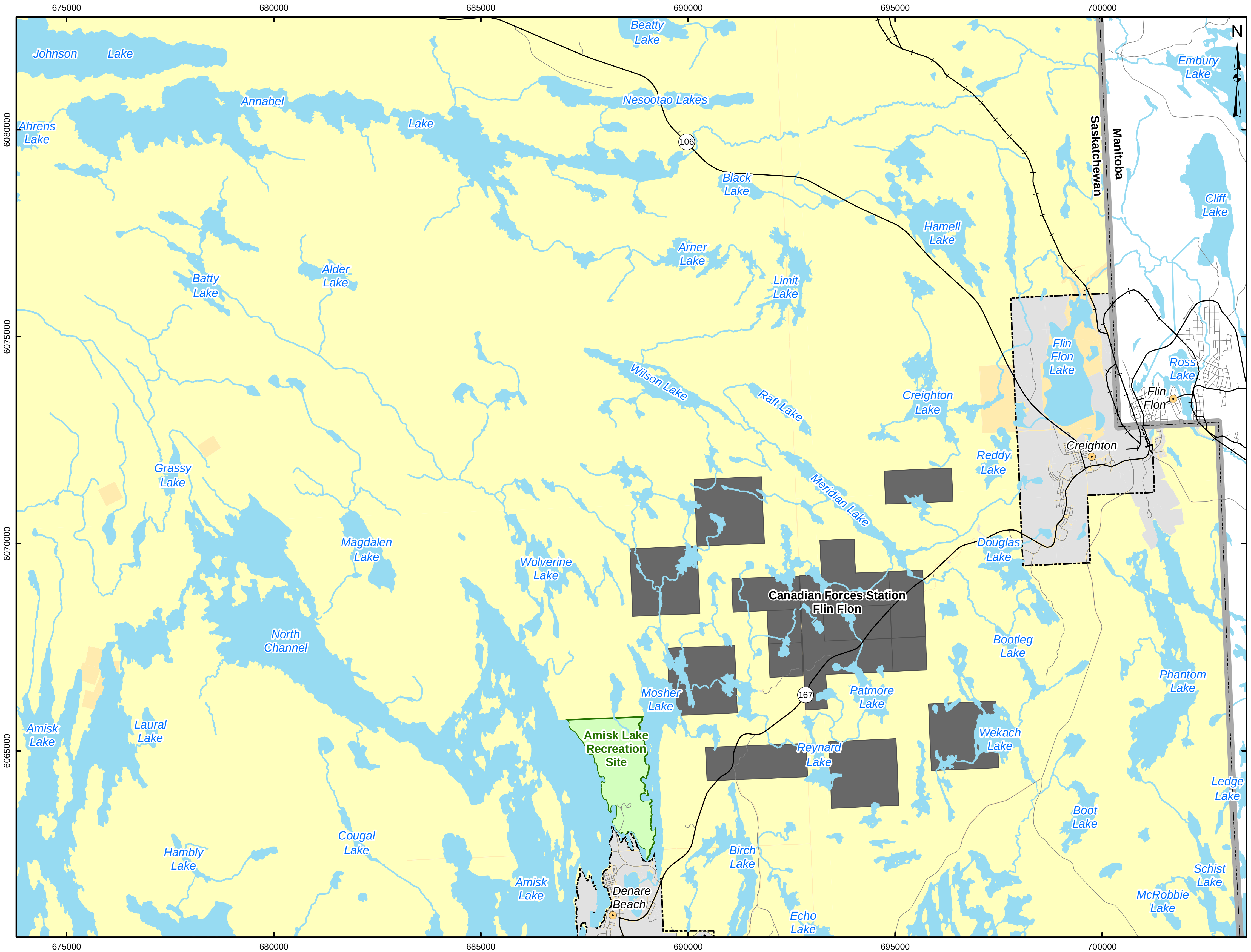
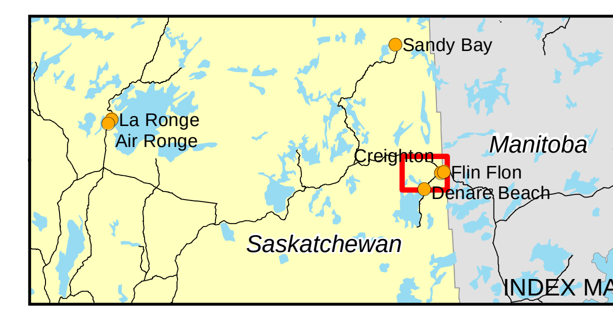


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Park and Recreation Area
- Crown Land
- Private Land
- Unclassified Land
- Crown Reserves



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Cadastral Data - Information Services Corporation of Saskatchewan, 2008
Crown Reserves - Saskatchewan Geological Atlas
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Land Disposition and Ownership within the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT No. 12-1152-0026			SCALE AS SHOWN	REV. 2.0
DESIGN	PM	1 May. 2012	FIGURE: 2.5	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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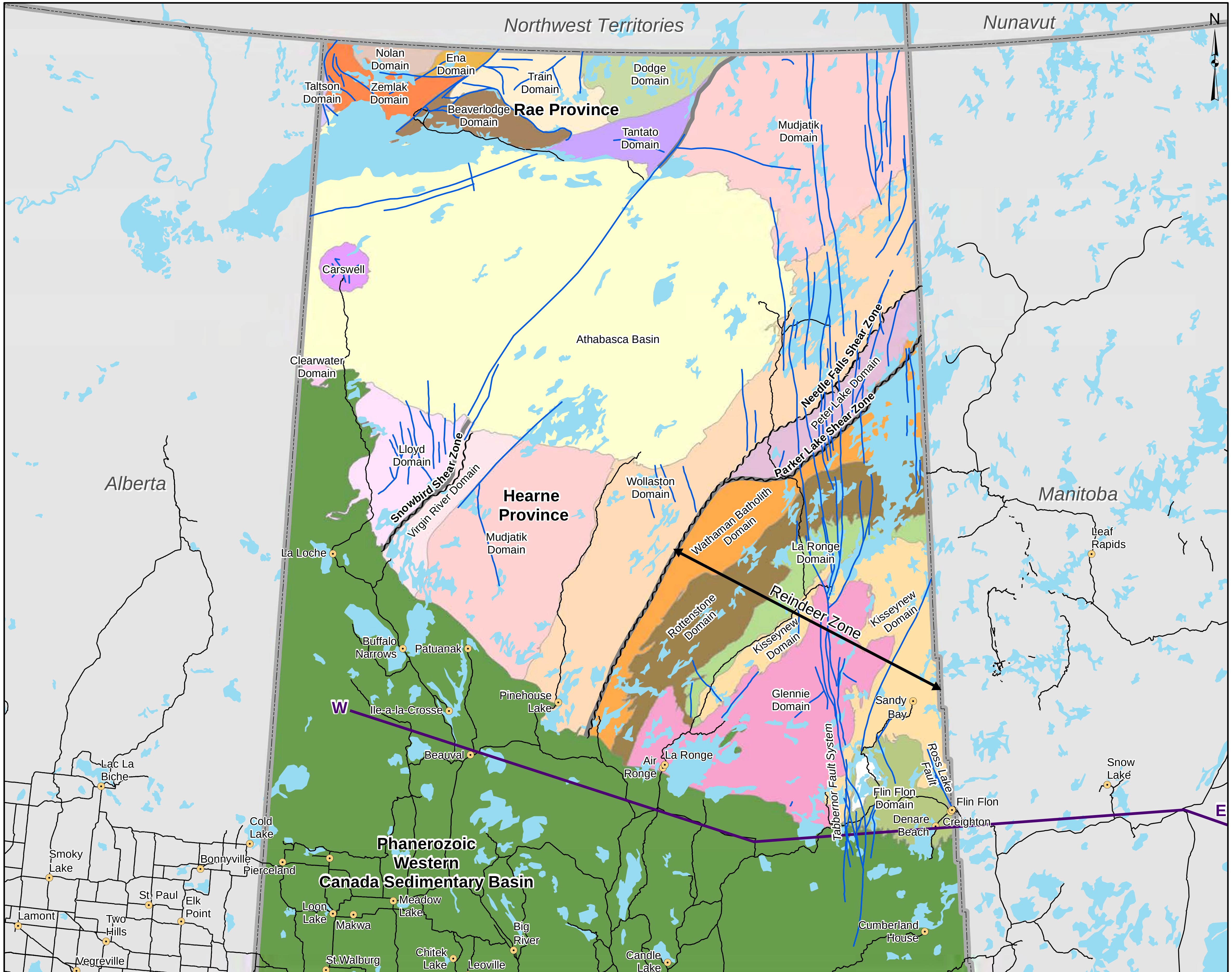


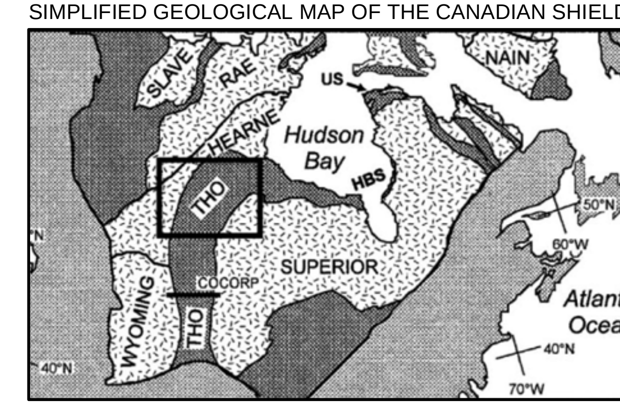
LEGEND

- Provincial Boundary
- Community
- Highway
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Geological Cross Section (see Figure 3.2)
- Precambrian Geological Province

Lithotectonic Domain

- Athabasca Basin
- Beaverlodge Domain
- Carswell Domain
- Clearwater Domain
- Dodge Domain
- Ena Domain
- Flin Flon Domain
- Glennie Domain
- Kisseynew Domain
- La Ronge Domain
- Lloyd Domain
- Mudjatik Domain
- Nolan Domain
- Peter Lake Domain
- Rottenstone Domain
- Taltson Domain
- Tantato Domain
- Train Domain
- Virgin River Domain
- Wathaman Batholith Domain
- Wollaston Domain
- Zemlak Domain
- Phanerozoic Western Canada Sedimentary Basin

SIMPLIFIED GEOLOGICAL MAP OF THE CANADIAN SHIELD



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Government of Canada, Natural Resources Canada, Centre for Topographic Information, 2001
Corrigan et al., "The Palaeoproterozoic Trans-Hudson Orogen: a prototype of modern accretionary processes", *Geological Society, London, Special Publications* 2009; v. 327; p. 457-479.
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

50 25 0 50 100 150

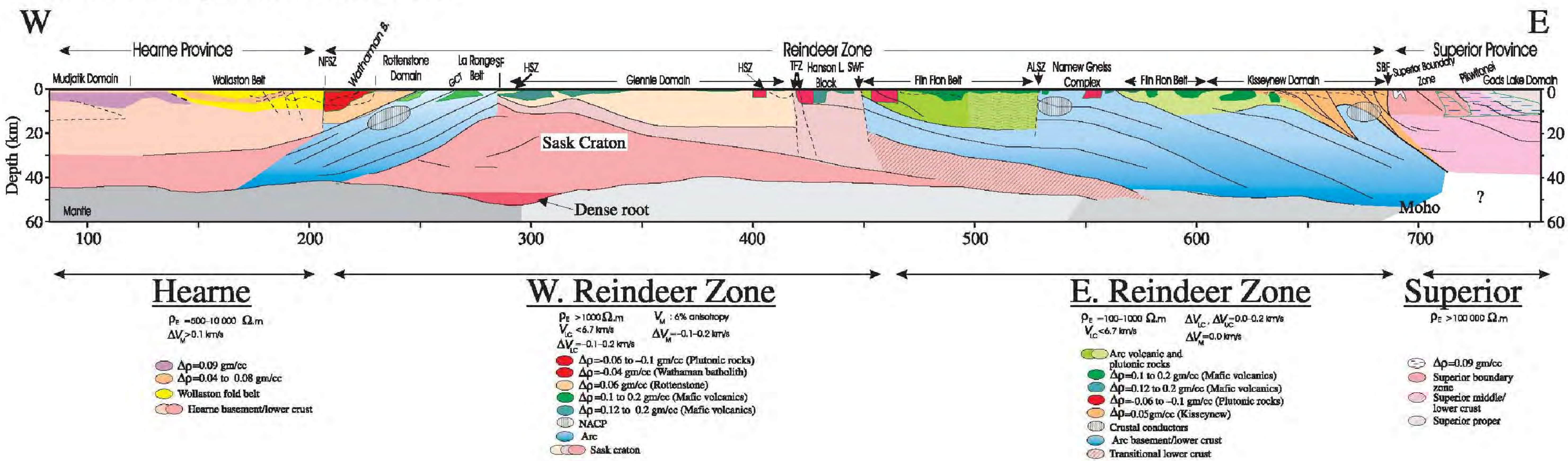
SCALE 1:3,000,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Lithostructural Domains of Northern Saskatchewan

Golder Associates
Mississauga, Ontario

PROJECT No. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	JB	8 Nov. 2012		
GIS	PM/JB	23 Aug. 2013	FIGURE: 3.1	
CHECK	AM	23 Aug. 2013		
REVIEW	GS	23 Aug. 2013		



REFERENCE

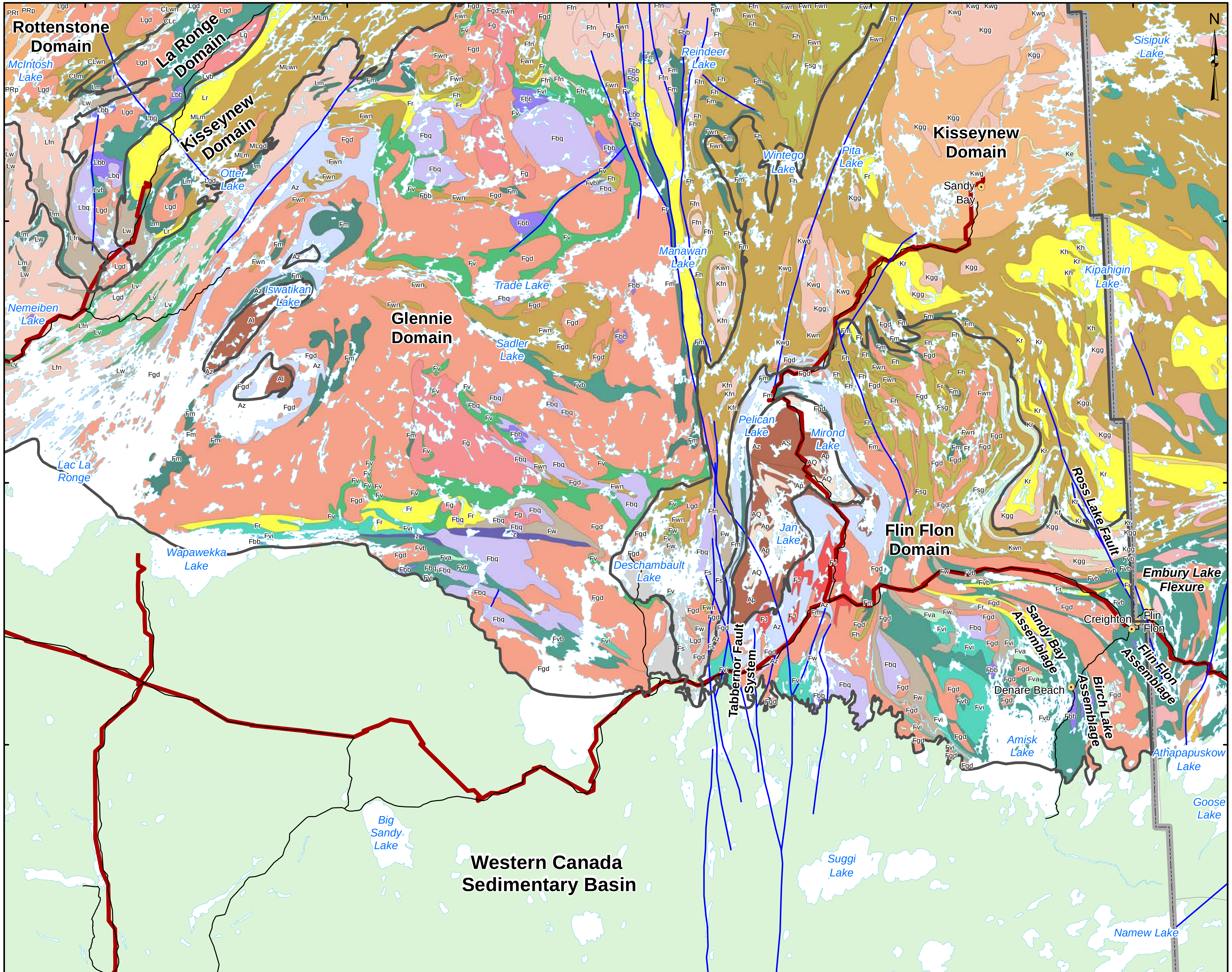
White, D.J., M.D. Thomas, A.G. Jones, J. Hope, B. Németh and Z. Hajnal, 2005, Geophysical transect across a Paleoproterozoic continent-continent collision zone; The Trans-Hudson Orogen. Canadian Journal of Earth Sciences, 42, pp. 385-402.

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Geological Cross Section Through Northern Saskatchewan

Golder Associates
Saskatoon, Saskatchewan

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	JB	8 Nov. 2012	FIGURE: 3.2	
GIS	BDS	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		



LEGEND

- Provincial Boundary
- Community
- Highway
- Waterbody
- Mapped Fault
- Lithoprobe Line
- Domain Boundary

Rottenstone Domain
- CLc - Crew Lake Calc-silicate rocks
- CLm - Metabasite/amphibolite (volcanic)
- CLwn - Crew Lake pelitic-psammitic gneiss
- Lbb - (Diorite)-gabbro(ultramafite)
- Lbq - Tonalite-diorite
- Lfn - Felsic orthogneiss
- Lgd - Granite-granodiorite-tonalite
- Lm - Metabasite/amphibolite (volcanic)
- Lva - Acid volcanics
- Lvb - Basic to intermediate volcanic
- Lw - Greywacke, local conglomerate
- PRp - Biotitic and hornblenic gneiss
- PRt - Trondjhemite-tonalite
- z - Mylonitic gneiss

Glennie Domain
- Az - Mylonitic gneiss
- Fbb - (Diorite)-gabbro-(ultramafite)
- Fbq - Tonalite-diorite
- Ffn - Felsic orthogneiss
- Fg - Granite to tonalite
- Fgd - Granite-granodiorite-tonalite
- Fgs - Plutonic/supracrustal gneisses
- Fh - Felsic to mafelsic gneiss (volcanic)
- Fm - Metabasite/amphibolite (volcanic)
- Fr - Arkose, conglomerate, psammitic gneiss
- Fsg - Interlayered supracrustals and orthogneiss
- Fv - Undivided volcanics
- Fva - Acid volcanics
- Fvb - Basic to intermediate volcanic
- Fvi - Acid to intermediate volcanics
- Fw - Greywacke, local conglomerate
- Fwn - Gneissic greywacke, psammopelite to pelite, conglomerate
- Kfn - Felsic orthogneiss
- Kwn - Greywacke, psammitic, pelitic gneiss
- Lbb - (Diorite)-gabbro(ultramafite)
- Lbq - Tonalite-diorite
- Lfn - Felsic orthogneiss
- Lgd - Granite-granodiorite-tonalite
- Lm - Metabasite/amphibolite (volcanic)
- Lr - Arkose, conglomerate, psammitic gneiss
- Lv - Undivided volcanics
- Lw - Greywacke, local conglomerate
- z - Mylonitic gneiss

La Ronge Domain
- CLc - Crew Lake Calc-silicate rocks
- Lbb - (Diorite)-gabbro(ultramafite)
- Lbq - Tonalite-diorite
- Lfn - Felsic orthogneiss
- Lg - Granite to tonalite
- Lgd - Granite-granodiorite-tonalite
- Lm - Metabasite/amphibolite (volcanic)
- Lr - Arkose, conglomerate, psammitic gneiss
- Lvb - Basic to intermediate volcanic
- Lw - Greywacke, local conglomerate

Flin Flon Domain
- Ap - Migmatitic pelite
- Az - Mylonitic gneiss
- FJ - Late aplogranite/pegmatite
- FP - Fiar Point: Pebbly to conglomeratic quartzarenite
- Fbb - (Diorite)-gabbro-(ultramafite)
- Fbq - Tonalite-diorite
- Ff - Felsic gneiss (volcanic)
- Fgd - Granite-granodiorite-tonalite
- Fh - Felsic to mafelsic gneiss (volcanic)
- Fm - Metabasite/amphibolite (volcanic)
- Fr - Arkose, conglomerate, psammitic gneiss
- Fsg - Interlayered supracrustals and orthogneiss
- Fv - Undivided volcanics
- Fva - Acid volcanics
- Fvb - Basic to intermediate volcanic
- Fvi - Acid to intermediate volcanics
- Fw - Greywacke, local conglomerate
- Fwn - Gneissic greywacke, psammopelite to pelite, conglomerate
- Kgg - Granodioritic diatexite
- Km - Marine quartzose sandstone mudstone, siltstone
- Kr - Psammitic gneiss
- Kwn - Greywacke, psammitic, pelitic gneiss
- Kws - Claystone-siltstone; mudstone+siltstone; shale+mudstone

Kisseynew Domain
- Fbq - Tonalite-diorite
- Ffn - Felsic orthogneiss
- Fg - Granite to tonalite
- Fgd - Granite-granodiorite-tonalite
- Fh - Felsic to mafelsic gneiss (volcanic)
- Fm - Metabasite/amphibolite (volcanic)
- Fr - Arkose, conglomerate, psammitic gneiss
- Fs - Schist, phyllite, siltstone
- Fv - Undivided volcanics
- Fw - Greywacke, local conglomerate
- Fwn - Gneissic greywacke, psammopelite to pelite, conglomerate
- Ke - Silty+clayey volcanic lithic sandstone, interbedded shale
- Kfn - Felsic orthogneiss
- Kgg - Granodioritic diatexite
- Kh - Felsic to mafelsic gneiss (volcanic)
- Kr - Psammitic gneiss
- Kwg - Diatexite derived from Greywacke, psammitic pelitic gneiss
- Kwn - Greywacke, psammitic, pelitic gneiss
- Lbq - Tonalite-diorite
- Lgd - Granite-granodiorite-tonalite
- Lm - Metabasite/amphibolite (volcanic)
- Lr - Arkose, conglomerate, psammitic gneiss
- Lvb - Basic to intermediate volcanic
- Lw - Greywacke, local conglomerate
- MLgd - Granite-granodiorite-tonalite
- MLm - Metabasite/amphibolite (volcanic)
- MLwn - Gneissic greywacke, psammopelite to pelite, conglomerate

Western Canada Sedimentary Basin
- Western Canada Sedimentary Basin

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas, Bedrock Geology and Legend (1:1,000,000); Manitoba Minerals Resource Division, Geological Map of Manitoba, Bedrock Geology (1:1,000,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

20 10 0 20 40
SCALE 1:750,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Regional Geology of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	JB	8 Nov. 2012	FIGURE: 3.3	
GIS	PM/JB	28 Aug. 2013		
CHECK	AM	28 Aug. 2013		
REVIEW	GWS	28 Aug. 2013		

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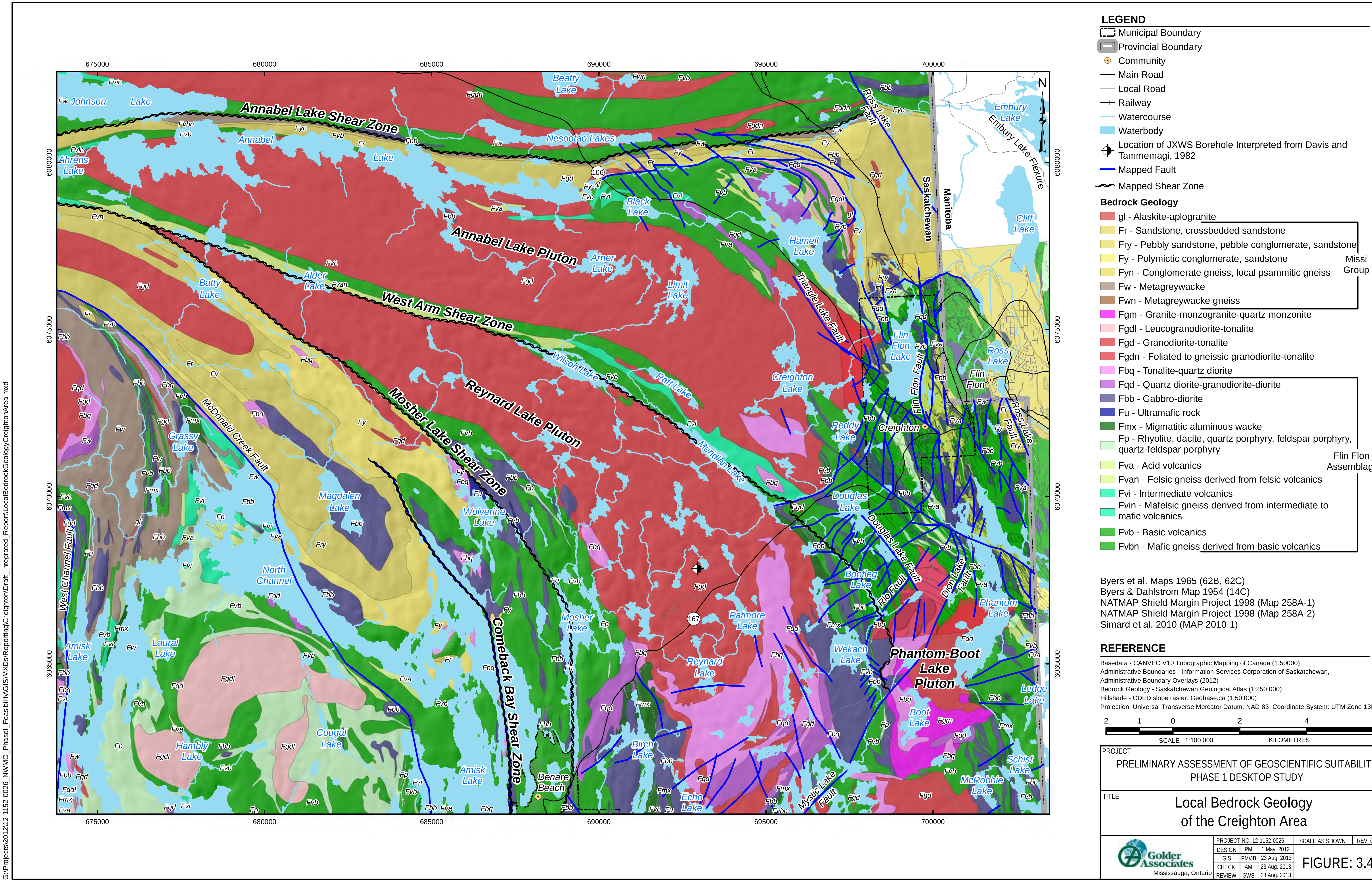
LEGEND
Municipal Boundary
Provincial Boundary
Community
Main Road
Local Road
Railway
Watercourse
Waterbody
Location of JXWS Borehole Interpreted from Davis and Tammemagi, 1982
Mapped Fault
Mapped Shear Zone
Bedrock Geology
gl - Alaskite-aplogranite
Fr - Sandstone, crossbedded sandstone
Fry - Pebbly sandstone, pebble conglomerate, sandstone
Fy - Polymictic conglomerate, sandstone
Fyn - Conglomerate gneiss, local psammitic gneiss
Fw - Metagreywacke
Fwn - Metagreywacke gneiss
Missi Group
Fgm - Granite-monzogranite-quartz monzonite
Fgdl - Leucogranodiorite-tonalite
Fgd - Granodiorite-tonalite
Fgdn - Foliated to gneissic granodiorite-tonalite
Fbq - Tonalite-quartz diorite
Fqd - Quartz diorite-granodiorite-diorite
Fbb - Gabbro-diorite
Fu - Ultramafic rock
Fmx - Migmatitic aluminous wacke
Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry
Fva - Acid volcanics
Fvan - Felsic gneiss derived from felsic volcanics
Fvi - Intermediate volcanics
Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics
Fvb - Basic volcanics
Fvbn - Mafic gneiss derived from basic volcanics
Flin Flon Assemblage
Byers et al. Maps 1965 (62B, 62C)
Byers & Dahlstrom Map 1954 (14C)
NATMAP Shield Margin Project 1998 (Map 258A-1)
NATMAP Shield Margin Project 1998 (Map 258A-2)
Simard et al. 2010 (MAP 2010-1)
REFERENCE
Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Hillshade - CDED slope raster: Geobase.ca (1:50,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N
2 1 0 2 4 6
SCALE 1:100,000 KILOMETRES
Annabel Lake Shear Zone
Annabel Lake Pluton
West Arm Shear Zone
Reynard Lake Pluton
Mosher Lake Shear Zone
Comeback Bay Shear Zone
Phantom-Boot Lake Pluton
McDonald Creek Fault
West Channel Fault
Ross Lake Fault
Triangle Lake Fault
Flin Flon Fault
Douglas Lake Fault
Rio Fault
Dion Lake Fault
Mystic Lake Fault
Embury Lake Flexure
Saskatchewan
Manitoba
Flin Flon
Creighton
Denare Beach
PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY
TITLE
Local Bedrock Geology of the Creighton Area
Golder Associates
Mississauga, Ontario
PROJECT NO. 12-1152-0026
SCALE AS SHOWN
REV. 0.0
DESIGN PM 1 May. 2012
GIS PM/JB 23 Aug. 2013
CHECK AM 23 Aug. 2013
REVIEW GWS 23 Aug. 2013
FIGURE: 3.4
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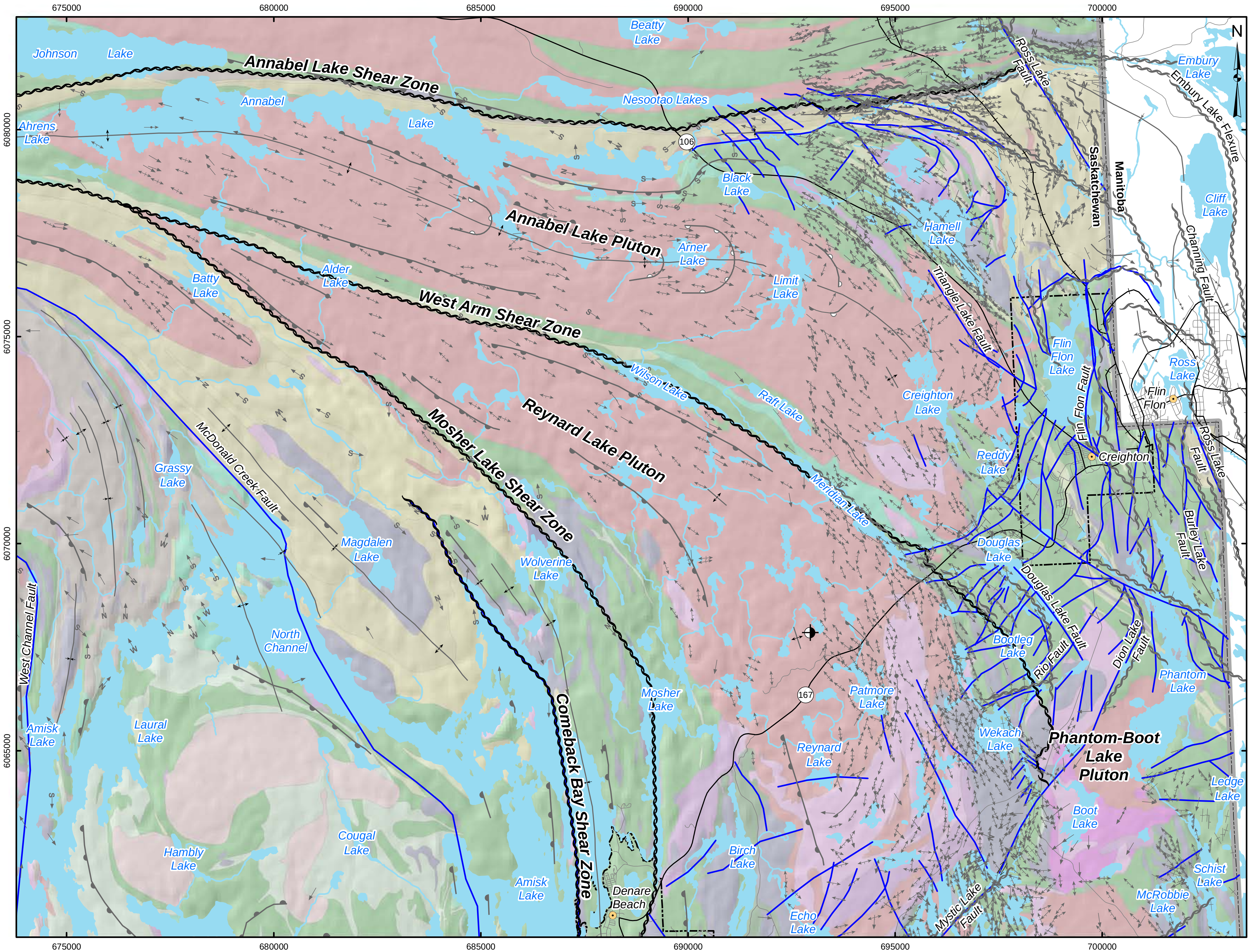

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LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Location of JXWS Borehole Interpreted from Davis and Tammemagi
- Mapped Fault

Structural Data

- Sinistral Fault
- Dextral Fault
- Bedding Inclined
- Bedding Vertical
- Bedding Inclined Unknown
- Fold
- Foliation Inclined
- Foliation Vertical
- Plunging Fold
- Lineation With Without Plunge
- Minor Fold (Shape and Plunge Known)
- Minor Fold (Shape and Plunge Known)
- Minor Fold (Shape and Plunge Known)
- Lineation
- Anticline - Overturned
- Anticline - Upright
- Syncline - Overturned
- Syncline - Upright
- Bedding or Foliation - Shallow
- Bedding or Foliation - Steep
- Bedding or Foliation - Vertical
- Fault or Shear Zone

Bedrock Geology

- gl - Alaskite-aplogranite
- Missi Group:
  - Fr - Sandstone, crossbedded sandstone
  - Fry - Pebbly sandstone, pebble conglomerate, sandstone
  - Fy - Polymictic conglomerate, sandstone
  - Fyn - Conglomerate gneiss, local psammitic gneiss
  - Fw - Metagreywacke
  - Fwn - Metagreywacke gneiss
- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Flin Flon Assemblage:
  - Fqd - Quartz diorite-granodiorite-diorite
  - Fbb - Gabbro-diorite
  - Fu - Ultramafic rock
  - Fmx - Migmatitic aluminous wacke
  - Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry
  - Fva - Acid volcanics
  - Fvan - Felsic gneiss derived from felsic volcanics
  - Fvi - Intermediate volcanics
  - Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics
  - Fvb - Basic volcanics
  - Fvbn - Mafic gneiss derived from basic volcanics

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Byers et al. Maps 1965 (62B, 62C); Byers & Dahlstrom 1954 (Map 14A, 14B, 14C)
NATMAP Shield Margin Project 1998 (Maps 258A-1, 2); Simard et al. 2010 (MAP 2010-1)
Hillshade - CDED slope raster: Geobase.ca (1:50,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6
SCALE 1:100,000 KILOMETRES

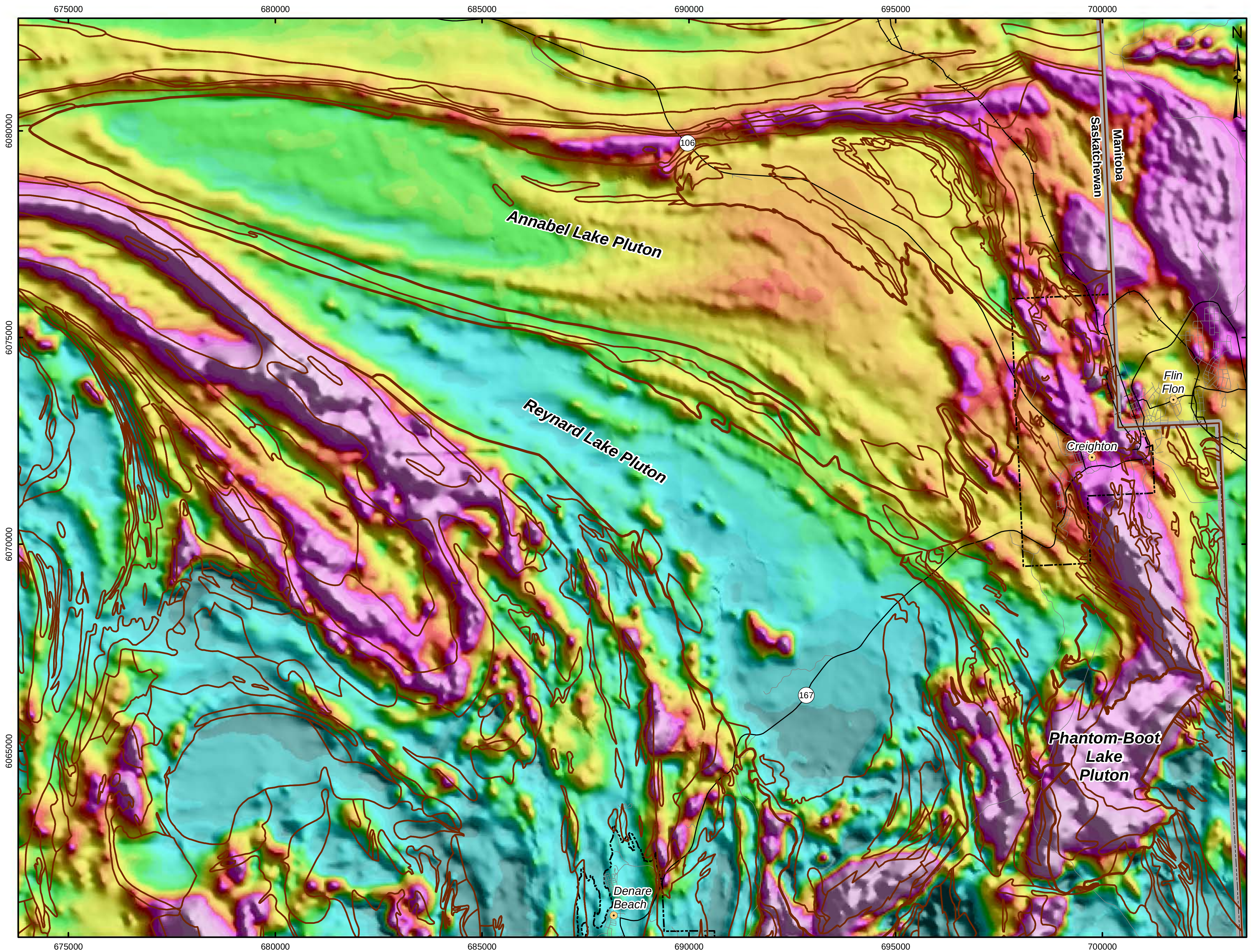
PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Structural Geology Data
of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012		
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

FIGURE: 3.5

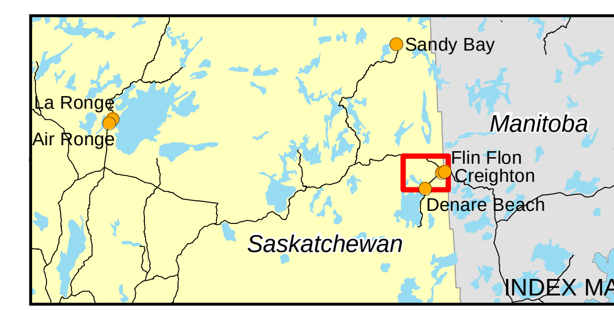


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Geological Contact
- Outline of Major Pluton

Residual Total Magnetic Field (nT)

303, 840, 470, 320, 230, 190, 150, 130, 100, 80, 60, 40, 30, 10, 0, -20, -30, -40, -50, -60, -80, -90, -110, -120, -140, -160, -190, -230, -918



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Geophysics - GSC Canada - 200m - Magnetic - Residual Total Field, 2008;
Canadian Aeromagnetic Data Base, Airborne Geophysics Section, GSC - Central Canada Division, Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Total Magnetic Field (Reduced to Pole) of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012	FIGURE: 3.6	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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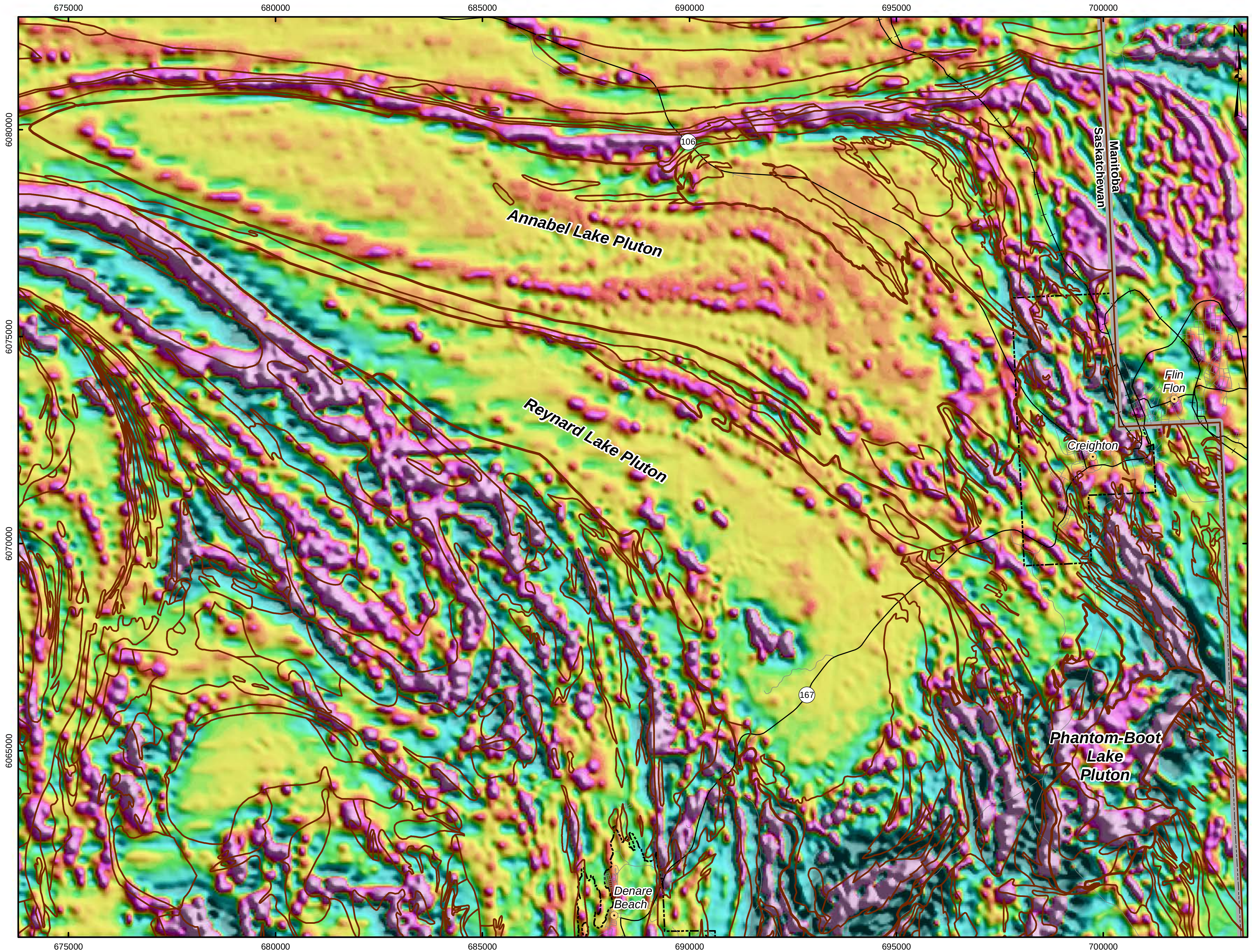
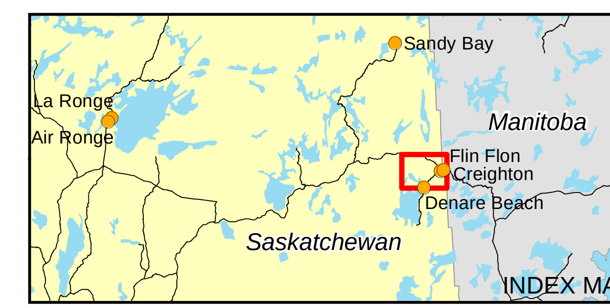


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Geological Contact
- Outline of Major Pluton

1st Vertical Derivative of the Residual Magnetic Field (nT/m)

43.06
1.66
0.88
0.56
0.36
0.24
0.16
0.10
0.04
0.02
0.00
-0.02
-0.04
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
-0.22
-0.24
-0.28
-0.32
-0.36
-0.42
-0.48
-0.58
-0.74
-1.08
-11.92



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Geophysics - GSC Canada - 200m - Magnetic - Residual Total Field, 2008; Canadian Aeromagnetic Data Base, Airborne Geophysics Section, GSC - Central Canada Division, Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
First Vertical Derivative (Reduced To Pole) of the Magnetic Field of the Creighton Area

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012		
GIS	PM/JB	23 Aug. 2013	FIGURE: 3.7	
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

Golder Associates
Mississauga, Ontario

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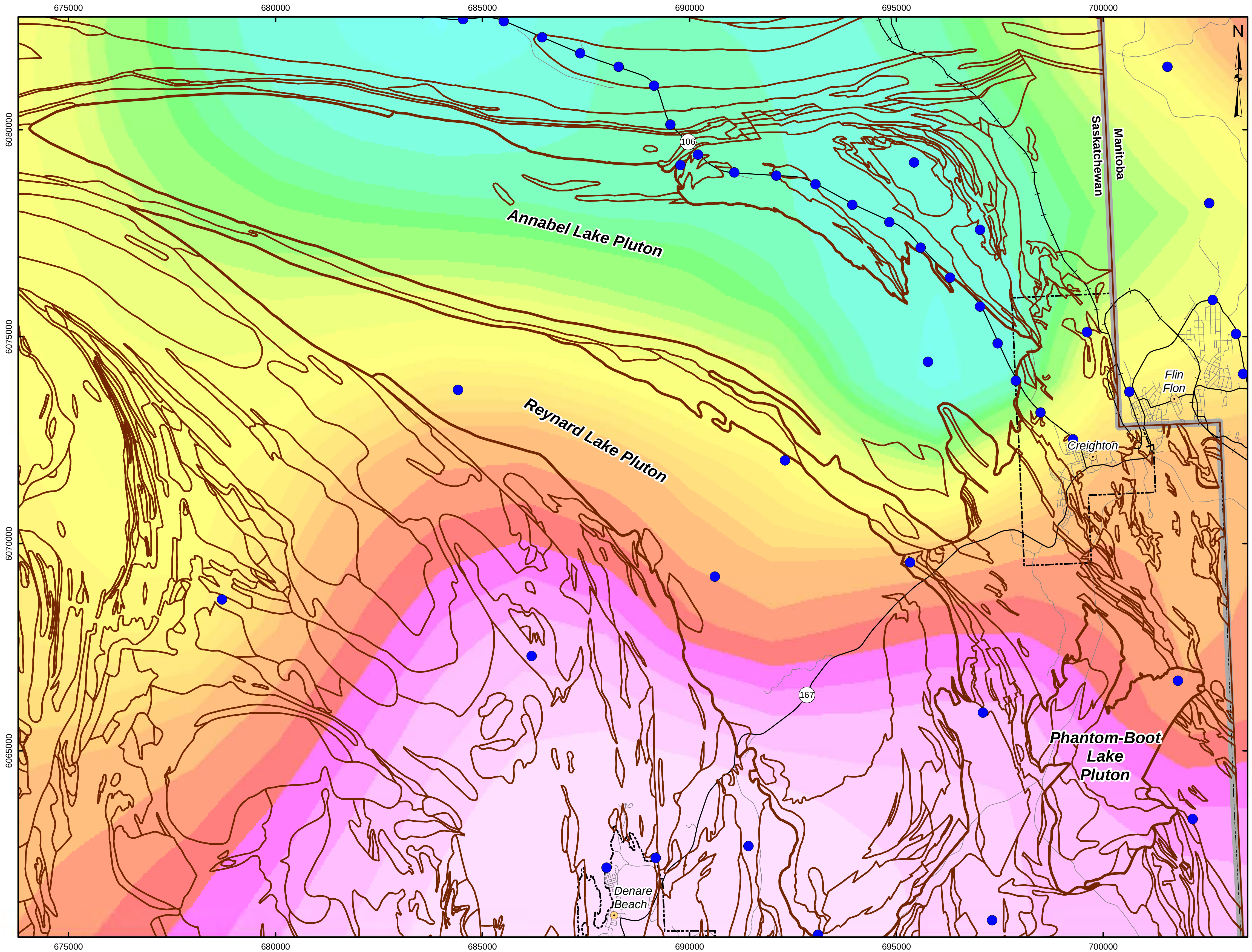
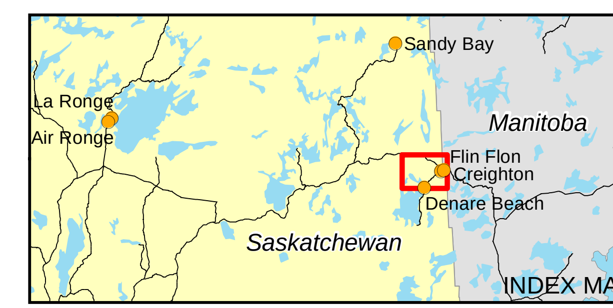


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Gravity Station
- Geological Contact
- Outline of Major Pluton

Gravity Anomaly (mGal)

-21.9, -35.0, -37.0, -39.0, -40.5, -42.0, -43.5, -45.0, -46.5, -47.0, -47.5, -48.0, -48.5, -49.0, -49.5, -50.5, -51.5, -52.0, -52.5, -53.5, -54.0, -54.5, -55.5, -57.0, -58.0, -59.5, -61.0, -64.0, -73.5



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Geophysics - GSC Canada - 2km - Gravity Anomalies, 2010;
Canadian Aeromagnetic Data Base, Airborne Geophysics Section, GSC - Central Canada Division, Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Bouguer Gravity of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012	FIGURE: 3.8	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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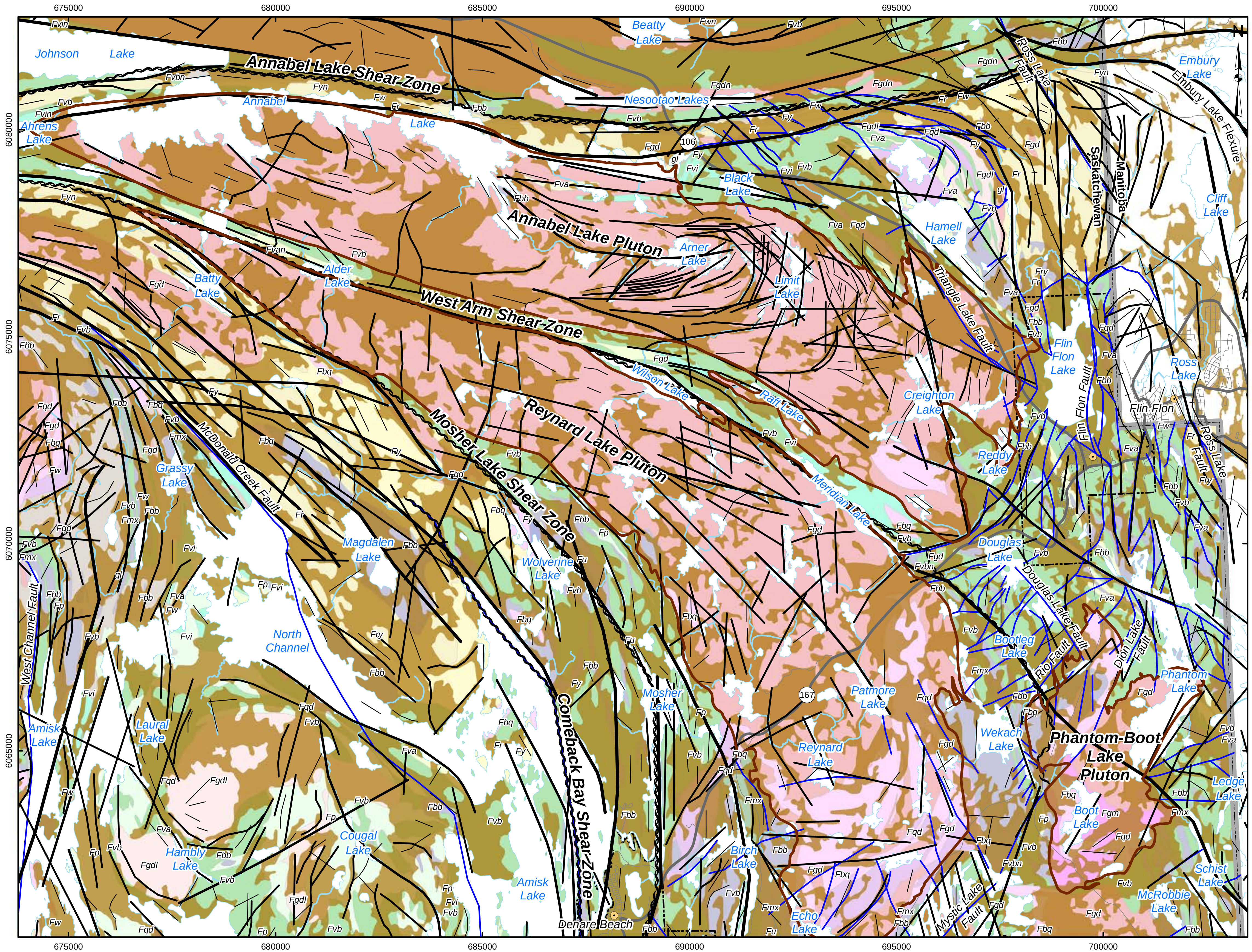


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Outline of Major Pluton
- Overburden Cover

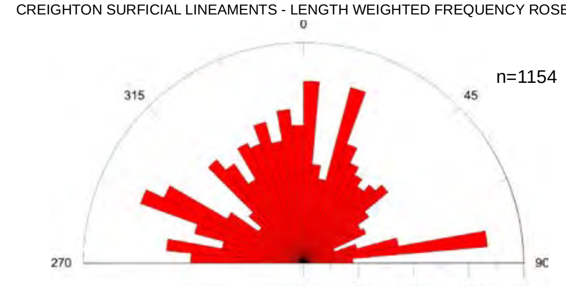
Surficial Lineaments (SPOT and CDED)

- < 1 km
- 1 - 5 km
- 5 - 10 km
- > 10 km

Bedrock Geology

- gl - Alaskite-aplogranite
- Fr - Sandstone, crossbedded sandstone (Missi Group)
- Fry - Pebbly sandstone, pebble conglomerate, sandstone (Missi Group)
- Fy - Polymictic conglomerate, sandstone (Missi Group)
- Fyn - Conglomerate gneiss, local psammitic gneiss (Missi Group)
- Fw - Metagreywacke (Missi Group)
- Fwn - Metagreywacke gneiss (Missi Group)
- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite (Flin Flon Assemblage)
- Fbb - Gabbro-diorite (Flin Flon Assemblage)
- Fu - Ultramafic rock (Flin Flon Assemblage)
- Fmx - Migmatitic aluminous wacke (Flin Flon Assemblage)
- Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry (Flin Flon Assemblage)
- Fva - Acid volcanics (Flin Flon Assemblage)
- Fvan - Felsic gneiss derived from felsic volcanics (Flin Flon Assemblage)
- Fvi - Intermediate volcanics (Flin Flon Assemblage)
- Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics (Flin Flon Assemblage)
- Fvb - Basic volcanics (Flin Flon Assemblage)
- Fvbn - Mafic gneiss derived from basic volcanics (Flin Flon Assemblage)

CREIGHTON SURFICIAL LINEAMENTS - LENGTH WEIGHTED FREQUENCY ROSE PLOT



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Overburden Cover - Surficial Geology, Saskatchewan (1:50,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

SCALE 1:100,000 — 2 1 0 2 4 6 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Surficial Lineaments of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 3.9	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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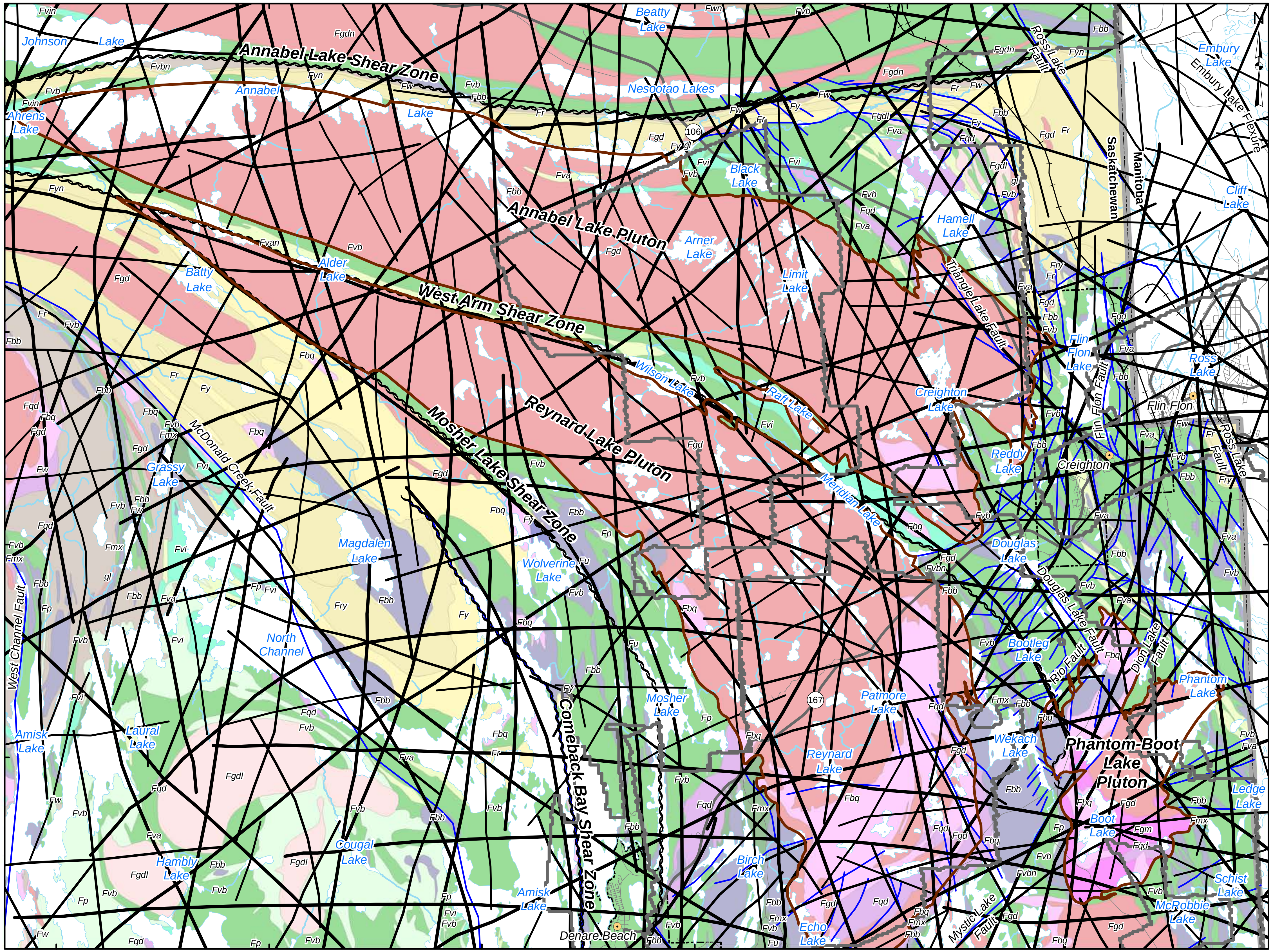


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Outline of Major Pluton
- Higher Resolution Geophysical Surveys

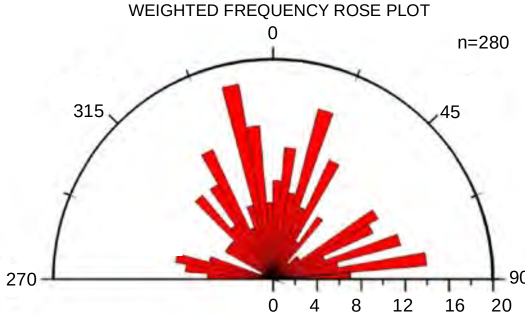
Geophysical Lineaments

- <1 km
- 1 - 5 km
- 5 - 10 km
- >10 km

Bedrock Geology

- gl - Alaskite-aplogranite
- Missi Group:
  - Fr - Sandstone, crossbedded sandstone
  - Fry - Pebbly sandstone, pebble conglomerate, sandstone
  - Fy - Polymictic conglomerate, sandstone
  - Fyn - Conglomerate gneiss, local psammitic gneiss
  - Fw - Metagreywacke
  - Fwn - Metagreywacke gneiss
- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Flin Flon Assemblage:
  - Fbq - Tonalite-quartz diorite
  - Fqd - Quartz diorite-granodiorite-diorite
  - Fbb - Gabbro-diorite
  - Fu - Ultramafic rock
  - Fmx - Migmatitic aluminous wacke
  - Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry
  - Fva - Acid volcanics
  - Fvan - Felsic gneiss derived from felsic volcanics
  - Fvi - Intermediate volcanics
  - Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics
  - Fvb - Basic volcanics
  - Fvbn - Mafic gneiss derived from basic volcanics

CREIGHTON GEOPHYSICAL LINEAMENTS - LENGTH WEIGHTED FREQUENCY ROSE PLOT



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Geophysical Lineaments of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 3.10	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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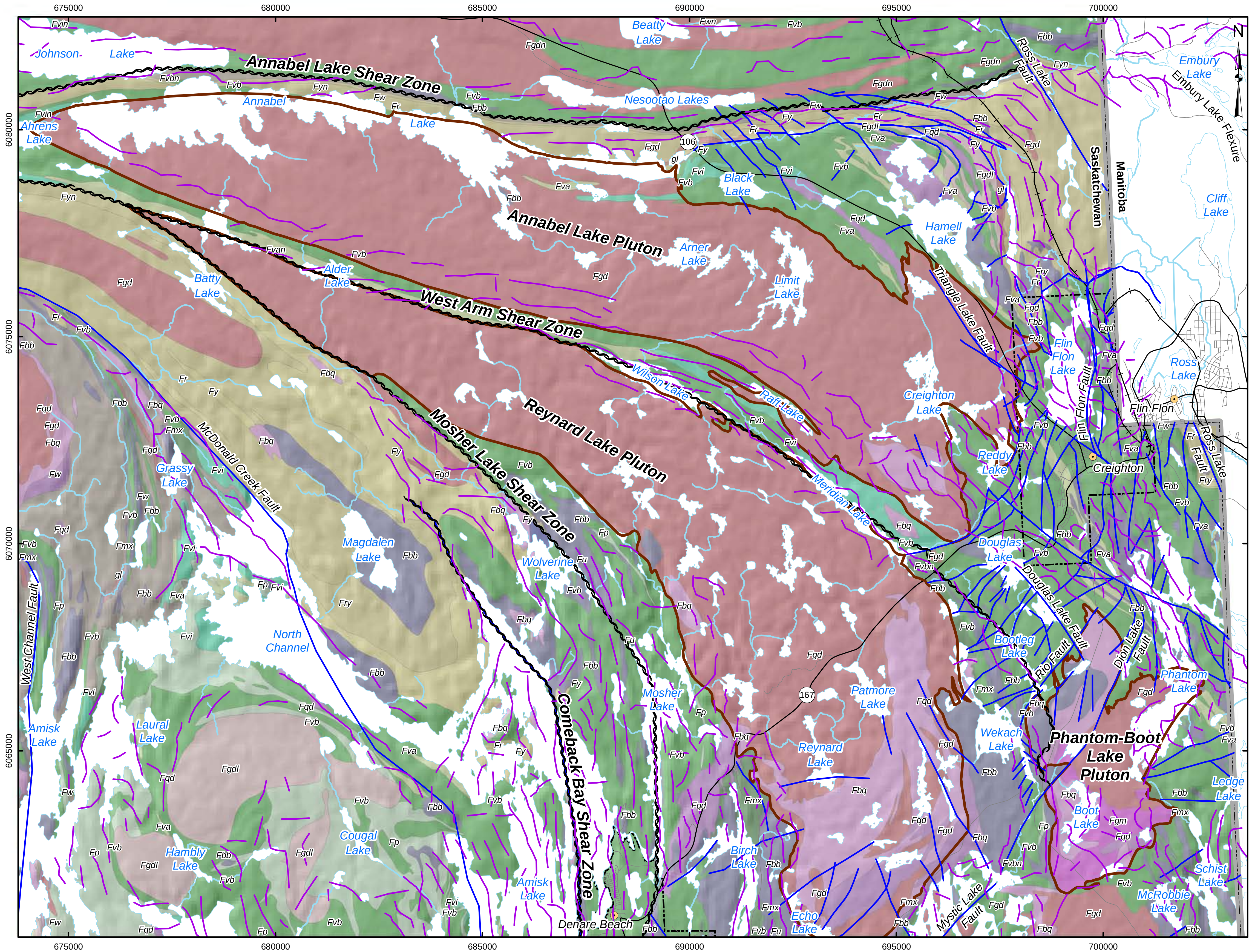


G:\Projects\2012\12-1152-0026_NWMO_PhaseI_Feasibility\GIS\MXDs\Reporting\Creighton\Draft_Integrated_Report\DuctileLineamentsCreightonArea.mxd

LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Ductile Lineament
- Outline of Major Pluton

Bedrock Geology

- gl - Alaskite-aplogranite

Missi Group:
- Fr - Sandstone, crossbedded sandstone
- Fry - Pebbly sandstone, pebble conglomerate, sandstone
- Fy - Polymictic conglomerate, sandstone
- Fyn - Conglomerate gneiss, local psammitic gneiss
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss

- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite

Flin Flon Assemblage:
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Migmatitic aluminous wacke
- Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Ductile Lineaments - Processing and Interpretation of Geophysical Data, Township of Creighton, Saskatchewan (PGW, 2013)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Hillshade - CDED slope raster: Geobase.ca (1:50,000)
Projection: Universal Transverse Mercator
Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6
SCALE 1:100,000 KILOMETRES

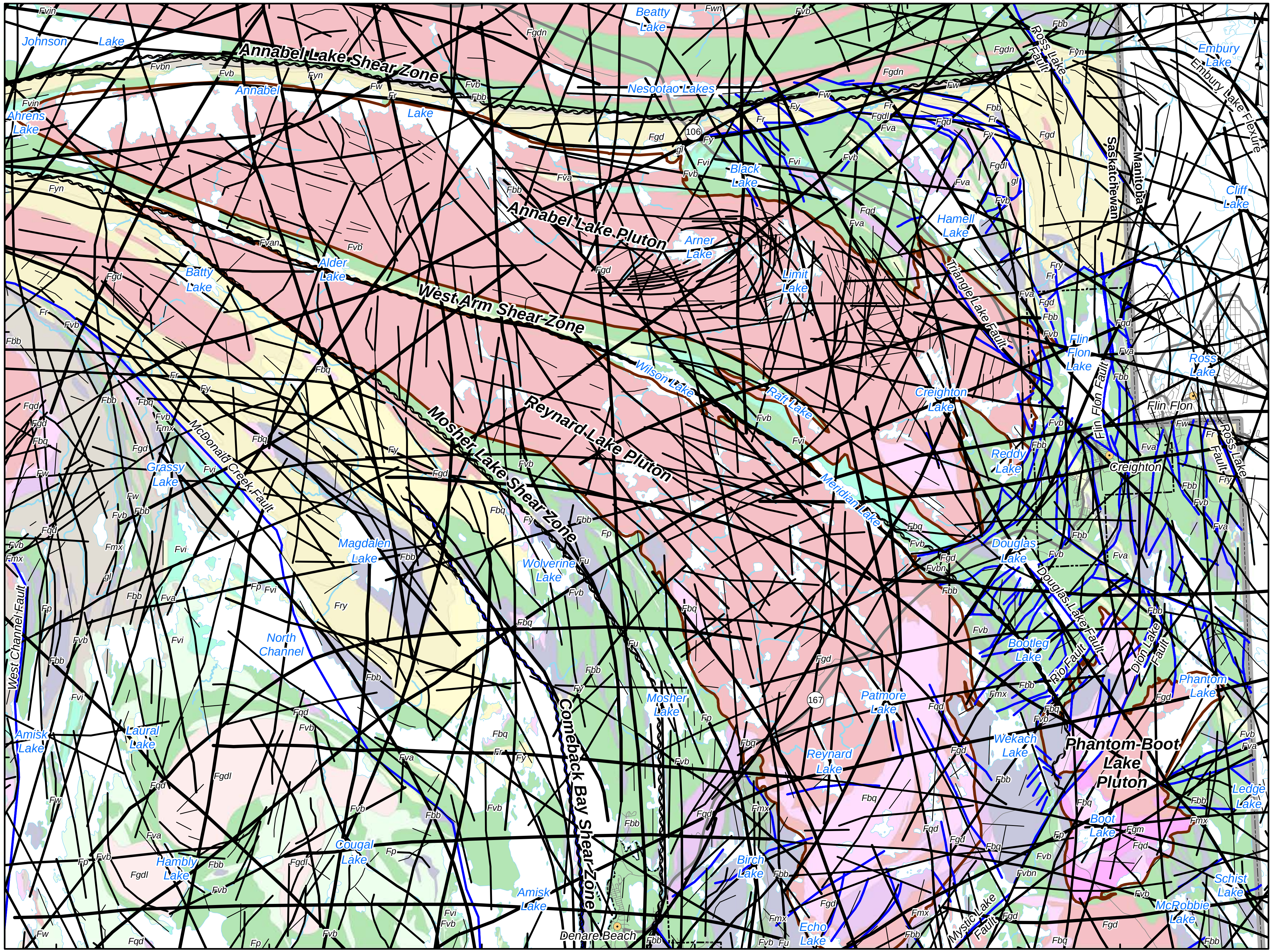
PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Ductile Lineaments of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012		
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

FIGURE: 3.11



LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Outline of Major Pluton

Brittle Lineaments (Surficial and Geophysical)

- <1 km
- 1 - 5 km
- 5 - 10 km
- >10 km

Bedrock Geology

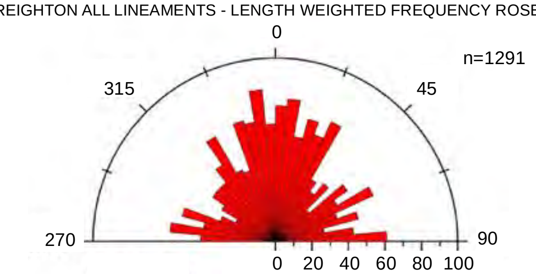
- gl - Alaskite-aplogranite

Missi Group:
- Fr - Sandstone, crossbedded sandstone
- Fry - Pebbly sandstone, pebble conglomerate, sandstone
- Fy - Polymictic conglomerate, sandstone
- Fyn - Conglomerate gneiss, local psammitic gneiss
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss

- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite

Flin Flon Assemblage:
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Migmatitic aluminous wacke
- Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

CREIGHTON ALL LINEAMENTS - LENGTH WEIGHTED FREQUENCY ROSE PLOT



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6
SCALE 1:100,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Brittle Lineaments of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 3.12	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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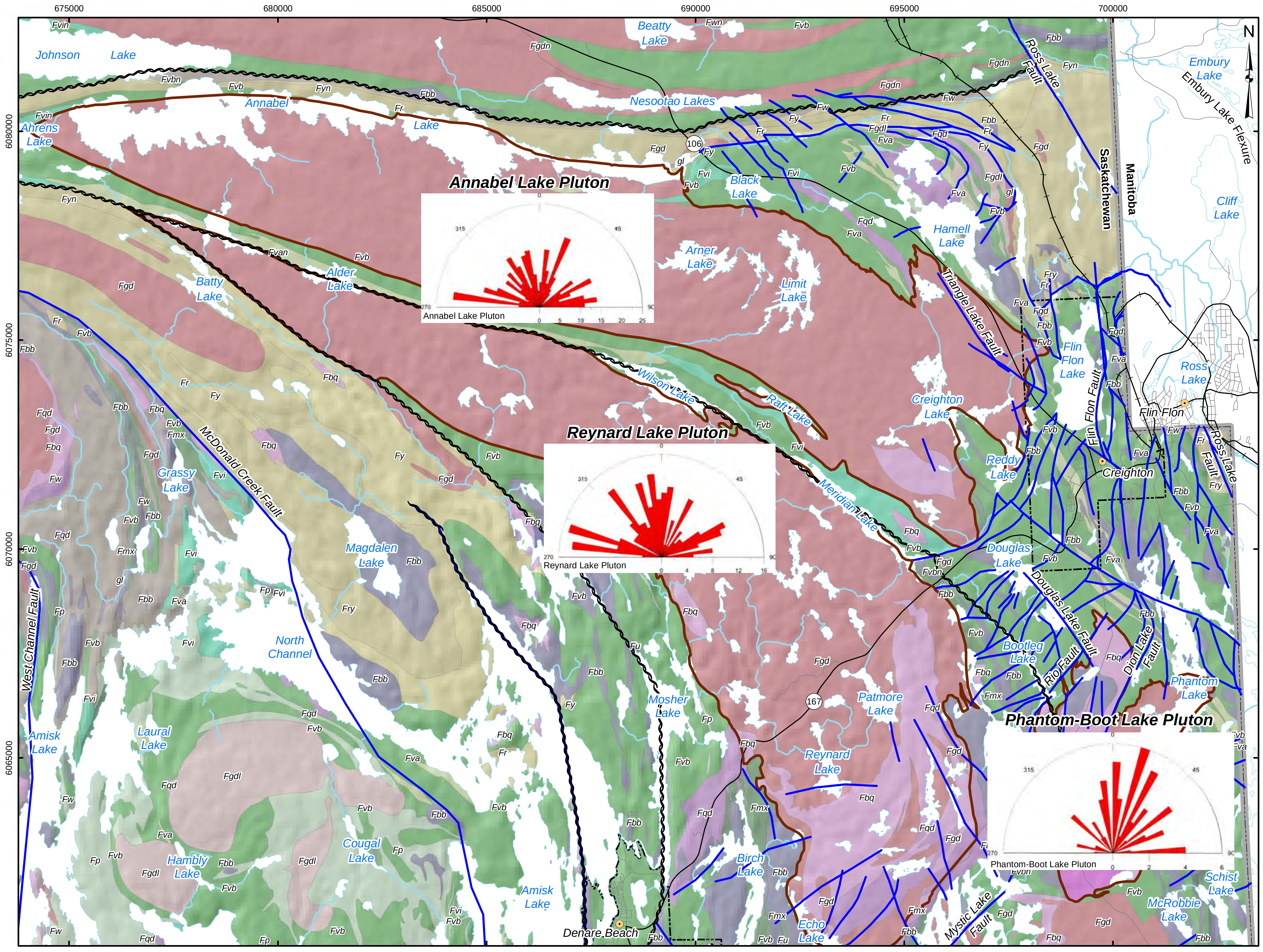


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone

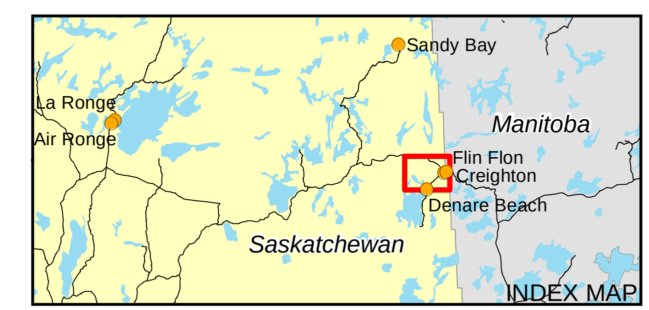
Bedrock Geology

- gl - Alaskite-aplogranite
- Fr - Sandstone, crossbedded sandstone
- Fry - Pebbly sandstone, pebble conglomerate, sandstone
- Fy - Polymictic conglomerate, sandstone
- Fyn - Conglomerate gneiss, local psammitic gneiss
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss

(Fr to Fwn: Missi Group)

- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Migmatitic aluminous wacke
- Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

(Fbq to Fvbn: Flin Flon Assemblage)



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Hillshade - CDED slope raster: Geobase.ca (1:50,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6
SCALE 1:100,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Lineament Orientations of Principal Plutons of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012	FIGURE: 3.13	
GIS	PM/JB	22 Aug. 2013		
CHECK	AM	22 Aug. 2013		
REVIEW	GWS	22 Aug. 2013		

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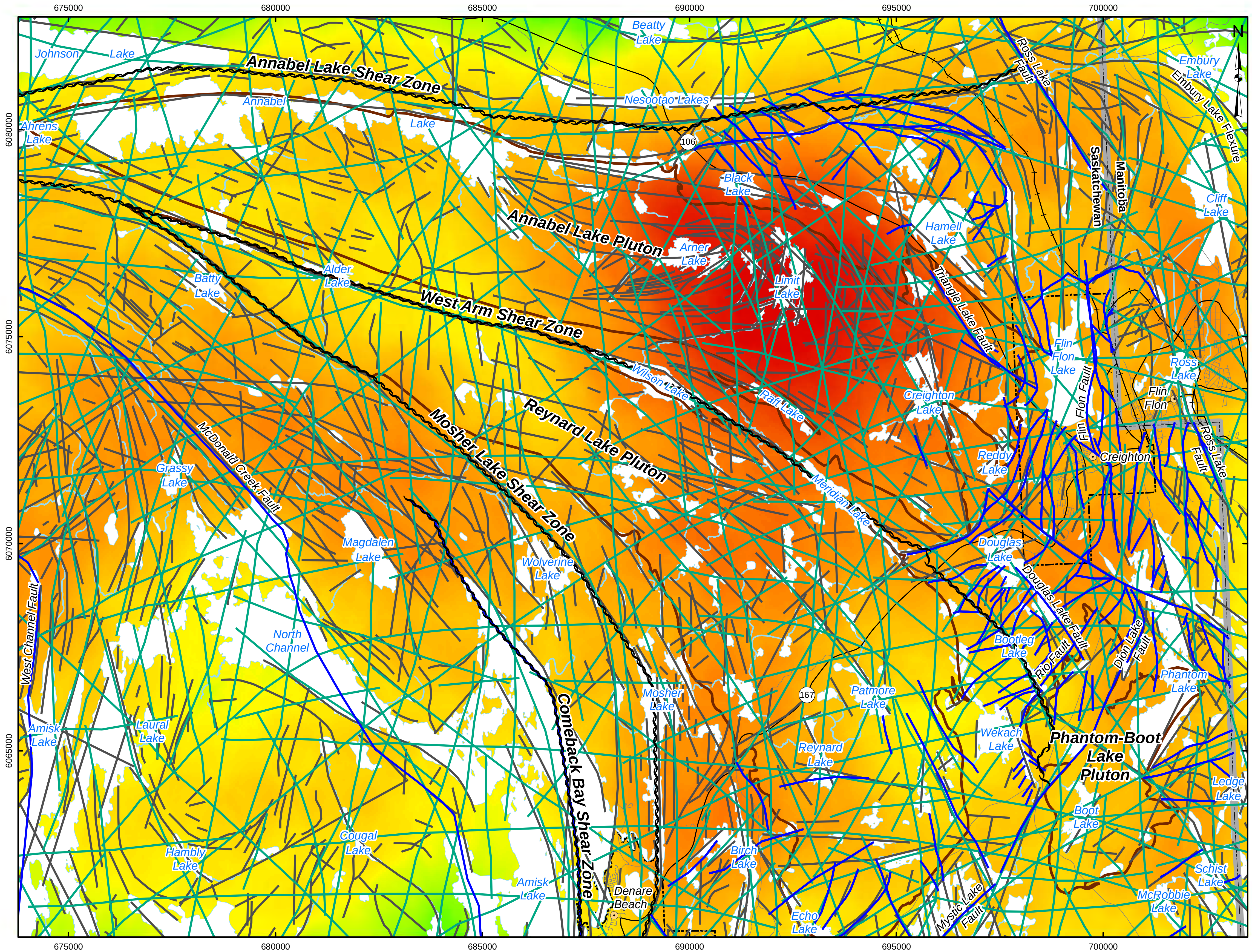


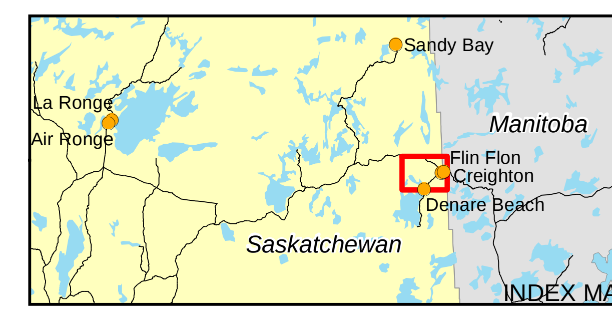
LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Outline of Major Pluton
- Geophysical Lineament
- Surficial Lineament

Lineament Density (km/km²)

High : 7

Low : 0



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Brittle Lineament Density Calculated for Lineaments in the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 3.14	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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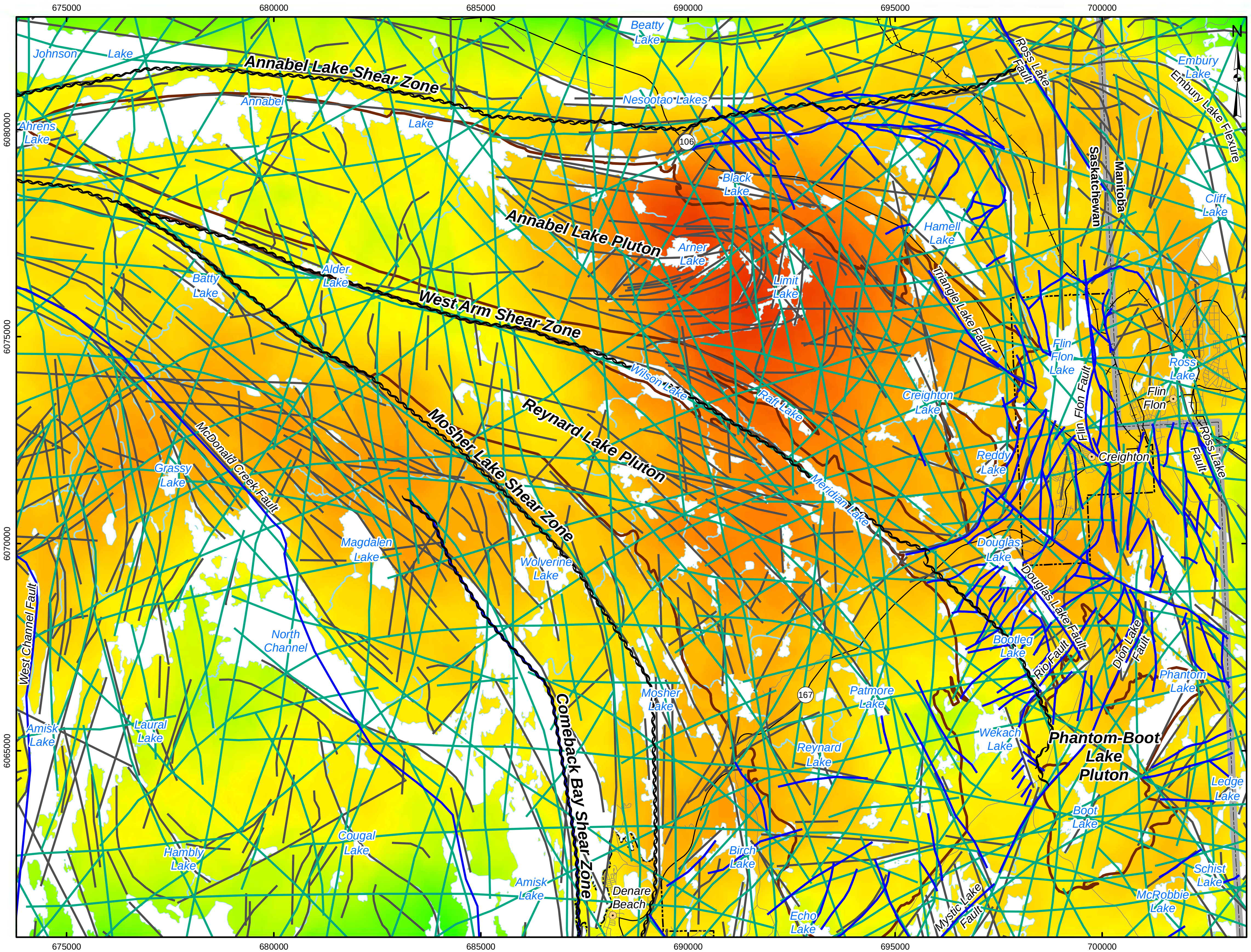


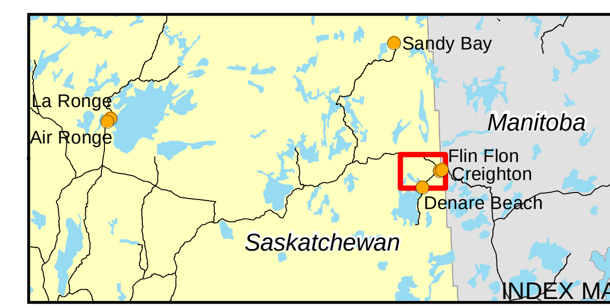
LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Outline of Major Pluton
- Geophysical Lineament (>1 km)
- Surficial Lineament (>1 km)

Lineament Density (km/km²)

High : 7

Low : 0



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Brittle Lineament Density Calculated for Lineaments >1 km in the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 3.15	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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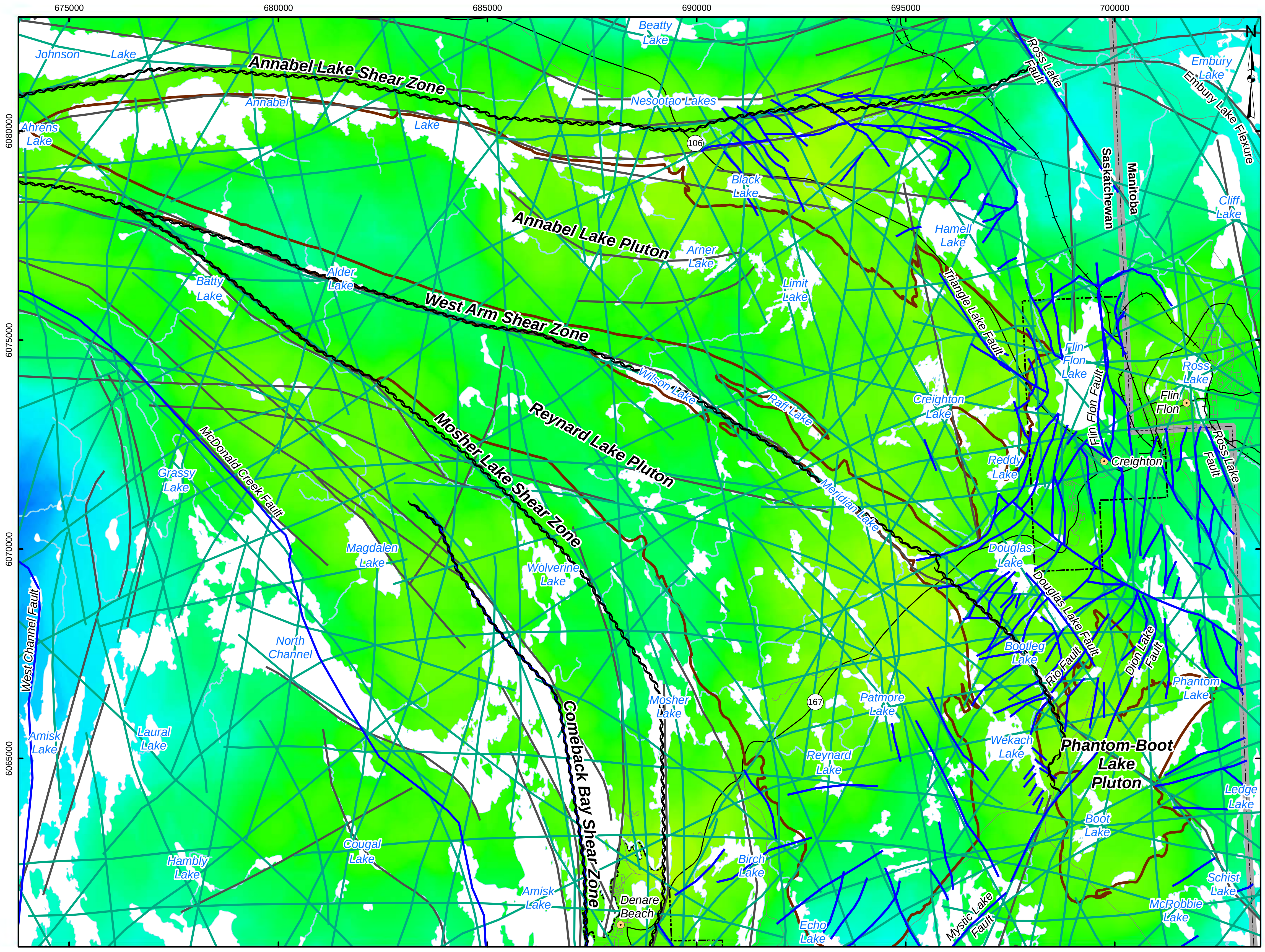


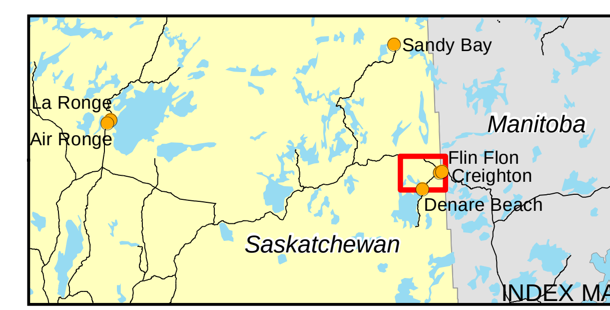
LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Outline of Major Pluton
- Geophysical Lineament (>5 km)
- Surficial Lineament (>5 km)

Lineament Density (km/km²)

High : 7

Low : 0



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan,
Administrative Boundary Overlays (2012)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Brittle Lineament Density Calculated for Lineaments >5 km in the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 3.16	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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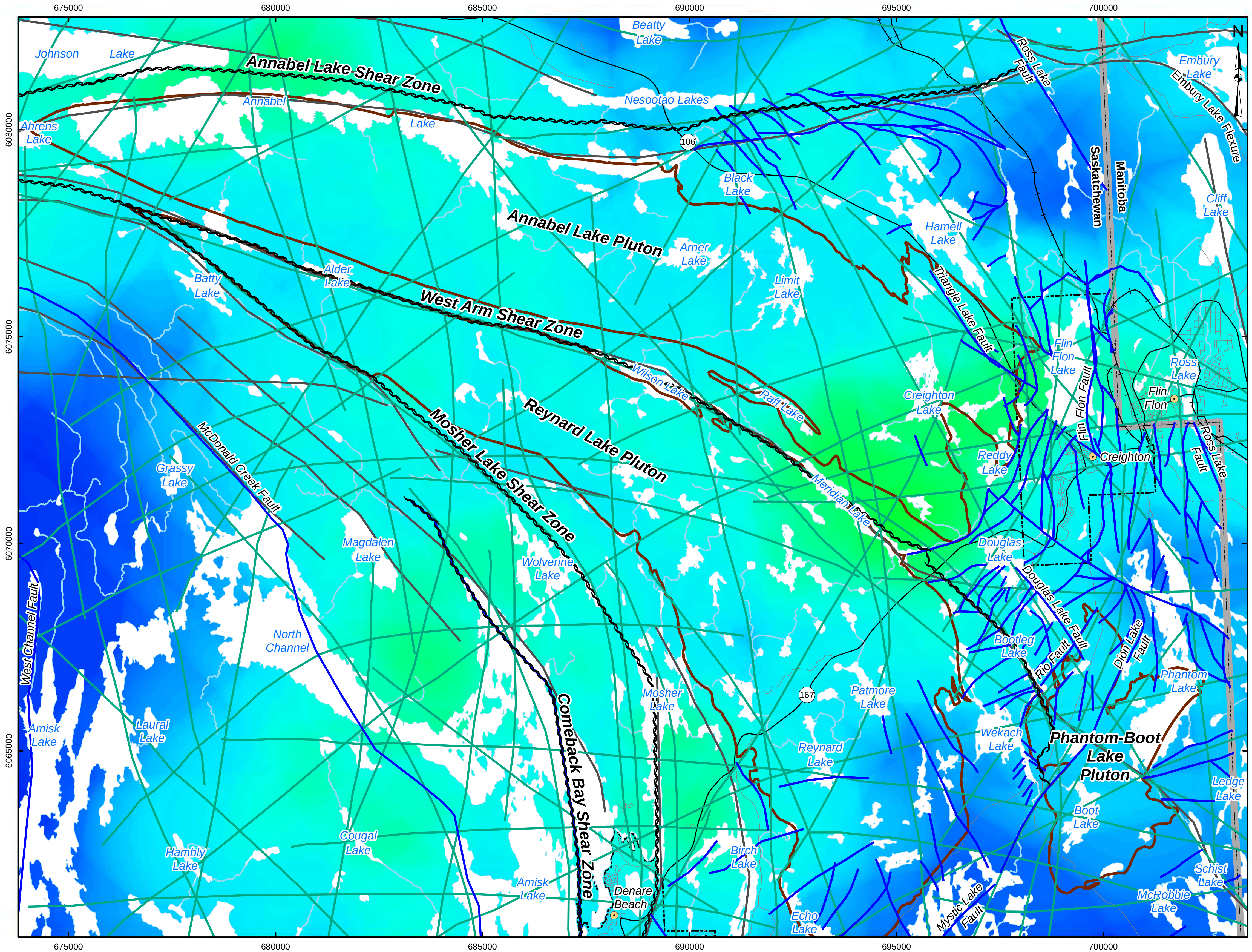


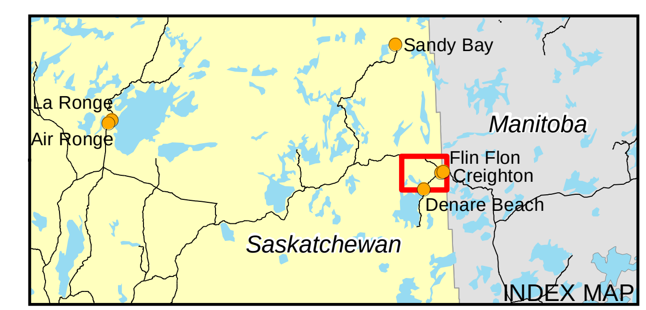
LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Outline of Major Pluton
- Geophysical Lineament (>10 km)
- Surficial Lineament (>10 km)

Lineament Density (km/km²)

High : 7

Low : 0



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Brittle Lineament Density Calculated for Lineaments >10 km in the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 3.17	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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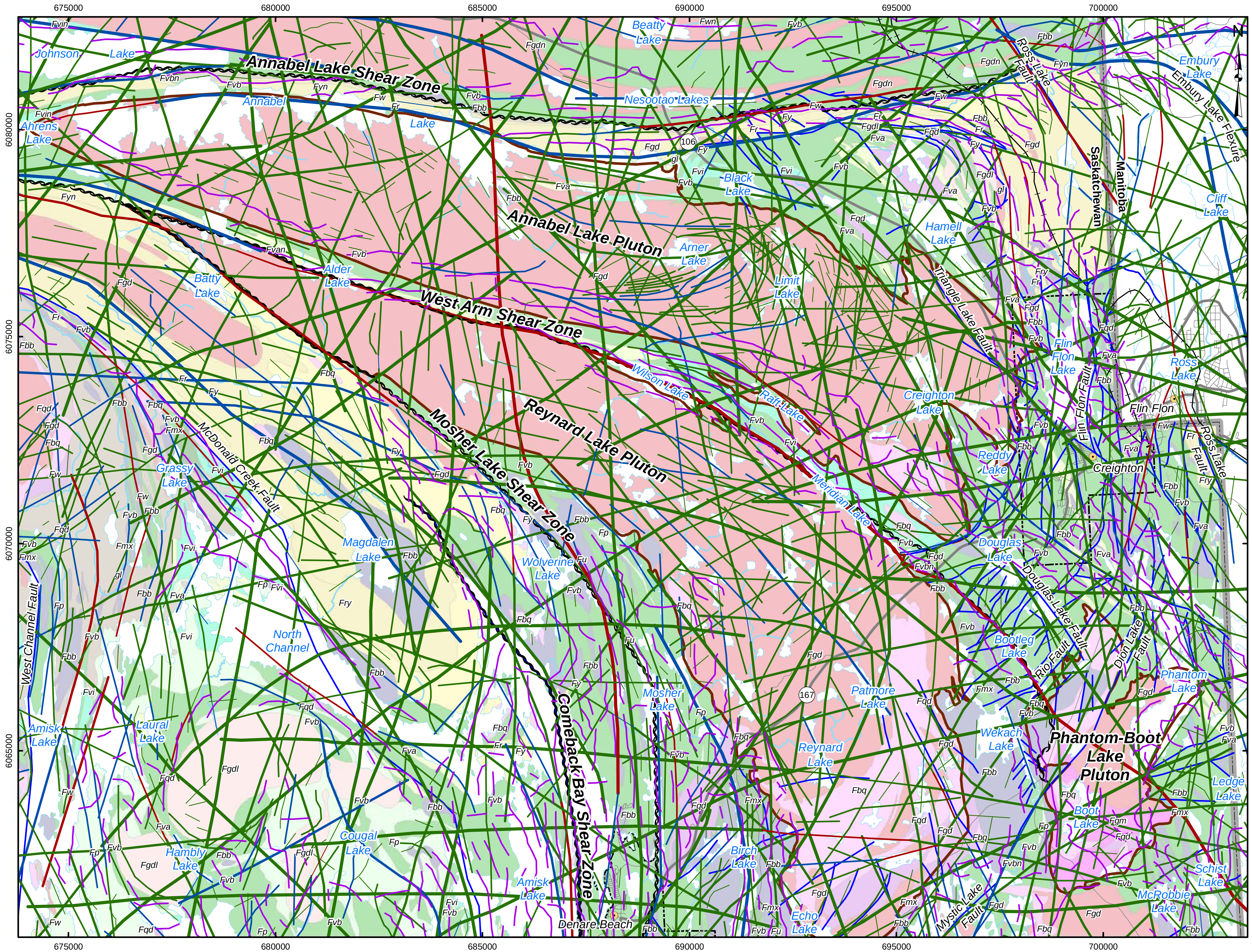

LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Mapped Fault
- Mapped Shear Zone
- Ductile Lineament
- Outline of Major Pluton

Lineament Length

- 1 - 5 km
- 5 - 10 km
- > 10 km

Lineament Reproducibility

- 1
- 2
- 3

Bedrock Geology

Missi Group:

- gl - Alaskite-aplogranite
- Fr - Sandstone, crossbedded sandstone
- Fry - Pebbly sandstone, pebble conglomerate, sandstone
- Fy - Polymictic conglomerate, sandstone
- Fyn - Conglomerate gneiss, local psammitic gneiss
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss

- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite

Flin Flon Assemblage:

- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Migmatitic aluminous wacke
- Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Ductile Lineaments - Processing and Interpretation of Geophysical Data, Township of Creighton, Saskatchewan (PGW, 2013)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6
SCALE 1:100,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Combined Structural Features of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 3.18	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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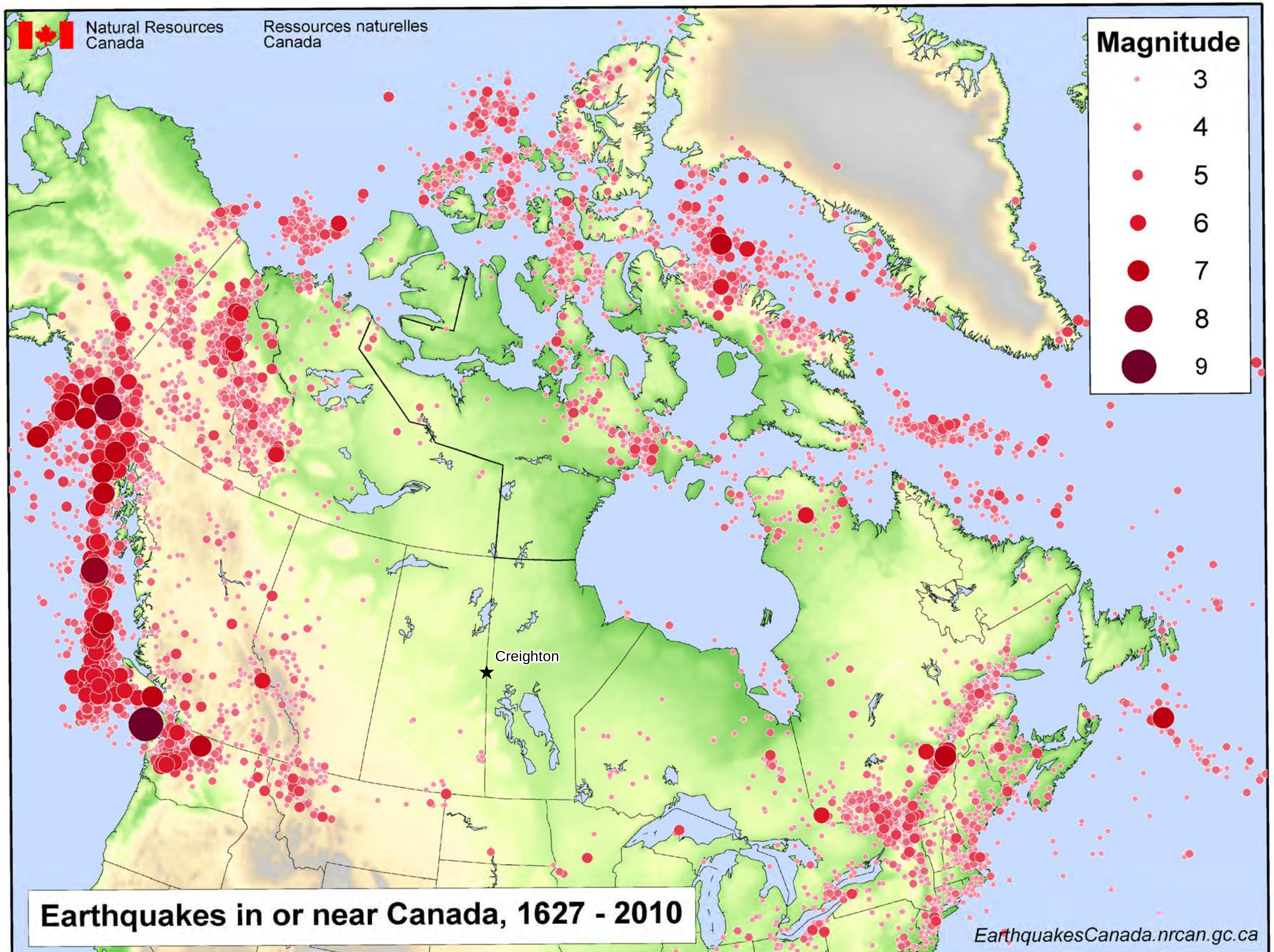

LEGEND

★ Creighton

REFERENCE

Seismic - Resources Canada (NRC). Earthquakes Canada Website. http://earthquakescanada.nrcan.gc.ca

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Earthquakes Map of Canada 1627-2010

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 2.0
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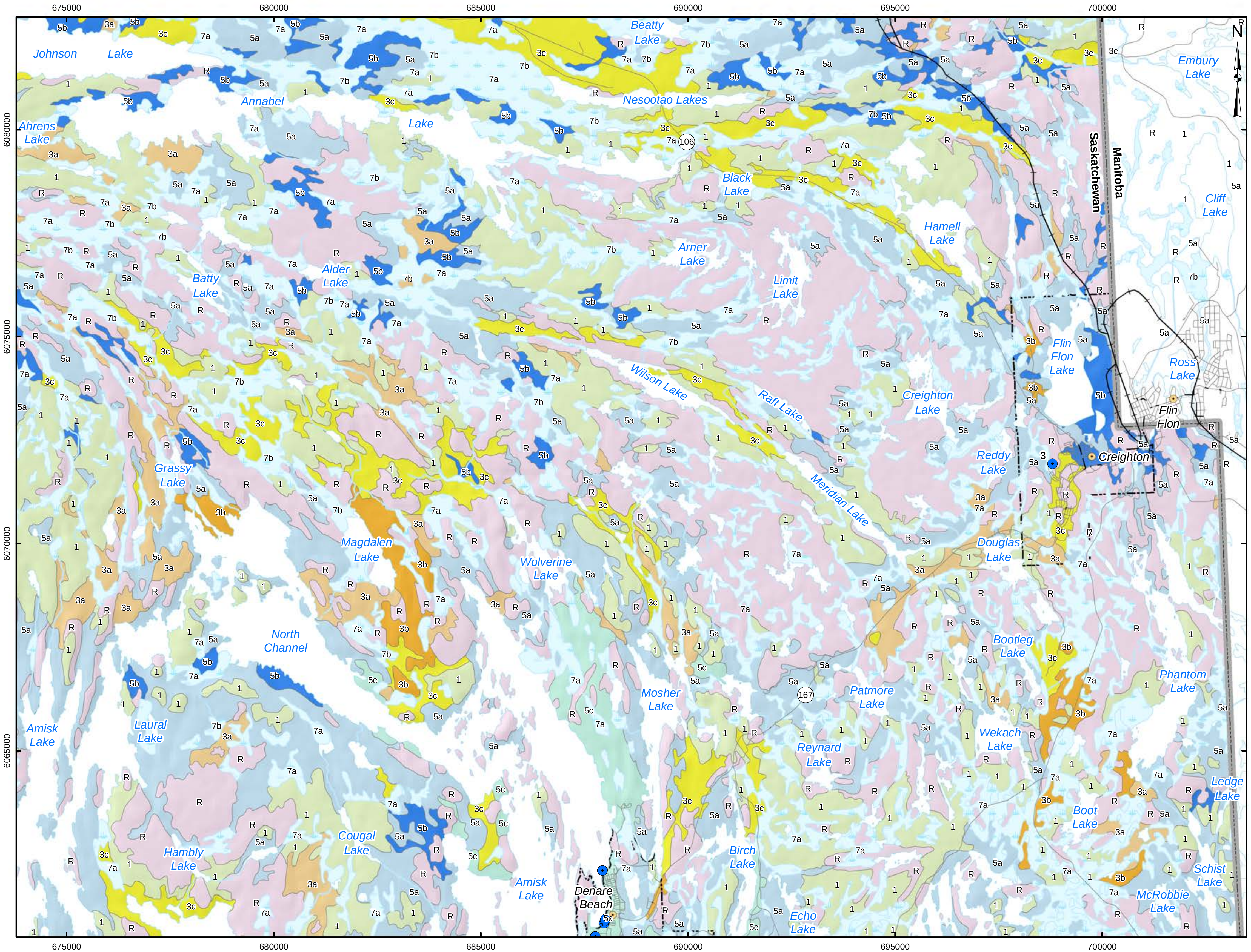
REVIEW	GWS	23 Aug. 2013		

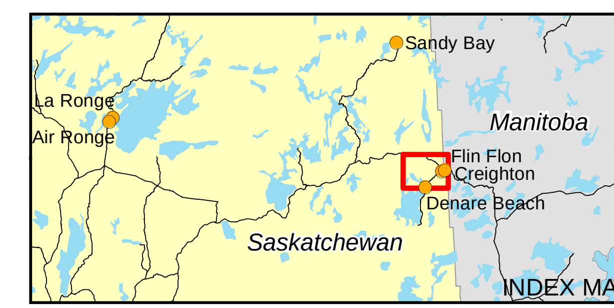


LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Groundwater Well
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Wetland

Landform

- 7b - Fen peat
- 7a - Bog peat
- 5c - Glaciolacustrine nearshore
- 5b - Glaciolacustrine offshore blanket
- 5a - Glaciolacustrine offshore veneer
- 3c - Glaciofluvial subaqueous outwash
- 3b - Glaciofluvial ice-contact
- 3a - Sand and gravel of undetermined origin
- 1 - Till veneer
- R - Bedrock



REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Landform - Surficial Geology, Saskatchewan (1:50,000)
Wells - Saskatchewan Watershed Authority Water Well Database
Hillshade - CDED slope raster: Geobase.ca (1:50,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSEMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Groundwater Wells within the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012	FIGURE: 4.1	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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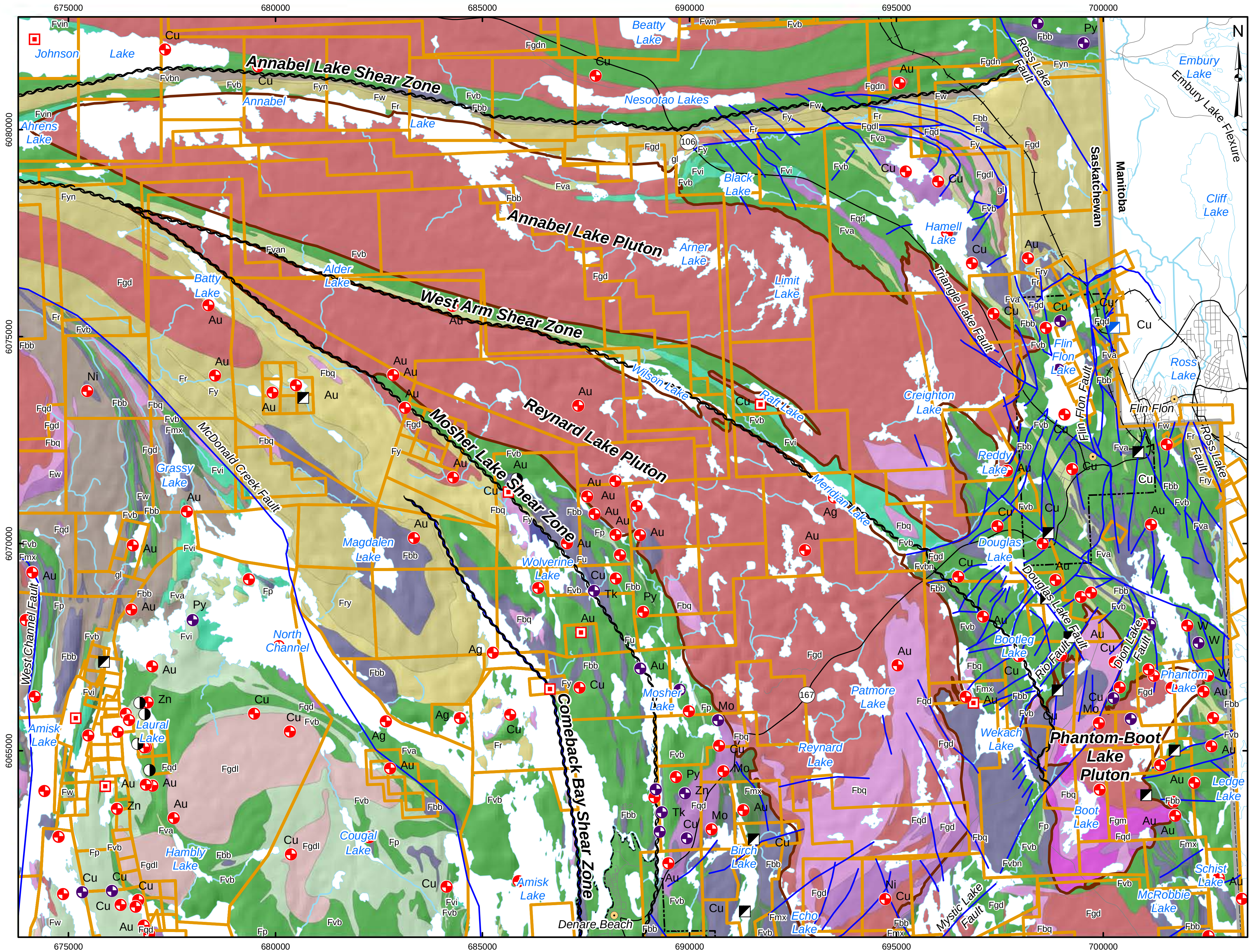

LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Developed Mineral Prospect
- Mineral Deposit - Reserve
- Past Producing Mine
- Producing Mine
- Showing Mineral Potential
- Showing Mineral Potential - No Assays
- Mapped Fault
- Mapped Shear Zone
- Outline of Major Pluton
- Mining Claims (March 2013)

Bedrock Geology

- gl - Alaskite-aplogranite
- Fr - Sandstone, crossbedded sandstone
- Fry - Pebbly sandstone, pebble conglomerate, sandstone
- Fy - Polymictic conglomerate, sandstone
- Fyn - Conglomerate gneiss, local psammitic gneiss
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss

Missi Group

- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Migmatitic aluminous wacke
- Fp - Rhyolite, dacite, quartz porphyry, feldspar porphyry, quartz-feldspar porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Mafelsic gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

Flin Flon Assemblage

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Mining Claims - Geological Atlas of Saskatchewan (Mar. 2013)
Hillshade - CDED slope raster: Geobase.ca (1:50,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Mineral Showings and Dispositions of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	1 May. 2012		
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

FIGURE: 5.1

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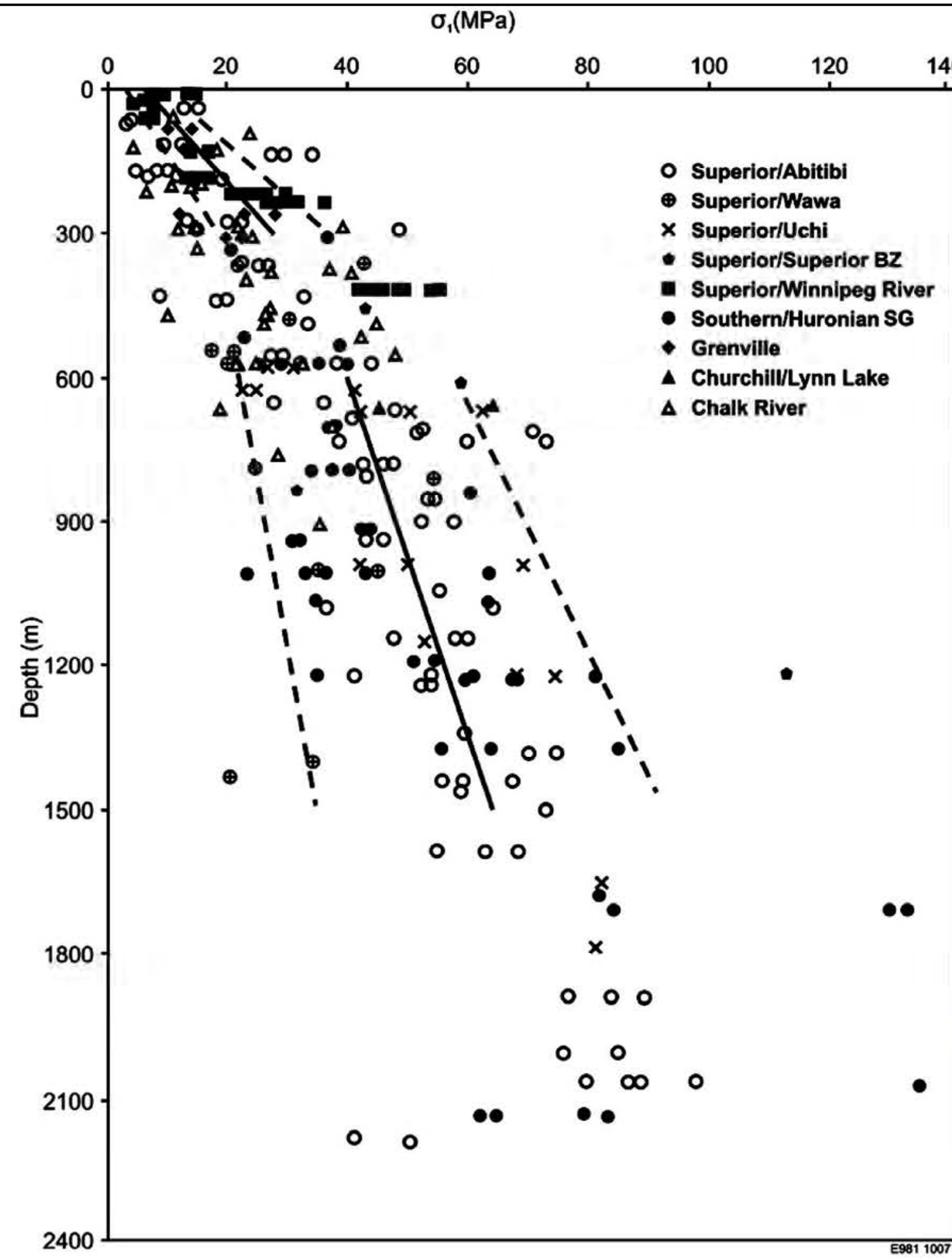

REFERENCE

Maximum Horizonal In Situ Stresses Measured in the Canadian Shield: After Maloney, Kaiser, and Vorauer, 2006.

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Maximum Horizontal In Situ Stresses Typically Encountered in Crystalline Rock of the Canadian Shield

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	6 Nov. 2012	FIGURE: 6.1	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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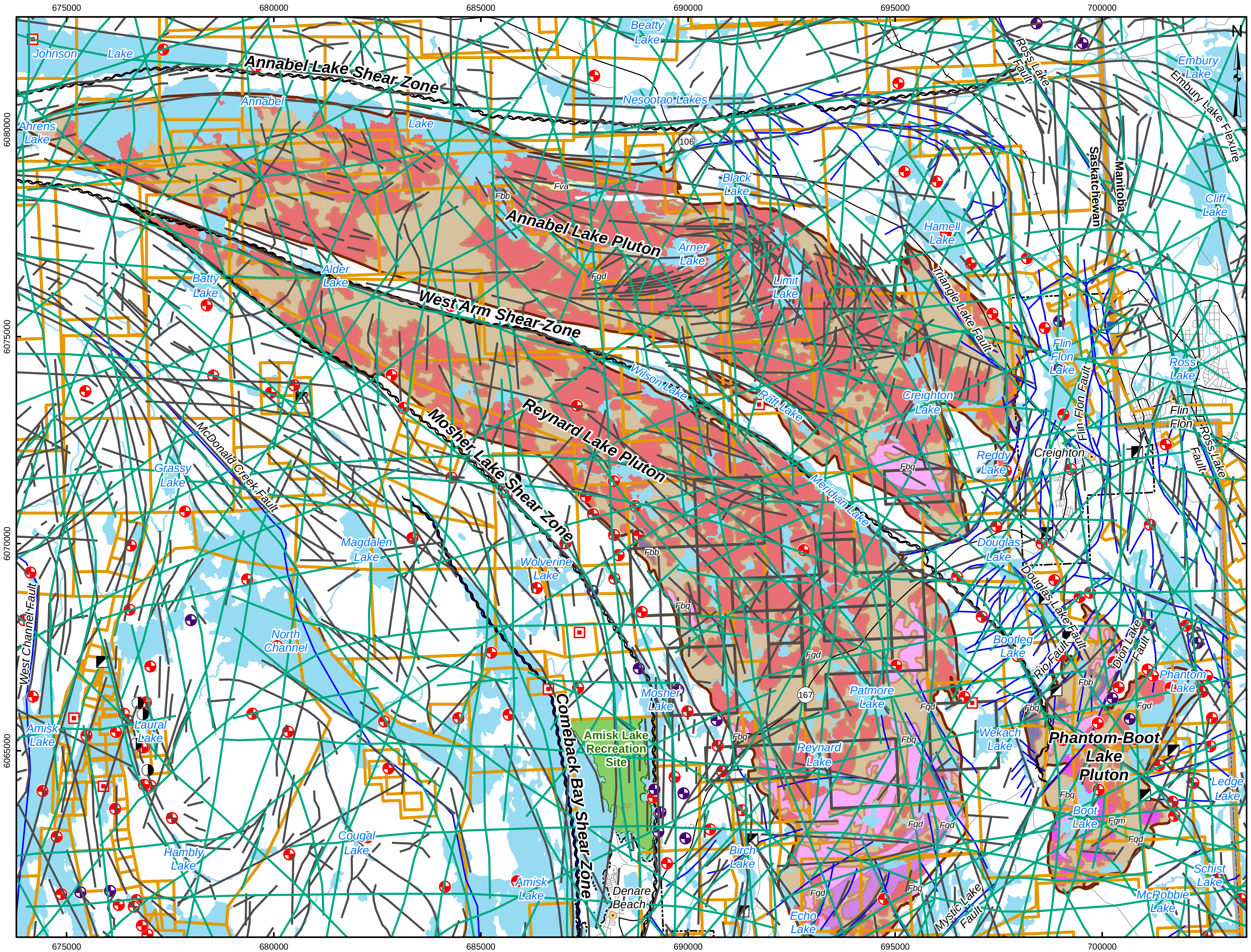

LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Watercourse
- Waterbody
- Developed Mineral Prospect
- Mineral Deposit - Reserve
- Past Producing Mine
- Producing Mine
- Showing Mineral Potential
- Showing Mineral Potential - No Assays
- Mapped Fault
- Mapped Shear Zone
- Geophysical Lineament
- Surficial Lineament
- Protected Area
- Crown Reserves
- Mining Claims (March 2013)
- Exposed (or Thinly Covered) Bedrock
- Overburden Cover

Bedrock Geology

- Fgm - Granite-monzogranite-quartz monzonite
- Fgd - Granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fva - Acid volcanics

Approximate Size of Repository Footprint

3 km

2 km

REFERENCE

Basedata - CANVEC V10 Topographic Mapping of Canada (1:50000)
Lineaments - Lineament Interpretation, Creighton, Saskatchewan (JDMA, 2012)
Administrative Boundaries - Information Services Corporation of Saskatchewan, Administrative Boundary Overlays (2012)
Bedrock Geology - Saskatchewan Geological Atlas (1:250,000)
Mining Claims - Geological Atlas of Saskatchewan (Mar. 2013)
Crown Reserves - Saskatchewan Geological Atlas
Overburden Cover - Surficial Geology, Saskatchewan (1:50,000)
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13N

2 1 0 2 4 6

SCALE 1:100,000 KILOMETRES

PROJECT

PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE

Key Geoscientific Characteristics of the Creighton Area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 0.0
DESIGN	PM	15 Aug. 2012	FIGURE: 7.1	
GIS	PM/JB	23 Aug. 2013		
CHECK	AM	23 Aug. 2013		
REVIEW	GWS	23 Aug. 2013		

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APPENDIX A

Geoscientific Factors

Table A-1: Safety Factors, Performance Objectives and Geoscientific Factors

Safety Factors	Performance Objectives	Evaluation Factors to be Considered
Containment and isolation characteristics of the host rock	**1.** The geological, hydrogeological and chemical and mechanical characteristics of the site should: ■ Promote long-term isolation of used nuclear fuel from humans, the environment and surface disturbances; ■ Promote long-term containment of used nuclear fuel within the repository; and ■ Restrict groundwater movement and retard the movement of any released radioactive material.	**1.1** The depth of the host rock formation should be sufficient for isolating the repository from surface disturbances and changes caused by human activities and natural events. **1.2** The volume of available competent rock at repository depth should be sufficient to host the repository and provide sufficient distance from active geological features such as zones of deformation or faults and unfavourable heterogeneities. **1.3** The mineralogy of the rock, the geochemical composition of the groundwater and rock porewater at repository depth should not adversely impact the expected performance of the repository multi-barrier system. **1.4** The hydrogeological regime within the host rock should exhibit low groundwater velocities. **1.5** The mineralogy of the host rock, the geochemical composition of the groundwater and rock porewater should be favourable to retarding radionuclide movement. **1.6** The host rock should be capable of withstanding natural stresses and thermal stresses induced by the repository without significant structural deformations or fracturing that could compromise the containment and isolation functions of the repository.
Long-term stability of the site	**2.** The containment and isolation functions of the repository should not be unacceptably affected by future geological processes and climate changes.	**2.1** Current and future seismic activity at the repository site should not adversely impact the integrity and safety of the repository system during operation and in the very long term. **2.2** The expected rates of land uplift, subsidence and erosion at the repository site should not adversely impact the containment and isolation functions of the repository. **2.3** The evolution of the geomechanical, hydrogeological and geochemical conditions at repository depth during future climate change scenarios such as glacial cycles should not have a detrimental impact on the long-term safety of the repository. **2.4** The repository should be located at a sufficient distance from geological features such as zones of deformation or faults that could be potentially reactivated in the future.

Safety Factors	Performance Objectives	Evaluation Factors to be Considered
Repository construction, operation and closure	**3.** The surface and underground characteristics of the site should be favourable to the safe construction, operation, closure and long-term performance of the repository.	**3.1** The strength of the host rock and in situ stress at repository depth should be such that the repository could be safely excavated, operated and closed without unacceptable rock instabilities. **3.2** The soil cover depth over the host rock should not adversely impact repository construction activities. **3.3** The available surface area should be sufficient to accommodate surface facilities and associated infrastructure.
Human intrusion	**4.** The site should not be located in areas where the containment and isolation functions of the repository are likely to be disrupted by future human activities.	**4.1** The repository should not be located within rock formations containing economically exploitable natural resources such as gas/oil, coal, minerals and other valuable commodities as known today. **4.2** The repository should not be located within geological formations containing exploitable groundwater resources (aquifers) at repository depth.
Site characterization	**5.** The characteristics of the site should be amenable to site characterization and site data interpretation activities.	**5.1** The host rock geometry and structure should be predictable and amenable to site characterization and site data interpretation.
Transportation	**6.** The site should have a route that exists or is amenable to being created that enables the safe and secure transportation of used fuel from existing storage sites to the repository site.	**6.1** The repository should be located in an area that is amenable to the safe transportation of used nuclear fuel. **6.2** The repository should be located in an area that allows appropriate security and emergency response measures during operation and transportation of the used nuclear fuel.

APPENDIX B

Geoscientific Data Sources

Table B-1: Summary of Geological Mapping Sources for the Creighton Area

Map Product	Title	Author	Source	Scale	Date	Coverage	Additional Comments
Rep. 2010-7	Geological Atlas of Saskatchewan	SGS	SER	1:1,000,000	2010	full	Regional mapping of Saskatchewan
258A Sheet 1	NATMAP Shield Margin Project Area (Flin Flon Belt)	NATMAP Shield Margin Project Working Group	GSC, SEM, MBEM	1:100,000	1998	full	Detailed bedrock lithology, shear zones and mapped faults including the Annabel Lake and Reynard Lake plutons
258A Sheet 2	NATMAP Shield Margin Project Area (Flin Flon Belt)	NATMAP Shield Margin Project Working Group	GSC, SEM, MBEM	1:100,000	1998	full	Detailed bedrock lithology, shear zones and mapped faults including the Phantom-Boot Lake pluton
Map 2010-1 (MGS) 2010-2 (SGS)	Geology of the Flin Flon area, Manitoba and Saskatchewan (part of NTS 63K12, 13)	Simard, R.L., K. MacLachlan, H.L. Gibson, Y.M. DeWolfe, C. Devine, P.D. Kremer, B. Lafrance, D.E. Ames, E.C. Syme, A.H. Bailes, K. Bailey, D. Price, S.Pehrsson, E. Cole, D. Lewis, and A.G. Galley	MGS, SER	1:10,000	2010	partial along the east boundary	Detailed bedrock lithology and structural geology focused on the Flin Flon Greenstone Belt to the east of the study area. Includes a northern portion of the Phantom-Boot Lake pluton and the eastern tip of the Annabel Lake pluton.
Rep. 2005-4.2	Bedrock geology, Phantom Lake Section, Creighton, Saskatchewan, (Part of NTS 63K/12)	Bailey, K.A.	SGS	1:2,000	2005	partial	West shore of Phantom Lake.
Project 80-23	Geology and Sample Locations, Annabel Lake Area	Gaskarth, J.W.	SGS	1:31,680	1981	partial	Annabel Lake shear zone.
Rep. 2001-4.2	Geology of the Millrock Hill Area, Flin Flon, Parts of NTS 63K-12NW and -13SW	Gibson, H.L., A.H. Bailes, G. Tourigny and E.C. Syme	SGS	1:500	2001	partial	Between Creighton and Flon Flon.
Rep. 226	Compilation Bedrock Geology: Pelican Narrows and Amisk Lake Area (63M, 63L, part of 63N and 63K)	MacDonald, R.	SGS	1:250,000	1981	partial	Pelican Narrows and Amisk Lake Area
Rep. 94-	Precambrian	MacDonald, R.	SGS	1:250,000	1994	partial	Amisk Lake

Map Product	Title	Author	Source	Scale	Date	Coverage	Additional Comments
4 (10)	Geology of the Amisk Lake Sheet Area (NTS 63L)	and A. Leclair					
Rep. 2006-4.2	Bedrock geology Douglas Lake area, Flin Flon Domain, (Part of NTS 63K/12)	MacLachlan, K.	SGS	1:3,000	2006	partial	Green Lake near Phantom Lake
Rep. 2006-4.2 (2.2)	Bedrock geoloy Green Lake area, Flin Flon Domain, (Part of NTS 63K/12)	MacLachlan, K.	SGS	1:3,000	2006	partial	Douglas Lake near Phantom Lake
Rep. 2007-4.2	Bedrock geology of the Hilary and Phantom Lakes Area, Flin Flon Domain, (Parts of NTS 63K12 and 13)	MacLachlan, K and C. Devine	SGS	1:8,000	2007	partial	Southwest of Flin Flon
Project 14	Flin Flon Base Metals Project: East Amisk Lake Area (Parts of NTS Areas 63K-12 and 63L-9, -16)	McDougall, F.H.	SGS	1:50,000	1979	partial	East Amisk Lake
Rep. 90-4	Bedrock Geological Mapping, Mystic Lake - West Arm, Schist Lake Area (Part of NTS 63K-12)	Reilly, B.A.	SGS	1:12,500	1990	partial	Mystic Lake
Rep. 91-4	Revision Bedrock Geology, Mystic Lake Area (part of NTS 63L-9 and 63K-12)	Reilly, B.A.	SGS	1:12,500	1991	partial	Mystic Lake
Rep. 91-4	Revision Bedrock Geological Mapping, Mystic-Kaminis Lakes Area (Parts of NTS 63K-12 and 63L-9)	Reilly, B.A.	SGS	1:12,500	1991	partial	Mystic-Kaminis lakes
Rep. 93-4	Revision Bedrock Geological Mapping of the Northwest Amisk Lake Area (Parts of NTS 63L-9 and -16)	Reilly, B.A.	SGS	1:12,500	1993	partial	Northwest Amisk Lake
Rep. 94-4 (2)	Revision Bedrock Geology, South-Central Amisk Lake	Reilly, B.A.	SGS	1:50,000	1994	partial	Amisk Lake

Map Product	Title	Author	Source	Scale	Date	Coverage	Additional Comments
	(part of NTS 63L-9)						
Rep. 93-4	Bedrock Geology of the Comeback Bay Area, Amisk Lake (Part of NTS 63L-9 and -16)	Slimmon, W.L.	SGS	1:12,500	1993	partial	Comeback Bay
Rep. 90-4	Bedrock Geology, Douglas-Phantom Lakes Area (parts of NTS 63K-12, -13)	Thomas, D.J.	SGS	1:12,500	1990	partial	Douglas-Phantom Lakes
Rep. 91-4	Revision Bedrock Geology, Bootleg and Birch Lakes Area (part of NTS 63L-9, 63K-12 and -13)	Thomas, D.J.	SGS	1:12,500	1991	partial	Bootleg and Birch Lakes
Rep. 92-4	Revision Bedrock Geology, Creighton Lake-Flin Flon Lake Area (part of NTS 63K-12 and -13)	Thomas, D.J.	SGS	1:12,500	1992	partial	Creighton Lake-Flin Flon Lake
Rep. 93-4	Revision Bedrock Mapping, Hamell Lake Area (parts of 63K-13, 63L-16)	Thomas, D.J.	SGS	1:12,500	1993	partial	Hamell Lake
Thesis	Structural Map, Amisk Lake Area	Gendzwill, J.W.	SRC	1:126,720	1968	partial	Major shear zones.
Map 62B	Geology and Mineral Deposits of the Flin Flon Area, Saskatchewan	Byers, A.R., S.J.T Kirkland and W.J. Pearson	SGS	1:66,700	1965	partial	Detailed bedrock lithology and structural geology in northeast corner of the Creighton area. Including the eastern lobe of the Annabel Lake pluton and Ross Lake fault.
Map 62C	Geology and Mineral Deposits of the Flin Flon Area, Saskatchewan	Byers, A.R., S.J.T Kirkland and W.J. Pearson	SGS	1:66,700	1965	partial	Detailed bedrock lithology and structural geology to the south of the Township of Creighton. Including all of the Phantom-Boot Lake pluton and the eastern end of the Annabel Lake pluton.
Map 62E	Geology and Mineral Deposits of the Flin Flon Area,	Byers, A.R., S.J.T Kirkland and W.J.	SGS	1:66,700	1965	partial	Structural geology to the south of the Township of

Map Product	Title	Author	Source	Scale	Date	Coverage	Additional Comments
	Saskatchewan	Pearson					Creighton. Parts of Flin Flon and Schist Lake.
Map 14A	Geology and Mineral Deposits of the Flin Flon Area, Saskatchewan	Byers, A.R., and C.D.A. Dahlstrom	SGS	1:63,360	1954	partial	Bedrock lithology and structural geology of the western 2/3rd of the Annabel Lake pluton and western 1/2 of the Reynard Lake pluton
Map 14B	Geology and Mineral Deposits of the Flin Flon Area, Saskatchewan	Byers, A.R., and C.D.A. Dahlstrom	SGS	1:63,360	1954	partial	Bedrock lithology and structural geology, part of Reynard Lake pluton
Map 14C	Geology and Mineral Deposits of the Flin Flon Area, Saskatchewan	Byers, A.R., and C.D.A. Dahlstrom	SGS	1:63,360	1954	partial	Structural geology of the western 2/3rd of the Annabel Lake pluton and western 1/2 of the Reynard Lake pluton. Includes dip directions for the shear zones bounding the plutons.
Map 221 A	Quaternary Geology of the Precambrian Shield, Saskatchewan	Schreiner, B.T.	SGS	1:1,000,000	1984	full (SK)	Quaternary geology up to the Saskatchewan-Manitoba border
Misc. Rep 87-4	Quaternary Geology of the East Amisk Lake Area	Campbell, J.E.	SGS	1:20,000	1987	partial	Incorporated by Map 1919A
Map 1919A	Surficial Geology, Denare Beach-Schist Lake, Saskatchewan-Manitoba	Campbell, J.E. and P.J. Henderson	GSC	1:50,000	1997	partial	Quaternary geology of the southern 1/3 of the Creighton area.
Map 2010A	Surficial Geology, Annabel Lake-Flin Flon, Saskatchewan	P.J. Henderson	GSC	1:50,000	2002	partial	Quaternary geology of the northern 2/3 of the Creighton area up the the Saskatchewan-Manitoba border
Open File 5828	Surficial Geology, Flin Flon, Manitoba-Saskatchewan	Henderson, P.J. and I. McMartin	GSC	1:50,000	2008	partial	Quaternary geology of the Manitoba portion of the study area.

GSC = Geological Survey of Canada

SEM = Saskatchewan Energy and Mines (1998)

SER = Saskatchewan Energy and Resources (current, 2010 to 2012 maps and mineral deposits)

SGS = Saskatchewan Geological Survey
MBEM = Manitoba Energy and Mines

Table B-2: Summary of Geophysical Mapping Sources for the Creighton Area

Product	Source	Type	Line Spacing/ Sensor Height	Line Direct-ion	Coverage	Date	Additional Comments
Flin A VTEM	Hudbay	Helicopter magnetic/TD EM	200 m/ 40 m (EM), 60 m (mag)	65°	East-central	2007	Focused on greenstones.
Konuto VTEM	Hudbay	Helicopter magnetic/TD EM	200 m/ 40 m (EM), 63 m (mag)	95°	South-central	2008	Focused on greenstones.
Flin Flon-Sherridon A	GSC	Fixed wing magnetic/VLF	300 m/150 m	88°	Entire area	1986	Navigation and flightpath based on photomosaics (?), digitally recorded, levelled to a nationwide magnetic datum, poor quality VLF.
Flin Flon-Sherridon B	GSC	Fixed wing magnetic/VLF	300 m/150 m	88°	Southern margin of Creighton area	1986	Navigation and flightpath based on photomosaics (?), digitally recorded, levelled to a nationwide magnetic datum, poor quality VLF.
Flin Flon (Queenair)	GSC	Fixed wing magnetic/VLF	300 m/150 m	178°	Eastern margin of Creighton area	1980	Navigation and flightpath based on photomosaics (?), digitally recorded, levelled to a nationwide magnetic datum, poor quality VLF.
Hanson Lake	GSC	Fixed wing magnetic/ radiometric/VLF	500 m/120 m	90°	Entire screening area	1993	Digitally recorded, used for radiometric and VLF data only.
GSC Gravity Coverage	GSC	Ground gravity measurements	5-15 km (1 km along Hwy 106)/ surface		Entire Creighton area	1950-93	Bouguer gravity field, first vertical derivative, horizontal gradient and the isostatic residual gravity field were extracted from the GSC gravity compilation. Station locations were extracted from the point data.
GSC Radiometric Coverage	GSC	Fixed wing radiometric	5000m/120 m		Southern margin of Creighton area	1978	Potassium, equivalent uranium, equivalent thorium, natural air absorbed dose rate, and ratios of eU/K, eTh/K and eU/eTh were extracted from the GSC's nationwide radiometric compilation.
Lithoprobe THOT Line 9	GSC	Lithoprobe surveys	50m geophone spacing, 100 m vibroseis source interval		20 km along Hwy 106	1991-1992	Shallow subsurface poorly resolved

Table B-3: Summary of Geoscientific Databases for the Creighton Area

Database	Description	Scale (Regional/Local)	Used? (Yes/No)
Geological Atlas of Saskatchewan	GIS maps and data for download. Includes all online geoscience data for Saskatchewan such as: surficial geology, bedrock geology, mine locations, mineral deposits index, crown dispositions, reserves, land claims, mineral assessment file maps, drill holes, EM conductors, kimberlite occurrences, lithogeochemistry, LITHOPROBE lines, aeromagnetic surveys, topographical base maps, dykes, faults. Surficial and bedrock geology is available at a scale of 1:250,000 and dyke and fault information is available at a scale of 1:1,000,000.	Regional and Local	Yes
SMAD, (MARS)	Saskatchewan Mineral Assessment Database (SMAD), after December 12, 2012 to be compiled in the Mineral Administration Registry Saskatchewan (MARS): contains active claims, alienations and dispositions. Data includes: links to available geological information. (http://www.er.gov.sk.ca/smad)	Regional	Yes
Drill Holes	SGS Diamond Drill Hole Database: contains information on surface and underground drilling done as outlined by assessment files. Data includes: company name, company hole number, township and a link to available drill hole records and/or reports.	Regional and Local	Yes
Earthquakes Canada	Geological Survey of Canada Earthquake Search (On-line Bulletin): http://www.earthquakescanada.nrcan.gc.ca/index-eng.php	Regional	Yes
Geoscience Publications	SGS Geoscience Publications Database. Includes: geophysical index maps, annual reports, base maps, cross-sections, economic information.	Regional and Local	Yes
Summary of Investigations	SGS Summary of Investigations Database. Consists of a summary of SGS field work from 1972 to the present.	Regional and Local	Yes
CDED	Geobase (http://www.geobase.ca) Canadian digital elevation data.	Regional	Yes
SPOT	Geobase (http://www.geobase.ca) Orthoimage.	Regional	Yes
Shuttle Radar Topography Mission (SRTM)	Consultative Group on International Agricultural Research – Consortium for Spatial Information	Regional and Local	Yes
SWA (Water Wells)	Saskatchewan Watershed Authority (SWA) Database containing water well records throughout Saskatchewan (https://gis.wsask.ca)	Regional	Yes

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